available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

Earth observations for estimating greenhouse gas emissions from deforestation in developing countries

Ruth DeFries[a,*], Frédéric Achard[b], Sandra Brown[c], Martin Herold[d], Daniel Murdiyarso[e], Bernhard Schlamadinger[f], Carlos de Souza Jr.[g]

[a] Department of Geography and Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20742, USA
[b] Institute for Environment and Sustainability Joint Research Centre of the European Commission 21020 Ispra, VA, Italy
[c] Winrock International, Ecosystem Services Unit 1621 N. Kent Street, Suite 1200, Arlington, VA 22207, USA
[d] Department of Geography, Friedrich Schiller University Jena, Loebdergraben 32, 07743 Jena, Germany
[e] Center for International Forestry Research, P.O. Box 6596, JKPWB, Jakarta 10065, Indonesia
[f] Joanneum Research, Elisabethstrasse 5, 8010 Graz, Austria
[g] Instituto Homem e Meio Ambiente da Amazônia, Imazon, Caixa Postal 5101, Belém, PA 66613-397, Brazil

ARTICLE INFO

Published on line 2 April 2007

Keywords:
Carbon emissions
Greenhouse gases
Climate change
Deforestation
Tropical forests

ABSTRACT

In response to the United Nations Framework Convention on Climate Change (UNFCCC) process investigating the technical issues surrounding the ability to reduce greenhouse gas (GHG) emissions from deforestation in developing countries, this paper reviews technical capabilities for monitoring deforestation and estimating emissions. Implementation of policies to reduce emissions from deforestation require effective deforestation monitoring systems that are reproducible, provide consistent results, meet standards for mapping accuracy, and can be implemented at the national level. Remotely sensed data supported by ground observations are key to effective monitoring. Capacity in developing countries for deforestation monitoring is well-advanced in a few countries and is a feasible goal in most others. Data sources exist to determine base periods in the 1990s as historical reference points. Forest degradation (e.g. from high impact logging and fragmentation) also contribute to greenhouse gas emissions but it is more technically challenging to measure than deforestation. Data on carbon stocks, which are needed to estimate emissions, cannot currently be observed directly over large areas with remote sensing. Guidelines for carbon accounting from deforestation exist and are available in approved Intergovernmental Panel on Climate Change (IPCC) reports and can be applied at national scales in the absence of forest inventory or other data. Key constraints for implementing programs to monitor greenhouse gas emissions from deforestation are international commitment of resources to increase capacity, coordination of observations to ensure pan-tropical coverage, access to free or low-cost data, and standard and consensual protocols for data interpretation and analysis.

1. Introduction

Official international discussions were initiated at the United Nations Framework Convention on Climate Change (UNFCCC) 11th Conference of Parties (COP) in December 2005 on issues relating to reducing emissions from deforestation in developing countries (UNFCCC, 2005). No such policies are currently in place during the first commitment period of the Kyoto

* Corresponding author.
E-mail address: rdefries@mail.umd.edu (R. DeFries).

1462-9011/$ – see front matter
doi:10.1016/j.envsci.2007.01.010

Protocol for countries without commitments, i.e. presently non-annex I countries. This paper contributes to these policy discussions by summarizing the technical capabilities and key constraints for estimating emissions from deforestation in developing countries.

Implementation of policies to reduce emissions from deforestation depends on accurate and precise estimates of emissions averted at the national scale (Santilli et al., 2005). Several components must be estimated: (1) loss of forest cover at the national level, (2) initial carbon stocks for the base period and their change caused by deforestation and degradation, and (3) emissions averted from a defined ‘‘baseline’’ or base period.

Remote sensing combined with ground measurements plays a key role in determining loss of forest cover. Technical capabilities have advanced since the early 1990s and operational forest monitoring systems at the national level are now a feasible goal for most developing countries (Mollicone et al., 2003; DeFries et al., 2005). Progress is also occurring in the development of new technologies and approaches to remotely sense forest carbon stocks using airborne sensors (e.g. Drake et al., 2003; Brown et al., 2005). Although the latter are currently too costly to cover extensive areas, the methods could be used to extrapolate carbon stock estimates over larger regions.

Multiple land use practices in forests lead to loss of carbon stocks and emissions of carbon dioxide and, if the biomass is burned during the clearing process, additional non-CO_2 gases are emitted (Penman et al., 2003a). Deforestation, defined as conversion from forest land to non-forest land (considering the UNFCCC definitions of forest) is most easily monitored and causes a relatively large loss of carbon stock per deforested area (Fig. 1). Forest degradation practices such as unsustainable timber production, overharvesting of fuel wood, and fires at the edge of forest fragments are less easily observed than deforestation but can contribute substantially to emissions. Forest degradation can also be a precursor to deforestation. On the other hand, some land use practices in forests, such as managed logging and shifting cultivation, result in a shifting mosaic of cleared areas without long-term net emissions unless the land use expands into previously intact forest areas or the shifting cultivation cycle is shortened. These multiple changes in land use and forest area need to be monitored at the national level.

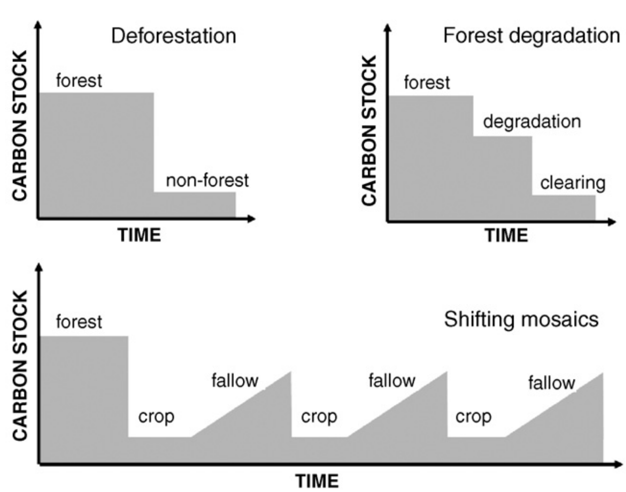

Fig. 1 – Changes in carbon stocks from different forest land use practices: deforestation, forest degradation, and shifting mosaics.

This paper was prepared as an outcome of a workshop organized through the ‘‘Global Observations of Forest Cover and Land Dynamics’’ (GOFC/GOLD, Townshend and Brady, 2006), a technical panel of the Global Terrestrial Observing System of the United Nations (GTOS), held in March 2006 (Herold et al., 2006). The objective was to assess technical capabilities for estimating emissions from deforestation in developing countries as input to ongoing policy discussions. We consider a range of issues for monitoring deforestation and forest degradation, evaluating changes in carbon stock, and estimating averted emissions. In addition, the paper raises key issues that need to be addressed in further development of more detailed guidelines and protocols.

2. Monitoring deforested area

Monitoring to support policies for reducing deforestation requires the capability to measure changes in forest area throughout all forests within a country's boundaries. Nationwide monitoring is needed to avoid displacement or leakage within a country where reduced deforestation could occur in one portion of the country but increase in another. Fundamental requirements of monitoring systems are that they measure changes throughout all forested area[1] within the country, use consistent methodologies at repeated intervals to obtain accurate results, and verify results with ground-based or very high resolution observations.

The only practicable approach for monitoring deforestation at a national level is through interpretation of remotely sensed data supported by ground-based observations. Remote sensing includes data acquired by sensors on board aircraft and space-based platforms. Since the early 1990s, changes in forested area have been monitored from space with confidence. Some countries, e.g. Brazil (INPE, 2005) and India (Forest Survey of India, 2004), have well-established operational systems in place for over a decade. Some countries are developing these capabilities and others have successfully monitored forests with aerial photographs that do not require sophisticated data analysis or computer resources. A variety of methods – applicable to varying national circumstances regarding forest characteristics, cost constraints, and scientific capabilities – are available and adequate for monitoring deforested area and verifying the accuracy.

[1] For this discussion we use the definition of forest adopted by COP6 for implementation of article 3: ‘‘Forest is a minimum area of land of 0.05–1.0 ha with tree crown cover (or equivalent stocking level) of more than 10–30% with trees with the potential to reach a minimum height of 2–5 m at maturity in situ. A forest may consist either of closed forest formations where trees of various stories, and undergrowth cover a high proportion of the ground or open forest.’’ (UNFCCC, 2001) COP6 further noted that parties recognize that there should be certain flexibility in applying the values in order to reflect national circumstances.

2.1. Technical methods for deforestation monitoring

2.1.1. What methods are appropriate for deforestation monitoring at national scales?

There are multiple methods that are appropriate and reliable for monitoring deforestation.[2] These methods include: (1) visual interpretation of aerial photos or satellite imagery that is labor-intensive but does not require high-level training in computer image processing or extensive computational resources (Skole and Tucker, 1993), (2) wall-to-wall mapping (i.e. country-wide) over the entire extent of a designated forest area using digital analyses of satellite imagery, e.g. (INPE, 2005), and (3) hot-spot analysis (i.e. locations of rapid change) using expert opinion or coarse resolution satellite data to identify locations for detailed digital analysis with high resolution satellite images, e.g. (Achard et al., 1998, 2002).

The appropriateness of the method depends on the following factors.

Costs of data and technical capabilities: Where technical capabilities and cost constraints do not enable digital analysis, visual interpretation of aerial photographs or satellite images is an appropriate monitoring method. The need for reproducible and verifiable results can be met through multiple interpreters and well-designed procedures. For countries with sophisticated data acquisition and analysis, more automated analysis with computer algorithms reduces the time required for monitoring and strengthens the efficiency of the monitoring system in the long term.

Clearing size and patterns of deforestation: Clearings for large-scale mechanized agriculture are detectable with medium resolution data (hundreds of meters spatial resolution) based on digital analysis. Small agricultural clearings or clearings for settlements require higher resolution data (tens of meters) to accurately detect clearings of 0.5–1 ha. Smaller clearings and more heterogeneous landscapes require data with higher spatial resolution (5–15 m) and greater involvement of an interpreter for visual analysis and more complex computer algorithms that detect less pronounced differences in spectral reflectances.

Seasonality of forest: For seasonal tropical forest, the appropriate method must ensure that annual climatic variations are not leading to false identification of variations in canopy cover as deforestation. Observations over multiple times a year might be required. Deforestation in moist evergreen forests could be observed at any time of year and is more dependent on the availability of cloud-free imagery. The use of Radar satellite observations has not been used operationally but can help where appropriate temporal coverage is not available due to cloud cover.

Overall size of country and forest area: It has been demonstrated that estimates of deforestation can be provided through remote sensing based methods at global or continental levels (FAO, 2001; Achard et al., 2002; DeFries et al., 2002) or at national and sub-national levels for very large counties such as Brazil and India (Forest Survey of India, 2004; INPE, 2005). These methods could be easily adapted to cope with smaller country sizes (see also next point). For countries with large forested areas, visual analysis may not be practical and instead more automated approaches are necessary. For countries with smaller forested areas, it may be possible to effectively monitor through visual interpretation and more ground-based data collection.

In sum, no single method is appropriate for all national circumstances. Many methods can produce adequate results. Guidelines and protocols can be developed based on forest types, deforestation patterns, and resources available. The key requirements to ensure consistency of results across countries lies in verification that the methods are reproducible, provide consistent results when applied at different times, and meet standards for assessment of mapping accuracy.

2.1.2. Are methods available to alleviate the practical limitations in monitoring the entire forested area within a country?

Monitoring to support policies for reducing emissions from deforestation can only ensure that leakage does not occur if the full forested area within a country is represented. Analysis that covers the full spatial extent of the forested areas, termed ''wall-to-wall'' coverage, ensures against leakage within the country. Wall-to-wall analysis is ideal, but may not be practical due to large areas and constraints on resources for analysis. Several approaches have been successfully applied to sample within the total forest area to reduce costs and time for analysis.

Identification of areas of rapid deforestation through expert knowledge: Subsampling based on knowledge of deforestation fronts identifies areas to be analyzed with high resolution data (Achard et al., 2002). Experts with detailed knowledge of the country are needed to ensure that areas of major change are not overlooked. The Brazilian PRODES monitoring system (INPE, 2005) identifies ''critical areas'' based on the previous year's monitoring to prioritize analysis for the following year. Other databases such as transportation networks, population changes in rural areas, and locations of government resettlement programs can be used to help identify areas where pressure to deforest is likely to be high and where more detailed analysis needs to be performed. Such an approach is appropriate where experts with detailed knowledge of a country's forest cover are available and computational resources to carry out digital analyses are not available.

Hierarchical, nested approach with medium resolution data: Analysis of medium and coarse resolution data can identify locations of rapid and large deforestation, though such data are generally unsuitable to determine rates of deforestation based on changes in forest area (DeFries et al., 2002; Morton et al., 2005). A nested approach in which medium resolution data is analyzed to identify locations requiring further analysis with more costly high resolution data can reduce the need to analyze the entire forested area within a country (Fig. 2). The appropriateness of this approach depends on whether computational resources are available for analysis of medium resolution data.

[2] We use the IPCC definition of deforestation adopted by COP6: ''Deforestation is the direct human-induced conversion of forested land to non-forested land''. Under current UNFCCC definitions a forest can contain anything from 10 to 100% tree cover; it is only when cover falls below the minimum crown cover as designated by a given country that land is classified as non-forest. To date, most countries are defining forests with a minimum crown cover of 30%.

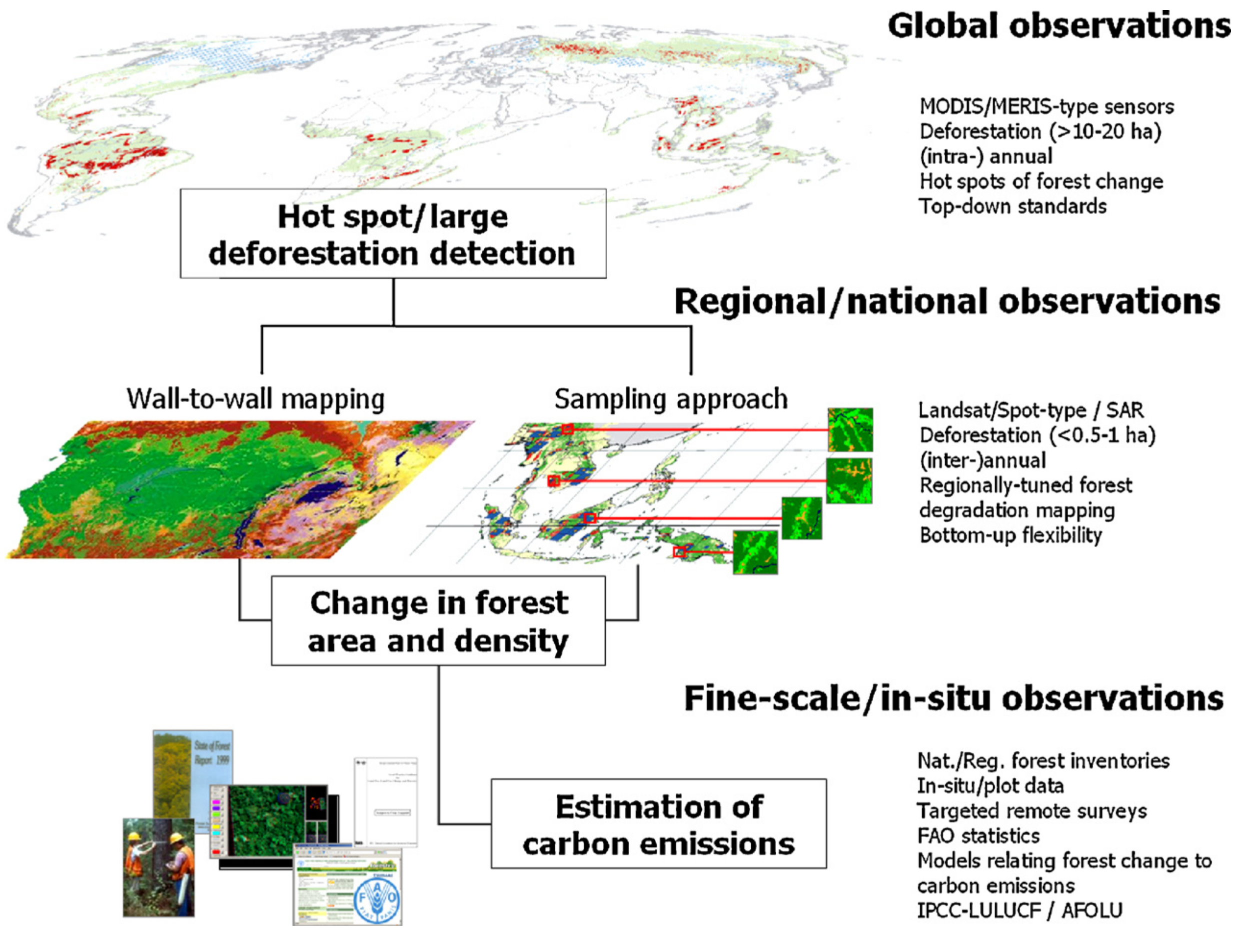

Fig. 2 – Conceptual observation framework for monitoring forest changes and related carbon emissions integrating information from different data sources.

Statistical sampling designed to capture deforestation patterns: A sampling procedure that adequately represents deforestation events can capture deforestation trends (Strahler et al., 2006). Because deforestation events are not randomly distributed in space (Tucker and Townshend, 2000), particular attention is needed to ensure that the statistical design is adequately sampling within areas of potential deforestation (e.g. in proximity to roads), e.g. through a high density systematic sampling (Mayaux et al., 2005).

2.1.3. *What approaches account for existing shifting cultivation and other temporary clearings to avoid false identification of new deforestation?*

Shifting cultivation results in a mosaic of clearings and fallow that change over time. Such clearings, if identified as new deforestation in a monitoring system, would falsely inflate deforestation rates in the long term. A longer time series of repeated observations, combined with expert knowledge of the land use patterns in the country, are needed to distinguish new deforestation from clearing dynamics associated with existing practices. A key requirement for a monitoring system is initial designation of the forest area under which future clearings are considered new deforestation. Guidelines and protocols for monitoring can be developed to identify and exclude these areas from the analysis using a baseline with annual updates over at least a 5 year time period or ancillary data to designate intact forests. However, the monitoring system needs to be able to identify intensification of the shifting cultivation cycle where the fallow period is shortened (Penman et al., 2003a).

2.2. *National capacity for deforestation monitoring*

Brazil and India are two examples of developing countries with operational systems in place to monitor forest cover. These countries have receiving stations to acquire remote sensing satellite imagery (Landsat or Terra data) and/or national satellites (IRS or CBERS, respectively). Other countries have carried out forest assessments using remote sensing products, e.g. Peru, Bolivia, and Indonesia.

A key constraint on other countries in developing similar capabilities is access to data at a reasonable cost and the technical infrastructure (hardware, software, and internet access). Technical capabilities vary, but many countries are developing sufficient expertise to enable monitoring systems. Regional partnerships for acquiring and developing appropriate methods can help address some of the needs.

The principal monitoring requirement to support policies for reducing deforestation falls at the national level. Analyses coordinated at an international level that span the tropics, using coarser resolution data that would be used at the national level, can supplement these efforts by providing consistency and ensuring that major areas of deforestation are detected. Products such as those derived from medium resolution data can be used for such detection (Hansen et al., 2003, 2005).

2.3. Accuracy and verification of deforestation monitoring

Reporting accuracy and verification of results are essential components of a monitoring system. Accuracies of 80–95% are achievable for monitoring with high resolution imagery to discriminate between forest and non-forest. Accuracies can be assessed through in situ observations or analysis of very high resolution aircraft or satellite data. In both cases, a statistically valid sampling procedure (Strahler et al., 2006) can be used to determine accuracy. Accuracy assessment is feasibly conducted on a forest/non-forest map at a single time. While it is difficult to verify change from one time to another on the ground unless the same location is visited at two different time periods, a time series of very high resolution data can be used to assess accuracy of identifying new deforestation.

Because different methods are applicable in different countries, verification of the monitoring by a third party would include review of the appropriateness of the method for the particular forest conditions and deforestation patterns, consistency in the application of the method, adherence to data management standards, and methods for assessing accuracy of the result.

2.4. Data availability and access

High resolution data with nearly complete global coverage are available at low or no cost for early 1990s and early 2000s, in particular Landsat satellite data from the U.S. National Aeronautics and Space Administration (NASA) (https://zulu.ssc.nasa.gov/mrsid) or from University of Maryland's Global Land Cover Facility (http://glcfapp.umiacs.umd.edu/) (Mollicone et al., 2003). These data serve a key role in establishing historical deforestation rates, though in some parts of the tropics (e.g. Central Africa) persistent cloudiness is a major limitation to using these data. Medium resolution data have been available for no cost since 2000.

Despite these data sources, the key constraints for monitoring deforestation are lack of adequate coverage of tropical forests in the current decade, coordination of observations to ensure coverage of all tropical forests in the future, and access to data. Costs of high resolution data are currently a limitation for many countries in establishing monitoring systems. Ensured data access through international coordination is needed for countries to implement monitoring systems to support policies for reducing deforestation.

Optical high resolution data have been the primary tool for deforestation monitoring (Table 1). Other types of sensors, e.g. Radar and Lidar, are potentially useful and appropriate. Radar, in particular, alleviates the substantial limitations of optical data in persistently cloudy parts of the tropics and has been demonstrated to be useful for mapping tropical forests (DeGrandi et al., 2000; Rosenqvist et al., 2000; Siegert et al., 2001). Lidar data have not been available with global coverage because there is no Lidar sensor currently onboard a satellite. Thus, their application to deforestation monitoring has been limited. Lidar observations provide information on the vertical structure of the forest by measuring returns from the signals emitted from the sensor. In the timeframe of the next commitment period, the utility of Radar and Lidar may be enhanced depending on data acquisition, access and scientific developments.

3. Monitoring forest degradation

There are many definitions of forest degradation relating to canopy cover, ecological function, carbon stocks, and other attributes of forests (Penman et al., 2003b). Of these definitions, degradation defined by changes in canopy cover is most readily observable with remote sensing.

Forest degradation (considered here as carbon stock degradation) results from human activities that partially remove forest carbon stocks without regeneration in a reasonable time frame (on the order of a decade). That is, the rate of biomass carbon removal is greater than the rate of regrowth resulting in a gradual decline in overall biomass carbon stocks. Though carbon emissions may not be as large per unit area as the complete removal of forest through deforestation, forest degradation occurs over large areas and can contribute significantly to overall emissions from forest loss (Asner et al., 2005). With the lower limit of the UNFCC definition of a forest set at between 10 and 30% tree crown

Table 1 – Utility of optical sensors at multiple resolutions for deforestation monitoring[a]

Sensor resolution	Examples of current sensors	Utility for monitoring	Cost
Very high (<5 m)	IKONOS, QuickBird	Validation over small areas of results from coarser resolution analysis	Very high
High (10–60 m)	Landsat, SPOT HRV, AWiFs LISS III, CBERS	Primary tool to identify deforestation	Low/medium (historical) to medium/high (recent)
Medium (250–1000 m)	MODIS, SPOT Vegetation	Consistent global annual monitoring to identify large clearings (>10–20 ha) and locate "hotspots" for further analysis with high resolution	Low or free

[a] Data from optical sensors have been widely used for deforestation monitoring. Data from Lidar and Radar (ERS1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS PALSAR) have been demonstrated to be useful in project studies, however, so far are not widely used operationally for tropical deforestation monitoring.

cover, substantial loss of tree cover can occur through degradation while maintaining designation as "forest." A location would not be considered non-forest until forest cover fell below the canopy cover threshold. Moreover, forest degradation may enhance susceptibility to fire and may result in substantial loss of below-ground carbon in peat areas (Page et al., 2002). Degradation is often a precursor to deforestation as areas that are logged often increase access and result in clearing.

Monitoring degradation is more technically challenging than monitoring deforestation. Differences in reflectances between forest and degraded forest are more subtle than in the case of deforestation, and degradation patches are generally small compared with clearings. For these reasons, methods for monitoring degradation are not as well established as those for monitoring deforestation.

3.1. *What processes lead to forest degradation?*

Degradation results directly from human uses of forest as well as from the indirect results of human activity. Managed and unplanned selective logging leaves forest gaps, although reduced impact logging greatly minimizes these effects. Woody removal for woodfuels, particularly charcoal, can result in degradation. Edges of forest fragments exposed through deforestation and logging leaves the forest susceptible to degradation through understory fires. All of these processes promote loss of forest cover and carbon stocks, and can be the first step towards total forest loss through deforestation.

3.2. *Are methods available to monitor forest degradation?*

Methods to identify forest degradation use high resolution data. Radar data can potentially detect degradation though this application needs further development (Saatchi et al., 2007). Visual interpretation of high resolution data can detect canopy damage in some cases. Spatial patterns of log landings (patios for logging trucks and river landings) and identification of other infrastructure (e.g. roads and rivers used for transportation) has been a successful approach for identifying degradation (Asner et al., 2005). Likewise deforestation and forest degradation can be mapped with different techniques, varying from visual interpretation to advanced image processing algorithms. For example Asner et al. (2005) developed automated algorithms to identify logging activity with Landsat data. Detection of active fires with thermal data can also indicate presence of subsequent burn scars (Roy et al., 2005). An effective solution for identifying degraded forests from proximity to infrastructure has recently been proposed to take advantage of existing observational approaches given the current limitation in knowledge on the spatial distribution of biomass (Mollicone et al., 2007).

Results in the research domain have demonstrated capabilities for monitoring degradation and show promise for implementation in operational monitoring systems (e.g. Souza and Barreto, 2000; Matricardi et al., 2001; Asner et al., 2005; Souza and Roberts, 2005; Mollicone et al., 2007). Annual monitoring may be needed to capture the dynamics associated with degradation. As is the case with deforestation monitoring, the key constraint is data continuity of high resolution imagery.

4. Monitoring changes in carbon stocks

Carbon emissions from deforestation and degradation depend not only on the area of forest change but also on the associated biomass loss (Brown, 2002). The IPCC (Penman et al., 2003a) compiled methods and good practice guidance for determining changes in carbon stocks in association with national inventories of greenhouse gas (GHG) emissions (Chapter 3 in Penman et al., 2003a) for changes in Land Use, Land Use Change, and Forestry (LULUCF) and with carbon sequestration projects (Chapter 4 in Penman et al., 2003a) in the first commitment period. With the updated version of the IPCC guidelines for conducting national GHG emissions from the LULUCF sector (Penman et al., 2003a; IPCC, 2006), methods are available for estimating GHG emissions from deforestation at the national and project scales.

There are currently no standard practices or capabilities for measuring forest biomass through remote sensing at regional and national scales. Pilot studies using airborne Lidar data and very high resolution optical data have been used in a sampling approach to estimate biomass of different forest types (Drake et al., 2003; Brown et al., 2005). Very high resolution digital optical data can be used to identify individual trees in the forest canopy, and the Earth observation community is developing new tools for automatically delineating tree crown areas in complex tropical forests. In addition, new field data for developing allometric models for converting data from remotely sensed observations to estimates of biomass stocks will need to be acquired and relationships between remotely sensed metrics of tree canopies and biomass will need to be established. These methods are currently costly, though more cost effective than traditional large field-based forest inventories, but not sufficiently developed for widespread operational use. Experimental data from Radar observations reveal potential for biomass mapping.

Based on current capabilities, emissions from deforestation can be estimated from various sources on carbon stocks in above-ground biomass in trees (Table 2) and from other forest pools using models and default data in the IPCC Good Practice Guidelines report (Penman et al., 2003a). Forest inventories can provide biomass values according to forest type and use, e.g. mature forest, intensely logged, selectively logged, fallow, etc.; however, many developing countries do not have sufficient forest inventories. The FAO data, though low confidence, provide default values for carbon stocks often stratified by main ecological zones (FAO, 2006). Compilation of data from ecological or other permanent sample plots may provide estimates of carbon stocks for different forest types but are subject to the design of particular scientific studies.

A variety of methods and models have been developed using a combination of remote sensing observations, spatial databases of key factors that are related to forest biomass (e.g. precipitation, temperature, elevation, growing season length, and the like), and field-based forest inventories to derive maps of estimated forest biomass at large regional scales (e.g. Africa (Gaston et al., 1998); Asia (Brown et al., 1993), and

Table 2 – Products for estimating change in carbon stocks from deforestation

Product	Scale	Weaknesses	Degree of uncertainty	Cost (1–3; low to high)
(1) Traditional forest inventories	National or regional	Many existing inventories are out of date and very few more recent ones exist, often focused on forests of commercial value	Depends on age of inventory and if updated—low to medium confidence based on date of inventory	3
(2) Forest inventory with additional data on canopy cover/type and related to high resolution RS data; update biomass stocks with new high resolution RS data interpreted for change in canopy density (models relate canopy density to biomass)	National to regional	Often focused on forests with commercial value	High to medium confidence	Costly initially to get field inventory (3), reducing costs with updates (2-1)
(3) FAO data	National and subregion	Default data	Low confidence	1
(4) Compilation of ''ecological'' plots	Selected locations	Not sampled from population of interest	Low confidence	1

Brazilian Amazon (Houghton and Hackler, 2001; Saatchi et al., 2007)).

Guidelines and appropriate practices for using these presently available sources of information on carbon stocks are available in the IPCC Good Practice Guidelines report (Penman et al., 2003a). Application of remote sensing data to improve biomass estimates is potentially useful but depends on international commitments to provide resources to deploy new sensors, acquire high resolution airborne imagery, data access, and new field-based data for converting metrics from the imagery to biomass estimates.

5. Estimating averted GHG emissions from reduced deforestation at the national level

Combining measurements of changes in forest area with estimates of changes in carbon stocks enables estimation of emissions from deforestation over large regions (DeFries et al., 2002; Achard et al., 2004; Houghton, 2005; Ramankutty et al., 2006). The IPCC has established methods for estimating carbon emissions as well as non-CO_2 GHGs at the national and project scales (see above, Penman et al., 2003a; IPCC, 2006).

Guidelines and protocols need to be established to determine historical estimates/measurements and develop agreed baselines or base intervals (e.g. using model interpolations of scenarios such as business as usual or expected deforestation trends). Unlike with fossil fuel emissions, it is problematic to extrapolate GHG emissions from a given year because inter-annual variability is high. Rather, the base period should encompass at least 5 or 10 years in the recent past. The time period for determining the historical quantities and emissions trajectory needs to recognize the large inter-annual variability in deforestation rates and be based on multiple rather than a single year's deforestation results.

Projections of future deforestation trajectories are challenging due to the complexity of factors that drive deforestation, including roads and other infrastructure, international economic demands, and national circumstances (Geist and Lambin, 2002). These complexities underscore the difficulties in using land use modeling to determine future deforestation rates based on current capabilities. Approaches based on historical estimates and/or future targets can be developed as reference points to determine averted emissions. Historical statistical data collected at national levels may be verified and used to construct deforestation rates for the base year.

6. Conclusions

Key points regarding the technical feasibility to implement policies to reduce greenhouse gas emissions from deforestation in developing countries include:

- Quantifying GHG emissions averted from reduced deforestation requires measurements of changes in forest cover and associated changes in carbon stocks. Analysis of remotely sensed data from aircraft and satellite is the only practical approach to measure changes in forest area at national and international scales. Since the early 1990s, changes in forest area can be measured from space with confidence.
- Various methods are available and appropriate to analyze satellite data for measuring changes in forest cover. These methods range from visual photointerpretation to sophisticated digital analysis, and from wall-to-wall mapping to hot-spot analysis and statistical sampling. A variety of methods can be applied depending on national capabilities, deforestation patterns, and characteristics of forests. Quantifying the accuracy of the result and ensuring that consistent methods are applied at different time intervals are more critical than applying standard methods across all countries.
- Removal of forest cover through deforestation is the primary contributor to GHG emissions from changes in forest area. Forest degradation from high impact logging, shifting cultivation, wildfires, and forest fragmentation also contributes to GHG emissions. Measuring forest degradation

from satellites is more technically challenging than measuring deforestation but methods are becoming available.

- Estimates of carbon stocks of forests undergoing deforestation and the subsequent carbon dynamic are uncertain for many developing countries, but default data and guidelines for carbon accounting already exist in the IPCC Good Practice Guidance Report (Penman et al., 2003a) and the upcoming revised IPCC methods for national inventories of GHGs. New technologies and approaches are developing for monitoring changes in carbon stocks using a combination of satellite and airborne imagery that potentially reduce uncertainties in accounting for changes in GHG emissions from deforestation. International coordination is needed to further test and implement these technologies.
- Several developing countries have operational systems in place for monitoring deforestation at national scales, notably India and Brazil. Other countries, e.g. Peru, Bolivia, Indonesia and others have gained experiences in project-based studies and demonstrated capabilities to develop national systems.
- Key constraints in implementing national systems for monitoring changes in forest cover are cost and access to high resolution data. International coordination is needed to ensure repeated coverage of the world's forests and access to quality data at a reasonable cost. Reliable and up-to-date data sources on the national distribution of carbon stocks in forests and changes in stocks under local practices of clearing and degradation is also needed. There is limited capacity in many developing countries to acquire and analyze the data needed for a national system of GHG reporting for deforestation and degradation.
- Data sources exist to determine base periods in 1990s as historical reference points. Averted emissions can be estimated from short term (about 5–10 years) extrapolations of current trends and historical deforestation rates and from existing estimates of forest carbon stocks.
- The following actions over the short term would improve capabilities for monitoring and measurement systems of reduced greenhouse gas emissions from deforestation.
  - Dedicated pilot projects and experiences establishing a deforestation monitoring system at sub-national to national scale;
  - compilation of existing satellite imagery of sufficient quality (cloud free for example) for developing accurate base periods for major countries in all three tropical regions;
  - assessment of national capacities and capabilities for analyzing data on land cover change and carbon stocks and efforts to improve them;
  - support for developing countries to build historical deforestation databases;
  - continuation of building databases from ground-based forest inventories to estimate changes in carbon stocks from observed changes in forest area and density.

Acknowledgements

The review presented in this paper is based on the outcome of an international workshop organized by the Global Observations of Forest Cover and Land Dynamics (GOFC/GOLD) held in March 2006. Representatives of the Earth observation community attended the workshop to consider technical capabilities for monitoring deforestation and estimating emissions to contribute to the UNFCCC policy discussions. A report based on the workshop was presented to the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) in August 2006 ((DeFries et al., 2006). The workshop report is published as a separate document (Herold et al., 2006). The authors thank all participants of the GOFC-GOLD workshop and contributors for building consensus and developing this joint technical document. In addition, we acknowledge the sponsors.

References

Achard, F., Eva, H., Glinnin, A., Mayaux, P., Richards, T., Stibig, H.J., 1998. Identification of deforestation hot spot areas in the humid tropics. In: Synthesis of the Results of an Expert Consultation Meeting, EUR 18079 EN. Publications of the European Communities, Luxembourg, p. 100.

Achard, F., Eva, H., Stibig, H.J., Mayaux, P., Gallego, J., Richards, T., Malingreau, J.P., 2002. Determination of deforestation rates of the world's humid tropical forests. Science 297, 999–1002.

Achard, F., Eva, H.D., Mayaux, P., Stibig, H.-J., Belward, A., 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochem. Cycles 18 (GB2008), doi:10.1029/2003GB002142.

Asner, G.P., Knapp, D.E., Broadbent, E., Oliviera, P., Keller, M., Silva, J., 2005. Selective logging in the Brazilian Amazon. Science 310, 480–482.

Brown, S., 2002. Measuring carbon in forests: current status and future challenge. Environ. Pollut. 116, 363–372.

Brown, S., Iverson, L.R., Prasad, A., Liu, D., 1993. Geographic distribution of carbon in biomass and soils of tropical Asian forests. Geocarto Int. 8 (4), 45–59.

Brown, S., Pearson, T., Slaymaker, D., Ambagis, S., Moore, N., Novelo, D., Sabido, W., 2005. Creating a virtual tropical forest from three-dimensional aerial imagery: Application for estimating carbon stocks. Ecol. Appl. 15, 1083–1095.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B., de Souza, C.J., 2006. Reducing Greenhouse Gas Emissions from Deforestation in Developing Countries: Considerations for Monitoring and Measuring. Rome, Italy. Report of the Global Terrestrial Observing System (GTOS), Report No. 26, 23 pp.

DeFries, R., Asner, G.P., Achard, F., Justice, C.O., LaPorte, N., Price, K., Small, C., Towshend, J., 2005. In: Mountinho, P., Schwartzman, S. (Eds.), Monitoring Tropical Deforestation for Emerging Carbon Markets. Tropical Deforestation and Climate Change. IPAM and Environmental Defense, Belem, Brazil and Washington, DC, pp. 35–44.

DeFries, R., Houghton, R.A., Hansen, M., Field, C., Skole, D.L., Townshend, J., 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 90s. Proc. Natl. Acad. Sci. 99 (22), 14256–14261.

DeGrandi, G., Mayaux, P., Rauste, Y., Rosenqvist, A., Simard, M., Saatchi, S., 2000. The Global Rain Forest Mapping Project JERS-1 radar mosaic of tropical Africa: development and product characterization aspects. IEEE Trans. Geosci. Remote Sens. 38 (5), 2218–2233.

Drake, J.B., Knox, R.G., Dubayah, R.O., Clark, D.B., Condit, R., Blair, J.B., Hofton, M., 2003. Above ground biomass estimation in closed canopy neotropical forests using lidar remote sensing: factors affecting the generality of relationships. Global Ecol. Biogeogr. 12, 147–159.
FAO, 2001. Global Forest Resources Assessment 2000. United Nations Food and Agriculture Organization, Rome, 511 pp.
FAO, 2006. Global Forest Assessment 2005. FAO Forestry Paper 147. Food and Agriculture Organization, Rome, Italy.
Forest Survey of India, 2004. State of Forest Report 2003. Ministry of Environment and Forest, Dehra Dun, India.
Gaston, G., Brown, S., Lorenzini, M., Singh, K.D., 1998. State and change in carbon pools in the forests of tropical Africa. Global Change Biol. 4, 97–114.
Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying forces of tropical deforestation. BioScience 52 (2), 143–150.
Hansen, M.C., DeFries, R.S., Townshend, J., Carroll, M., Dimiceli, C., Sohlberg, R., 2003. Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS Vegetation Continuous Fields algorithm. Earth Interact. 7 (10), 1–15.
Hansen, M.C., Townshend, J., DeFries, R., Carroll, M., 2005. Estimation of tree cover using MODIS data at global, continental and regional/local scales. Int. J. Remote Sensing 26 (19), 4359–4380.
Herold, M., DeFries, R., Achard, F., Skole, D., Townshend, J., 2006. Report of the workshop on monitoring tropical deforestation for compensated reductions. In: GOFC-GOLD Symposium on Forest and Land Cover Observations, Jena, Germany, 21–22 March 2006.
Houghton, R.A., 2005. Aboveground forest biomass and the global carbon balance. Global Change Biol. 11, 945–958.
Houghton, R.A., Hackler, J.L., 2001. Carbon Flux to the Atmosphere from Land Use Changes: 1850–1990. Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, 86 pp.
INPE, 2005. Monitoramento da Floresta Amazônica Brasileira por Satelite. Projeto PRODES: available on line at http://www.obt.inpe.br/prodes/index.html, Monitoring of the Brazilian Amazonian.
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, HS., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (eds.), Published: IGES, Japan.
Matricardi, E.A.T., Skole, D.L., Chomesntowski, M.A., Cochrane, M.A., 2001. Multi-Temporal Detection of Selective Logging in the Amazon Using Remote Sensing. Special Report BSRSI Research Advances. Tropical Forest Information Center, Michigan State University, p. 27.
Mayaux, P., Holmgren, P., Achard, F., Eva, H., Stibig, H.J., Branthomme, A., 2005. Tropical forest cover change in the 1990s and options for future monitoring. Philos. Trans. Roy. Soc. B 360, 373–384.
Mollicone, D., Achard, F., Eva, H., Belward, A., Federici, S., Lumicisi, A., Risso, V.C., Stibig, H.-J., Valentini, R., 2003. Land Use Change Monitoring in the Framework of the UNFCCC and its Kyoto Protocol. Report on Current Capabilities of Satellite Remote Sensing Technology. European Communities, Luxembourg, p. 48.
Mollicone, D., Achard, F., Federici, S., Eva, H.D., Grassi, G., Belward, A., Raes, F., Seufert, G., Matteucci, G., Schulze, E.-D., 2007. An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. Climatic Change, doi:10.1007/s10584-006-9231-2, in press.
Morton, D., DeFries, R., Shimabukuro, Y., Anderson, L., Espirito-Santo, F., Hansen, M., Carroll, M., 2005. Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data. Earth Interact. 9 (8), 1–22.
Page, S., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A., Limin, S., 2002. The amount of carbon released from peat and forest fires in Indonesia. Nature 420 (6911), 29–30.
Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., 2003a. Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC National Greenhouse Gas Inventories Programme and Institute for Global Environmental Strategies, Kanagawa, Japan. , available at:In: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.htm.
Penman, J., Gytarsky, T., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., 2003b. Definitions and Methodological Options to Inventory Emissions from Direct Human-Induced Degradation of Forests and Devegetation of Other Vegetation Types. The Institute for Global Environmental Strategies for the IPCC an The Intergovernmental Panel on Climate Change, Hayama, Kanagawa, p. 32.
Ramankutty, N., Gibbs, H., Achard, F., DeFries, R., Foley, J., Houghton, R.A., 2006. Challenges to estimating carbon emissions from tropical deforestation. Global Change Biol. 12, 1–16.
Rosenqvist, A., Taylor, V., Chapman, B., Shimada, M., Freeman, A., DeGrandi, G., Saatchi, S., Rauste, Y., 2000. The global rain forest mapping project—a review. Int. J. Remote Sensing 21 (6–7), 1375–1387.
Roy, D.P., Jin, Y., Lewis, P.E., Justice, C.O., 2005. Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time-series data. Remote Sensing Environ. 97, 137–162.
Saatchi, S., Houghton, R.A., Alvala, R.C., Soares, J., Yu, Y., 2007. Distribution of aboveground live biomass in the Amazon Basin. Global Change Biol. 13, 816–837.
Santilli, M., Moutinho, P., Schwartzman, S., Nepstad, D.C., Curran, L.M., Nobre, C.A., 2005. Tropical deforestation and the Kyoto Protocol: an editorial essay. Climatic Change 71, 267–276.
Siegert, F., Ruecker, G., Hinrichs, A., Hoffmann, A., 2001. Increased damage from fires in logged forests during droughts caused by El Nio. Nature 414, 437–440.
Skole, D., Tucker, C., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 260, 1905–1910.
Souza Jr., C.M., Barreto, P., 2000. An alternative approach for detecting and monitoring selectively logged forests in the Amazon. Int. J. Remote Sensing 21, 173–179.
Souza Jr., C.M., Roberts, D., 2005. Mapping forest degradation in the Amazon region with Ikonos images. Int. J. Remote Sensing 26 (3), 425–429.
Strahler, A.H., Boschetti, L., Foody, G.M., MFriedl, M., Hansen, M., Herold, M., Mayaux, P., Morisette, J., Stehman, S., Woodcock, C.E., 2006. Global Land Cover Validation: Recommendations for Evaluation and Accuracy Assessment of Global Land Cover Maps. European Communities, Luxembourg, p. 51.
Townshend, J., Brady, M., 2006. A Revised Strategy for GOFC-GOLD. GOFC-GOLD Report 24.
Tucker, C.J., Townshend, J.R.G., 2000. Strategies for tropical forest deforestation assessment using satellite data. Int. J. Remote Sensing 21 (6 and 7), 1461–1472.
UNFCCC, 2001. Definitions, Modalities, Rules and Guidelines Relating to LULUCF Activities under the Kyoto Protocol.
UNFCCC, 2005. Draft Conclusions for Agenda Item 6: Reducing Emissions From Deforestation in Developing Countries UNFCCC/COP-11 Draft Decision. Available at: http://unfccc.int/resource/docs/2005/cop11/eng/l02.pdf.

Ruth DeFries is professor at the University of Maryland, College Park with joint appointments in the Department of Geography and Earth System Science Interdisciplinary Center. Her research focuses on observing land use change with remote sensing tools and assessing the consequences for climate, biodiversity, and other ecosystem services. Previously, Dr. DeFries worked at the National Research Council with the Committee on Global Change and taught at the Indian Institute of Technology in Bombay. She is a fellow of the Aldo Leopold Leadership Program. She was elected to the U.S. National Academy of Sciences in 2006.

Frédéric Achard completed his PhD in tropical ecology and remote sensing from Toulouse University in 1989. He first worked at the Institute for the International Vegetation Map in Toulouse. In 1992 he became a research officer at the JRC where he started a research activity in the framework of the TREES project. His current research interests include development of Earth observation techniques for global and regional forest resources monitoring, and assessment of the implications of forest cover changes in the Tropics and boreal Eurasia on the global carbon budget.

Sandra Brown has a PhD in systems ecology from the Department of Environmental Engineering Sciences, University of Florida, a MS in engineering science from the University of South Florida, and a BS in chemistry from the University of Nottingham, England. She is senior scientist in the Ecosystems Services Unit of Winrock International since 1998. Previously, she was professor in the Department of Forestry at the University of Illinois in Champaign, Urbana. Dr. Brown has more than 25 years of experience in planning, developing, implementing, and managing government and private-sector-funded projects focusing on understanding the role of forests in the global carbon cycle and their present and potential future role in climate change and mitigation, resulting in more than 180 peer-reviewed publications.

Martin Herold holds a PhD from the Department of Geography, University of California, Santa Barbara, with a dissertation entitled: 'Remote Sensing and Spatial Metrics for Mapping and Modeling of Urban Structures and Growth Dynamics'. Since 2004, Dr. Herold is coordinating the ESA GOFC GOLD land cover project office at the Friedrich Schiller University Jena, Germany, where his interests are interest are in the harmonization and validation of global land cover datasets, and the development on implementation of large land cover monitoring system in the context of UNFCCC/RED-DC, the Group on Earth Observation (GEO), GLOBCOVER, Integrated Global Observations for Land (IGOL), and FAO's FRA 2010 remote sensing survey.

Daniel Murdiyarso received his first degree in forestry from Bogor Agricultural University (IPB), Indonesia. His PhD was obtained from the Department of Meteorology, University of Reading, UK. He is a professor at the Department of Geophysics and Meteorology, IPB. His research works and publications are related to land-use change and biogeochemical cycles, climate change mitigation and adaptation. Dr. Murdiyarso was a convening lead author of the IPCC Third Assessment Report and the IPCC Special Report on Land-use, Land-use Change and Forestry. In 2000, he served the Government of Indonesia as deputy minister of environment for 2 years. He is currently senior scientist at the Center for International Forestry Research (CIFOR).

Bernhard Schlamadinger is a senior scientist at Joanneum Research, Austria's second largest independent research organization. His main focus of work is in carbon balances of bioenergy and forestry, and in climate policy. He leads the EC-funded CarboInvent project dealing with carbon budget methods for European forests, and the International Energy Agency's collaborative network on "Greenhouse Gas Balances of Biomass and Bioenergy Systems". He coordinated chapters of the IPCC Special Report on LULUCF, and the IPCC Good Practice Guidance for LULUCF Inventories, and co-authored the first approved baseline and monitoring for CDM reforestation projects.

Carlos Souza Jr. completed BSc in Geology, in Brazil, at the Pará State Federal University, a masters degree in Soil Science at Penn State University, and a PhD in Geography at University of California in Santa Barbara. Since 1992, he has been working at Imazon, an NGO dedicated to promote sustainable development in the Amazon through research, dissemination and training. His research in Brazil has focused on GIS analysis to identify priority areas for conservation in the Amazon, and applications of remote sensing to map land cover and land use changes, and forest degradation caused by selective logging, fires and fragmentation.