Pan-tropical monitoring of deforestation

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Abstract
This paper reviews the technical capabilities for monitoring deforestation from a pan-tropical perspective in response to the United Nations Framework Convention on Climate Change (UNFCCC) process, which is studying the technical issues surrounding the ability to reduce greenhouse gas emissions from deforestation in developing countries. The successful implementation of such policies requires effective forest monitoring systems that are reproducible, provide consistent results, meet standards for mapping accuracy, and can be implemented from national to pan-tropical levels. Remotely sensed data, supported by ground observations, are crucial to such efforts. Recent developments in global to regional monitoring of forests can contribute to reducing the uncertainties in estimates of emissions from deforestation. Monitoring systems at national levels in developing countries can also benefit from pan-tropical and regional observations, mainly by identifying hot spots of change and prioritizing areas for monitoring at finer spatial scales. A pan-tropical perspective is also required to ensure consistency between different national monitoring systems.

Data sources already exist to determine baseline periods in the 1990s as historical reference points. Key requirements for implementing such monitoring programs, both at pan-tropical and at national scales, are international commitment of resources to increase capacity, coordination of observations to ensure pan-tropical coverage, access to free or low-cost data, and standardized, consensus protocols for data interpretation and analysis.

Keywords: pan-tropical, remote sensing observations, deforestation monitoring

1. Introduction

1.1. Role of tropical deforestation in global carbon emissions and related uncertainties

Multiple land use practices in forests, in particular those that end in deforestation, lead to emissions of carbon dioxide (CO2) and, if the biomass is burned during the clearing process, additional non-CO2 gases are emitted (Penman et al 2003, Denman et al 2007). Deforestation, defined as conversion from forest land to non-forest land (table 1), causes a large loss of carbon stock per deforested area relative to other land use changes in forests, such as degradation. Practices such as unsustainable timber production, over-harvesting of fuel wood, and fires at the edge of forest fragments are less easily observed than deforestation but can contribute substantially to carbon emissions. Forest degradation can also be a precursor to deforestation.

Tropical deforestation contributes approximately 20% of the world’s greenhouse gas emissions, mainly through CO2 emissions. Global net carbon flux resulting from land use changes, predominantly deforestation in the tropics, during the 1990s have been estimated at 1.6 (0.5–2.7) GtC yr⁻¹, compared to fossil fuel and cement emissions of 6.4 ± 0.4 GtC yr⁻¹ for the same decade (Denman et al 2007).
Table 1. UNFCCC definitions of forest and deforestation adopted by COP-6 (UNFCCC 2001) for implementation of article 3.

| Term            | Definition                                                                                                                                                                                                 | Comment                                                                                                                                                                                                 |
|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Forest          | 'Forest is a minimum area of land of 0.05–1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10–30 per cent with trees with the potential to reach a minimum height of 2–5 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.' | COP-6 further noted that parties recognize that there should be certain flexibility in applying the values in order to reflect national circumstances. Under this definition 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%. |
| Deforestation   | 'Deforestation is the direct human-induced conversion of forested land to non-forested land.'                                                                                                                    |                                                                                                                                                                                                          |

However, uncertainties in this land use change flux of the global carbon budget are high. As reported in the IPCC 4th Assessment report (Solomon et al 2007): ‘the land use carbon source has the largest uncertainties in the global carbon budget’. This has crucial importance for the residual terrestrial sink because a high value for the land use source in the global budget would correspond to a large residual land uptake over undisturbed ecosystems and vice versa (the fraction of carbon emitted by fossil fuel burning, cement production and land use changes that does not accumulate in the atmosphere must be taken up by land ecosystems and by the oceans). Indeed a study by Stephens et al (2007) suggests that net tropical emissions are lower than previous consensus estimates of $-2.2 \text{ GtC yr}^{-1}$ for the 1990s (Houghton 2003) and consequently after subtracting land use emissions, tropical ecosystems may currently be strong sinks for CO$_2$, as reported by other authors (Solomon et al 2007).

To obtain accurate and precise estimates of emissions from forest cover changes in the tropics several components must be estimated accurately and precisely, in particular: (1) area of deforestation, (2) initial carbon stocks for the base period, and (3) processes of changes in the carbon stocks caused by deforestation and degradation (Houghton 2005, Ramankutty et al 2007). Accurate reference figures of forest cover changes are needed to reconcile the land use change emissions from different sources which are presently calculated from different databases: Houghton (2003, 2005) uses deforestation estimates from the FAO country survey (FAO 2001), while Achard et al (2002, 2004) and DeFries et al (2002) use their own remote sensing derived deforestation estimates. Reference data on biomass and accepted procedures to estimate the fluxes are equally essential, as described in Gibbs et al (2007).

1.2. Reducing emissions from deforestation in the tropics

Although uncertainties in emissions from deforestation are high, their contribution to the global carbon budget is recognized as being very significant. As a consequence, official international discussions were initiated at the United Nations Framework Convention on Climate Change (UNFCCC) 11th Conference of Parties (COP) on the issue of reducing emissions from deforestation and degradation (REDD) in developing countries (UNFCCC 2005). At COP-11 the UNFCCC launched a process for investigating the technical issues surrounding the feasibility of reducing greenhouse gas (GHG) emissions from deforestation. Reducing deforestation would not only reduce such emissions, but would also act to preserve tropical forests which are considered as a strong sink.

A monitoring activity in support of policies for reducing deforestation necessitates a capacity to estimate changes 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.

1.3. Use of remote sensing technology to estimate deforestation in the tropics

Estimating deforestation would be a major challenge without the use of satellite imagery, in particular for remote regions. Satellite 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). However, reducing uncertainties in the land use change flux of the global carbon budget requires the capability to estimate changes in forest area throughout all forests of the tropical belt.

Improved pan-tropical observations can support a potential REDD mechanism to be included in a UNFCCC post-2012 agreement. While primary reporting would occur at national levels, pan-tropical monitoring could contribute through (1) identifying critical areas of change, (2) helping to establish areas within countries that require detailed monitoring, and (3) ensuring consistency among national efforts.

We consider here a range of issues for monitoring deforestation from pan-tropical to national scales. We address deforestation, i.e. the conversion of forests to non-forest, as the primary contributor to emissions from land use changes in forests. de Souza et al (2007) address the capability to monitor degradation. In addition, the paper raises future perspectives for monitoring forest cover at the pan-tropical level.
Subsequently in the late-1990s global or pan-continental maps were produced at around 1 km spatial resolution from a single (i.e. locations of rapid change) using expert opinion or coarse for pan-tropical forest cover monitoring—hot-spot analysis monitoring forest cover change. Firstly, they serve as a baseline area. However, land cover maps fulfill several functions in cover. It does not on its own indicate change in forest 2.1. Global land cover mapping

Land cover mapping provides a static depiction of land cover. It does not on its own indicate change in forest area. However, land cover maps fulfill several functions in monitoring forest cover change. Firstly, they serve as a baseline against which future change can be assessed. Secondly, they help establish forest areas that need to be monitored for change. When using a land cover map to assess future change, consistent methodology and spatial resolution are critical for interpretation of results.

For the first time in the mid-1980s the land cover of a whole continent was mapped in a consistent way for a specific year using 4 km spatial resolution imagery (Tucker et al. 1985). Subsequently in the late-1990s global or pan-continental maps were produced at around 1 km spatial resolution from a single data source: the AVHRR sensor onboard the US NOAA satellites (table 2).

In the early 2000s, new global land cover datasets were produced at similar resolution—1 km—from advanced Earth observation sensors (VEGETATION on board SPOT-4 and SPOT-5 and MODIS on board the Terra and Aqua platforms). These products (GLC-2000 and MODLAND) allowed for a spatial and thematic refinement of the previous global maps owing to the greater stability of the platforms and spectral characteristics of the sensors. An international initiative was also carried out to harmonize existing and future land cover datasets at the 1 km resolution to support operational earth observation of land (Herold et al. 2006).

More recently new global land cover datasets at finer resolution (250–500 m) were generated from TERRA-MODIS or ENVISAT-MERIS sensors. Initial examples at this scale include the MODIS vegetation continuous fields (VCF) products depicting sub-pixel vegetation cover traits at a spatial resolution of 500 m (Hansen et al. 2003). The systematic geometric and radiometric processing of MODIS data has enabled the implementation of operational land cover characterization algorithms (Wolf et al. 1998, Vermote et al. 2002). Currently, six years (2000–2006) of global VCF tree cover are now available to researchers and are being incorporated into various forest cover and change analyses (figure 1). A new 500 m version of the MODIS Land Cover product (Friedl et al. 2002) is also being generated.

The GLOBCOVER initiative will produce a global land cover map using the 300 m resolution mode from the MERIS sensor onboard the ENVISAT satellite (Arino et al. 2007).

| Map title | Reference | Domain | Sensor | Method |
|-----------|-----------|--------|--------|--------|
| IGBP discover | Loveland et al (1999) | Global 1 km | NOAA-AVHRR | 12 monthly vegetation indices from April 1992 to March 1993 |
| University of Maryland (UMD) | Hansen et al (2003) | Global 1 km | NOAA-AVHRR | 41 multi-temporal metrics from composites from April 1992 to March 1993 |
| TREES | Achard et al (2001) | Tropics 1 km | NOAA-AVHRR | Mosaics of single date classifications (1992–1993) |
| FRA-2000 | FAO (2001) | Global 1 km | NOAA-AVHRR | AVHRR updated from the IGBP dataset |
| MODIS-land-cover (MODLAND) | Friedl et al (2002) | Global 1 km | TERRA MODIS | 12 monthly composites from October 2000 to October 2001 |
| Global Land-Cover 2000 (GLC-2000) | Bartholomé and Belward (2005) | Global 1 km | SPOT-VGT | Global 365 daily mosaics for year 2000 |
| Vegetation continuous fields | DeFries et al (2000) | Global 1 km | NOAA-AVHRR | Annually derived phenological metrics |
| Hansen et al (2003) | | Global 500 m | TERRA MODIS | |
| GLOBCOVER | Arino et al (2007) | Global 300 m | Envisat MERIS | 6 bi-monthly mosaics from mid-2005 to mid-2006 |

2. Initiatives for forest mapping and monitoring at pan-tropical scale using coarse resolution satellite imagery

Fundamental requirements of pan-tropical monitoring systems are that they measure changes throughout all forested area, use consistent methodologies at repeated intervals to obtain accurate results, and verify results with ground-based or high resolution observations.

Multiple methods are appropriate and reliable for forest cover mapping or monitoring at pan-tropical scales using remote sensing data acquired by space-based platforms supported by ground-based observations. The wall-to-wall approaches using digital analysis of coarse resolution (250 m–1 km) satellite imagery for global forest cover (or land cover) mapping are reviewed in section 2.1. The approaches used for pan-tropical forest cover monitoring—hot-spot analysis (i.e. locations of rapid change) using expert opinion or coarse resolution satellite data to identify locations—are reviewed in section 2.2.
Red = percent tree cover
Green = percent other vegetation
Blue = percent bare ground
Yellow = cropland thresholded at 95 percent likelihood
Black = tree canopy cleared from 2000 to 2005.

Figure 1. MODIS 500 m vegetation continuous field product centered on the Amazon Basin.

MERIS mosaic at 300 m resolution from period mid 2005 – mid 2006
Image size: circa 200 km x 250 km
Composite: channels 8/13/2 as Red/Green/Blue
(Forested areas appear in green tones)

VEGETATION mosaic at 1 km resolution from period 1999 – 2000
Image size: circa 200 km x 250 km
Composite: channels 4/3/2 as Red/Green/Blue
(Forested areas appear in green tones)

Figure 2. Comparison between satellite imagery at 300 m resolution and 1 km resolution over central Vietnam.
of the absolute geo-location of the ortho-rectified MERIS FRS product is less than 80 m and thus stays largely below 1/3 of the pixel size required for multi-temporal analysis. Bi-monthly, seasonal and annual mosaics have been created over a one year period (between mid-2005 and mid-2006) in the plate-carrée projection. A global land cover map will be generated from these mosaics from automatic classification tools using equal-reasoning areas, and spectral and temporal characteristics of the mosaics.

These global or regional products can also be used as complementary forest maps when they do not already exist at the national level, in particular for ecosystem stratification to help in the estimation of forest biomass through spatial extrapolation methods (Saatchi et al. 2005). Static forest cover maps used in concert with change detection studies provide the basis for establishing rates of change, and are particularly useful as a stratification tool in developing sampling approaches for forest change estimation (Mayaux et al. 2005).

2.2. Pan-tropical forest monitoring and detection of deforestation hot spots

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 than would be used at the national level, can supplement these efforts by providing consistency and ensuring that major areas of deforestation are detected (Hansen et al. 2003, 2005).

A global map of the main deforestation fronts in the 1980s and 1990s has been produced by Lepers et al. (2005). This map combines the knowledge of deforestation fronts in the humid tropics through expert knowledge (Achard et al. 1998), a time-series analysis of tree cover based on NOAA AVHRR 8 km resolution data (DeFries et al. 2000) and, for the Amazon basin, deforestation maps derived from time-series of Landsat TM data (Skole and Tucker 1993). In this exercise the use of expert knowledge ensured that areas of major change not detected with the satellite-based approaches were not overlooked.

The Brazilian PRODES monitoring system for the Brazilian Amazon uses a hot-spot approach to identify ‘critical areas’ based on the previous year’s monitoring (INPE 2005). These ‘critical areas’ are priorities for analysis in 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.

Analysis of coarse resolution data can identify locations of rapid and large deforestation fronts, though such data are unsuitable on their own to determine rates of deforestation based on changes in forest area (DeFries et al. 2002, Morton et al. 2005). A nested approach in which coarse resolution data are analyzed to identify locations requiring further analysis with more costly mid-resolution data (10–50 m) can reduce the need to analyze the entire forested area within a country. The appropriateness of this approach depends on whether computational resources are available for analysis of coarse resolution data, as opposed to visual interpretation of mid-resolution data (figure 3). Coarse resolution data have been available from the MODIS sensor for no cost since 2000.

In some cases, it is possible to identify deforestation directly with coarse resolution data. Clearings for large-scale mechanized agriculture are detectable with coarse resolution data (100s of metres spatial resolution) based on digital analysis (Morton et al. 2005). Small agricultural clearings or clearings for settlements require higher resolution data (10s of metres) 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.

3. Initiatives for estimating forest cover changes from pan-tropical to national scales with mid-resolution satellite imagery

Many methods for the analysis of the satellite imagery can produce adequate results from pan-tropical to national scales. The key requirements of ensuring consistency of results across continents or countries lies in verification that the methods are reproducible, provide consistent results when applied at different times, and meet standards for assessment of accuracy. An analysis that covers the full spatial extent of the forested areas, termed ‘wall-to-wall’ coverage, is ideal, but may not be practical due to large areas and constraints on resources for analysis. It has been demonstrated that estimates of deforestation can be provided through remote sensing based methods from pan-tropical or continental levels to national and subnational levels (DeFries et al. 2007). At pan-tropical or continental levels for detailed digital analysis with mid-resolution (10–50 m) satellite images, several approaches have been successfully applied by sampling within the total forest area so as to reduce costs and time for analysis (Czaplewski 2003).

3.1. The FAO FRA 2010 global remote sensing survey

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

For its next global assessment, the Forest Resources Assessment 2010 programme—FRA 2010—the FAO is continuing to develop its monitoring of forest cover changes at global to continental scales to complement national reporting (FAO 2006). Technological improvements and better access to remote sensing data make it possible to expand the scope of the
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Figure 3. Monitoring forest changes in Brazil: example of Alta Floresta from 1984 to 2005.

Figure 4. Sampling scheme of the FAO Forest Resources Assessment 2010 over Papua New Guinea.

survey (compared with both FRA 1990 and FRA 2000). The remote sensing survey (RSS) of FRA 2010 will be extended to all lands (not just the pan-tropical zone). The survey aims at estimating forest change for the periods 1990–2000–2005 based on a sample of mid-resolution satellite imagery (e.g. Landsat TM, ETM+, ASTER, etc.). A historical trend will be added by looking back to the year 1975 (with Landsat MSS). Estimates of forest areas and change rates should be statistically valid at global, continental and sub-regional levels. The survey will be based on a much higher number of smaller samples than the previous FRA exercises, sampled systematically; a $10 \times 10$ km$^2$ sample with 5 km buffer (i.e. size of $20 \times 20$ km$^2$ for forest cover contextual information) will be located at each intersection of the 1 degree lines of latitude and longitude that overlie land. These dimensions were chosen to allow spatially explicit monitoring at a scale relevant to land management. Time-series of mid-resolution remote sensing data will be attached to each sampling location through a quality-controlled, standardized and decentralized process.

This sampling scheme leads to c. 13 500 for the terrestrial part of the globe or c. 9000 when excluding desert areas and represents c. 1% of the land surface (0.8% along the equator) with the geographical grid (figure 4). This approach is expected to deliver regionally accurate estimates of forest cover change, as well as national estimates for those countries where sampling intensity is sufficient.
The general legend to be used includes 8 land cover classes: forest (trees $\geq 5$ m height, forest proportion $> 70\%$, canopy cover $> 10\%$, shrub cover $< 5$ m), mosaics of trees and other land cover, other vegetated land cover, other non-vegetated land cover, burnt areas, water, clouds and no data. A minimum mapping unit (MMU) of 5 ha (or 50 pixels at 30 m spatial resolution) will be considered for the interpretation of the satellite imagery combined with a finer ‘detection unit level’ at about 1 ha for the change detection. These criteria are based on initial tests performed on datasets for Papua New Guinea.

3.2. NASA land cover and land use change program global forest monitoring

Another sampling approach to global forest cover change estimation is currently being implemented by the South Dakota State University within the NASA Land Cover and Land Use Change program. This method relies on MODIS change indicator maps to stratify biomes into regions of varying change likelihood. Using a block sampling strategy based on the aggregated MODIS-indicated change, Enhanced Landsat Thematic Mapper image pairs are analyzed to quantify biome-wide areas of forest clearing. Coarse spatial resolution sensor data, such as MODIS, are imaged daily over the globe, providing the best possibility for cloud-free observations from a polar-orbiting platform. However, coarse spatial resolution data do not directly allow for change area estimations, given that most change occurs at sub-pixel scales. Mid spatial resolution Landsat data, on the other hand, do allow for more accurate change area measures. By using MODIS data as a stratification tool and Landsat data to estimate forest area cleared, an integrated method is attained. The targeted sampling of change reduces the overall resources typically required in assessing biome-scale change and overcomes the problem encountered in previous studies of imprecise estimates of forest clearing attributable to the rarity of such clearing (Czaplewski 2003, Stehman 2005). Figure 5 illustrates a sampling frame for analyzing change at a national scale (Indonesia) using this approach. Sample blocks are 18.5 km per side. Each block is then analyzed using Landsat imagery from 2000 and 2005.

3.3. Example of regional forest cover change estimation

A test of the systematic sampling approach presented in section 3.1 has been carried out in central Africa to derive area estimates of forest cover change (Duveiller et al 2007). The proposed systematic sampling approach using mid-resolution imagery (Landsat) was operationally applied to the entire Congo River basin to accurately estimate deforestation at regional level and, for large-size countries, at national level. The survey was composed of $10 \times 10$ km$^2$ sampling sites systematically distributed every $0.5\,$ over the whole forest domain of central Africa, corresponding to a sampling rate of $3.3\%$. For each of the 571 sites, subsets were extracted from both Landsat TM and ETM+ imagery acquired in 1990 and 2000, respectively. The satellite imagery was analyzed with object-based (multi-date segmentation) unsupervised classification techniques (Desclée et al 2006).

Around 60% of the 390 cloud-free images do not show any forest cover change. For the other 165 sites, a change matrix is derived for every sample site describing 4 land cover change processes, e.g. deforestation, reforestation, forest degradation and forest recovery (Hansen et al 2007). The exercise illustrates that the statistical precision depends on the sampling intensity (table 3). For a region like central Africa (with 180 million ha), using 400 samples, corresponding to a
sampling rate of 3.3%, the exercise estimates the deforestation rate at 2.08% over a 10 year period with a statistical confidence interval of ±0.48%.

Intensifying the sampling rate from a systematic grid can be used within special areas of interest (e.g. hot-spot areas) or the level of country. Moreover, a few very large countries, e.g. Brazil (INPE 2005) and India (FSI 2004), have already demonstrated that operational wall-to-wall systems can be established based on mid-resolution satellite imagery. Brazil has been measuring deforestation rates in Brazilian Amazonia since the 1980s. These methods could be easily adapted to cope with smaller country sizes.

Reporting the overall accuracy (i.e. not only the statistical accuracy, but also the ‘interpretation’ accuracy) and verification of results are essential components of a monitoring system. Interpretation accuracies of 80–95% are achievable for monitoring changes in forest cover with mid-resolution imagery when using only two classes, forest and non-forest (Desclee et al. 2006). Interpretation 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 such accuracies. While it is difficult to verify change from one time to another on the ground unless the same location is visited at different time periods, a time series of high (to very high) resolution data can be used to assess accuracy of identifying 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. In the example of central Africa the overall accuracy of the land cover classifications used for deriving forest change dynamics was assessed by an independent interpreter to 91%.

3.4. Availability of mid-resolution imagery for year 2005/2006

By the late-1960s, the first satellites specifically dedicated to land resource monitoring entered the planning stages. NASA (National Aeronautics and Space Administration of the US) designed and launched a satellite mid-resolution sensor which was able to collect land information at a landscape scale. ERTS-1 (Earth Resources Technology Satellite) was launched on 23 July 1972. This satellite, renamed ‘Landsat’, was the first in a series (seven to date) of Earth-observing satellites that have permitted continuous coverage since 1972. Subsequent satellites have been launched every 2–3 years. Landsats 4, 5 and 7, from a 705 km altitude, cover the same ground track again every 16 days.

Nearly complete pan-tropical coverage from these Landsat satellites are available at low or no cost for the early 1990s and early 2000s data from NASA (https://zulu.ssc.nasa.gov/mrsid), the USGS (http://edc.usgs.gov/products/satellite/landsat_ortho.html) 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. Up to 2003, Landsat, given its low cost and unrestricted license use, has been the workhorse for mid-resolution data.

Unfortunately, on April 2003 the failure of the Landsat 7 ETM+ scan line corrector resulted in data gaps outside of the central portion of the acquired images, seriously compromising data quality for land cover monitoring. Given this failure, there is a need to explore how the ensuing data gap might be filled at a reasonable cost with alternative sources of data in order to meet the needs for operational decision-making. Alternative sources of data include Landsat 5 TM (still in operation), ASTER, SPOT HRVIR, IRS, CBERS or DMC data (table 4). NASA, in collaboration with USGS, initiated an effort to acquire and compose appropriate imagery to generate a mid-decadal (around 2005/2006) dataset from such alternative sources, in particular using Landsat-5 TM as the main source to complement Landsat-7 ETM+. It has been assessed that the combined Archived Coverage in EROS Archive of the Landsat 5 and Landsat-7 ETM+ reprocessed fill product for the years 2005/2006 would cover more than 90% of the land area of the Earth. These data will be processed to a new orthorectified standard using data from NASA’s Shuttle Radar Topography Mission (Rabus et al. 2003).

Optical mid-resolution data have been the primary tool for deforestation monitoring. Other types of sensors, e.g. radar (ERS1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS PALSAR) and lidar, are potentially useful and appropriate. Radar, in particular, alleviates the substantial limitations of optical data in persistently cloudy parts of the tropics. Data from lidar and radar have been demonstrated to be useful in project studies: however, so far are not widely used operationally for tropical deforestation monitoring over large areas. In the timeframe of the next commitment period, the utility of radar may be enhanced depending on data acquisition, access and scientific developments (Rosenqvist et al. 2007). 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

### Table 3. Estimates of forest cover change for the Congo Basin (total forest area = 180.4 million ha) over the period 1990–2000 with five different sampling schemes.

| Resolution of sample grid | Number of available samples | Average rate | Confidence interval |
|---------------------------|-----------------------------|--------------|--------------------|
| 1° × 1° starting 5°E7°N   | 101                         | 2.20%        | 0.88%              |
| 1° × 1° starting 5°30′E7°N| 104                         | 1.48%        | 0.74%              |
| 1° × 1° starting 5°E6′30′N | 98                          | 1.94%        | 1.02%              |
| 1° × 1° starting 5°30′E6′30′N | 97                          | 2.73%        | 1.22%              |
| 1/2° × 1/2°               | 400                         | 2.08%        | 0.48%              |
the future, and access to data. Costs of mid-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. Improved data access policies from space agencies—such as European Space Agency, National Aeronautics and Space Agency, Japan Aerospace Exploration Agency, Centre National d’Etudes Spatiales—would allow for a true forest monitoring capability. As the science of earth observation monitoring has matured, the providers of the data necessary to make monitoring a reality have not kept pace with the science.

4. Conclusions

The ability to monitor changes in forest area at the pan-tropical level is one crucial component for reducing uncertainties in the estimates of greenhouse gas emissions from tropical deforestation (i.e. mainly carbon emissions).

Analysis of remotely sensed data from satellite is the only practical approach to measure changes in forest area at national to pan-tropical scales. Various methods are available and appropriate to analyze satellite data for measuring changes in forest cover, depending on institutional capabilities, deforestation patterns, and characteristics of forests. These methods range from wall-to-wall mapping to hot-spot analysis and statistical sampling. With remote sensing technology, one can produce independent and up-to-date estimates of both forest cover and cover change. 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.

Since the early 1990s, changes in forest area at the pan-tropical level can be measured from space with confidence, although uncertainties in estimates of deforestation need to be reduced for policy implementation and follow-up. Monitoring of forest resources at pan-tropical scale contributes to the UNFCCC REDD by developing standard methods across regions or continents, reducing uncertainties in a global or regional context and assessing deforestation trends. Such pan-tropical or regional monitoring is also particularly relevant for monitoring potential leakage effects (displacement of deforestation) and for providing pan-tropical and regional historical references.

A multi-resolution, multi-scale observing global (or at least pan-tropical) framework is recommended to provide national forest ecosystems stratifications when they do not exist, provide consistent global (or pan-tropical) perspective independent from national monitoring activities, delineate areas with large changes, drive acquisition strategies for mid-resolution datasets (stratification for sampling, clouds, seasonality, etc) and assist in the preprocessing of mid-resolution datasets (DeFries et al 2006).

National, international and academic institutions have made considerable progress in developing methods and prototypes for pan-tropical monitoring based on satellite data. However, it has not been possible to deliver routine information for policy implementation. One prominent reason has been the inability of the agencies concerned to establish a commonly accepted, independent, cost-effective and long-term mechanism to deliver remote sensing data to users. In particular, key constraints in implementing large scale systems for monitoring changes in forest cover are cost and access to mid-resolution data (10–50 m). International coordination is needed between space agencies and implementing institutions to ensure repeated coverage of the world’s forests and access to quality data at a reasonable cost.

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