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Tropical forest monitoring and remote sensing: A new era of transparency in forest governance?

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The extent of tropical deforestation is now being tracked by actors in the nongovernmental, academic, private and government sectors using several different sources of satellite imagery. This paper presents an overview of the satellite systems that can be used for operational forest monitoring in the tropics and examines some recent trends in their use. It also reviews various satellite-based studies to map moist tropical forests and draws upon lessons learned from land cover mapping projects in several countries and regions. The case of Indonesia, examined as a nation undergoing rapid conversion of forest to other land uses, is contrasted with Brazil where satellite-based deforestation monitoring is fully operational. In Indonesia, the paper argues, the creation of a national monitoring system for tropical forest conversion is needed to create a source of transparent, reliable information on forest cover and condition. Such a system is likely to succeed if based on multitemporal, moderate-resolution optical data such as imagery provided by MODIS (Moderate Resolution Imaging Spectrometer). When MODIS images are complemented by radar and fine-resolution imagery from sensors such as IKONOS and QuickBird, areas of abrupt change can be identified and the causes potentially discerned. Thus, satellite imagery at multiple temporal and spatial resolutions can effectively increase transparency in the forestry sector by revealing the rate and extent of deforestation on an annual basis and identifying potential areas of illegal logging.

Keywords: tropical deforestation, remote sensing, MODIS, Indonesia, forest monitoring

Introduction: A forest of statistics

Since the colonial period, developed countries have maintained an abiding interest in the extent, quality and management of tropical forest resources. Whereas earlier interest was motivated mainly by the demand for industrial timber resources and land suitable for cash crop production, since decolonization, a greater concern about the negative consequences of tropical deforestation has been evident. Major drivers of tropical deforestation include large-scale timber extraction, agricultural expansion and infrastructure development, all of which have increased dramatically in many parts within the tropics over the past two decades (Geist & Lambin, 2002). The more recent attention given to tropical deforestation stems from concerns over various consequences, including the massive loss of biological diversity (Myers *et al.*, 2000), loss of an important sink for atmospheric carbon dioxide (Houghton, 1999), impacts on local and regional climate (Shukla *et al.*, 1990) and negative effects on the livelihoods of people in tropical forests (Stone & D'Andrea, 2001).

Considerable controversy often surrounds the statistics that emanate from governments, international agencies and research projects on the extent and rates of tropical deforestation. In part, this may be due to overestimation of precolonial forest extent and also to the subjective means used to arrive at periodic figures on the extent of tropical forest in different countries (Fairhead & Leach, 1998). In addition, definitions of the term 'forest' may vary (Table 1). For example, the definition used by the International Geosphere-Biosphere Program (IGBP) for evergreen broadleaf forest includes 'lands dominated by woody vegetation with a per cent cover >60 per cent and height exceeding 2 m' (Giri *et al.*, 2005:126). In contrast, the United Nations (UN) Food and Agricultural

Table 1. Major land cover mapping initiatives and definitions of 'forest' used.

Organization/project	Reference	Class	Definition
FAO/Forest Resources Assessment 2000	Zhu and Waller (2003)	Closed forest	>40% canopy cover >5 m height
Land Cover Classification System of FAO/Global Land Cover 2000	Giri *et al.* (2005)	Tropical rain forest	>15% canopy cover >3 m height
IGBP/MODIS land cover	Giri *et al.* (2005)	Evergreen broad leaf forest	>60% cover >2 m height
European Space Agency, Joint Research Centre/Tropical Ecosystem Environment observation by Satellite (TREES)	Mayaux *et al.* (1998)	Evergreen and semideciduous forest	>70% cover in an AVHRR pixel

Organization (FAO) uses the term 'closed forest' to represent 'tropical/subtropical moist forest', which they define as 'land covered by trees with a canopy cover of more than 40 per cent and height exceeding 5 m' (Zhu & Waller, 2003:370). Furthermore, the FAO definition includes both plantations and 'natural forests'. Given the variable definitions in use, it is not surprising that confusion arises over both tropical forest extent and spatial distribution when deforestation estimates are derived from different land cover maps (Giri *et al.*, 2005).

Traditionally, forest cover maps were derived mainly by foresters who used field and aerial surveys and then scaled these figures to reflect the extent of national forest cover as a whole. These national figures were then transmitted to international agencies such as the FAO, which compiles global estimates of forest cover every 10 years (Zhu & Waller, 2003). In most cases sampling methods and standards adopted by different national agencies charged with forest monitoring were never harmonized. Moreover, in national forest statistics the definition of 'forest' may include barren land that can potentially support forest as well as degraded forest in which canopy cover has been reduced to below 40 per cent (Zhu & Waller, 2003). Despite this obvious source of error, recent analysis of satellite imagery suggests that FAO country data tended to overestimate tropical deforestation in the 1990s (Achard *et al.*, 2002; DeFries *et al.*, 2002).

DeFries and Townshend (1999) further highlighted large discrepancies in the extent of broad-leaved, evergreen forest among widely used global land cover maps and emphasized the need for a more consistent use of remote sensing technology to adjust and update global land cover estimates. International efforts to establish remotely sensed forest monitoring have emerged recently, such as Global Observation of Forest Cover and Land Cover Dynamics (GOFC-GOLD), which aims to provide ongoing space-based and *in situ* observations of forests to assist the sustainable management of terrestrial resources. Largely due to the launch of earth-observation sensors in the 1970s, operational satellite sensors have supplanted the traditional estimation of forest cover from field samples and aerial surveys, and more routine application of satellite imagery suggest that the traditional approach is no longer the most efficient or accurate means to map forest cover at regular intervals. The widespread availability of digital data and rapid dissemination through the Internet means that official estimates of national forest cover may now be independently verified and challenged by actors outside government agencies.

Although the application of satellite imagery for forest mapping has increased greatly over the past decade, different methodologies and ways of interpreting satellite imagery still produce results that can generate controversy (Fearnside & Barbosa, 2004). Close scrutiny of government-sponsored forest monitoring schemes suggests that some independent verification is useful, if not necessary, as government agencies have sometimes produced interpretations of satellite imagery that are biased, poorly documented or timed to satisfy certain political agendas (Kummer, 1992; 1995). Examples include delays by Brazil in releasing news about deforestation in the Legal Amazon after an upturn in deforestation rates there beginning in 1992 and delayed release of the very high 1995 deforestation figures in the Legal Amazon, which amounted to 29.1×10^3 km^2 yr^{-1}, only after the 1997 Kyoto conference on global warming (Fearnside & Barbosa, 2004).

Despite ongoing debate over deforestation in the Legal Amazon, Brazil deserves recognition for implementing an operational, space-based forest monitoring programme to track deforestation (Laurence *et al.*, 2004). Brazil's application of Landsat and radar imagery dates from the 1970s and was intended originally for an inventory of the Brazilian Amazon forest cover and the identification of arable land for colonization. The impetus to monitor forest cover in the Legal Amazon was both a practical response to the challenge of mapping forest over an area of this magnitude (5.8 million km^2) and a response to political pressures originating from within and outside the country. Other nations, regions and international agencies that face similar challenges of producing more accurate and timely estimates of forest cover have increasingly adopted the use satellite imagery as their principal source of data (e.g. Canada; see Wulder *et al.*, 2004). This is particularly relevant for countries that have ratified the UN Framework Convention on Climate Change (FCCC) and wish to receive credits for sustainable management of their forests as carbon sinks (Cairns & Lasserre, 2004).

Improved monitoring of forest cover itself is unlikely to produce any change in behaviour unless it is linked to research, forest policy and management and assessment. Basic research in remote sensing drives what techniques may best be applied to detect changes in tropical forest cover at different spatial scales, from individual trees to large blocks of unbroken canopy. Parr *et al.* (2003) outline a feedback loop wherein long-term monitoring leads to improved prediction of environmental change, which feeds into policy/management decisions, and then to an explicit assessment that addresses if policy/management is working to produce a change in behaviour. A potentially important component in any monitoring programme is sharing of satellite imagery with the news media to inform citizens about the extent and location of deforestation (so-called deforestation hotspots). If such information can influence public opinion, it can exert pressure on policymakers in democratic societies to strengthen enforcement and tighten regulations to improve forest management and protection.

Indications are that estimates of tropical forest cover may be converging with more routine application of satellite imagery (Skole *et al.*, 1994; Hansen & Reed, 2000; Zhu & Waller, 2003). However, global land cover maps derived from satellite imagery may disagree substantially as to the extent and distribution of tropical forest. For example, Giri *et al.* (2005) found important differences in forest distribution between two prominent land cover products, namely the Global Land Cover-2000 (available at http://www-gvm.jrc.it/glc2000) and MODIS (Moderate Resolution Imaging Spectrometer) land cover prepared by researchers at Boston University. At regional-to-national scales, the adoption and application of satellite technology lags in certain countries in the tropics that are faced with scarcities of technology, funding and human capital. Therefore, the objective of this paper is to review relevant advances in the use of remote sensing for mapping and monitoring tropical forests in different contexts, and to point out possibilities and constraints that emerge in the use of the technology for operational monitoring of the relatively undisturbed moist tropical forests that remain. In relation to this, the case of

Indonesia is examined as an example where forest conversion and degradation have occurred simultaneously and on a massive scale, and where timely and accurate data on deforestation are still largely lacking.

Mapping tropical forests with satellite remote sensing

A review of the literature on the application of satellite remote sensing to tropical forests suggests a geographically uneven use of the technology. Remote sensing studies of tropical forest tend to differ as to their objectives. In some studies cited below, the principal objective is to detect major changes in land cover such as deforestation, whereas in many others the main goal is to derive improved land cover maps that may serve as a basis for national forest inventories and future change detection studies. Thus, the two types of studies tend to complement and reinforce one another. According to the Institute for Scientific Information (http://isiwebofknowledge.com), of 245 papers published during 1995–2003 in refereed journals that deal with remote sensing and tropical forests, nearly two-thirds focused on the Amazon Basin; the remainder concerned either Central Africa (18 per cent) or Southeast Asia (17 per cent). This indicates a bias towards the use of remote sensing for Amazonian studies, which may reflect the long use of remote sensing by Brazil and the continued support of the Brazilian INPE (National Institute for Space Research) for satellite imagery development. An apparent western hemisphere bias may also be a reflection of the longstanding interest of the US's National Aeronautics and Space Agency (NASA) in Latin America and its past cooperation with INPE, as evidenced by the recent 'Large Scale Biosphere-Atmosphere Experiment in Amazonia' multilateral research initiative (Roberts *et al.*, 2003).

Of the different satellite sensors used in studies of tropical forest, the literature suggests that Landsat imagery has been the most commonly applied (for a list of sensors, see Baker & Williamson, 2006: Table 1). Since its launch in 1972, the Landsat satellite platforms have carried three main sensors, which have evolved since the system was first designed: the MSS (Multispectral Scanner), TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper Plus). Several factors explain the widespread and recent use of ETM+ imagery, including its moderate cost relative to previous Landsat imagery, centralized and improved online search and download through the Internet, a rational globally comprehensive data acquisition policy (Arvidsen *et al.*, 2001) and a spatial resolution (30 m for the six optical bands) appropriate for the detection of change in canopy condition, extent as well as land use around forested areas. In recent years, several Landsat data archives have greatly improved the availability of imagery over tropical areas to the user community, including the Global Land Cover Facility at the University of Maryland (http://glcf.umiacs.umd.edu/index.shtml) and Tropical Rain Forest Information Center (http://bsrsi.msu.edu/trfic/) at Michigan State University. Such increased availability of inexpensive Landsat imagery has stimulated a number of change detection studies that have helped to identify drivers of land cover change in the tropics (Pereira *et al.*, 2002; Dennis & Colfer, 2006). In addition, Landsat TM and ETM+ data are particularly appropriate for detection and mapping of logging roads and burn scars, which serve as indicators of forest exploitation in the near future or recent past. While not an indicator of the extent or condition of forest per se, logging roads derived from Landsat imagery are used by certain nongovernmental initiatives such as Global Forest Watch (GFW) and its local affiliates worldwide to monitor compliance with forestry codes and standards in both Central Africa and Indonesia (FWI/GFW, 2002).

Landsat imagery generally provides a clear delineation between forest and non-forest cover types and allows both manual (Townshend *et al.*, 1995) and semi-automated interpretation (Achard *et al.*, 2002). In addition, as each Landsat scene covers approximately 170 km × 170 km and many scenes may be required to cover a large area – 215 scenes are needed for the Legal Amazon in Brazil – a sample of scenes is often used as a way to reduce costs and to expedite estimation of deforestation relative to so-called wall-to-wall coverage (Fearnside & Barbosa, 2004). Critical questions remain, however, about the appropriate sample size (number of scenes) and spacing of scenes to ensure adequate estimation of the deforested area. Tucker and Townshend (2000) established sampling criteria based on an assessment of Landsat coverage needed to estimate deforestation with +/–20 per cent error 90 per cent of the time. They determined that random sampling was inadequate to meet their criteria but also that adequate sampling may not necessarily reduce processing time and effort, as shown by the small difference between the number of scenes required for accurately estimating deforestation compared to that required for wall-to-wall coverage in their studies of Bolivia (37/40), Colombia (55/61) and Peru (37/45). However, by focusing on forested areas where land use is likely to change (i.e. areas proximate to past land cover conversions), it may be feasible to target sampling in a nonrandom fashion to estimate deforestation accurately, as INPE currently does for the Brazilian Amazon (see http://www.obt.inpe.br/prodes/).

One of the principal limitations of the use of Landsat and other optical imaging systems is that these technologies cannot penetrate clouds, which persist over many parts of the tropics during the wet season and, indeed, throughout the year in many tropical upland and montane environments. This effectively reduces the number of Landsat passes that researchers may use to map and monitor tropical forest as months or years may transpire before cloud-free Landsat imagery becomes available for certain cloudy locations (Trigg *et al.*, 2006). Thus, low temporal coverage over cloudy regions can render Landsat and similar polar-orbiting systems virtually useless for periodic (annual scales or less) forest monitoring. Researchers have therefore turned increasingly to cloud-penetrating radar imagery provided by such satellite platforms as the Japanese Earth Resources Satellite (JERS-1) and the European Remote Sensing Satellite (ERS) as an alternative to study tropical forest cover. Most notable is the JERS-1 mosaic of Southeast Asia, Central Africa and the Amazon produced by the global moist forest monitoring project undertaken jointly between government space agencies in Japan, USA and the European Union (EU) (Podest & Saatchi, 2002). These JERS-1 mosaics provide a robust measure of canopy texture and allow detection of forest vegetation at 100 m spatial resolution. Although such radar imagery generally do not provide as much spatial detail on land use and cover as cloud-free Landsat imagery, Sgrenzaroli *et al.* (2002) and Podest and Saatchi (2002) reported acceptable forest classification accuracies and thus recommend this type of synthetic aperture radar (SAR) imagery for upscaling deforestation estimates to the continental scale due to its all weather capability.

For studies at regional and landscape scales, radar imagery provided by ERS-2 may be used to locate and assess the extent of burning and tree damage in tropical forests. For example, Siegert *et al.* (2001) reported on the use of 25 m ERS-2 imagery to map burned areas in East Kalimantan Province, Indonesia, during the massive wildfires that occurred between 1997 and 1998. They coupled their imagery with field data to show that 24 per cent of the burned area had moderate fire damage (25–50 per cent of trees killed), 42 per cent had severe fire damage (50–80 per cent of trees killed), and the remainder total fire damage (>80 per cent of trees killed). Their study helped to demonstrate the high potential of moderate-resolution radar data for the study of tropical forest conditions after large-scale disturbances such as fire.

Despite the all-weather capability of radar imagery, moderate- to fine-resolution (30 m or less) optical imagery is still more frequently used in studies of tropical forests than spaceborne radar. Reasons for this include the greater spatial detail on land cover type, numerous image classification algorithms and software that apply to optical imagery, and its greater availability in image archives. However, some sources of optical imagery are clearly more suitable than others for tropical forest classification. For example, Thenkabail *et al.* (2004) evaluated four optical sensors – Hyperion, IKONOS, ALI (Advanced Land Imager) and ETM+ – for classifying complex moist forest vegetation such as young fallow, old fallow, secondary forest and primary forest in the Congo Basin. The 30 m Hyperion hyperspectral sensor, which consists of 220 individual narrow spectral bands, performed best and was able to distinguish nine different vegetation classes with an overall accuracy of 96.1 per cent when 23 of 157 useable bands were employed in a discriminant model. The other three sensors, including the 4 m multispectral IKONOS imagery, performed relatively poorly and were able to distinguish the same classes with overall accuracies of 42–51 per cent. These results underscore the limited information content of multispectral (usually less than eight broad spectral bands) relative to hyperspectral imagery.

This point is reinforced by a branch-level analysis of Amazonian species conducted by Cochrane (2000), who found that use of a red-edge derivative could separate 10 species based on foliar reflectance. However, generally speaking, the prospect of detailed mapping of moist tropical forest species using reflectance spectra remains limited in future applications given the small number of factors common to most plants that control leaf and branch-level spectral response (Price, 1994). Moreover, when viewed from above, many subcanopy tree crowns generally present in primary and secondary forests are likely to be obscured. Thus, over closed forest, sensor response is mainly a function of composite reflectance from many overlapping tree crowns, even at fine spatial resolutions of 4 m or less. The relative dearth of hyperspectral satellite sensors is also likely to make routine forest monitoring with such systems unlikely in the near future.

Similarly, fine-resolution multispectral commercial systems such as IKONOS, Quickbird and OrbView 3 are unlikely to meet the needs for routine monitoring of moist forest canopies because they suffer from the same general limitations as Landsat ETM+, namely low temporal resolution and relatively small-area coverage (e.g. 11 × 11 km for a standard IKONOS scene). Fine spatial resolution may increase classification errors due to the increased internal variability of canopy reflectance from sunlit, shaded and background components in such data. Interestingly, one seminal study showed that the optimum spatial resolution for detecting broad-area land cover change is likely to be around 250 m (Townshend & Justice, 1988). Nevertheless, cloud-free fine-resolution imagery is likely to be useful for resolving cultural features associated with deforestation (e.g. buildings, logs and skid trails) and therefore provide a source of verification of forest cover maps derived from coarse-resolution imagery. Information provided by shadows, for example, may be used to infer the presence of canopy gaps (Asner & Warner, 2003), which may indicate different forest disturbance regimes such as reduced-impact logging, a strategy implemented in certain forests that minimizes the impact of logging on forest biodiversity and canopy structure (Asner *et al.*, 2004).

Innovative coupling of field data with remotely sensed observations from Landsat TM imagery of certain moist tropical forests has enabled some researchers to predict tree diversity and regrowth and thus move beyond simplistic forest/non-forest classifications. For example, Foody and Cutler (2003) used neural network algorithm with TM imagery to predict biodiversity indices with some level of success, as well as to classify forest types based on their tree species composition with an overall classification accuracy of 95.8 per cent. Steininger (2000) was able to predict the age of forest regrowth (<15 years old) from plots in the Brazilian and Bolivian Amazon by using different TM bands and band ratios. These and other methods are likely to support fine-scale local mapping of moist tropical forest canopies and help to eliminate confusion among different forest classes, such as regrowth and timber plantations, derived from coarse-resolution observations (Fuller *et al.*, 2004).

For global- and regional-scale monitoring, coarse-resolution sensors (250 m or greater) are generally considered superior to moderate- and fine-resolution systems because they possess wide swaths, and thus high overpass frequency. As such, these systems can obtain a sufficient number of cloud-free views of the land surface in the tropics to enable observations at monthly-to-annual intervals. Perhaps the best known coarse-resolution system is the AVHRR (Advanced Very High Resolution Radiometer) on board the US National Oceanic and Atmospheric Administration's (NOAA) TIROS satellites. Both NOAA and NASA provide AVHRR data at spatial resolutions in the range of 1–8 km, although several frequently cited recent studies have focused on global vegetation mapping using 1 km data (DeFries & Townshend, 1999; Hansen *et al.*, 2000).

Many AVHRR-based studies have been used for monitoring biomass burning in tropical forests (Fuller, 2000), which constitutes a major disturbance as a means to convert forest to pasture or agriculture and an indication of deforestation hotspots and future forest conversion (Cochrane, 2003). Several important studies have demonstrated the use of multitemporal AVHRR for global land cover mapping and for distinguishing broad-leaf evergreen forest formations in the tropics in particular (Belward *et al.*, 1999; Hansen & Reed, 2000; Hansen *et al.*, 2000; Loveland *et al.*, 2000). These studies provided complementary estimates of the amount of moist tropical forest remaining in 1992–93, which was taken as a year during which AVHRR 1 km data were processed to a high standard and distributed to the user community as a global land cover dataset (DeFries & Belward, 2000).

Although the AVHRR has provided an important source of temporally continuous data, other sensors are beginning to replace the AVHRR for land cover mapping, including the MODIS on board NASA's Terra satellite (Townshend & Justice, 2002), and the 1 km SPOT Vegetation sensor on board SPOT-4 (Mayaux *et al.*, 2004). Both MODIS and SPOT-4 have improved geolocation and calibration relative to the AVHRR series. MODIS data, in particular, represent a quantum leap in data availability as these are pre-processed as a set of validated land cover products and provided free of charge over the Internet. MODIS researchers associated with NASA and the Geography Departments at the University of Maryland and Boston University have developed a series of land products including calibrated surface reflectance, land surface temperature, thermal anomalies (active fires), albedo, vegetation index and land cover type, among others (Justice *et al.*, 2002), all of which are potentially useful to researchers interested in mapping and monitoring tropical deforestation and other forms of land degradation.

Townshend and Justice (2002) point out that a number of AVHRR users have yet to adopt MODIS data for land-based monitoring. Several explanations for delayed adoption may be advanced, including the widespread investment in locally-based AVHRR receiving stations in many countries in the tropics which tends to encourage continued use of these data, the limited high-speed Internet access in certain parts of sub-Saharan Africa and Southeast Asia in particular, and concerns about the frequent reprocessing of MODIS data such that 'new and improved' products tend to devalue previous product versions. For example, MODIS fire products are now in their fourth version, as researchers continue to fine tune their fire detection algorithms in line with validation data (see the MODIS Fire and Thermal Anomalies website: http://modis-fire.umd.edu/). However, researchers are not limited to processed MODIS data products but also have the opportunity to download calibrated georeferenced image data to develop and apply their own algorithms for land cover mapping.

Beyond new MODIS-based products, the EU has helped to establish coarse-resolution satellite systems and projects for mapping global land cover. Most notable in this regard, the 1 km SPOT Vegetation sensor possesses four spectral bands, two in the visible, one in the near infrared and a shortwave infrared band. Like MODIS data, SPOT Vegetation data are supplied to the user community through the Internet and are available as three standard products: a per-orbit top-of-atmosphere reflectance, a daily multi-orbit remapped mosaic of top-of-canopy reflectance, and a 10-day synthesis product that retains the maximum value of the Normalized Difference Vegetation Index (NDVI) (see *Vegetation User Guide*, 1999). Mayaux *et al.* (2004) relied mainly on the 10-day synthesis product to derive annual NDVI seasonal profiles for Africa for the year 2000, which were then converted to a set of distinct land cover classes. The result is a new land cover map for the African continent, which allows a breakdown of dense forest area by country. This product is likely to provide an important benchmark to which future researchers can refer for estimating moist forest loss in Central and West Africa (see http://www-gvm.jrc.it/).

One of the distinct limitations of broad-scale categorical maps derived from satellite data is that each pixel is generally labelled as a member of a single land cover class, whereas fine-resolution observations generally suggest that pixels of 250–1000 m are likely to contain complex mixtures of different cover types. In response to this problem, DeFries *et al.* (1999) and Hansen *et al.* (2002) have applied mixture modelling and regression tree classifiers to both 1 km AVHRR and 500 m MODIS imagery as a way to estimate the fractions of tree, bare soil and herb cover per pixel on a global basis. These so-called ‘continuous fields’ provide a more realistic portrayal of complex mixtures and vegetation mosaics that result from swidden agriculture, selective logging and other land uses in and around moist tropical forests. A major advantage of the per cent tree product is that users can query the data to obtain information on the density of tree canopy cover at any location in the wet tropics and make a determination a priori regarding the level of disturbance. Researchers are already using the continuous fields products as a way to validate their own broad-scale land cover maps (Fuller *et al.*, 2004; Mayaux *et al.*, 2004), which make rigorous field validation methods impractical because of their small map scales (Congalton & Green, 2001).

Indonesia: A case of rapid forest loss and inadequate monitoring

A number of global- and regional-scale studies have revealed that forest cover in Southeast Asia has experienced rapid decline over the past two decades (Bernard & DeKoninck, 1996; Rudel, 2002; Mayaux *et al.*, 2005; Yen *et al.*, 2005). The loss and degradation of forest has been of particular concern in Indonesia, which once possessed the world’s third largest area of moist tropical forest and has faced intense scrutiny over weak governance in the forestry sector (Sunderlin & Resosudarmo, 1994; Jepson *et al.*, 2001; FWI/GFW, 2002). The process of deforestation there is related both to selective logging, which generally results in fine-scale changes in forest structure and small openings, and to massive clearance for agricultural plantations. Furthermore, many areas that are undergoing large-scale clearance have been selectively logged in the past (FWI/GFW, 2002). In particular, both Sumatra and Indonesian Borneo (Kalimantan) have undergone rapid conversion of forest from logging and conversion to commercial plantation crops, particularly oil palm (Casson, 2000; Jepson *et al.*, 2001; Siegert *et al.*, 2001). Much of the deforestation during the New Order era of President Suharto (1967–1998) was blamed on smallholders, or the large timber concessions distributed to friends and relatives of the president. In the waning years of the Suharto presidency, a great deal of selectively logged forest remained and many of these areas have been burned repeatedly and, in some instances, converted to industrial plantations or left as degraded grassland (Siegert *et al.*, 2001; Stolle, 2003; Curran *et al.*, 2004; Fuller *et al.*, 2004). A number of different estimates of deforestation rates and extent have been produced that have varied widely depending on the source (Sunderlin & Resosudarmo, 1994). According to Mayaux *et al.* (1998) a comparison of different forest cover maps derived in the 1990s reveals estimates for Indonesia that ranged from 86.39 million ha to 114.84 million ha. Some of the discrepancy between different sources may be due to annual deforestation, which is projected at 2.4 million ha yr^{-1} (FWI/GFW, 2002), and the different years represented in each map, while different methods and definitions of 'forest' may account for significant differences as well.

Recent policy changes may have exacerbated deforestation in Indonesia since the 1990s. In 1998, after President Suharto stepped down, the government of Indonesia approved new legislation for a programme of decentralization, which granted control over forest resources to local government officials and paved the way for many new timber concessions. The effect of the decentralization on deforestation rates and extent are largely unknown, although several Indonesian government agencies are said to be compiling satellite data and planning to issue new figures on national forest cover. However, foresters and conservationists outside of the government have generally taken the lead in providing deforestation estimates rather than relying on government figures, which are seldom released to the public (FWI/GFW, 2002).

Researchers focusing on Indonesian forests have used both coarse- and moderate-resolution sensors to study disturbance and forest loss. Although Indonesia maintains several AVHRR receiving stations which provide regular coverage of the major western islands from Sumatra to Sulawesi, these do not provide coverage of the eastern portion of the archipelago and are meant mainly for fire rather than deforestation monitoring. At the June 2004 workshop at the Center for International Forestry Research (CIFOR) in Bogor, Indonesia (from which this paper derives), image analysts with the Indonesian Ministry of Forestry bureau charged with forest monitoring and planning reported that they had acquired wall-to-wall Landsat coverage and were using these images to revise current estimates of forest coverage. Although nongovernmental organization (NGO) representatives present at the same CIFOR workshop had pressed forestry officials to produce official estimates of the forest coverage and rates of deforestation, as of late 2004, the Ministry had yet to provide any comprehensive data on either current forest cover or national rates of deforestation.

Indonesia, like the Brazilian Amazon, spans a large area, and 241 Landsat scenes are needed to cover the entire archipelago (nearly 5500 km from east to west), although many of these are not relevant for assessing deforestation as they cover only small islands or marine environments exclusively. Given the large amount of work involved in interpreting so many Landsat scenes, it is understandable that the Indonesian government has been slow to produce a new estimate of forest cover. Therefore, coarse-resolution imagery provided by MODIS or SPOT Vegetation appear to provide a more viable means for regular monitoring and updating of forest cover estimates for a territory of this magnitude. In particular, MODIS imagery appear particularly promising owing to low cloud cover in daily observations relative to Landsat (Trigg *et al.*, 2006); the large number of spectral bands (36) relative to most medium-resolution sensors (including SPOT); spatial resolution appropriate to detect large forest clearings (as opposed to logging per se); improved geolocation relative to AVHRR and ease of data access through archives supported by NASA and the US Geological Survey. Successful application of MODIS for monitoring tropical deforestation will depend on several factors, including the scale of the openings in the forest canopy and the persistence of clouds. In the case of the Amazon, Morton *et al.* (2005) recently showed that MODIS data were useful for mapping clearings greater than 20 ha in extent. However, persistence of cloud cover in Indonesia, particularly in mountainous regions, may limit the use of MODIS and lead to very large gaps in forest cover information. For example, Fuller and Murphy (2005) obtained a 91 per cent forest classification accuracy over Indonesia from 500 m MODIS data if validation polygons less than 5000 ha were excluded. Thus, preliminary application of MODIS imagery covering Indonesia suggests that fine-scale disturbance related to selective logging, or small clearings from swidden agriculture and small burn scars are likely to go undetected. Ideally, finer resolution imagery should be used in place of MODIS imagery in cases where illegal activities (e.g. logging outside concessions) are suspected in areas of special concern, such as national parks and reserves.

Other examples of recent studies that have used MODIS for moist tropical forest mapping in Indonesia include Curran *et al.* (2004) and Fuller *et al.* (2004), both of which focused on Kalimantan, where deforestation has been rampant in recent years (Jepson *et al.*, 2001). Using a combination of Landsat and MODIS imagery, Curran *et al.* (2004) showed that lowland forest loss in 1985–2001 in the protected areas of Kalimantan had surpassed 56 per cent, or roughly 29 000 km^2. Similarly, Fuller *et al.* (2004) used MODIS data and showed that some 30 000 km^2 of forest was lost between 1996 and 2002 in Kalimantan, of which 23 700 km^2 was from existing and proposed protected areas (including parks, game reserves and nature reserves). Overlays of concession boundaries with protected area boundaries suggest that many of the protected areas have been designated as timber concessions. Furthermore, as lowland forest becomes scarce outside protected areas, illegal logging has been increasing, which puts pressure on legitimate concessionaires to cut or exceed their timber quotas in order to harvest logs in their concessions before illegal loggers get to them (Jepson *et al.*, 2001).

The upsurge in illegal logging has received a significant amount of attention in the Indonesian and international media, which in turn has led to an increasing politicization of the issue. During the 2004 presidential campaign, however, only one major candidate (Amien Rais) made a major policy speech about illegal logging and the need to stop it (*Jakarta Post*, 2004a). Meanwhile, NGOs such as the Forest Watch Indonesia (FWI) have initiated projects to monitor areas where illegal logging is particularly problematic, such as Central Kalimantan. As reported at the 2004 CIFOR workshop, FWI uses logging roads digitized from Landsat ETM+ imagery as the principal means of identifying encroachment of illegal activities in protected areas and concessions where timber harvesting is (theoretically) regulated. One problem with this approach is that the boundaries of many concessions are poorly delineated and may, in some instances, be in error by several kilometres. Therefore, roads that apparently penetrate only hundreds of metres inside purported concessions may not be indicative of illegal activities per se. Until demarcation of concession boundaries improves, it will remain difficult, although not impossible, to pinpoint illegal logging within specific timber concessions using satellite imagery. Moreover, the relatively low overpass frequency of Landsat and new commercial fine-resolution imagery makes monitoring of illegal activity in real time impractical. ERS-2 imagery remains a viable alternative, but radar images are more difficult and costly to obtain and process than most optical data sources. Identification of illegal logging is most likely to succeed if restricted to existing protected areas, many of which are monitored on the ground by both local and international NGOs.

Conclusions

Compared with military reconnaissance satellites, which have played a role in monitoring military developments and arms control treaties, imagery from earth observation satellites possess two advantages. First, it can be widely shared among many users in many countries because it is unclassified, commercially available, or free of charge in some instances; and second, it is highly accessible to a broad range of potential users, including national governments, NGOs and the news media (Baker, 2002). Despite both the wealth of satellite imagery available and the rising concern over deforestation, satellite-based monitoring of forests is still a relatively new activity and varies in quality and consistency depending on the commitment of government and nongovernmental actors. Brazil and several other countries (e.g. India, China, Canada, Japan, USA and in the EU) have invested heavily in satellite technology for environmental monitoring in real time. In theory, the new satellite imagery and mapping techniques coupled with rapid delivery through the Internet should usher in a new era of global transparency in the forestry sector as in other sectors of the environment. In practice, however, several constraints remain, including limited Internet bandwidth in certain parts of the world, lack of transparency and willingness to share image data in a timely fashion (e.g. Indonesia today and Brazil in the recent past), and a dearth of personnel trained in the latest satellite image processing technologies. Improving land cover classification accuracy from satellite imagery, which generally ranges from 80 to 90 per cent, will help to improve confidence in remotely sensed measurements and encourage further adoption of the technology for operational monitoring. Geographers have made a number of key contributions that have improved land cover classification accuracy, including development of novel classification algorithms, addition of ancillary geographic data such as digital elevation, and improved ground reference data (for a more complete description of these contributions, see Franklin & Wulder, 2002). More work is clearly needed, however, on the development of global monitoring standards and methods, which tend to vary from project to project (Table 1).

Perhaps the most encouraging example of applied forest monitoring using remote sensing comes from Brazil, which has released reliable annual estimates of deforestation since 1988. In July 2004, Brazil also began joint-operation of the CBERS-2 environmental satellite for monitoring the Amazon, thus replacing its dependence on the ailing Landsat-7 ETM+ (see Baker & Williamson, 2006; Trigg *et al.*, 2006). Despite the challenge of dealing with deforestation, Brazil has undertaken several successful experiments to slow and even reverse forest loss. Examples include giving private landowners responsibilities and incentives – private landowners in the Legal Amazon are required by law to keep 80 per cent of their land as forest – which may be monitored directly with CBERS-2 and other satellite imagery. In addition, private landowners can receive exemptions from the rural property tax on land that they establish as a privately protected area (*Jakarta Post*, 2004b). Although such land use laws pertaining to the Amazon have been changed several times in the past two decades, satellite imagery can and do provide an important check on whether such laws are having an impact on particular deforestation hotspots.

The Brazilian case stands in stark contrast with that of Indonesia, where transparency and accountability in the forestry sector appears to lag by comparison. However, this may soon change as several NGOs and research institutes have initiated a number of independent forest mapping and monitoring projects. FWI's work provides one example; others include new work by CIFOR, which recently established a programme to map Indonesia's forest nationwide using MODIS imagery. SarVision, a group based in the Netherlands and affiliated with Wageningen University, represents another effort in Kalimantan using ERS-2 and fine-resolution commercial imagery to closely monitor certain areas of forest under threat. International conservation NGOs, such as the Worldwide Fund for Nature, The Nature Conservancy and Conservation International employ satellite imagery to map and monitor areas where they have ongoing biodiversity conservation projects. Yet, despite these disparate efforts, full-scale cooperation among NGOs, private firms, academics and government agencies to share their expertize, satellite data and field information as part of a harmonized forest monitoring system has yet to be realized. At a minimum, such a system could use MODIS or SPOT Vegetation data to produce internally consistent annual estimates of change in forest cover nationwide. An important corollary is that the definition of 'forest' must remain consistent through time and with comprehensive international definitions, such as that put forth by IGBP. Moderate-to-fine spatial resolution systems and information from field surveys could be used to verify coarse-resolution forest maps and discern causes of land cover changes in and around extant forests. Until such a system is established, those concerned with the future of Indonesia's dwindling forests may have to rely on data provided as part of global land cover products released on an ad hoc basis (Hansen *et al.*, 2002; Mayaux *et al.*, 2004), or the new efforts of multinational organizations and research institutes (e.g. CIFOR). However, because of different definitions of forest and classification methods applied to coarse-resolution imagery, such sources may produce different estimates of forest area and distribution and complicate analysis of the situation. Thus, dependence solely on international research institutions is unlikely to meet the needs of a national monitoring programme, which can, nevertheless, stir public debate, reinvigorate policy discussion and enforcement action to reduce illegal logging and further loss of Indonesia's remaining moist tropical forest.

The multinational character of tropical deforestation and its consequences on climate change and biodiversity make it an important emerging global concern that increasingly transcends individual nations and their boundaries. Satellite monitoring of tropical forest cover at various scales and spatial resolutions can play an important role in mitigating conflicts over land use in tropical hinterlands where the rule of law is sometimes weak, as in the case of Indonesia. Countries interested in demonstrating compliance with international agreements and treaties (e.g. FCCC) can buttress claims of sustainable forest management by establishing transparent monitoring regimes that produce reliable annual estimates of forest cover and forest conversion. The frequent forest and agricultural fires and the resultant haze that blankets parts of the tropical world each dry season serve as stern reminders that destruction of tropical forests can negatively affect regional economies and sour relations between neighbouring countries. Thus, if forest monitoring is promoted explicitly as part of regional and global cooperation, it can help defuse regional conflicts and tensions by enhancing transparency and promoting common interests in sustainable environmental management and economic wellbeing.

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