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Tropical forest cover change in the 1990s and options for future monitoring

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Despite the importance of the world's humid tropical forests, our knowledge concerning their rates of change remains limited. Two recent programmes (FAO 2000 Forest Resources Assessment and TREES II), exploiting the global imaging capabilities of Earth observing satellites, have recently been completed to provide information on the dynamics of tropical forest cover. The results from these independent studies show a high degree of conformity and provide a good understanding of trends at the pan-tropical level.

In 1990 there were some 1150 million ha of tropical rain forest with the area of the humid tropics deforested annually estimated at 5.8 million ha (approximately twice the size of Belgium). A further 2.3 million ha of humid forest is apparently degraded annually through fragmentation, logging and/or fires. In the sub-humid and dry tropics, annual deforestation of tropical moist deciduous and tropical dry forests comes to 2.2 and 0.7 million ha, respectively. Southeast Asia is the region where forests are under the highest pressure with an annual change rate of −0.8 to −0.9%. The annual area deforested in Latin America is large, but the relative rate (−0.4 to −0.5%) is lower, owing to the vast area covered by the remaining Amazonian forests. The humid forests of Africa are being converted at a similar rate to those of Latin America (−0.4 to −0.5% per year).

During this period, secondary forests have also been established, through re-growth on abandoned land and forest plantations, but with different ecological, biophysical and economic characteristics compared with primary forests. These trends are significant in all regions, but the extent of new forest cover has proven difficult to establish.

These results, as well as the lack of more detailed knowledge, clearly demonstrate the need to improve sound scientific evidence to support policy. The two projects provide useful guidance for future monitoring efforts in the context of multilateral environmental agreements and of international aid, trade and development partnerships. Methodologically, the use of high-resolution remote sensing in representative samples has been shown to be cost-effective. Close collaboration between tropical institutions and inter-governmental organizations proved to be a fruitful arrangement in the different projects. To properly assist decision-making, monitoring and assessments should primarily be addressed at the national level, which also corresponds to the ratification level of the multilateral environmental agreements. The Forest Resources Assessment 2000 deforestation statistics from countries are consistent with the satellite-based estimates in Asia and America, but are significantly different in Africa, highlighting the particular need for long-term capacity-building activities in this continent.

Keywords: tropical forests; deforestation; Earth observation; forest monitoring; 1990s; remote sensing

1. INTRODUCTION

The value of forests to the world's human population is becoming increasingly evident. The importance of their role in our planet's functioning is clearly reflected in multilateral environmental agreements such as the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity. Yet demographic, economic and social changes around the world continue to exert considerable pressure on forest cover and condition.

Among the various factors affecting biodiversity on Earth, land use change in the tropical forest biome is considered as a major one for three reasons:

(i) Tropical forests, although covering less than 10% of the land area, represent the largest terrestrial reservoir of biological diversity, from the gene to the habitat level. For example, more than 50% of known plant species grow in tropical forests.

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(ii) Tropical forests suffer from rapid land use changes (Achard *et al.* 2002). Agricultural expansion, commercial logging, plantation development, mining, industry, urbanization and road building are all causing deforestation in tropical regions (Geist & Lambin 2002).
(iii) Recent studies (Sala *et al.* 2000) have suggested that land use changes are likely to have a greater impact on biodiversity reduction than climate change, nitrogen deposition, biotic exchange or increased carbon dioxide concentrations.

A proper evaluation of tropical forest resources implies a response to a set of simple questions:

(i) Where are the forested areas?
(ii) How much tropical forest remains?
(iii) What are the changes that have affected and will affect those ecosystems?

While many developed countries have built up detailed national forest inventories, global scale assessments of tropical forest distribution and how it is changing have received attention from the scientific community only since the early 1990s, and current programmes still vary in terms of methods and results. Our understanding of the magnitude and the location of deforestation is imprecise owing to the geographically concentrated pattern of the phenomenon, which reduces the efficiency of the sampling techniques.

Some important tropical countries, like Brazil, India and Malaysia, are putting considerable effort into producing accurate forest inventories at the national level. The Forest Survey of India was created in 1981 with the objective of monitoring periodically (every 10 years) the changing situation of land and forest resources. Nowadays, it produces, every 2 years, vegetation maps that combine high-resolution remote sensing images with ground data. The Brazilian Space Agency (INPE 2003) has, for the last 15 years, produced annual deforestation estimates based on an exhaustive coverage of high-resolution satellite images. Those surveys conducted at the national level have the clear advantage of being closely linked both to ground surveys and to decision-makers.

The current paper addresses the progress, needs and requirements for monitoring of forest extent and condition at the pan-tropical level. We distinguish different types of tropical forest based on the duration of the dry season (FAO 2001): tropical rain forests or humid forests (0–3 months dry), tropical moist deciduous forests (3–5 months dry) and tropical dry forests (5–8 months dry), with a dry month defined as one where the total rainfall (expressed in mm) is lower than twice the mean temperature (expressed in °C).

Pan-tropical forest monitoring should fulfil the following requirements: it should be based on a forest map at continental scale, have consistency in data acquisition and interpretation, possess minimal error in forest area estimates and be capable of delivering measurements of change. Earth observation images, thanks to their synoptic and repetitive view, provide suitable data for mapping the spatial extent of large and inaccessible tropical forests and how this changes over time. Different techniques have been developed combining the daily frequency of coarse spatial resolution images with the high spatial detail of less frequent images.

The paper reviews the state of the art of programmes dealing with tropical forest assessment, including the inventory and monitoring components. We begin by examining what we know about the spatial distribution and the areal extent of tropical forests and move on to look in detail at methods for measuring overall deforestation rates (by sampling) and deforestation in specific locations (from exhaustive coverage around protected areas or in sensitive ecosystems). We explore these issues using results from three recently completed programmes (FAO 2000 Forest Resources Assessment, TREES II and Advanced Very High-Resolution Radiometer (AVHRR) Pathfinder), all of which exploit the global imaging capabilities of Earth observing satellites. The results from these independent studies show a high degree of conformity and provide a good understanding of trends at the pan-tropical level.

2. GLOBAL TROPICAL FOREST MAPS AND INVENTORIES

The first World Forest Inventory was proposed by FAO in 1945 (Holmgren & Persson 2002), followed by regional assessments and global synthesis in the 1970s (e.g. Persson 1974; Sommer 1976). The first assessments of the world's tropical forest cover incorporating aspects of deforestation are relatively recent (Myers 1980; Lanly 1982). They were based on country studies that were summed to provide global estimates. Owing to the lack of reliable data, much discussion has focused on the accuracy of the information. Myers (1989, p.9) recommended the use of remote sensing data to improve the global assessments and he commented that "it is curious that remote sensing data are not available on a biome-wide basis to establish the present status of all tropical forests". In the early 1990s, a few initiatives based on remote sensing data were launched by several organizations, including the Food and Agriculture Organization of the United Nations (FAO), the European Commission Joint Research Centre (JRC) and the National Aeronautics and Space Administration (NASA), in order to establish a reliable baseline inventory of tropical forest resources.

Estimates based on Earth observation images were conducted, some using a sampling procedure (as in traditional forest inventories), and others adopting exhaustive mapping. This latter option has the clear advantage of providing data on the spatial distribution of forests for geographical analysis, while the sampling technique provides accurate estimates with error bars (Czaplewski 2002), but without information on spatial distribution.

(a) *Global land-cover and forest mapping*

Tucker *et al.* (1985) and Townshend *et al.* (1987) demonstrated that it was possible to map land-cover

Table 1. Main global land-cover maps derived from remote sensing data 1 km spatial resolution.

title	author	domain	sensor	methods
International Geosphere–Biosphere Program (IGBP)	Loveland *et al.* (1999)	global	AVHRR	12 monthly vegetation indices from April 1992 to March 1993
University of Maryland (UMD)	Hansen *et al.* (2000)	global	AVHRR	41 multi-temporal metrics from composites from April 1992 to March 1993
TREES	Mayaux *et al.* (1999) and Eva *et al.*(1999)	humid tropics	AVHRR	Mosaics of single date classifications of cloud-free images (1992–1993)
FRA-2000	FAO (2001)	global	AVHRR	Updated from the IGBP dataset
MODIS-land-cover	Friedl *et al.* (2002)	global	MODIS-Terra	12 monthly composites of 8 parameters from October 2000 to October 2001
Global Land-Cover (GLC) 2000	Eva *et al.* (2004), Mayaux *et al.* (2004) and Stibig *et al.* (2003)	global	SPOT-VEGETATION	365 daily mosaics of 4 channels + 36 temporal vegetation indices profiles for 2000

of a whole continent in a consistent way for a specific year using 4 km spatial resolution imagery (Global Area Coverage) obtained daily from the AVHRR on board the US National Oceanic and Atmospheric Administration's polar orbiting meteorological satellites. DeFries *et al.* (1998) produced global land-cover maps at 8 km resolution. Under the auspices of the International Geosphere–Biosphere Program (IGBP), Loveland *et al.* (1999) published the first pan-continental map at 1.1 km spatial resolution derived from a single data source (the AVHRR local area coverage), and made over a fixed time period (April 1992 to end of 1993). From the same dataset, the University of Maryland (Hansen *et al.* 2000) proposed a new legend and new classification techniques.

In the tropical forest domain, AVHRR 1.1 km data were also used for producing pan-tropical forest maps, with classification techniques adapted to the ecological conditions of this area, e.g. low seasonality, and nearly permanent cloud coverage (Achard *et al.* 2001; Eva *et al.* 1999; Mayaux *et al.* 1999). These AVHRR-based products have been well received by the global change community, but did not satisfy new user communities, such as biodiversity NGOs and aid agencies, who required better spatial and thematic detail. Indeed, the AVHRR dataset had shown its radiometric and geometric limitations for land-cover mapping at 1 km resolution and a unique global legend was not appropriate to national or continental studies (table 1).

Recently, new sensors, MODIS on board the Terra and Aqua platforms (Friedl *et al.* 2002) and VEGETATION on board SPOT-4 and SPOT-5, 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. In order to increase the global acceptance by most users, the JRC decided to produce a global land-cover map (Global Land-Cover (GLC) 2000) in partnership with 30 institutions, using SPOT-4 VEGETATION data for the year 2000 (Bartholomé & Belward 2004). Teams of regional experts mapped each continent independently. Each regional team participating in the project had experience of mapping their area through the use of data from Earth observing satellites. This ensured that optimum image classification methods were used, that the land-cover legend was regionally appropriate, and that access could be gained to reference material. The GLC 2000 philosophy dictates that these regionally detailed classes also be aggregated into a thematically simpler global legend, especially that of Loveland *et al.* (1999). To achieve this, the classes for the regional GLC 2000 maps have been described through the land-cover classification system (LCCS). LCCS was developed by the FAO to analyse and cross-reference regional differences in land-cover descriptions (Di Gregorio & Jansen 2000). LCCS describes land-cover according to a hierarchical series of classifiers and attributes (vegetated or non-vegetated; terrestrial or aquatic/flooded; cultivated and managed; natural and semi-natural; life-form; cover; height; spatial distribution; leaf type and phenology).

Figure 1 illustrates the distribution of tropical forests in the GLC 2000 map. The spatial detail is shown in the insets from three continents. Note the concentration of forest in protected areas, both in the fringes of the Amazon basin and in continental Southeast Asia. The forest cover in Central Africa is fragmented by a dense network of tracks.

(b) *Global forest area estimates*

Different approaches have been developed for producing statistics on the global extent of tropical forests:

- (i) compilation of national inventories or maps (FAO 1993; Collins *et al.* 1991; Sayer *et al.* 1992; Harcourt & Sayer 1996);
- (ii) statistical sampling with high spatial resolution satellite images (FAO 1996);
- (iii) global coverage of forested areas by remote sensing data at fine spatial resolution (Skole & Tucker 1993) or at coarse resolution (Malingreau *et al.* 1995).

Each method suffers from its own limitations, detailed in Mayaux *et al.* (1998), but the main problems are as follows:

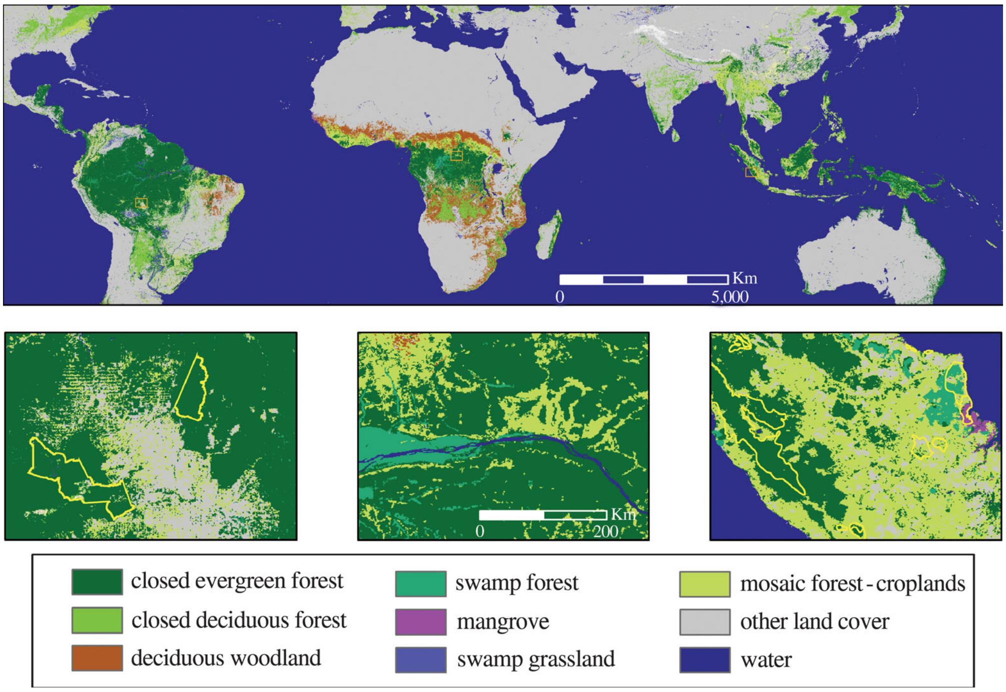

Figure 1. Tropical forest distribution derived from the Global Land-Cover 2000 map with insets from South America, Central Africa and Southeast Asia. One can see that in South America and Southeast Asia, protected areas (in yellow) are threatened by deforestation.

Table 2. Tropical forest areas derived from the GLC 2000 map (Bartholomé & Belward 2004), from the FRA-2000 national statistics (FAO 2001; table 5) and from the FRA-2000 remote sensing survey.
(GLC 2000 and FRA CS statistics presented here cover only the tropical countries; the FRA RS estimates refer to forest definition, which includes closed forest, open forest, long fallow and one third of fragmented forest.)

	GLC 2000 (TREES) humid tropical forests (10^6 ha)	dry tropical forests (10^6 ha)	flooded tropical forests (10^6 ha)	FRA CS closed forest (10^6 ha)	open forest (10^6 ha)	FRA RS forest (10^6 ha)
South America	630.5	146.7	25.3	858.3	68.9	780.2
Africa	232.7	415.1	13.1	352.7	288.9	518.5
Asia	230.6	144.8	13.5	416.2	58.3	272.2
Global	1093.8	706.6	51.9	1627.2	416.1	1571.9

(i) Differences in forest definition and in inventory methodologies reduce the consistency of compilation of national data.
(ii) In the case of spatially correlated data, such as forest distribution, sampling may yield a more accurate estimate when it is based on a large number of small units, but the current studies instead used a sample of a few large units (Landsat scenes).
(iii) The estimation of land-cover proportions directly from broad-scale maps is associated with a systematic bias owing to spatial aggregation effects (Mayaux & Lambin 1995). A correction procedure has then to be applied to account for the spatial aggregation errors (Mayaux & Lambin 1997).

Moreover, in each assessment, 'forest' is defined in very different terms, based on a different cover threshold and with some land-use characterization. Therefore, forest area figures differ considerably among the projects, as illustrated in table 2.

3. GLOBAL TROPICAL FOREST MONITORING

(a) *Assessing overall deforestation rates at regional and global scales*

As tropical deforestation is considered a major environmental problem, many studies have aimed to measure the extent of the phenomenon and model the drivers of change (Geist & Lambin 2002). Most studies have been conducted at a local or national level and have been based on wall-to-wall coverage of satellite images or aerial photographs (e.g. Nelson & Holben 1986; Lucas *et al.* 2000; Alves 2002). For a complete review of the change detection techniques used in remote sensing, see Lu *et al.* (2003) and Coppin *et al.* (2004).

When scaling up the estimates to the global scale, three main methods have been tested:

(i) Gathering information through reports, national statistics and independent expert opinions (FAO 1993, 2001). This approach can focus on specific national situations, but is limited by heterogeneity across countries in methods and in definitions of forests.

(ii) Measuring change using fine resolution satellite imagery on a sampling basis (FAO 1996, 2001; Achard *et al.* 2002). This approach exploits the fine spatial resolution of the Landsat Thematic Mapper (TM) and SPOT high-resolution visible images but requires a sampling strategy designed to take account of their spatial variability. Czaplewski (2002) demonstrated the sampling approaches used can provide accurate estimates at regional level.
(iii) Measuring change using coarse resolution satellite imagery (DeFries *et al.* 2002). This novel approach measures changes in per cent tree cover (PTC) and can detect forest degradation, but must be carefully calibrated with local studies.

We now move on to describe in more detail the main programmes underway for assessing tropical deforestation at a global scale.

(b) *The FAO Forest Resources Assessment 2000*

The global Forest Resources Assessment (FRA) is based primarily on available information provided and validated by national authorities on a range of forest-related topics, including forest area and area change. Classifications and methodologies used in the forest inventories often differ from country to country, as they are adapted to national objectives and to the local ecological context. Another important conclusion from FRA has been that in many countries, especially developing ones, information and knowledge on forestry remains poor: data are often obsolete, partial or lacking. Very few countries have established a stable monitoring system to generate time-series data on forest resources in a way that is consistent over time, and can thereby produce reliable information on forest trends. This is particularly true in Africa, where major capacity-building efforts are needed.

Addressing these concerns, the FRA programme has implemented, since FRA 1990, independent remote sensing surveys (RS) of forest cover changes to complement the approach based on country information. The main objective of the FAO RS is 'to contribute to the improvement of the global forest area estimate and to achieve the highest level of consistency and precision in the assessment of forest cover changes at global and regional levels' (FAO 1996). The FAO RS has been based on a sample of 117 multi-date Landsat TM scenes covering 10% of the tropical forest. A two-stage stratified random sampling method has been applied, using first the geographical region and second, the forest cover derived from vegetation maps. Multi-date Landsat scenes from three points in time (around 1980, 1990 and 2000 $\pm$2 years) have been analysed by local teams using interdependent interpretation of satellite image prints at a scale of 1:250 000. Nine land-cover classes have been identified, out of which, four are 'forest' classes, namely closed forest (canopy cover $>$40%), open forest (canopy cover 10–40%), long fallow (forest affected by shifting cultivation) and fragmented forest (forest/non-forest mosaic). The area estimates have then been based on dot-grid counting applied to the visual interpretations with a grid-size of 2×2 km^2. The multi-date analysis provides estimates of forest cover area and forest cover changes with associated confidence intervals. Land-cover transition matrices between 1980 and 1990 can also be derived from the multi-date analysis. Those matrices characterize the changes and can provide useful insights on the deforestation processes themselves. The surveys produced estimates of state and change at the regional, ecological and pan-tropical levels but not at the national level. The FAO RS forest statistics are thus comparable to those of other surveys only at the continental scale.

(c) *TREES*

Initiated in the early 1990s, the TREES project was designed to help develop forest cover assessment throughout the tropics. This project made use of an extensive set of satellite data. The main objectives of the TREES I project were:

(i) to develop techniques for global tropical forest mapping;
(ii) to develop techniques for monitoring areas of active deforestation;
(iii) to set up a comprehensive tropical forest information system.

The ultimate goal was to establish an operational observing system that could detect and identify changes in global tropical forest cover.

The primary objectives of the TREES II phase were to use a new remote sensing-based approach to produce relevant information, more accurate than that currently available, on the state of humid tropical forest ecosystems, and to analyse this information in terms of deforestation and forest degradation trends. This involved six main technical steps:

(i) the establishment of sub-continental forest distribution maps for the early 1990s at 1:5 000 000 scale, derived from 1 km^2 spatial resolution satellite images;
(ii) The generation of a deforestation risk map, identifying so-called 'deforestation hot spot areas' using knowledge from environmental and forest experts from each region;
(iii) The definition of five strata defined by the 'forest' and 'hot spot' proportions obtained from the previous steps;
(iv) The implementation of a stratified systematic sampling scheme with 100 sample sites covering 6.5% of the humid tropical domain. The precision of the estimates of change was enhanced by having higher sampling probabilities in deforestation hot spots;
(v) The assessment of change at each site, based on fine spatial resolution (20–30 m) satellite imagery acquired at two dates closest to our target years (1990, 1997), interpreted by local partners using a common approach (figure 2);
(vi) The statistical estimation of forest and land-cover transitions at continental level using linear

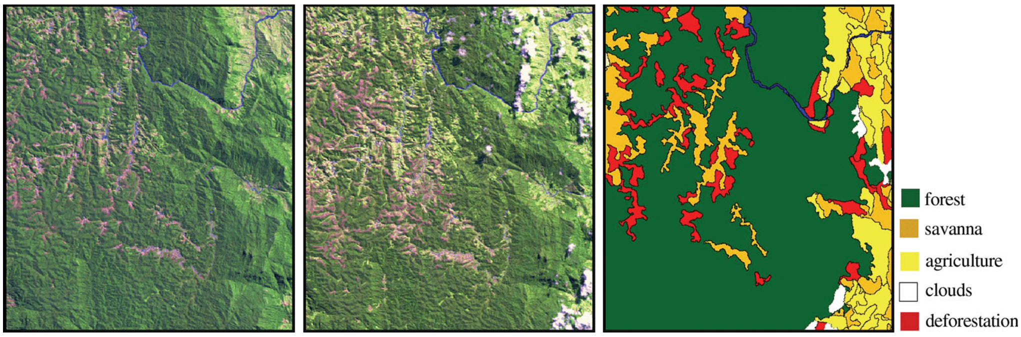

Figure 2. Image interpretation procedure over an observation unit of the TREES II project in Madagascar.

Table 3. Technical specifications of the FRA 2000 and TREES II strategies for sampling and interpretation.

	FRA 2000 (RS)	TREES II
domain	dry and humid tropics	humid tropics
dates	1980, 1990, 2000	1992, 1997
sampling strategy	two-stage stratified random sampling based on regions and forest cover	two-stage stratified random sampling based on regions, deforestation hot spots and forest cover
sampling frame	Landsat reference system	hexagonal tessellation (equal-area)
sampling units	117 (population = 1203)	104 (population = 740)
imagery	Landsat full scenes	Landsat (full and quarter scenes according to the landscape complexity)
interpretation	visual interdependent interpretation	visual interdependent interpretation
legend	2 levels: 9 fixed classes + 12 options	hierarchical scheme (life form, cover, water regime…)
digital files	grid 2×2 km^2	full interpretation
aggregation	continent, global, ecological zone	continent, global

interpolation between the two reference dates: 1 June 1990 and 1 June 1997.

Table 3 details the technical differences between the FRA 2000 and TREES sampling strategies and interpretations.

(d) *AVHRR Pathfinder*

Work funded by NASA provides a complementary approach to the TREES and FRA 2000 projects (DeFries *et al.* 2002). While the TREES and FRA 2000 projects examine deforestation with samples of high-resolution Landsat imagery, the NASA-funded project examines the full spatial extent of the tropics but at a much coarser resolution of 8 km. The study uses the 8 km Pathfinder dataset acquired by the AVHRR—the only dataset with comprehensive global coverage extending back in time—to estimate subpixel PTC from the early 1980s to the late 1990s. For each year, the PTC is estimated by a regression analysis using a global network of training areas derived from over 200 Landsat scenes and aggregated to the 8 km resolution of the AVHRR data. Inputs to the regression are monthly data from the AVHRR channels that characterize the vegetation's spectral reflectance and phenology. For each pixel, the median value of three periods (1982–1987, 1988–1992 and 1992–1999) is computed. A pixel is labelled as changed when its estimated PTC has changed by more than 14%. The area affected by the changes and the equivalent area deforested is then calculated after calibration with the results of five regional relevant Landsat-based studies. By calibrating the changes in PTC with available analyses from high-resolution data, the study provides the spatial extent and location of changes in tropical forest area for the past two decades.

(e) *Comparative global results from the different studies*

In the following section, we examine how the results of the three programmes compare with one another, using the definitions reported by FRA 2000 (FAO 2000). Deforestation refers to depletion of tree crown cover to less than 10%. Changes within the forest class (e.g. from closed to open forest) which negatively affect the stand or site and, in particular, lower the production capacity, are termed forest degradation. Thus, degradation is not reflected in the estimates of deforestation. Reforestation refers to establishment of forest on land that had recent tree cover, whereas afforestation refers to land that has been without forest for much longer.

(i) *Deforestation rates*

As already mentioned the initiatives aiming at measuring deforestation adopt different methods and use different forest definitions and different source data. However, it is possible to synthesize the results from TREES and FRA 2000 (table 4). The continental FRA 2000 statistics aggregate all the tropical forest types (rain forest, moist deciduous forest and dry forest), while the deforestation figures by forest type are only available at the global scale. This precludes any direct comparison with the TREES results at the continental level, since TREES covers only the humid tropics. At pan-tropical scale, the annual deforestation area for the humid tropics is estimated by the two studies at 4.9 and

Table 4. Humid tropical forest cover estimates for the TREES II project, the FRA 2000 programme and the AVHRR time-series analysis.

	Latin America	Africa	Southeast Asia	pan-tropical
TREES[a] *(1990–1997)—humid tropical forests*				
forest cover in 1997 (10^6 ha)	653	193	270	1116
net annual deforested area (10^6 ha)	2.2 ± 1.2	0.7 ± 0.3	2.0 ± 0.8	4.9 ± 1.3
annual regrowth area (10^6 ha)	0.28 ± 0.22	0.14 ± 0.11	0.53 ± 0.25	1.0 ± 0.32
annual degraded area (10^6 ha)	0.83 ± 0.67	0.39 ± 0.19	1.1 ± 0.44	2.3 ± 0.71
mean deforestation rate (%)	0.33	0.36	0.71	0.43
FRA 2000 Remote Sensing Survey[b] *(1990–2000)*				
forest cover in 2000 (10^6 ha)	780	519	272	1571
Net annual deforested area (10^6 ha; all tropical forests)	4.2 ± 1.1	2.1 ± 0.4	2.3 ± 0.6	8.6 ± 1.3
mean deforestation rate (%)	0.51	0.34	0.79	0.52
net annual deforested area (10^6 ha; humid tropical forests)	—	—	—	5.7 ± 1.2
mean deforestation rate (%; humid tropical forests)	—	—	—	0.51
FRA 2000 Country Survey[c] *(1990–2000)*				
net annual deforested area (10^6 ha)	2.7	1.2	2.5	6.4
AVHRR Pathfinder (1990s)				
net loss of tree cover, calibrated to Landsat-based studies (10^6 ha)	3.18 (1.69–4.04)	0.38 (0–0.66)	2.01 (0.82–3.17)	5.56 (2.51–7.87)

[a] Area estimates can differ from table 2 because the TREES and GLC 2000 domains are different in Africa (Angola, Ethiopia and East Africa are not included in the TREES domain) and because semi-deciduous forests (dry dipterocarp forests) are included in the TREES study in Asia. Latin America also includes Central America in this table.
[b] The FRA RS estimates refer to forest definition, which includes closed forest, open forest, long fallow and one third of fragmented forest.
[c] Only the national statistics of the countries covering the TREES domain are included in the current table.

5.7 million ha respectively, an area approximately twice the size of Belgium. A further 2.3 million ha per year of humid forests are detected as degraded by fragmentation, logging or fires. In the sub-humid and dry tropics, annual deforestation for the tropical moist deciduous and the tropical dry forests comes to 2.2 and 0.7 million ha, respectively.

In respect to the 2010 Biodiversity Target, it is difficult to provide reliable information on the temporal evolution of the deforestation rates. FAO compared the deforestation rates in the 1980s with the 1990s, but found no statistically significant trends, except for a decreasing rate in tropical moist deciduous forests (FAO 2001). The AVHRR analysis indicates that the net rate of tropical forest clearing increased approximately 10% from the 1980s to the 1990s, but with a standard error for the three 5-year intervals considered (1982–87, 1988–92 and 1992–99) at 11% (DeFries *et al.* 2002). Clearly, more investigation is needed on temporal changes in deforestation rates.

(ii) *Deforestation hot spots*

Deforestation risk areas were identified by the TREES project using the baseline forest cover maps of the early 1990s in conjunction with knowledge from forestry and environmental experts (Achard *et al.* 1998). DeFries *et al.* (2002) also provided a map of the most active deforestation zones derived from analysis of the time-series of PTC. For the Amazon basin, Skole and Tucker (1993) produced deforestation maps from Landsat time-series. A graphical synthesis of the three approaches is presented in figure 3 (from Lambin *et al.* 2003).

The hot spot maps dramatically illustrate that deforestation is an ongoing process. The apparently irreversible decline of natural forest resources leads one to seriously consider whether conservation efforts should maintain a focus on sustainable forest management practices. Considering that agricultural expansion is the main cause of deforestation (Geist & Lambin 2002), one may wish instead to concentrate on the preservation of a few intact areas not identified as current or impending hot spots, that one might call ‘cool spots’.

(f) *Regional variation*

The three continents reveal considerable differences in change rates measured by the TREES project. In relative terms, Southeast Asia has the highest annual rate of deforestation while Africa is losing its forests at about half this rate. Latin America shows the lowest relative deforestation rate but at 2.5×10^6 ha yr^{-1}; in absolute terms this is almost the same as that estimated for Southeast Asia. Forest degradation shows a similar overall pattern. It is most prominent in Southeast Asia, intermediate in Africa, and lowest in Latin America. It is worth mentioning that these estimates represent only those elements of degradation that can be identified from satellite imagery, and do not include processes such as selective removal of trees. Reforestation is most evident in Southeast Asia, where it arises mainly from the transition of former mosaics and woodland to forest. It is less widespread in Latin America and is limited in Africa.

(i) *Latin America*

The South American tropical rain forests are currently being cleared along a large belt extending from the

Figure 3. Main tropical deforestation fronts in the 1980s and 1990s from Lambin *et al.* (2003) and Lepers *et al.* (in press). The map is based on the deforestation hotspots in the humid tropics of the TREES project (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 & Tucker 1993). The map indicates the number of times each 0.1° grid was identified as being affected by rapid deforestation by the different datasets (pink = 1, red = 2, dark red = 3).

eastern to the southern portions of the Amazon basin. Large areas of deforestation are found on the Peruvian and Ecuadorian lower foothills of the Andes. Inside the basin, pockets of deforestation are associated with settlements and roads. Deforestation is reported to be on the increase in the coastal forests of Colombia and Ecuador and in Guyana (Jimeno *et al.* 1995). In Central America, the forest remnants are highly fragmented. Fragments are being progressively reduced and only those areas which are inaccessible or legally protected seem to be somewhat secure. Large areas of forest are also becoming isolated at the regional level, highlighting the urgent need for establishing biological corridors. Agricultural expansion and new settlements are the main causes of deforestation on this continent. The transformation from closed, open or fragmented forests to agriculture by clear-cutting is a predominant factor. Moreover, about 4 million ha of mosaic or savannah woodland have been transformed into agriculture. Two-thirds of this transformation is happening in the Brazilian Amazon region (Achard *et al.* 2002).

(ii) *Africa*

Deforestation in the Congo basin is still limited to relatively few areas, and large-scale clear-cutting or significant agricultural expansion is not expected to take place very soon. Furthermore, the secondary forest vegetation may act as a buffer if an acceleration of slash-and-burn cultivation takes place locally. The causes of deforestation are manifold, ranging from agricultural encroachment and illegal logging in Cameroon to urban expansion and fuel wood supply around the major cities and refugee migrations in Liberia and eastern Democratic Republic of Congo (DRC). Shifting cultivation mainly occurs in secondary forest mosaics and only partially affects the closed primary forests. Agricultural colonization follows a diffuse spatial pattern, with population pressure being particularly high in eastern DRC. Selective logging plays an indirect role, with logging roads facilitating greatly increased hunting pressure from poachers. The upper Guinea forest in West Africa and eastern forests of Madagascar contain exceptional biological diversity. Both are under severe deforestation owing to slash-and-burn agriculture, logging and mining.

(iii) *Southeast Asia*

In Southeast Asia, most of the forest remnants of both continental Southeast Asia and the Indo-Malay Archipelago fall within current hot spots. The extensive forest resources of northeastern India are under intensive exploitation for timber and conversion to agriculture. Selective logging and clear-cutting affect many forests of Myanmar, central and southern Laos and Cambodia. Shifting cultivation has led to further forest loss in northeastern India and the northern parts of Myanmar, Laos and Vietnam. In Myanmar the impact of shifting cultivation is believed to be on the increase. Plans for China to open various access roads and railways from Yunnan to the Andaman Sea are likely to have a serious impact on the forest remnants of the 'golden triangle'. In Vietnam, conversion of the remaining natural forest is still widespread in the central highlands, while the forest fragments in the north are rapidly being eroded. The forests in Indonesia have in recent years suffered some of the most severe deforestation of anywhere. In Sumatra, forests have virtually disappeared under the pressure of agriculture and plantations along a wide central south-north belt. A similar situation has developed in Kalimantan, where plantations, but also extensive exploitation and large-scale fires, have taken their toll. No reversal of such trends is likely to emerge in the near future.

(g) *Estimating deforestation in specific areas*

Global or regional statistics, although very useful for evaluating long-term extinction risks of species or families, can hide very dramatic local situations in areas of high biological interest or in regions where forests represent the major source of revenue. In those areas, specific strategies must be developed for refining the estimates. We will now illustrate possible strategies for two specific domains: protected areas and

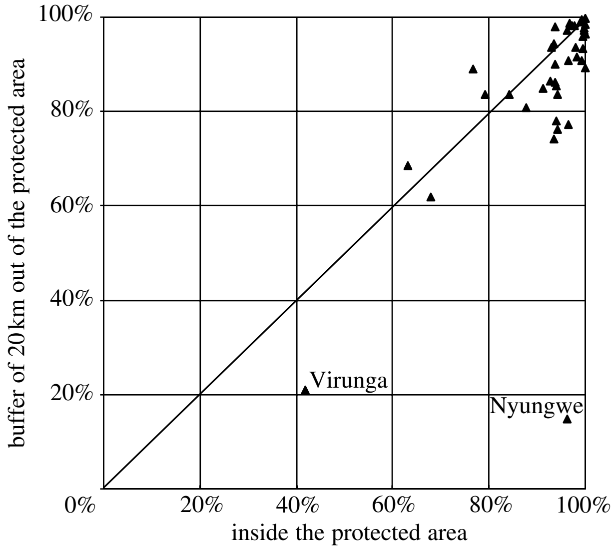

Figure 4. Forest percentage extracted from the GLC 2000 map for 40 Central African protected areas and their 20 km buffer zone.

mangroves. Other high biodiversity areas, such as swamp forests, mountain forests or Important Bird Areas, may benefit from similarly detailed analysis.

(i) *Protected areas*

The Convention on Biological Diversity defines a protected area as: 'a geographically defined area which is designated or regulated and managed to achieve specific conservation objectives'. These objectives range from the preservation of endangered species or landscapes to the protection of natural ecosystems. About 15% of tropical rain forests fall in protected areas, a similar proportion to that for other forest types (FAO 2001).

In the humid tropics, protected areas have often been imposed on and therefore resented by local people, resulting in opposition to their establishment and erosion of their resources. New conservation approaches developed since the early 1990s, have sought to involve local populations far more closely, but land-cover changes are still widespread in protected areas. For example, Curran *et al.* (2004) showed from a series of Landsat data, that from 1985 to 2001, Kalimantan's protected lowland forests declined by more than 56% (more than 2.9 million ha). They note that even uninhabited frontier parks have been logged to supply international markets, while buffer zones have been subject to considerable degradation.

Coarse resolution maps also allow for measurement of the forest cover of protected areas and surrounding regions. In Central Africa, forest cover percentage was assessed from the GLC 2000 map in 40 protected areas and in their buffer zone (within two concentric circles of 20 and 40 km) by pixel-counting. The forest cover within the protected areas is on average 94.2%, i.e. 4.6% higher that the cover in the 0–20 km buffer (figure 4), with no difference between the 0–20 and 20–40 km buffer rings. Two specific cases are noted: the Nyungwe National Park in Rwanda and the Virunga National Park in DRC, both in the densely settled fringes of the Congo basin. In both cases, remaining forest cover is now confined to the protected areas.

DeFries *et al.* (2004) derived data from the AVHRR Pathfinder dataset on the progressive isolation of protected areas in the three tropical continents between the early 1980s and 2001. Across 163 protected areas, mean forest cover was reduced from 85.3 ± 11.5 to $83.5 \pm 12.6\%$. The largest reduction was noted in tropical Asia (from 82.3 to 79.6%). The loss of forests was more dramatic in the surrounding zones (from 74.7 ± 19.5 to $69.6 \pm 20.5\%$ in a 50 km buffer). These results emphasize the need for the integrated management of the protected areas of tropical forest.

(ii) *Mangroves*

Mangroves are among the most productive ecosystems on Earth. In addition to protecting the coast against erosion owing to wind, waves and water currents, mangroves also host very many animal species (including endangered mammals, reptiles, amphibians and birds), provide nutrients to the marine food web, and act as spawning grounds for a variety of fishes and shellfish, including several commercial species (FAO 1994). However, the world's mangroves are under pressure as they often lie close to areas that are densely settled, or used for potentially damaging activities such as oil extraction. Mangroves are being lost as rivers are dammed, their waters diverted, and the intertidal zone developed for agriculture or aquaculture. Large tracts have been converted to rice fields, fishes and shrimp ponds, industrial and land development and other non-forest uses.

A recent initiative by the FAO aims at facilitating access to comprehensive information on the current and past extent of mangroves in all countries and areas in which they exist. More than 2800 national and sub-national datasets have been collected, covering 121 countries, with the earliest estimates dating back to 1918 (http://www.fao.org/forestry/site/1720/en). This represents the largest dataset available on temporal changes in mangrove extent. Inconsistencies in definitions and methods between assessments and surveys make it difficult to compare results over time and extrapolation to 2000 has been constrained by the lack of recent information from a number of countries. The resulting estimate (table 5) is thus indicative only and is likely to change when results from on-going and future assessments become available.

Nevertheless, the results suggest that current mangrove area worldwide has now fallen below 15 million ha, down from 19.8 million ha in 1980, and that mangrove deforestation continued in the 1990s, albeit at a slightly lower rate ($\sim 1\%\ yr^{-1}$) than in the 1980s ($\sim 2\%\ yr^{-1}$, Valiela *et al.* 2001) reflecting the fact that most countries have now banned the conversion of mangroves for aquaculture purposes and require environmental impact assessments prior to large-scale conversion of mangroves for other uses. It must be stressed that the deforestation rate of mangroves is about double the rate observed for rain forests. Mangrove area figures derived from the

Table 5. Mangrove area and annual changes in area estimated from national statistics by FAO, together with mangrove area calculated from the GLC 2000 map.

region	mangrove area 1990(10^3 ha)	mangrove area 2000 (10^3 ha)	annual change 1990–2000		area GLC 2000 (10^3 ha)
			10^3 ha	%	
Africa	3659	3351	−12	−0.3	3278
Asia	7857	5833	−86	−1.4	5074
South America	3802	1974	−23	−1.1	1789
World	19 809	14 653	−171	−1.1	—

GLC 2000 map are very similar to those extrapolated by the FAO.

4. FUTURE MONITORING OPTIONS

(a) *Mapping global land-cover at medium resolution*

New prospects for global forest and land-cover mapping emerge from recent developments of satellite sensors that acquire satellite imagery at 'medium' spatial resolution (180–300 m). While still maintaining a global or regional view of the Earth's surface, the improved spatial detail of such images raises the prospect of better addressing land-cover information needs at global and regional, but also at sub-regional and national levels. Indeed such data could establish the link between global and local observations. The first GLC mapping approaches, such as the mapping of percentage tree cover (Hansen *et al.* 2003), highlight the advantages provided by the new sensors. A study on vegetation mapping in northern India has demonstrated the suitability of the new satellite imagery for mapping even complex land-cover patterns at sub-regional scales (Roy & Joshi 2002). Moreover, preparatory studies (Townshend & Justice 1988) have shown that monitoring of land-cover change should be feasible in a regional context. Ponzoni *et al.* (2002) showed that the optimal value for a simple discrimination between forest and non-forest areas was 200 m. In terms of forest cover, conversion and clear cuts of 10–20 ha may be documented. In order to provide the scientific community with more precise information on the spatial distribution of habitat types, the JRC and the European Space Agency are now starting the production of a GLC map for the year 2005 at 300 m spatial resolution.

(b) *Estimating global and regional deforestation rates*

The main lesson for future operational assessments of forest cover change in the tropics is to make use of approaches similar to those adopted by FRA 2000 and TREES II, with the following recommendations:

(i) to orient the sampling procedure towards 'change', i.e. make use of stratified sampling;
(ii) to integrate coarse resolution satellite results in the stratification procedure as *a priori* information on broad forest distribution and fragmentation;
(iii) to integrate knowledge on deforestation hot spots in order to make sampling and stratification more efficient;
(iv) to use a higher number of observations in tropical forests, in order to increase precision and accuracy;
(v) following the example of FRA 2000, to expand assessment to the dry tropical domain, and consider global coverage. Most attention to date has been paid to humid tropical forests, while uncertainty remains regarding changes in dry forests;
(vi) to expand the temporal cover of the assessments (back to the 1980s, and after 1997) to improve understanding of temporal changes in deforestation trends.

For the next global assessment, the FRA programme is continuing to develop its monitoring of forest cover changes to complement national reporting. Technological improvements and better access to remote sensing data make it possible to expand the scope of the survey (compared with both FRA 1990 and FRA 2000). The survey will be extended to all lands (not just the pan-tropical zone), and will be based on a much higher number of smaller samples (about 10 000), covering 1% of total land area, sampled systematically. A 10×10 km^2 sample will be located at each intersection of the 1 degree lines of latitude and longitude that overlies land. These dimensions were chosen to allow spatially explicit monitoring at a scale relevant to land management. Time-series of high or very high-resolution remote-sensing data will be attached to each sampling location through a quality-controlled, standardized and decentralized process. This approach should deliver regionally accurate estimates of forest cover change, as well as national estimates for those countries where sampling intensity is sufficient.

(c) *Monitoring protected areas and sensitive regions*

Forest degradation around and within tropical protected areas will not stop under current economic, demographic and social conditions. A permanent monitoring system is required over sensitive areas because they represent the keystone of conservation policy in many countries. Biodiversity conservation in logged forests can be promoted in relatively intact areas like Central Africa, but seems illusory in tropical Asia, for example. The size of protected areas and the possibility of acquiring high-resolution satellite images at low cost allow for a monitoring strategy based on an exhaustive coverage of such data. This strategy is already being adopted by some organizations (such as Conservation International) for monitoring biodiversity hotspots, and will soon be tested over 1200 Important Bird Areas by Birdlife International and the JRC. The successful use of such information by conservationists will depend on close matching of remotely sensed data with field observations.

5. CONCLUSIONS

Since the 1970s it has been realized that forest monitoring is required not only at national but also at regional and global levels. Regional and sub-regional organizations rely on consistent information on forest resources for developing forest and environmental strategies above the national level. The need for global data has further increased in the context of environmental conventions (e.g. Convention on Biological Diversity) and of growing interest in global climate modelling.

For a number of tropical countries no reliable information on forest cover is available. Furthermore, the aggregation of national statistics has proved to be extremely difficult, owing to incompatible definitions and the continued use of often outdated inventory methods. Reliable information on forest cover change is even more difficult to obtain. As a consequence, IPCC (Watson *et al.* 2000) stated that deforestation figures for individual tropical countries could be in error by as much as 50%.

With remote sensing technology, one can produce independent and up to date estimates of both forest cover and cover change. However, national, international and academic institutions have had difficulties delivering accurate information in a way that is useful and relevant for policy formulation, implementation and follow-up. 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. Such a framework is still needed.

However, the ground validation of remotely sensed information is often insufficient to produce accurate and well-accepted figures. Although it can be observed globally from space, forest cover change occurs at a very local scale and requires good ecological and socio-economic knowledge to correctly interpret the reflectance registered by the satellite. A permanent network of local observation could produce very useful information for combating deforestation.

The involvement of local partners from the conception to the validation of such a monitoring system is also essential. It augments the reliability of the interpretations, ensures relevance to the local context, provides important elements of capacity-building, and crucially, also leads to greater acceptance of the final estimates by local communities.

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