DETERMINATION
OF
THE WORLD'S HUMID TROPICAL DEFORESTATION RATES DURING THE 1990'S

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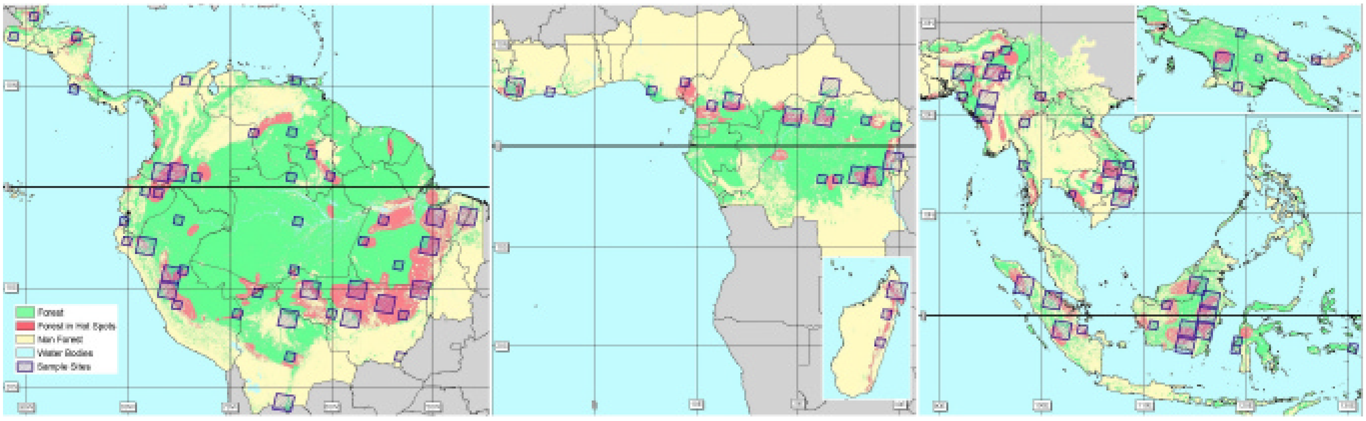
Methodology and results of the TREES-II research programme



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Determination of
The World's Humid Tropical Deforestation Rates during the 1990's

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Methodology and results of the TREES-II research programme

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The full list of partners and contributors to the programme is given in section 1.2.

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ABSTRACT

In spite of the importance of the world's humid tropical forests, our knowledge concerning their rates of change remains limited (IPCC, 2000). The second phase of a research programme (TREES-II) exploiting the global imaging capabilities of Earth observing satellites has just been completed to provide the latest information on the status of these forests.

The results of the TREES II programme show that in 1990 (the Kyoto Protocol baseline year) there were some 1,150 ±54 million hectares of humid tropical forest. Furthermore the 1990–1997 period showed a marked reduction of dense and open natural forests: the annual deforestation rate for the humid tropics is estimated at 5.8 ±1.4 million hectares with a further 2.3 ±0.7 million hectares of forest degradation visible from satellite imagery. Large non-forest areas were also re-occupied by forests. But this consists mainly of young re-growth on abandoned land and partly of new plantations, both of which are very different from natural forests in ecological, biophysical and economic terms, and therefore not appropriate in counterbalancing the loss of old growth forests.

These new figures are the most consistent estimates currently available. They show that Southeast Asia is the continent where forests are under the highest threat (0.91% annual deforestation rate). The annual area deforested in Latin America is similarly large, but the rate (0.37%) is lower, due to the vast Amazonian forest. The humid forests of Africa are being depleted at a similar rate to that of Latin America.

At the global level, these figures indicate a 23% lower net forest cover change rate for the tropical humid forests than was generally accepted until now. This has major repercussions on the calculation of carbon fluxes in the global budget resulting in a terrestrial sink smaller than previously inferred.

FOREWORD

This report provides a detailed description of the European Commission's TREES-II research programme. The project, managed by the Joint Research Centre in close co-operation with DG Environment, used the global imaging capabilities of a number of satellites, including Europe's SPOT 4 and ERS satellites to provide the latest information on the state of the World's Humid Tropical Forests.

The project has now created the most complete, up-to-date set of maps available documenting the distribution of the World's remaining humid tropical forests. These maps provide an unprecedented view of one of the most important biomes on the Planet.

TREES-II's results clearly show that deforestation in the humid tropics is still a major global environmental issue. The project provides the most accurate, consistent figures on rates of deforestation throughout the humid tropics currently available. Between 1990 and 1997 a staggering 5.8 million hectares of humid tropical forest was lost each year. This is an area approximately twice the size of Belgium. A further 2.3 million hectares per year of forest are detected as highly degraded - becoming increasing fragmented, heavily logged and / or burnt. Although the statistics document the trends up to 1997 the most recent maps from the project (from 1999 and 2000) provide no grounds to believe that this situation is improving.

Although a global phenomenon, the spatial detail and ability to compare different regions of the world provided by TREES-II reveals considerable variation around the world. The regional networks of experts built up by the TREES-II programme also add depth to the analysis. TREES-II partners in Africa for example have shown how forest logging opens up the forest with roads that then increase the hunting pressure from poachers – a key problem in Central Africa.

The maps, information on forest cover status and rates of change are based on uniform, independent and repeatable methods. These new data have already reduced uncertainties in dealing with carbon sink issues, they provide accurate baseline views of this hugely valuable global resource and help in planning strategies for effective conservation of its biological diversity.

The TREES-II project clearly demonstrates the important role of sound scientific evidence to support policy. The close collaboration with local partners in Developing Countries and international governmental or non-governmental organisation combined with state-of-the-art analysis of satellite imagery has proved a powerful combination. The need for reliable, accurate and consistent information on our planet's resources is steadily growing; both in the context of multilateral environmental agreements, such as the Framework Convention on Climate Change or the Convention on Biological Diversity, and in the context of international aid, trade and development partnerships. The TREES-II project has shown what can be achieved and paves the way for future global resource monitoring initiatives.

Alan Belward
Global Vegetation Monitoring Unit Head

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1. Introduction

1.1. General objectives of the study

The value of forests to the world's 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. Because of their importance to us all, international activities such as those undertaken by the Food and Agriculture Organisation (FAO) of the United Nations (FAO, 2001a & 2001b) aim to document the status of the world's forests. This is an enormous undertaking and perhaps it is inevitable that not all the world's forests will be documented to the same level of detail.

The humid tropical forests deserve our special attention. Agricultural expansion, commercial logging, plantation development, mining, industry, urbanization and road building are all causing deforestation in tropical regions (Geist and Lambin, 2001). The loss of the forests affects the Earth's physical processes driving our climate and has a profound impact on the biodiversity of our planet. Yet in spite of their importance our knowledge concerning their distribution and rates of change remains surprisingly limited. The Intergovernmental Panel on Climate Change in its recent report on land use, land-use change and forestry (IPCC, 2000) points out that "for tropical countries, deforestation estimates are very uncertain and could be in error by as much as ±50%". The estimates of land-use change at global level suggest emissions in the range of +0.6 to +2.5 $GtCyr^{-1}$ for 1980s (Prentice *et al.*, 2001, Schimel *et al.*, 2001) and an equivalent large range +0.8 to +2.4 $GtCyr^{-1}$ for the 1990s (Houghton, 2000; Schimel *et al.*, 2001). The work of the TREES project was aimed at addressing the shortfall of deforestation estimates in the humid Tropics.

Initiated in the early 1990s, the TREES project was dedicated to the development of forest cover assessment throughout the Tropics. This project made use of an extensive set of remote sensing satellite data. The main objectives of the TREES project were:

- To develop techniques for global tropical forest mapping;
- To develop techniques for monitoring active deforestation areas;
- 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 the tropical forest cover of the world.

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

The second phase of the TREES project (TREES II) has developed a methodology to identify deforestation hot spots and to estimate deforestation rates in the tropical humid domain during the 1990's.

The driving force behind this methodology is an attempt to map and monitor deforestation as comprehensively as possible by a selective examination of a relatively small percent of the forest domain.

1.2. Partners in the project

A number of external (i.e. non-JRC) partners, mainly from tropical countries, contributed to the TREES exercise. The main tasks of the partners were (i) to assess forest cover changes from satellite images for selected locations, (ii) to analyse the change processes within the selected areas and (iii) to establish a geographical digital data set containing the information obtained. The list of these partners is given with the geographical region or the methodological aspect in which they took part.

Local partners for Latin America

- Michael Schmidt, CONABIO, Mexico City, Mexico
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Local partners for Africa

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- Djoda Mabi (deceased), CETELCAF, Yaoundé, Cameroon
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- Suwit Ongsamwang, Royal Forest Department of Thailand, Bangkok
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- Hartono Dess, PUSPICS, University of Yogjakarta, Indonesia
- Ronna Dennis, CIFOR, Bogor, Indonesia
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- Florian Siegert, RSS, München, Germany
- J. Wong- Basuik, FOMISS Project, Forestry Department/GTZ, Kuching, Sarawak, Malaysia
- Job Suat, UNITECH, Lae, Papua New Guinea

Other partners

In addition to the direct contribution of the local partners, we would like to acknowledge the following experts who took part to specific actions in the study

- Rudi Drigo, IAO, Italy, team leader of the consistency assessment study and the review
- Francois Blasco, LET, France, team leader of the global assessment of mangrove cover
- Conrad Avelling, ECOFAC programme, Brazzaville-Congo

Internal database/GIS support

We thank Pascale Janvier, Alex Tournier, Bernard Glénat, Margherita Sini, Andreas Brink and Steffen Fritz for their participation and assistance in designing, developing and managing the spatial database, as well as in preparing the Geographical Information System (GIS) products. Andrew Hartley reviewed the text.

2. Methodological approach

Summary

The domain covered by the TREES-II study is:

(i)	**The tropical humid forest biome of Latin America excluding the Atlantic forests of Brazil**
(ii)	**The tropical humid forest biome of Africa**
(iii)	**The tropical forest biome of Southeast Asia and the tropical humid forest biome of India**

The method is based on the following main technical steps:

(i)	**The establishment of sub-continental forest distribution maps for the early 1990's 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' with 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 scheme was designed for change assessment by higher sampling probabilities in deforestation hot spot areas**
(v)	**The change assessment for each site based on interpretation of fine spatial resolution (20-30m) satellite imagery acquired at 2 dates closest to our target years (1990-1997), performed by local partners using a common approach**
(vi)	**The statistical estimation of forest and land cover transitions at continental level using the data linearly interpolated between the two reference dates: 1st June 1990 and 1st June 1997**

2.1. Domain covered by the study

The evergreen and seasonal forests of the tropical humid bioclimatic zone covered by our work correspond closely to those forests defined by FAO as “Closed Broadleaved Forest” (FAO, 1993) and by IUCN, The World Conservation Union, as “Closed Forest” (Harcourt & Sayer, 1996). We do not document the woodlands and dry forests of the dry domains except for the monsoon forests in the continental part of Southeast Asia where they are intermixed with the humid forests (Table 1).

The initial definition of the domain covered by the TREES-II study is:

(i) The tropical humid forest biome of Latin America excluding the Atlantic forests of Brazil

(ii) The tropical humid forest biome of Africa: the Guineo-congolian zone and Madagascar

(iii) The tropical humid forest biome of Southeast Asia and India, including the seasonal monsoon forests of continental Southeast Asia.

The figures of forest cover change reported at the end of the document correspond to this domain with the exclusion of Mexico, due to issues of quality in the image interpretations.

Deforestation is defined as the conversion from forest (closed, open or fragmented forests, plantations and forest regrowths) to non-forest lands (mosaics, natural non forest such as shrubs or savannas, agriculture and non vegetated). Reforestation (or re-growth) is the conversion of non-forest lands to forests. Degradation is defined as the process within the forests whereby there is a significant reduction in either tree density or proportion of forest cover (from closed forests to open or fragmented forests).

Table 1: Main regional forest types included and excluded in the study

Included forest types

Bioclimatic domain	*Latin America*	*Africa*	*Southeast Asia*
Humid	Evergreen lowland forest Evergreen mountain forest Semi-evergreen forest Heath forest (Caatingas) Varzea / swamp forest and swamp forest with palms Coniferous Mangrove	Evergreen lowland forest Evergreen mountain forest Semi- evergreen forest Swamp forest Mangrove	Evergreen lowland forest Evergreen mountain forest Semi-evergreen forest Moist mixed deciduous forest Heath forest Coniferous Swamp and peat swamp forests Mangrove
Dry			Mixed deciduous forest Dry dipterocarp forest

Excluded forest types

Bioclimatic domain	*Latin America*	*Africa*	*Southeast Asia*
Dry	Deciduous forest Woodland (Cerradão, Cerrado, Chaco)	Deciduous forest Woodland savanna Tree savanna	Deciduous forest of south eastern India

2.2. Design of the methodological approach

2.2.1. Rationale

Background on existing approaches

The different methods of measuring tropical deforestation at a global scale can be grouped into two main categories:

- Gathering information through reports
- Measuring change using remote sensing satellite imagery

1. Gathering information through reports

Deforestation rates in the tropics are estimated by FAO using national statistics and independent expert reports (1997, 2001a, 2001b).

2. Measuring change using remote sensing satellite imagery

Recent estimates (dated early 1990's) of remaining tropical humid forest *area* have been produced by the TREES project (Mayaux *et al.*, 1998) using an original multi-scale remote sensing approach. But this method did not allow assessing accurately forest *area change* over a short time period because of the potential errors of using maps from coarse spatial resolution satellite data for *area* estimation. Indeed the TREES group were one of the first research groups to point out that such an approach was unsuitable unless a calibration process was carried out regarding the fragmentation of the land cover class to be estimated (Mayaux & Lambin, 1995, 1997). In our previous work (Mayaux *et al.*, 1998), a correction procedure was developed in order to reduce the area estimate errors due to the spatial aggregation in the 1km resolution maps. The procedure uses 36 fine resolution (Landsat scenes) sample sites. The residual errors of the forest *area* estimates after correction computed on an independent sample vary from 1-1.5% (South America and Africa) to 3.5% (Southeast Asia and Central America). These residual errors explain why we chose not to produce our new estimates from this source of information (coarse spatial resolution maps).

Development of an ad-hoc statistical sampling strategy

Using a sample of fine spatial resolution satellite imagery (e.g. from Landsat-satellites' sensors) the FAO FRA (Forest Resources Assessment) remote sensing survey produced estimates on deforestation rates in the tropics at continental levels for the period 1980-1990 and 1990-2000. But the sampling was more specifically designed for area estimation (i.e. it was not optimised for change estimation) and was targeted for all tropical forest types (humid and dry domain all together). Furthermore there was no spatial identification or stratification of deforestation areas.

Our objective was to develop an ad-hoc statistical sampling strategy to allow for a reliable determination of forest cover change in the humid tropics during the early 1990's from satellite imagery with uniform, independent and repeatable procedures.

A dedicated sampling approach with fine spatial resolution imagery was selected as the most cost-effective solution. A stratified statistical sampling scheme over the humid Tropics was expected to improve existing estimates of deforestation (Czaplewski, 2002).

When a spatial phenomenon, such as the deforestation process, is not distributed homogeneously stratification reduces the variance of the estimator of a statistical sample. The limitation of the observed area to the humid tropical domain only and the higher intensity of the sampling on forested areas where most of the deforestation takes place, were aimed at making the sampling scheme as efficient as possible and at reducing the variability of the change estimates, resulting in higher confidence.

2.2.2. Description of the technical steps of the method

The different steps of the methodology are described in the different chapters of this document:

Chapter 3 describes the first step - *forest distribution baseline maps for the early 1990's*

> The daily global imaging capabilities of a number of satellites were used to build up forest distribution baseline maps for the early 1990's. These maps provide detail down to 1 km^2 (Achard & Estreguil, 1995; Eva *et al*., 1999; Mayaux *et al.*, 1999; Stibig *et al.*, 2002)

Chapter 4 describes the second step - *deforestation hot spot areas*

> The deforestation areas were identified using the forest cover maps in conjunction with knowledge from forestry and environmental experts. These areas were spatially delineated and documented on regional maps for the 3 continents, the so-called 'deforestation hot spot areas' (Achard *et al*., 1998).

Chapter 5 describes steps 3 and 4 – *stratification and sample selection*

> Based on the two information layers ('forest' and 'hot spot' proportions) stratification was established for the selection of a pre-sample. Five strata were defined using a *hotness index*, from low change rate, i.e. areas with no hot spot and high forest cover, to high change rate, forest areas within the hotspots.
> The stratification was used for the selection of a sample of 100 observation sites covering 6.5% of the humid tropical domain. The selection was made in a statistical systematic manner with higher sampling probabilities for fast changing areas. From a sample frame based on a tessellation grid of hexagons a systematic sampling on the stratification with different sampling rates for each of the five stratums was selected (Richards *et al*., 2000).

Chapter 6 describes step 5 - *interpretation of the satellite imagery*

> *Forest cover* and *forest cover change* were measured exhaustively over the 100 observation sites by visual interpretation of the fine spatial resolution (20m to 30 m) satellite imagery. The interpretations were carried out with a common standardised method on computer screen by a network of over 30 local experts or institutions having an extensive knowledge of the local ecosystems conditions and change processes.

Chapter 7 describes step 6 – *statistical estimation*

Forest cover and land cover transitions were estimated statistically at continental level using the data linearly interpolated to the two reference dates: 1st June 1990 and 1st June 1997. The individual site measurements were integrated in a statistical calculation, which takes into account their selection probabilities. As each observation site does not belong necessarily to a single sampling stratum, we fall in a situation of unequal probability sampling rather than stratified sampling. Two correction steps were applied to handle this situation of unequal probability sampling: (i) correction of the initial probabilities of the clusters of hexagons to fit with the Landsat TM observation sites and (ii) calibration estimator using two proxies (or co-variables) available at regional scale. The statistical sampling accuracy was estimated through a re-sampling (bootstrap) method.

3. Mapping forest distribution at 1 km resolution

Summary

The daily global imaging capabilities of a number of remote sensing satellites were used to build up continental forest distribution baseline maps for the early 1990's.

These maps provide spatial detail down to 1 km^2.

These maps were then improved and updated using satellite imagery of the year 2000.

The first activity of the TREES project relates to the base line inventory of humid tropical forests. The TREES concept was to provide a wall-to-wall coverage from coarse spatial resolution satellite data (Malingreau *et al.*, 1995). The results of this first task consist of the 1.1 km resolution map of the tropical humid forest cover for the early 1990's. From this database three vegetation maps have been elaborated and reviewed by a panel of regional experts:

- The vegetation map of Central Africa at 1:5M (Mayaux *et al.*, 1997, 1999)
- The vegetation map of South America at 1:5M (Eva *et al.*, 1999)
- The forest classification of Southeast Asia at 1:5M. (Achard & Estreguil, 1995)

These vegetation maps cover most of the humid regions (defined as wet or moist with short dry season) of the tropical belt. At the same time as producing these coarse spatial resolution maps, a sample of fine spatial resolution data across the Tropics was collected so as to perform the accuracy assessment and area correction exercises needed to extract quantified estimates of deforestation.

These baseline maps are restricted to the tropics and to essentially one thematic class (humid forest) and as such achieve a higher labelling and spatial accuracy by aiming for a lower thematic sophistication. The methods were optimised for this specific class: interpretation of cloud-free single-date images at the middle of the dry season, supervised geometric registration, consultation of many national documents. The relationship between the forest cover derived from the fine resolution interpretations and the forest cover derived from the 1 km maps (see Chapter 7) indicates a correlation coefficient of $R^2 = 0.942$.

This chapter looks at how the TREES project mapped the pan-tropical humid forest belt using coarse spatial resolution satellite imagery and presents also the accuracy assessment and correction procedures.

3.1. Mapping exercise

3.1.1. The thematic legend

The maps produced by the TREES project are a combination of single image classifications derived from the analysis of NOAA AVHRR data. Such data were collected during the early 1990s (around 1992 and 1993, depending on availability of data for the different regions). Whilst landscape features may be evident from visual analysis, their extraction from the digital data can be highly problematic. As a result mapping of a few broad classes was preferred to uncertain mapping of a larger number of detailed classes.

The 1-km resolution NOAA AVHRR data and available analysis techniques allowed the mapping of a few main types in the tropical humid forest domain: evergreen lowland or mountain forest, seasonal forest (where existing) and degraded or fragmented types. This base-line thematic data can be supplemented with new thematic classes, as information becomes available from new sensors. Spatial information on the humid evergreen tropical forest was the most valuable information.

Requirements for the legend

The TREES thematic legend was elaborated with the following requirements:

- To separate the main ecological forest types relevant for global and regional studies (climate change, biodiversity…);
- To be valid at the continental level;
- To be consistent at a simplified level for the whole tropical belt.

As remote sensing and ancillary spatial data are used to produce the map, we selected a hierarchical classification system (legend) focusing on the vegetation cover. Three classification criteria have been defined:

1. Physiognomy (mainly the tree crown closure or forest cover percentage)
2. Seasonality (within-year evolution of the vegetation canopy greenness)
3. Topography (altitude thresholds from topographic dataset)

The successive application of the three criteria leads to the definition of the vegetation classes. Preliminary analysis of the spectral and temporal AVHRR characteristics in relation to the forest cover has shown that the physiognomy and seasonality criteria are most compatible with such data (Achard & Estreguil, 1995; D'Souza *et al.*, 1995) while the topography at such regional scale can presently only be depicted using ancillary data (global topographic dataset).

Criteria for the legend definition

Physiognomy

Crown cover is the dominant factor as it is the only parameter easily accessible from optical remotely sensed images. To be compatible with the scale of observation, the classification scheme is defined at the forest landscape level as observed with the coarse spatial resolution sensor. The crown cover is measured as the percentage of trees cover as determined on a 1-km^2 area basis and categorised into a small number of broad classes:

- A crown cover higher than 70% defines a *dense forest*.
- A crown cover of between 20% and 70% includes:
  - *Open forest* (continuous coverage by trees crowns in low density: dry forest type in continental Southeast Asia),
  - *Degraded forest* (continuous coverage by degraded forest vegetation: generally inside the humid bioclimatic zone)
  - *Mosaic of forest / non-forest* (fragmented coverage by trees crowns: generally at the border of the humid bioclimatic zone)
- Any vegetation type with a crown cover lower than 20 % is classified as *non - forest*.

These crown cover threshold values, which have been defined a priori before the analysis, have been later controlled through the calibration phase using fine spatial resolution imagery.

Seasonality

Seasonality refers here mainly to the phenological characteristics of natural vegetation such as leaf shedding. The seasonal parameter allows the discrimination between evergreen forest and deciduous forest types. In the deciduous forests the majority of trees shed their leaves synchronously in response to water stress during the dry season, and in the evergreen forests the majority of the trees remain in leaf throughout the year. Deciduous forests of the humid zone (> 1000 mm rainfall) with a short dry season (less than 4 dry months) are of high importance in continental Southeast Asia (Collins *et al*., 1991) and have been taken into account only in that continent as elsewhere their spatial extension is inter-mixed with the evergreen forests.

Topography

Various environmental properties can be used to help in discriminating between vegetation types. These can be related to factors such as climate, topography or soils. One ancillary parameter was used predominantly: elevation threshold from a global topographic database to discriminate between lowland forests and sub-mountain forests (above 700 m or 900 m in Latin America and Southeast Asia respectively) from mountain forest types (above 2000 m or 3000 m in Latin America and Southeast Asia respectively).

The overall classification system is given in Table 2.

Table 2: Classification scheme used for the humid tropical forest maps

1st criterion Physiognomy	2nd criterion Seasonality	3rd criterion Topography	Classes
Dense **CC** >70%	Evergreen including semi-evergreen and Mixed deciduous	Lowland (<700m or 900m)	Lowland Moist Forest Mangrove or Swamp Forest
		Sub-Mountain (> 700m or 900m)	Sub-mountain Forest
		Mountain (> 2000m or 3000m)	Mountain Forest
Fragmented or open 20%< **CC** <70%	Evergreen		Secondary Forest Mosaic
	Deciduous		Deciduous Forest / Woodland
Non Forest **CC** < 20%			Agriculture Mosaic Grassland Shrubland Mosaic Subdesertic Vegetation Inland Water Ocean

CC= Crown Cover in 1 km^2

3.1.2. Use of satellite imagery

Background on existing methods

During the 1990's global data sets from coarse spatial resolution sensors have become more and more readily available. The arrival of new coarse-to-medium spatial resolution sensors, combined with higher capacity ground segments means an increasing range of data with global coverage. The information content of this remotely sensed data from Polar orbitors and geostationary satellites is also increasing, in terms of spatial and spectral resolution, temporal sampling and spectral precision. Thus we have moved from the sole choice of NOAA Advanced Very High Resolution Radiometer (AVHRR) data at 1.1 km resolution at widely available medium and multi resolution (1 km -100m) data.

In conjunction with these technological advances the space agencies themselves along with other programmes are providing a range of various pre-processed data. The global data sets that were already available in the early 1990's include NOAA AVHRR Global Vegetation Indices at 16 km (Gutman, 1992), NOAA AVHRR 8 km and 5 km data sets (Malingreau & Belward, 1994), global 1.1 km NOAA AVHRR (Townsend *et al*, 1994). Pantropical data sets have also been created: from the JERS Synthetic Aperture Radar (SAR) (Rosenqvist, 1998) and from the Landsat Thematic Mapper (TM) or Multi Spectral Scanner (MSS) (Skole & Tucker, 1993).

The 5 km and 1.1 km resolution NOAA AVHRR data sets have been used in their entirety or in regional applications, with examples being found in land cover mapping both continentally (Stone *et al.*, 1994) and globally (Loveland & Belward, 1997). Whilst the advantages of using such data are evident at global to continental scales – global coverage, synoptic view, single source – a number of methodological issues need to be addressed before using these data: definition of an appropriate classification scheme (in relation to the characteristics of the sensor) and design and testing of an accuracy assessment phase and of a correction method to derive statistics.

A mapping exercise is always a compromise between the desirable (most suitable information output) and the achievable (availability of raw data and the feasibility of the information processing). The classification system and the output scale have to balance the study objectives, the area covered and the source of information.

At the same time users need to be fully aware of the many error sources. These issues may contribute to the errors in the thematic mapping products, in turn creating errors of over- and under-estimation in the area estimates. It is therefore of utmost importance that the resulting errors in the final product are quantified and documented, and that correction methods are applied for the production of statistics.

Use of coarse spatial satellite remote sensing dataset

At the start of the TREES project no centralised AVHRR 1.1 km data archive existed, though subsequently such a lack was made good by the IGBP 1 km effort (Townshend *et al.* 1994).
Consequently a set of AVHRR 1.1 km data had to be collected from different sources: local receiving stations (e.g. Bangui, Baton Rouge, Bangkok, Beijing) or through Space agencies (European Space Agency, NOAA, CSIRO) during the early 1990s: mostly from the beginning of 1991 to the end of 1993.

The first component of the NOAA-AVHRR data pre-processing chain is the search for acceptable images (i.e. close to nadir and cloud free) through a screening process. From the near-daily NOAA-AVHRR data-set collected, some scenes were selected after visual analysis of colour composite quick-looks (channels 3, 2 and 1 in red, green and blue display channels, sub-sampling rate: 1/16). The criteria of selection in this screening phase were:

- presence of limited cloud and haze cover or other perturbations;
- representativity of temporally-sampled data over the dry season for seasonal ecosystems;
- closeness to nadir conditions in order to optimise the spatial resolution and to decrease the atmospheric and bi-directional effects.

The selected data were radiometrically calibrated and geometrically corrected using a single procedure (Achard & D'Souza, 1994). Where many images were required to complete the data set, a master template was constructed, and subsequent images were corrected to the master template to improve the geometric fidelity of the data set. The geometric residual error is about 1 km. The full 10-bit resolution of the data for all five channels was retained for analysis, including reflectances in the red and near infra-red channels, radiance of AVHRR sensor channel 3, and brightness temperature of AVHRR sensor channels 4 and 5.

Data analysis and processing

The best quality cloud-free images NOAA-AVHRR images were selected during the appropriate period (between the middle and the end of the dry season for the corresponding region) and single date five-channels scenes were classified by unsupervised methods (Achard & Estreguil, 1995, Defourny *et al.* 1994, D'Souza *et al.*, 1995). Unsupervised classification was preferred to supervised classification for two main reasons: training samples are difficult to identify over large extent areas and the variation of spectral signatures over full NOAA-AVHRR scenes due to seasonality, cloud contamination, view angle and bi-directional effects renders a supervised approach problematic (Roujean *et al.*, 1992).

The clusters derived from the single-image classifications were then analysed and labelled into the classification system defined in § 3 with the physiognomic and seasonal criteria as first and second criteria respectively. The labelling of classes was based on a convergence of evidence approach (Loveland & Belward, 1997) using available knowledge such as field information or existing vegetation maps, and on a visual analysis of spatial distribution pattern. For each class Normalized Difference

Vegetation Index (NDVI) statistics were generated. This operation requires a good knowledge of the main vegetation types of the region as well as a background understanding of spectral responses of particular feature vegetation types.

Post-labelling analysis of spectral responses demonstrated that the NOAA-AVHRR sensor channel 3 (3.5 μm) radiance and channel 2 (near infrared) reflectance were found most powerful discriminators for the forest, degraded forest and non-forest class separation (Estreguil & Malingreau, 1995). The channel 3 radiance response is mainly sensitive to the temperature contrast between a green forest canopy (cool) and drier vegetation with less dense cover (hot). The key periods during the dry season (middle and end) were confirmed as most relevant periods for remote sensing observations when the spectral signatures of the forest areas contrast strongly with the non-forest areas. The evergreen forest types or deciduous forest types before leaf shed are characterised by a high NDVI and a low channel-3 radiance signature (Achard & Estreguil, 1995). Conversely, the non-forest types or the seasonal forest types after leaf senescence are characterised by a low NDVI and a high channel-3 radiance signature. The temporal variations of the spectral signal as captured through NOAA-AVHRR time series, appears to be a powerful key to the identification of tropical forest ecosystems. The channel 2 (near infrared) reflectance is higher for the degraded forest ecosystems than for the dense forest ecosystems allowing their discrimination.

The resulting partial single-date classifications are then combined and assembled in a single mosaic.

Use of ancillary layers

Once the forest classifications based on the two first criteria (physiognomy and seasonality) were assembled, ancillary information was integrated to create three continental map outputs. Ancillary spatial data were used to cope with the third criteria (physiography) and to label the *non-forest* class for each continent:

- elevation data from the US Geological Survey 1 km digital terrain model were used to apply the thresholds for the separation between lowland and montane forest types.
- for the central Africa map the ‘non-forest’ class was labelled from the analysis of NOAA AVHRR GAC data
- for South America the ‘non-forest’ class labels have been imported from another vegetation map source (UNESCO, 1981).

The different class labels of these regional maps reflect the three specific regional ecosystems. For continental Southeast Asia, the non-forest class have been left labelled as *non-forest*.

3.1.3. Results

The results of this first activity consist of the 1.1 km resolution digital map of the tropical humid forest cover for the early 1990’s. From this database three vegetation maps have been elaborated covering most of the humid tropics:

- The vegetation map of Central Africa at 1:5M (Mayaux *et al.*, 1997, 1999)
- The vegetation map of South America at 1:5M (Eva *et al.*, 1999)
- The forest classification of Southeast Asia at 1:5M. (Achard & Estreguil, 1995)

3.2. *Forest area estimates from the 1km resolution maps*

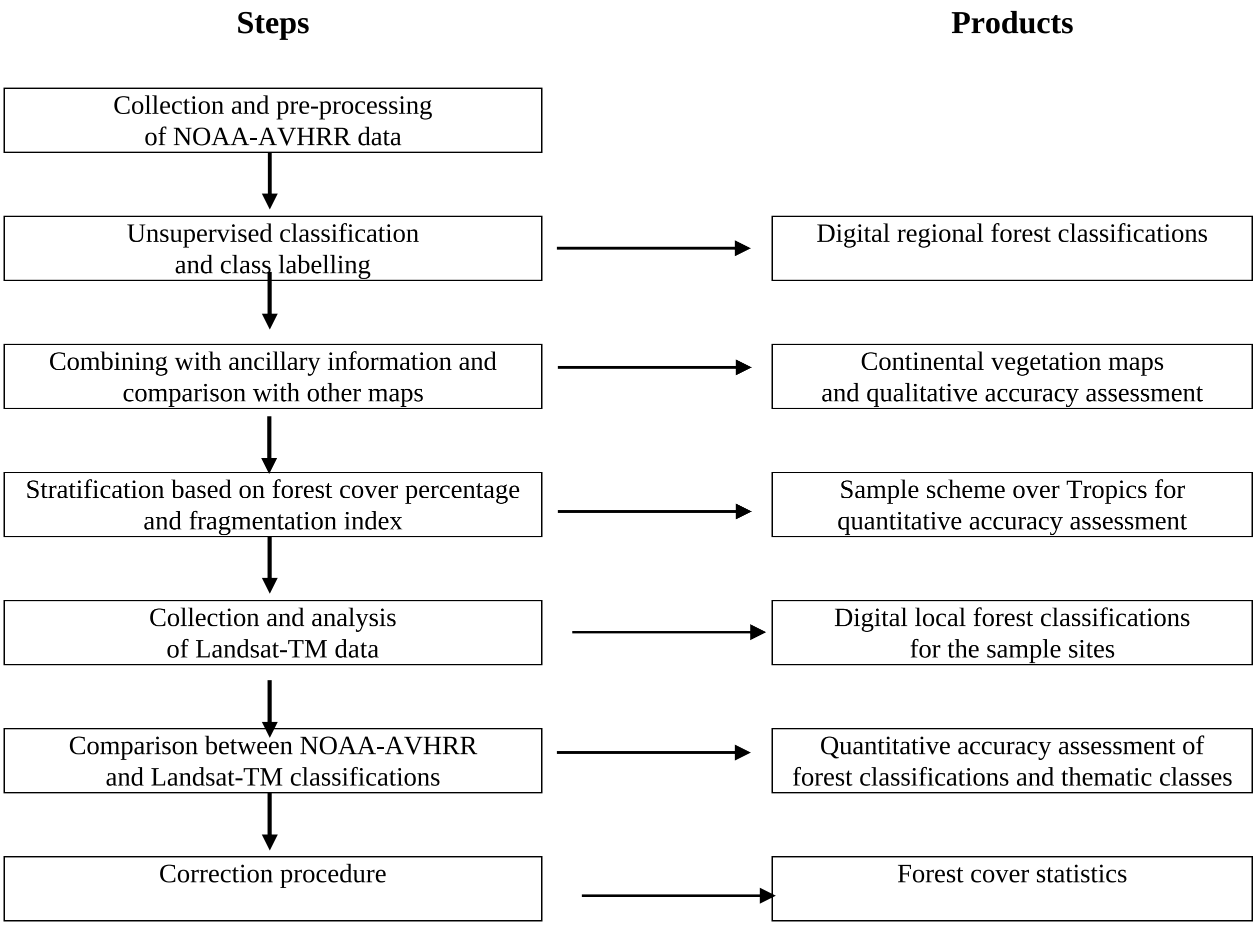
3.2.1. Accuracy assessment of the continental forest maps

The final products are regional maps of forest cover distribution at 1.1 km resolution. Since few products have been generated at that scale and no specific accuracy assessment technique was available at that time for such a large area assessment, it was necessary to develop new validation methods.

Accuracy assessment of the TREES forest maps has been carried out in both qualitative and quantitative ways (Figure 1):

- Qualitatively, the products have been compared with existing national maps. This check forms a general control on the spatial distribution and class labels of the maps. Secondly the maps were sent out to over 50 regional experts for their comments on the legend, label and spatial accuracy of the classes.
- Quantitatively, a sample of fine spatial resolution maps (derived mostly from Landsat Thematic Mapper imagery) was used to evaluate the accuracy of the coarse spatial resolution products (Mayaux & Lambin, 1995).

Figure 1: **Schematic of the accuracy assessment and correction exercises**



This exercise pursues two objectives: (i) to confirm the two class definition thresholds (20 % and 70% forest cover percentage) and (ii) to assess the accuracy of the maps in order to evaluate if a correction function for forest area statistics can be derived.

Objectives of the accuracy assessment

Various approaches have been adopted for designing a robust accuracy assessment procedure of small-scale products:

- using independent cartographic sources or ancillary data;
- using a number of field test sites for some specific products such as active fire maps;
- using a sample of finer spatial resolution remote sensing data (Scepan, 1999).

The third approach is being progressively considered as the most effective for global scale studies. Several sampling schemes have been used: (i) empirical selection based on data availability or interpretation constraints (Defries *et al.*, 1998), (ii) random samples throughout the data set or by ecological strata (FAO, 1996), (iii) stratified on the basis of land cover class (Loveland & Belward, 1997) or of proxy variables (this approach).

Though it assumes that fine spatial resolution data i) are a surrogate for truth, ii) can be accurately geolocated with the coarse spatial resolution data, iii) acquisition date matches the coarse spatial resolution data acquisition date, and that (iv) classes are equally interpretable on both fine and coarse spatial resolution data. In particular the limited availability of fine spatial resolution data can also severely affect the implementation of an accuracy assessment scheme, especially in the very humid Tropics due to the near permanent cloud cover and the lack of sufficient ground stations. The fine spatial resolution maps can also suffer from misclassifications, but we did not have the means to assess quantitatively the accuracy of such a large data set of fine spatial resolution products spread over the Tropics.

Selection of a sample of calibration sites

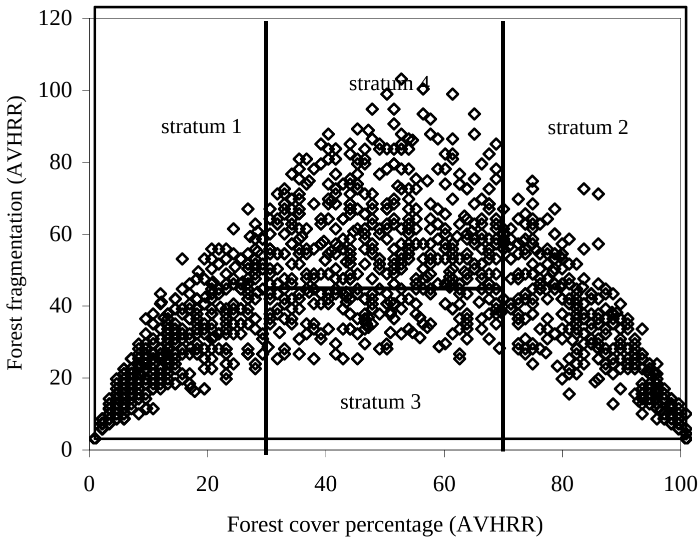
Discrepancies between the fine scale observations and the broad scale classifications can be due to misclassification errors as well as to cartographic artefacts associated with the different levels of spatial aggregation of the products being compared. Studies have been led to model the relationships governing the scaling process (Mayaux and Lambin, 1995, 1997).

In a first step, a catalogue of examples of forest / non-forest interfaces was generated (Husson *et al.*, 1995) to document and analyse the relationships between the fragmentation patterns of these interfaces that exist at the coarse and fine spatial resolutions. At the same time, from the TREES fine spatial resolution data archive and corresponding AVHRR images, and despite the differences in resolution, a significant relationship was demonstrated between the forest cover percentages measured at the 1.1 km resolution map level and at the fine spatial resolution map level (Mayaux & Lambin, 1995). This relationship is controlled by the forest fragmentation that can be measured by some indices. Various indices were tested and the Matheron index (Matheron, 1970) was the most performing. The Matheron index is defined as:

$$M = \frac{number \text{ of runs between forest and other cover type pixels}}{\sqrt{\text{number of forest pixels}} * \sqrt{tot\text{al number of pixels}}}$$

This important finding led to the idea of selecting sites over the tropics using a 1.1 km resolution forest map fragmentation index as a stratification layer in a statistical sampling scheme in order to reduce the variance of the parameter to be measured (forest cover area). A forest fragmentation map based on the Matheron index was produced from the pan-tropical TREES forest cover maps. Using a random sample of 1,800 blocks of 9 by 9 pixels corresponding to around 2% of the total number of blocks over the pan-tropical area extent, the forest cover percentage and forest fragmentation index were extracted and plotted so as to examine the distribution of these parameters. At low forest coverage the fragmentation index is also low. As the percentage of forest cover raises so does the fragmentation index until the largest range of possible values is reached for a forest cover percentage at around 50%. Then the fragmentation index range falls as more and more of a region is covered by forest. The population can be divided into four main strata (Achard *et al.*, 2001): stratum 1 with a low forest cover percentage (< 30%), stratum 3 and stratum 4 with medium forest cover (between 30% and 70%), and low and high fragmentation indices respectively (threshold at 50) and stratum 2 with high forest coverage (> 70 %).

Figure 2: Stratification of the blocks population from the forest percentage and the forest fragmentation.



Whilst under an a-priori stratified statistical sampling scheme a particular weighting would be assigned to each of these strata and images acquired correspondingly to populate the scheme, three external factors came into the selection of the fine spatial resolution data set:

- Firstly TREES wished to ensure a representativity of sample sites in each region,
- Secondly as the emphasis of the project was on dense forest mapping, priority was given in each region to sites with higher forest coverage
- Thirdly the choice of fine spatial resolution data acquisitions over the sites was found to be limited due to data availability constraints.

The selection of the sites was undertaken using these three factors. The final distribution by strata of the 36 sites from across the tropical belt shows that each stratum is represented by at least 7 sites.

The sites were then analysed using one fine spatial resolution (Landsat TM) scene for each site. The individual Landsat scenes were classified and interpreted by external teams having expertise in large-scale tropical forest mapping. The fine spatial resolution product accuracy was not assessed quantitatively but these products were considered as the best material available for our objectives.

Accuracy assessment of the 1km resolution maps

After registering the equivalent area from the coarse spatial resolution classifications to the fine spatial resolution classifications, forest-cover proportions were extracted over equal-size pixel blocks (9 by 9) from the two spatial resolutions. This block size (approximatively 10 km x 10 km) was chosen to accommodate two constraints: (i) the minimisation of the impact of geometric mis-registration between the classifications at the two spatial resolutions and (ii) the requirement to measure forest-cover proportion as a continuous variable.

On the one hand, simulation studies showed that, when relating forest-cover proportions extracted at the 1.1 km and 30 m resolutions in blocks with a size of 5.5 km by 5.5 km (5 by 5 pixels), the impact of a 0.5 pixel mis-registration error is negligible (Klein *et al.*, 1996). On the other hand, the block size cannot be reduced under a certain threshold to allow the extraction of forest-cover proportion from the coarse spatial resolution map as a near-continuous variable. With a block size of 9 by 9 pixels, forest-cover proportion can be measured in 81 levels - i.e. with a unit increment of 1.23%. This is close enough from a continuous measure to assume that the variable can be normally distributed.

Figure 3 shows the relationship between the forest cover percentage measured on NOAA AVHRR-derived maps and the forest cover percentage measured on the corresponding Landsat TM-derived classifications for the 36 sites. In this case, all the blocks coming from the same site were averaged into one value in order to estimate the general agreement. The overall correlation is very high (R^2=0.94 with n=36). It provides a first indication about the global accuracy of the maps at the site level. However, dispersion is important for scenes with between 30 and 70% of forest cover percentage.

The thematic class labels were also investigated, extracting pure (100 %) forest and non-forest blocks from the NOAA AVHRR-derived classifications and assessing the distribution of Landsat TM-derived forest percentage for each pure class. For the fragmented class very few pure NOAA AVHRR-derived classification blocks exist, as might be expected, given the nature of the class. For this class blocks with over 50 % of fragmented class pixels from the AVHRR-derived classifications were analysed. The three distributions demonstrate the accuracy of the thresholds of the dense forest class (Achard *et al.*, 2001) being between 70 to 100 percent forest cover. The non-forest class, defined to be lower than 20 percent forest cover, shows some “contamination”, up to around 10 percent. Meanwhile the accuracy of the fragmented forest class thresholds (between 20 and 70 percent forest cover) is also demonstrated.

Single site regressions were also computed for each scene between the fine spatial resolution and the coarse spatial resolution forest cover percentages. The resulting regressions were individually plotted and showed that whilst high correlation occurred for single sites between the two data sets, the regression line parameters (slope and intercept) were not unique (examples of three single site regressions in Figure 4). Whilst having demonstrated that the coarse spatial resolution class labels do indeed reflect globally the situation at the fine spatial resolution level, the analysis of the single site regressions confirmed that a simple linear adjustment of NOAA-AVHRR derived forest class areas is not accurate for obtaining forest cover area figures at local levels (for small areas, such as Landsat scene area size), as the two regression coefficients are not constant from one sample site to another.

Figure 3: Relationship between forest cover from 30 m and 1km resolution classifications for TREES-I sites

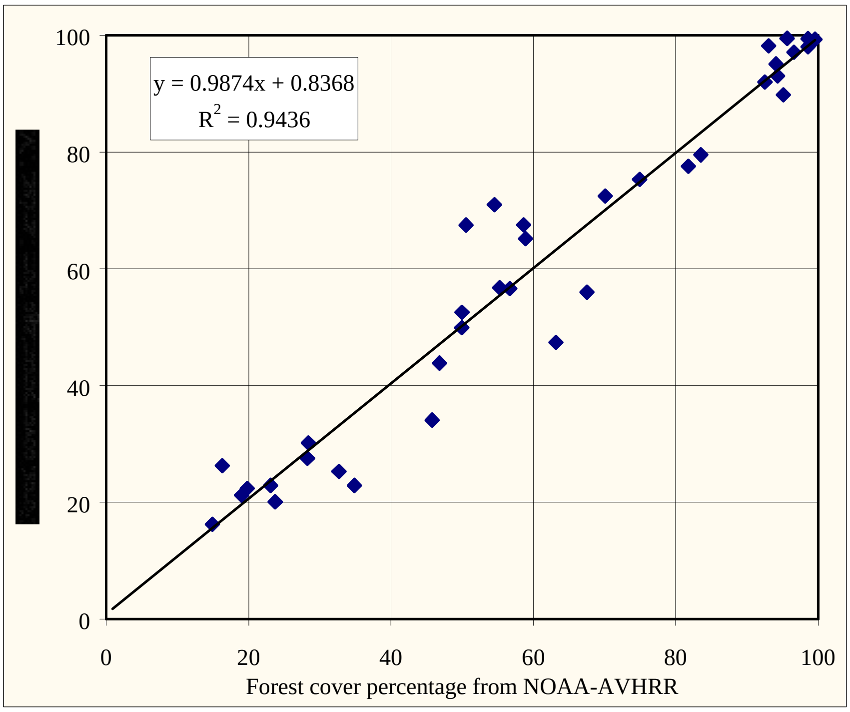
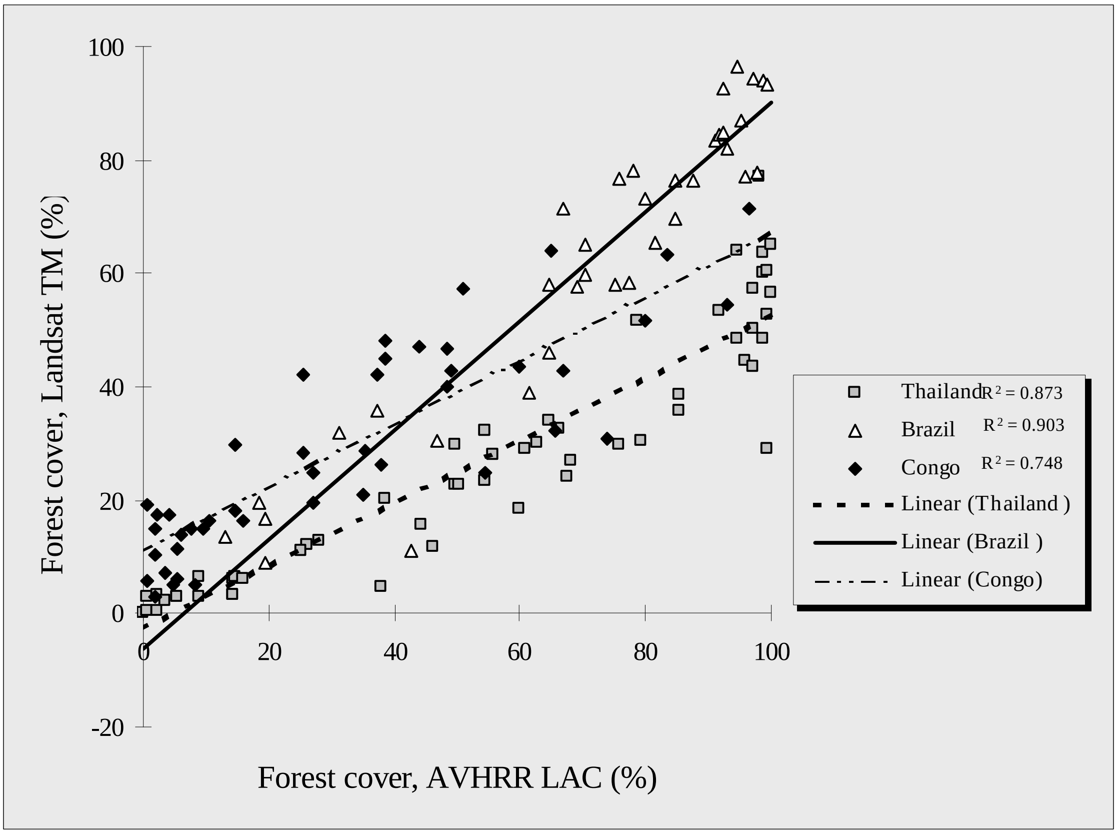


Figure 4: Examples of sample site regressions between forest cover from 30m resolution and 1km resolution classifications



3.2.2. Estimation of forest area from the 1km resolution maps

Once the errors in the coarse spatial resolution classification have been quantified, those errors must be corrected if meaningful quantitative measures are to be extracted. Various correction techniques have been presented using regression against fine spatial resolution classifications (Zhu, 1994), mixture modelling or neural networks (Foody *et al.*, 1997).

The previous section demonstrated the need to develop a more complex correction procedure to derive forest area measurements from the NOAA-AVHRR derived classifications.

Development of an correction procedure

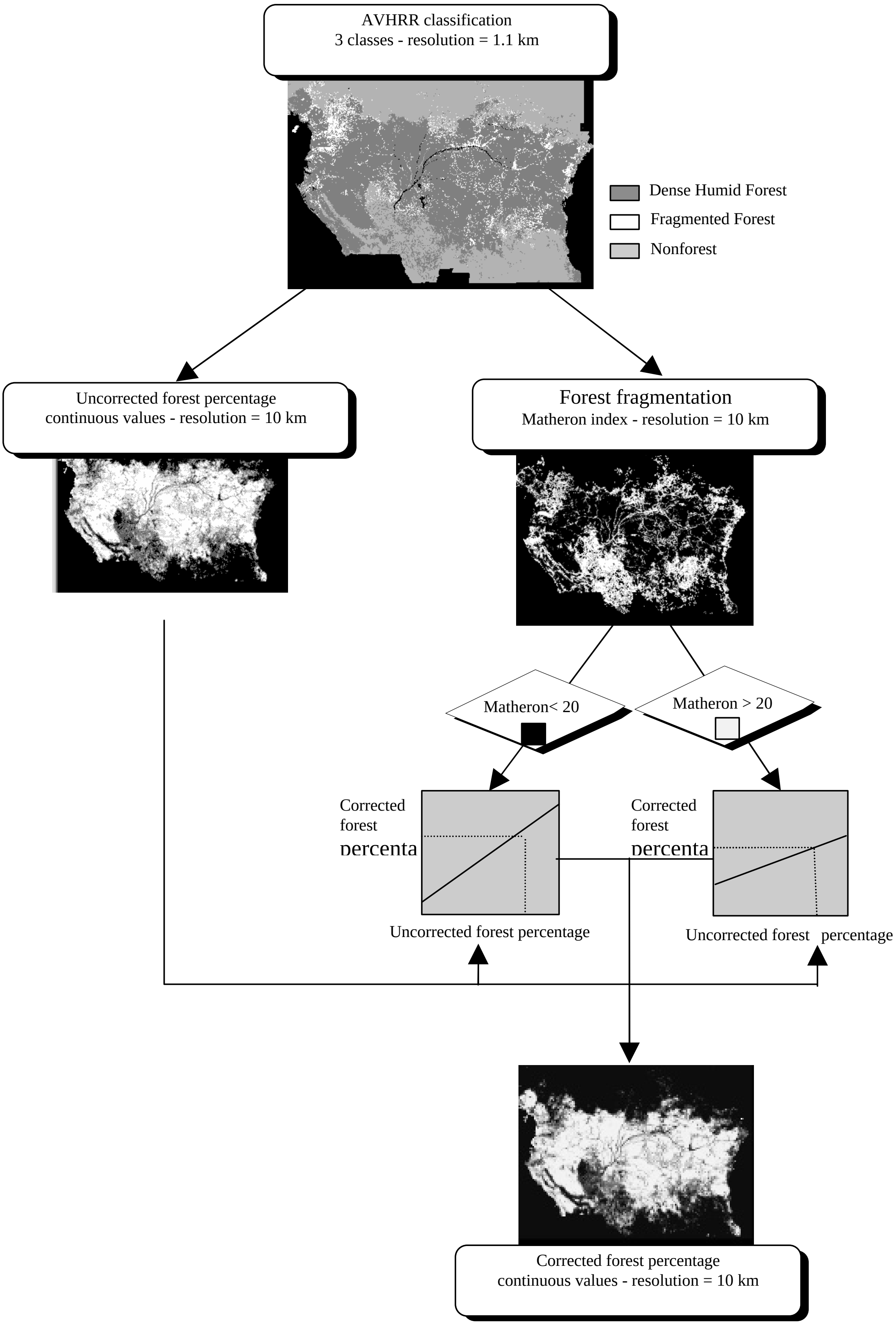
A specific estimation procedure had to be built, taking into account the forest fragmentation Matheron index. The estimation procedure is divided in two phases, namely the 'regression step', which computes the regression between NOAA AVHRR-derived and Landsat TM-derived classifications on a limited sample of sites, and the 'correction step', which applies the computed functions to the NOAA-AVHRR derived classification over the three tropical continents.

In a first step ('regression step'), the Matheron fragmentation index is calculated for each 9 x 9 pixel block on the forest map at the coarse spatial resolution. As shown previously, this measure controlled the relationship between forest cover percentage at fine and coarse spatial resolutions.

A statistical regression between the forest proportion estimated at coarse spatial resolution (auxiliary variable) and the forest proportion estimated at fine spatial resolution (target variable) is then computed. As shown above, the regressions are different in highly fragmented and homogenous landscapes. The correction function is thus split in two strata, namely pixel blocks with low fragmentation and pixel blocks with high fragmentation. Distinct regressions are computed for each stratum. In the first stratum (low fragmentation), a simple regression is computed between the forest cover measured at coarse and fine spatial resolution. In the second stratum (high fragmentation), the parameters of the regression between the forest cover measured at coarse and fine spatial resolution (slope and intercept) are related to the fragmentation measure.

This correction procedure accounts for two estimate errors: (1) a spatial aggregation bias, which is consistent across the tropical belt since the spatial resolutions of the two sensors considered (NOAA-AVHRR and Landsat-TM) strongly influences this bias and, (2) possible misclassifications of NOAA-AVHRR derived classifications due to spectral variations in image quality (cloud or haze contamination, viewing angle,) and interpretation errors by the continental experts. Therefore, correction functions have been computed separately for each continent, namely Africa (including West and Central Africa), Continental and Insular Southeast Asia, Central America and South America. In each continent, around 20 % of the available fine spatial resolution classifications were reserved as independent samples for verification. The residual errors after correction computed on this independent sample vary from 1-1.5% (South America and Africa) to 3.5% (Southeast Asia and Central America) of the forest cover. Forest area figures are then extracted from the corrected classifications at the national level, or at the sub-national level in the case of large countries, that is Brazil, Democratic Republic of Congo or Indonesia (Mayaux *et al.*, 1998).

Figure 5: Correction procedure for retrieving forest areas from coarse resolution maps.



Comparison of the derived estimates with other estimates (FAO and IUCN)

Table 3 compares the derived forest area estimates for the year 1992 with other global or continental data sources for the early 1990's: the 'Closed Broad-leaved Forest' class figures from the Forest Resources Assessment 1990 Project (FAO, 1993) and the 'Closed and Monsoon forests' class figures from the IUCN (International Union for Conservation of Nature and Natural Resources) (Collins *et al.*, 1991, Hartcourt & Sayer, 1996, Sayer *et al.*, 1992). The TREES forest class includes all the dense forest types. The differences between the three estimates is less than 10% in most countries with the exceptions of Brazil (FAO estimate), Colombia (both other estimates), Myanmar (IUCN estimate), Congo-Brazzaville, Gabon, Cameroon and West Africa (both other estimates). Most of the problems observed from the TREES classification derived results occur when coarse spatial resolution data of satisfying quality are missing (Mayaux *et al*., 1998). Some discrepancies are also due to the definition of "forest " classes, e.g. in countries where woodland savannas (or 'cerrado' in Brazil) are included into the term forest, but not in others. Whilst such inter-comparison is vital it does also serve to highlight the need for fully documented accuracy figures. Users of the TREES data now benefit from statistically valid estimates of error.

Table 3: Global synthesis of tropical forest area assessment from TREES-I, FAO and IUCN databases.

Region	TREES-I 'Dense Forest' (10^6 ha)	FAO 'Closed Broadleaved Forest' (10^6 ha)	IUCN 'Closed Forest' (10^6 ha)
Central Africa	184	158	186
West Africa	18	16	13
Total Africa	*202*	*174*	*199*
Central America & Caribbean	51	28	77
South America	653	637	616
Total Latin America	*704*	*665*	*693*
Continental South-East Asia	84	72	74
South Asia	22	30	19
Insular South-East Asia	174	143	178
Total Tropical Asia	*280*	*246*	*268*
Total Tropics	**1,186**	**1,084**	**1,162**

Notes: All figures are in million (10^6) ha
Reference for FAO data: FAO, 1993.
References for IUCN data: Collins *et al.*, 1991; Harcourt & Sayer, 1996; Sayer *et al.*, 1992.

3.3. Updating of the early 1990's maps to the year 2000

Characteristics of the forest cover maps for the early 1990's

An extensive geo-referenced digital database on tropical rainforest cover around the tropics has been produced. The main particularities of the NOAA-AVHRR derived regional vegetation maps can be summarised as follows:

- An homogeneous view of dense forest extent; achieved by an uniform method (unlike national maps); albeit with continental adaptations;
- Whilst exhibiting lower thematic content than conventional small scale maps, the spatial accuracy is known;
- An availability in a digital format (which allows the update of the maps easily and regularly with new information coming from medium to coarse spatial resolution sensors);
- Readily integrated into Geographic Information System.

Accuracy of the TREES forest maps was further assessed using fine spatial resolution classifications that can also be used for more detailed local analysis. Although differences in forest definition exist between other global forest estimation exercises, a satisfying overall agreement (differences < 10%) has been found when comparing the derived statistics from the TREES forest maps with these external sources (FAO and IUCN).

Both the accuracy assessment and correction exercises show that these maps can be considered as the most reliable geo-referenced information available at a regional level, i.e. 1:5M scale. They are also the first demonstration ever at this scale (1.1 km resolution) and over such a large area (humid Tropics) that the mapping exercise and the statistical area assessment are not exclusive and can be carried out jointly in a satisfying manner. Having demonstrated that global scale products can be validated it is now more than ever important for the debate on validation of global scale data sets to continue.

These forest cover maps of the early 1990's were then used in conjunction with knowledge from forestry and environmental experts to identify deforestation risk areas (next chapter).

Production of forest cover maps for the early 2000's

Developments using new relevant coarse spatial resolution optical data (VEGETATION, ERS-ATSR) and integrating radar (ERS-SAR, JERS-SAR) data in the accuracy assessment process have been made to update and refine the assessment of status and conditions in the forest areas at the pan-tropical level.

From this new coarse resolution remote sensing imagery database three new continental vegetation maps of the tropical humid forest cover have been elaborated at 1.1 km resolution for the early 2000's:

- Vegetation map of Central Africa at 1:5M (Mayaux & Malingreau, 2000)
- Forest map of Madagascar at 1:5M (Mayaux *et al*., 2000)
- Vegetation map of South America at 1:5M (Eva *et al.*, 2002)
- Forest cover map of insular Southeast Asia at 1:5M. (Stibig *et al*., 2002)

For Central Africa, the middle infrared channel from the ERS-ATSR is sensitive to moisture content and as such helps discriminate forest areas that are periodically flooded (Mayaux *et al.*, 2002).

4. Identification of ‘deforestation hot spot’ areas

Summary

Deforestation risk areas were identified using the baseline forest cover maps of the early 1990’s in conjunction with knowledge from forestry and environmental experts. These areas were spatially delineated and documented on regional maps for the 3 continents, the so called “deforestation hot spot areas” (Achard *et al*., 1998).

This chapter is a synthesis of the information collected from the experts during the consultation held in November 1997 and updated before being used as input for the sampling phase.

The results of the forest change assessment exercise (Chapter 7) were used to demonstrate the validity of the hot spots and further work was carried out to establish whether fires detected from Earth Observation systems could help in identifying deforestation areas.

4.1. Objectives and approach

4.1.1. Expert consultation meeting

A group of experts met at the Joint Research Centre in Ispra on the 24-25 November 1997 at the invitation of the TREES project to collectively identify areas of current and potential deforestation in the moist zone of the tropical belt. This approach of assessing deforestation is rather unconventional (in the sense that it does not directly lead to quantification) but was deemed important in the framework of the TREES project.

The consultation with leading experts in the field of forest cover assessment held in November 1997 was seen as an important step in the TREES project in order to produce a reference source of identified ‘hot spots’ (deforestation risk areas).

The group of high level experts coming from Europe and from the three concerned continents was chosen for their recognized expertise on deforestation processes.

The experts were invited from key institutions in the three concerned continents and from international organisations involved in monitoring deforestation. At the same time, an intensive consultation of key contacts and documents that might indicate centres of deforestation, was undertaken by Internet. International experts came from the FAO, IUCN, WCMC, IGBP, CIFOR, CIRAD, ETFN. Expert opinion for Southeast Asia came from IIRS, CIFOR Bogor, FIMP, BIOTROP along with Prof T. Whitmore and Dr. F. Blasco. For Africa representation came from ECOFAC, ICRAF FORAFRI, ICRA. Representatives from INPE, IBAMA, CIAT, CATIE, EPOMEX, UNA, with Prof. H. Puig and Prof. Lenzi-Grillini provided information on Latin America.

Table 4: List of external contributors to the 'deforestation hot spot' exercise.

Participants to the meeting

Global Aspects	*Latin America*	*Africa*	*Southeast Asia*
Dr. R. Drigo, UN-FAO, Rome Dr. S. Iremonger, WCMC, Cambridge, UK Prof. E. Lambin, Louvain-la-Neuve Univ., Belgium	Dr. J.R. Dos Santos, INPE, Brazil Dr. G. Leclerc, CIAT, Colombia Prof. C.R. Lenzi-Grillini, University of Firenze, Italy Dr. C. A. Llerena, Univers. National Agraria, Peru Prof. H. Puig, Toulouse University, France	Dr. C. Aveling, ECOFAC, Gabon Prof. P. Defourny, Univ. Louvain-la-Neuve, Belg. Dr. J. Imbernon, ICRAF-Nairobi, Kenya Mr. J. Y. Ipalaka, SPIAF, RD Congo Dr. R. Nasi, FORAGRI, Gabon	Dr. F. Blasco, LET, France Dr N. Byron, CIFOR, Indonesia Prof. P.S. Roy, IIRS, DehraDun, India Prof. T.C. Whitmore, Cambridge University, UK

Consulted Experts

Global Aspects	*Latin America*	*Africa*	*Southeast Asia*
	Prof. E. Amodio, Central Universidad Caracas, Venez Mr. F. Del Gatto, COSPE, La Ceiba, Honduras Mr. G. Galli, UN Mission, Guatemala City Dr. J.-F. Mas, Universidad Campeche, Mexico Mr. J. A. Raposo Pereira, IBAMA MMA, Brasilia DF	Prof. C.-M. Evrard , Univ. Louvain-la-Neuve, Belgium Mr. J.-M. Froment, ECOFAC, Brazzav., Congo Mme D. Joiris, APFT, Univ. Libre de Bruxelles, Belgium Mr. J.-P. Vautherin, ECOFAC, Yaoundé, Cameroon	Mrs. R. Dennis, CIFOR, Bogor, Indonesia Mrs. E. Eller, FOMISS, Sarawak, Malaysia Dr. Y. Laumonier, FIMP, Jakarta, Inonesia Dr. D. Murdiyarso, BIOTROP, Bogor, Indonesia

The basic task of the group was to locate on maps (one for each of the three tropical continents), areas of current or impending deforestation in the mid 1990s and to characterise the main drivers. The evidence on which the areas were designated was based on the personal experiences of the participants, with the understanding that the information upon which it is based would be subject to continuing revision.

The scope of investigation was restricted to the continental scale so as to allow the exercise to be carried out along the full extent of the humid tropical belt.

Keeping in mind the “global” objective of the TREES project, the expert consultation was expected to agree on aspects of deforestation that should be measured and whether this is possible with the remotely sensed methods used.

A main distinction was made between *recent past* or *present* changes, which referred to the period 1992-1997 and *recent future* changes, which referred to the period 1998-2002. Recent past change could be identified and measured in a descriptive way while future change could only be modelled in a predictive manner. The same priority was given to the recent, present or future change during the meeting.

The ‘hot spot’ document has to be regarded as a ‘first pass’ attempt that will need further improvements and updating in an iterative process. This attempt was probably the first ever completed with such a broad range of expertise.

4.1.2. ‘Deforestation hot spot area’ concept

The concept of ‘hot spots’ was first studied by Myers (1993). Fourteen (14) deforestation hot spots were identified and described around the tropical belt. It has been felt that a more exhaustive study was needed to sollicite agreement from a wider community of recognised experts.

A ‘deforestation hot spot area’ is an area where major changes of the forest cover were thought to be occurring during the 1992-1997 period, or were expected to take place in the subsequent years: 1998-2002.

The final objective was to use the hot spot delineation in the framework of a more complex remote sensing based monitoring system. In this monitoring system a stratified sampling approach based on the hot spots is used to measure the recent changes in forest cover through the analysis of Earth Observation data (see Chapter 5).

Although the conservation aspects or the biodiversity was deemed important by some of the experts, particularly when considering the future threats, the main focus of the exercise was the at the time (1997) current dynamics of forest cover. The fact that a change was planned or controlled (construction of a dam, national agriculture project, etc) did not omit an area from the list.

The hot spot areas include the following cases:

- Areas with deforestation during the 1992-1997 period associating the combination of different speed/intensities of forest cover change (high, medium and low) and different forest cover status (dense, fragmented, low density);
- Areas at high risk of forest cover change in the late 1990s and beyond.

4.1.3. Use of spatial indicators

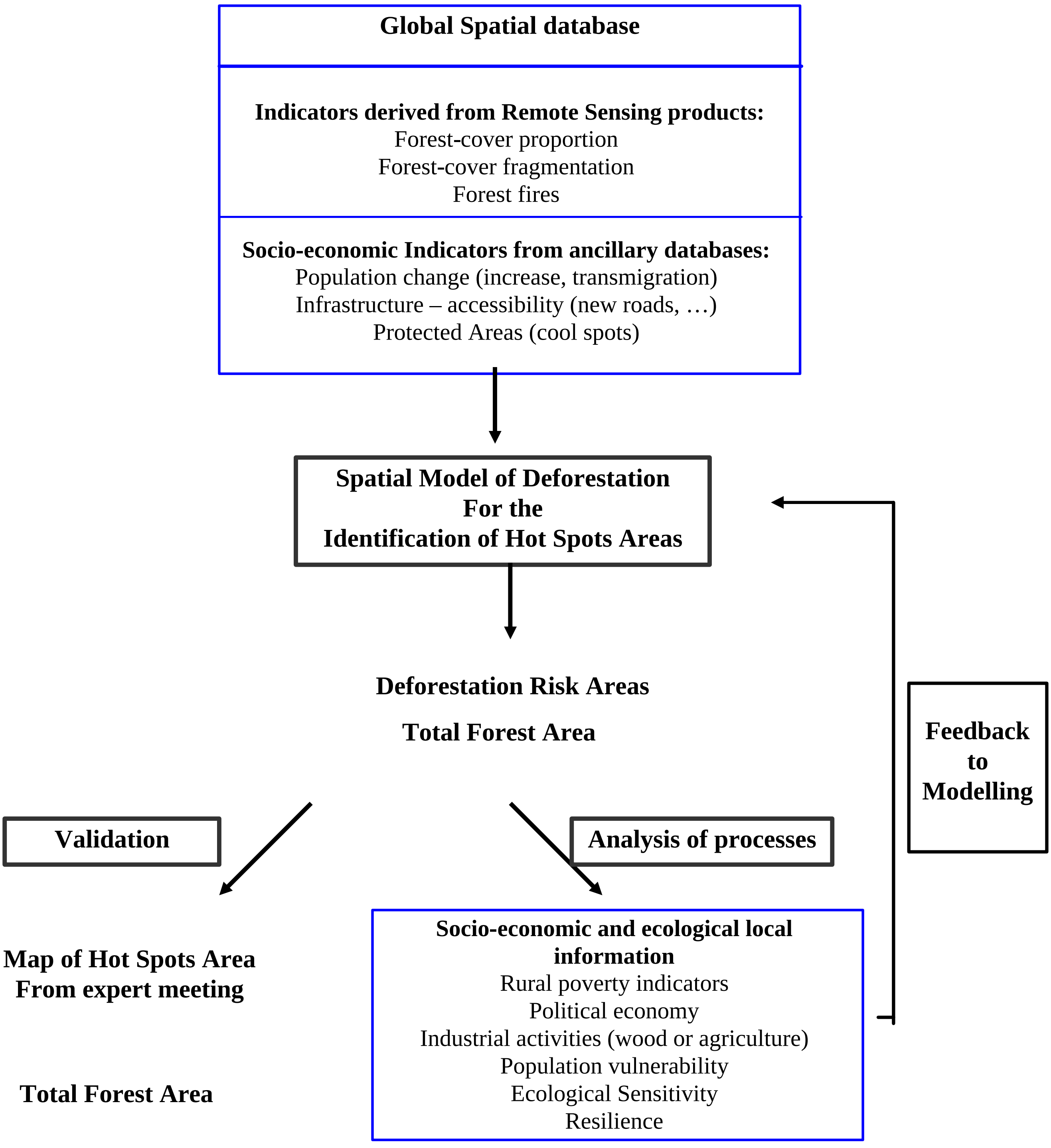
The TREES project developed a methodology for the identification and analysis of hot spots, which is adapted from a hierarchical structure approach, from the general (broad scale) remotely sensed criteria to regional socio-economic indicators to finer scale potential impact indicators (Lambin & Ehrlich, 1997).

The method (Figure 6) combines together potential indicators derived from remote sensing products such as forest cover percentage, occurrence of fires or distance to forest, with indicators coming from ancillary socio-economic database. The selection of these parameters is strongly related to their global availability and their relation to the deforestation processes. The expert consultation contributed to define the best set of potential indicators by which deforestation hot spot areas can be delineated around the tropical belt.

Change detection methods have been developed using coarse or fine resolution data at different dates. Most change detection studies have either used only fine spatial resolution imagery (Skole & Tucker, 1993) or only coarse spatial resolution imagery (Lambin & Strahle,r 1994). Very few studies have been undertaken with multi-spatial resolution satellite imagery. A change detection method based on a combination of NOAA-AVHRR, Landsat-TM and SPOT-HRV imagery has been developed on a case study in Vietnam (Jeanjean & Achard, 1997).

The experts were provided with data relating to forest distribution (*i.e.* regional maps of forest cover) and with potential disturbance indicators (*i.e.* maps of forest fragmentation, fire occurrence and access to the forest). While socio-economic data were thought to be important, it was found that i) the availability of data varied widely across the tropics and ii) they were rarely spatially located in enough detail to enable meaningful analysis. Similar problems presented themselves with the locations of roads and settlements.

Figure 6: Theoretical approach for the identification of deforestation hot spot areas



4.2. Continental ‘deforestation hot spots’ maps

The exercise conducted during the TREES expert meeting held in November 1997 led to the production of three continental tropical forest “hot spot” maps, which include the main areas of active present or expected near-future forest cover change.

These deforestation ‘hot spots’ maps were then updated after the expert meeting with more recent information and were restricted to the active deforestation areas during the early 1990’s.

4.2.1. Analysis by continent

Southeast Asia

The situation in Southeast Asia is more worrisome considering that current or near-future “hot spots” cover the majority of the forest remnants of the continental Southeast Asia and of the Indo-Malay Archipelago.

The extensive forest resources of northeastern India are under intensive exploitation for timber and conversion to agriculture. Selective to clear-cut logging affects many parts of Myanmar and Cambodia. The impact of shifting cultivation of forest resources of Myanmar is believed to be on the increase. Laos has little forest left in the North and the Southern forest cover is increasingly threatened by logging. Plans for China to open various access roads/railways from Yunnan to the Andaman Sea are likely to have a serious impact on the forest remnants of the “golden triangle”. Forest conversion is taking place on a large scale in Central Vietnam and forest fragments in the North are rapidly being eroded. The situation in Sumatra is particularly striking; forests have virtually disappeared under the pressure of agriculture and plantations along a wide Central South-North belt. A similar situation is developing in Kalimantan. No reversal of such trends is likely to emerge in the near future.

Central Africa

In Central Africa, significant deforestation is limited to a few areas.

Deforestation is mainly associated with logging in Cameroon and Gabon, and with the supply of fuel wood to major urban centres of the region. Deforestation / forest expansion in the “zone périforestière” is an important element of the sub continental forest cover budget. The situation in the Eastern part of the République Démocratique du Congo is said to be ripe for a major push in deforestation (i.e. logging and conversion to pastures in Ituri) pending improvement in access and security. The situation in the Congo Basin is still relatively quiet on the deforestation front. Large-scale logging or significant agricultural expansion are not expected to take place very soon. Furthermore, the secondary forest vegetation may act as a buffer if an acceleration of swidden cultivation takes place at the local level.

Latin America

The South America tropical rain forest domain is currently exploited along a large belt extending from the 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. In Central America, the forest remnants are highly fragmented. Fragments are being progressively reduced and only inaccessible and conservation areas seem to be somewhat secure. Agricultural expansion and new settlements are the main causes of deforestation for this continent.

4.2.2. Conclusions of the expert meeting

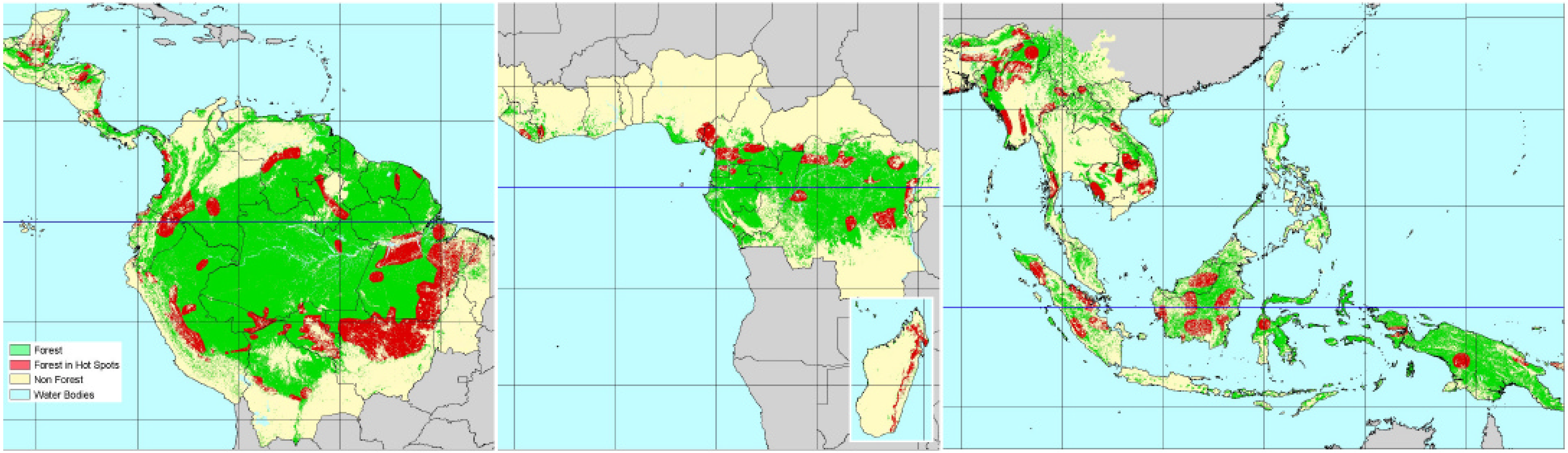
The picture, which emerged at the end of the analysis conducted during the 'hot spot' meeting, was a relatively bleak one. The hot spot maps dramatically illustrate that deforestation is an on-going process, which insidiously continues to affect larger areas. The information presented on these maps is cause for concern because it seems to indicate that the processes are steam rolling over large areas and may be irreversible. One cannot avoid adopting a very fatalistic attitude when confronted with these facts. The apparent irreversible decline of natural forest resources leads one to seriously consider whether conservation efforts should maintain a focus on sustainable forest management practices (Peres & Terborgh, 1995). Considering that agricultural expansion is probably the main cause of deforestation, 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'.

The analysis was extensive but not truly comprehensive since a few regions like West Africa and Irian Jaya were not properly covered in the analysis.

The evidence on which the areas were designated was often subjective, based on the personal experiences of the participants. Consequently these hot spot maps should not be taken as an unqualified picture of reality. Instead it should be recognised as a strong 'good-faith' effort to locate important risk areas along the tropical belt, with the understanding that the information upon which it is based will be subject to continuing revision. A clear need was expressed to continue the personal contacts with individuals and organisations that can provide local information on existing hot spots. While errors of commission are probably few in such an exercise, those of omission are more difficult to quantify.

Information on potential criteria was also collected during the consultation in order to define a set of indicators by which deforestation areas can be stratified at broad scales. For example the fire information, which can be derived from Earth observation data, has been considered as a useful indicator in the Central America, Latin America and Southeast Asia regions. The use of these spatial indicators in future spatial modelling exercises will allow more automatic identification of hot spot areas.

Figure 7: Deforestation "hot spot" areas of the humid tropical forests delineated in 1997



4.3. Updates and retrospective analysis

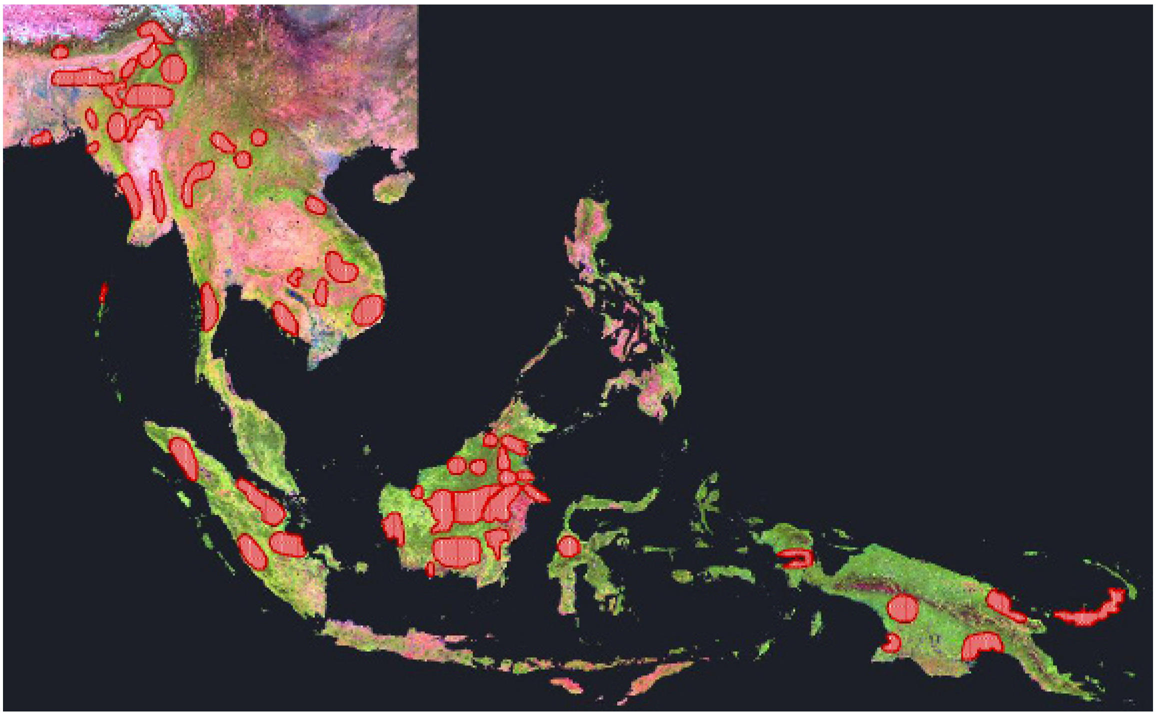
4.3.1. Updating the hot spot maps

The three maps prepared during the hot spot meeting feature areas where forest cover was considered to change at high speed during the period 1992 - 1997 or areas at high risk in a near future after 1997. These maps are intended to represent sensitive areas of high priority for any monitoring system. The information upon which these maps are based was subject to continuing revision. Such revision came through further ad hoc expert consultations and improved forest maps derived from Earth observation data.

Missing information on 'deforestation hot spots' was collected and added to the information gathered during the Hot Spot meeting. In particular additional information was provided for Papua New Guinea by Australian experts and the National Forest Service of PNG. Three areas were added for Papua New Guinea: Madang, New Britain and Golf province. Four more specific areas replaced the previous spot on Sarawak, provided by a Sarawak forestry project.

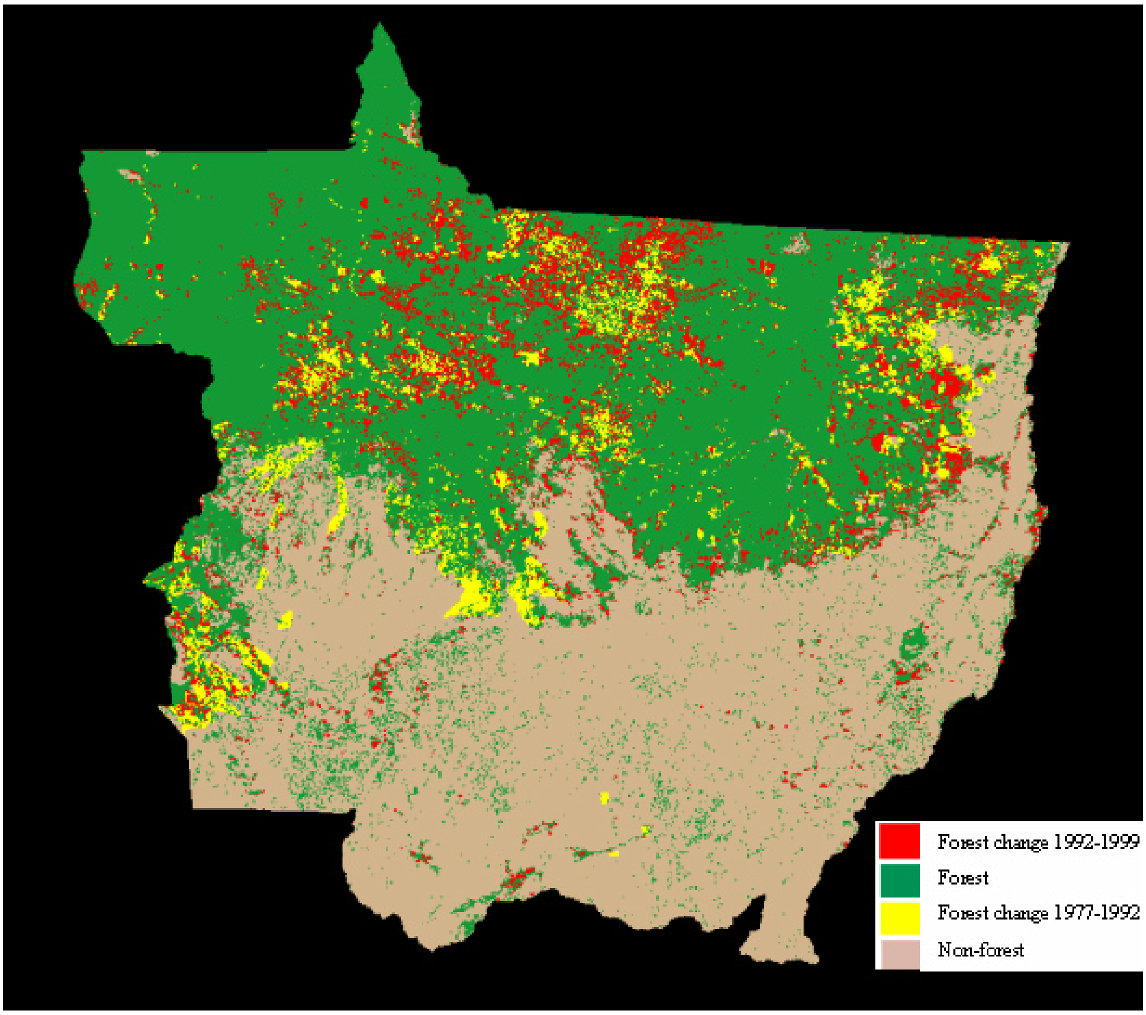
The present 'Hot Spot' map is considered to provide the full overview on the areas in Southeast Asia undergoing presently high change or under high threat. For each 'Hot Spot' there is detailed information on processes and causes of deforestation.

Figure 8: Updated deforestation 'Hot Spot' map of Southeast Asia



In South America analysis of new data from the Along Track Scanning Radiometer (ATSR) sensor in 1999, showed a significant increase in agricultural expansion in the Mato Grosso state of Brazil (Figure 9). Improved data on protected areas, helped to better define the cool spots.

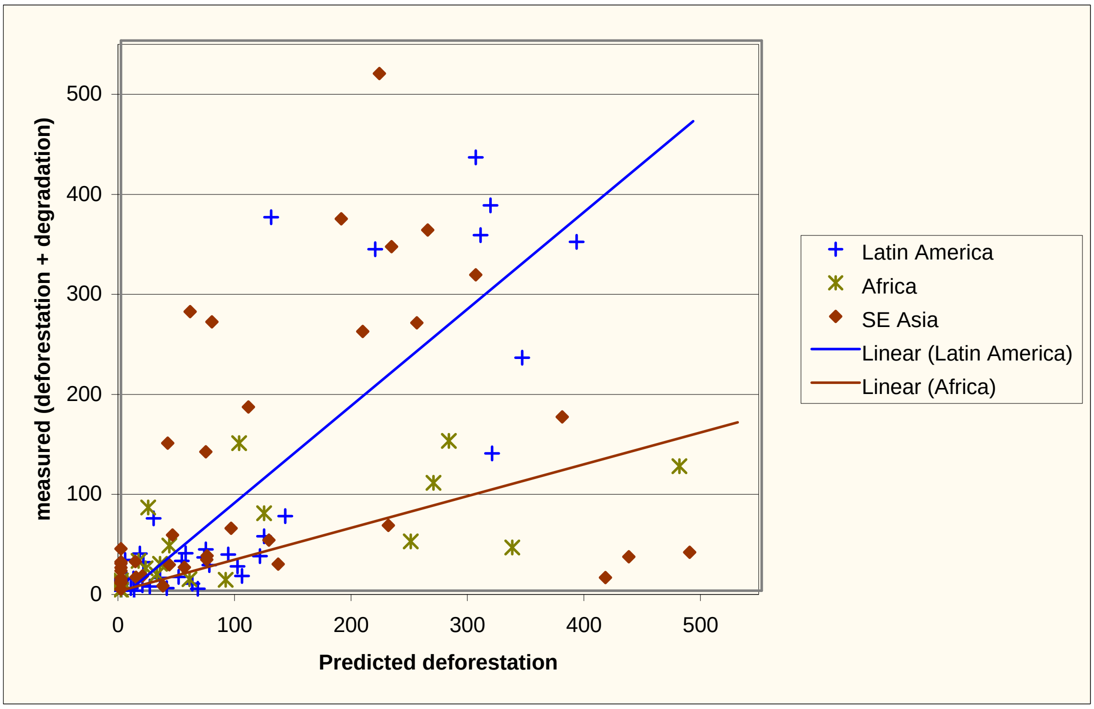
Figure 9: Expansion of the agricultural front in Mato Grosso in the 1990s



4.3.2. A retrospective analysis of the hotspots

For the analysis of pan-tropical forest change the hot spots were used in the stratification of the survey area (chapter 5). The subsequent interpretation of 104 satellite image pairs across the tropical forest domain (see Chapter 6) provided an opportunity to access the validity of the hot spots indicated by the expert consultation process. For each sample site in the forest change exercise as hotness index was calculated on the basis of the percentage of hot spot and forest in the site (Richards *et al.* 2000). The relationship between this predicted deforestation and that subsequently measured is shown in Figure 10.

Figure 10: Relationship between predicted and measured deforestation for all samples

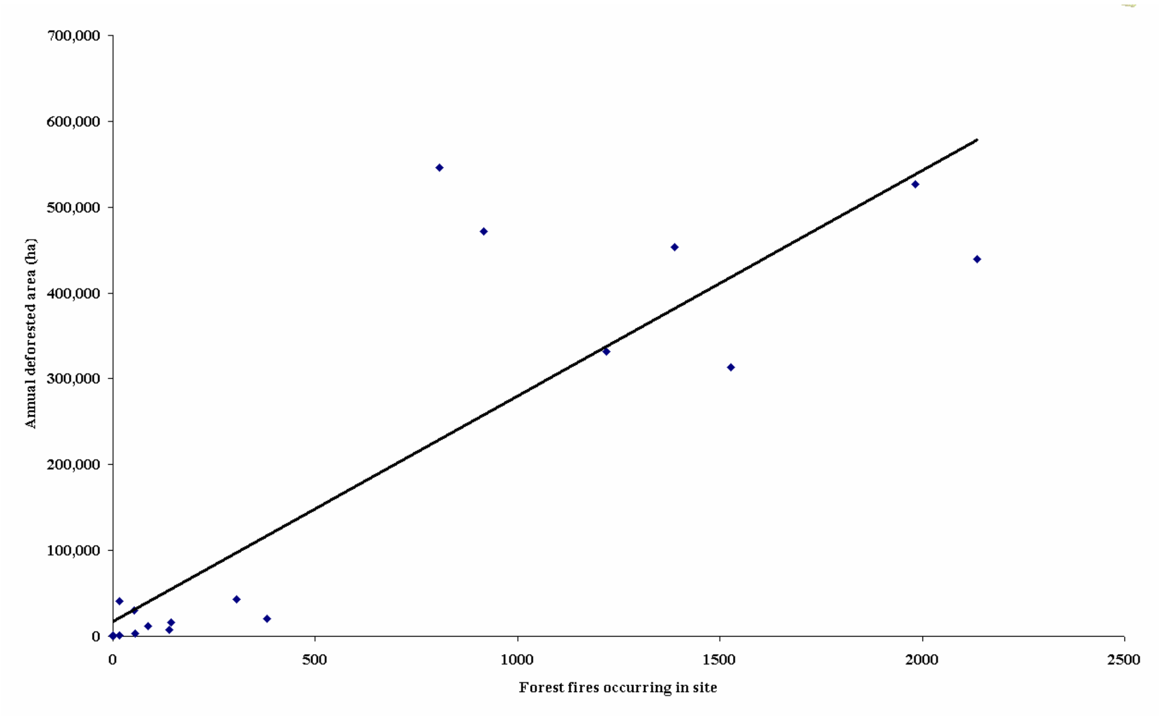


The results show that differences occur by continent. Generally, for Asia and Latin America the majority of sites have a similar close relationship between predicted and measured deforestation. The main exceptions are three sites in Asia, which were deemed to be at high risk (predicted deforestation between 400 and 500) but in fact had low deforestation rates. In Africa the predicted deforestation (on the X axis) resulted in a lower deforestation rate than was generally found for Asia and Latin America. This confirms the expert conclusions on Africa, where it was cited that deforestation was limited. The high levels of "predicted deforestation" come from the weighting of the hot spot areas by the FAO continental deforestation rates (see Chapter 5). In the case of Africa, much of this rate comes from dry forest areas, rather than the measured humid forests. Never the less, Figure 10 demonstrates that in general the hot spot locations are correct, however, in a future sampling system the spatial delineation of the hot spots could be more precise by using low resolution satellite data.

4.3.3. Analysis of fire data and deforestation hot spots

One of the possible indicators of deforestation is the presence of fires in the tropical forest belt. Fire is used widely in the tropics as a land management tool, for clearing forests and for maintaining savannah areas against the invasion of woody species and for preparing the land for cultivation. While this would suggest that the detection of fires from space might help determine deforestation fronts, both cultural practices and climate play a major part in determining fires' role in the deforestation process (Eva & Lambin, 2000). As with the hot spot index (previous section) it was possible to use the results of the forest change assessment exercise to test the role of fire in the deforestation processes occurring in the 104 test sites sampled. Fires detected from the NOAA-AVHRR satellite between 1992 and 1993, were correlated with the subsequent deforestation in the TREES test sites between 1992 and 1997. The analysis was carried out both at the individual site level, correlating the spatial distribution of fires across a test site and the deforestation across the site, and at the regional level, equating the total fires and total deforestation per site for a set of sites. At the individual site level the results show that fire and deforestation were equated in nearly half of the cases studied (15/30 South East Asia, 25/48 Latin America and 8/18 for Africa) and a further 7 sites showed neither fire occurrence nor deforestation. Despite this, at the regional level, results are not easily exploited as the relationship between fires and deforestation varies markedly between sites. Thus while in one test site 10 fires may relate to 100 ha of deforestation, in a nearby site 100 fires may produce the same result. It was also found that for a number of sites, in the hyper humid areas, that significant deforestation could occur without the presence of fires. This indicates that topography, vegetation type, access, culture and climate all play a role in the use and extent of fire in land management. The stratification of the tropics into areas of similar fire typology may help in the utilisation of this type of data. For the Brazilian "arc of deforestation" similar climate and cultural practices exist. In this region a clear relationship between fire and deforestation was demonstrated (Figure 11 from Eva & Fritz, 2002).

Figure 11: Number of forest fires versus annual deforestation for the Brazilian samples



Notes: Forest fires represent the total number of fires occurring between April 1992 and December 1993
Annual deforestation is taken as average during the 1990-1997 period
The Pearson coefficient of correlation is given as 0.87

5. Design of a sampling scheme for forest cover change measurement over the Tropics

Summary

This chapter describes the design of a sampling scheme for the measurement of tropical deforestation rates from 1990 to 1997 using fine spatial resolution imagery.

Based on the two information layers: forest cover baseline (chapter 3) and the deforestation hot spot areas (chapter 4), a framework was established for the selection of a sample of around 100 observation sites across the tropics selected in a statistical manner with higher sampling probabilities for fast changing areas (Richards *et al*., 2000).

In order to make the sampling scheme as efficient as possible and at reducing the variability of the change estimates (for higher confidence), the observed area was restricted to the humid tropical domain only and the higher intensity of the sampling on forested areas where most of the deforestation takes place.

A stratification was established for the selection of a pre-sample. Using a *hotness index*, five strata were defined ranging from low change rate, i.e. areas with no hot spot and high forest cover, to high change rate, forest areas within the hotspots. The stratification was used for the selection of 102 compulsory observation sites covering 6.5% of the humid tropical domain.

The 102 samples were selected in a statistical systematic manner with higher sampling probabilities for fast changing areas: from a sample frame based on a tessellation grid of hexagons, a systematic sampling with different sampling rates for each of the five stratum was selected (Richards *et al*., 2000).

To summarize 3 steps were used: first, the sampling units were points, then these points were used to select regular hexagons from a tessellation of the earth, and finally the hexagons were related to observation units with boundaries determined by the Landsat TM image frames (full scenes or quarters of scene). The extent of TM scenes was shrunk to avoid overlaps, so that these units also constitute a tessellation of the study area (tropical belt).

5.1. Definition of the sampling area

The TREES forest cover information layer was considered as a starting point for the definition of the sampling area. The boundary of the TREES maps area derives mainly from the processing windows adopted for the coarse spatial resolution imagery. For the change assessment an extension of the previously considered region was required. Some variations between the continents occur, which are described below.

A notable omission from the TREES early 1990's maps area was the region covering eastern Africa, Madagascar and India. Whilst this region contains mainly fragments of moist tropical forest rather than significant large blocks, it has been included in the current study area definition because:

- The aggregated spatial extent of the fragments is not insignificant
- In terms of biodiversity these areas are important
- It will allow to derive more accurate estimates at regional levels

The initial definition of the sampling area includes all countries in which tropical humid forest occur - either defined by TREES (Malingreau *et al.*, 1995) or by IUCN (Iremonger *et al*., 1997). The countries or part of countries included in this area are as follows by region:

- Mexico and Central American countries
- South America*:* Columbia, Venezuela, Guyana, Surinam, French Guiana, Ecuador, Peru, Bolivia and Brazil.
- Africa: Guinea-Bissau, Guinea, Sierra Leone, Liberia, Ivory Coast, Ghana, Togo, Benin, Nigeria, Cameroon, Central African Republic, Gabon, Congo-Brazzaville, Democratic Republic of Congo, Uganda, Rwanda, Burundi, Ethiopia, Kenya, Tanzania, Madagascar, northern Angola, south western Senegal.
- Southeast Asia: India, Bangladesh, Sri Lanka, Bhutan, Burma, Thailand, Laos, Vietnam, Indonesia, Papua New Guinea, Philippines, Cambodia, Yunnan & Hainan provinces of China and Taiwan.
- Australia is omitted.

The area considered for the deforestation hot spots exercise includes all of the countries mentioned above with the exceptions of:

- South America: Panama and non Legal Amazonian Brazil
- Africa: Ethiopia, Uganda, Kenya, Tanzania, Rwanda & Burundi
- Southeast Asia India except North Eastern India, Yunnan & Hainan Provinces China, and the Philippines[1].

[1] It is thought that there was no 'deforestation hot spot' areas in the Philippines. Areas were delineated in Papua New Guinea but without reliable field knowledge.

5.2. Design of a stratified systematic sampling scheme

A new sampling scheme has been designed to measure deforestation rates with better accuracy and in a more consistent manner across the humid tropical belt.

5.2.1. Background on spatial sampling

During the first phase of the TREES project efforts concentrated on mapping tropical forest cover using a "wall to wall" approach with coarse spatial resolution imagery (NOAA AVHRR) from the early 1990’s.

In the second phase of the project recent 1km resolution imagery (ERS ATSR-2 or SPOT-4 VEGETATION from 1997 to 2000) has again been used for wall-to-wall mapping. However, because of the spatial characteristics of this type of imagery, accurate forest change measurements are not possible to derive with confidence. The only comparison possible is between the small scale (1/5,000,000) maps from 1990-1992 and from 1997-2000.

Therefore fine spatial resolution imagery (such as available from Landsat and SPOT satellites) is needed for the forest change assessment. Because of the cost implications of using fine spatial resolution imagery for a ‘wall to wall’ change assessment, a sampling approach had to be adopted.

Stratified sampling

When a spatial phenomenon, such as the deforestation process, is not distributed homogeneously a stratification reduces the variance of the estimator.

Some authors consider that “because tropical deforestation is spatially concentrated, it is very improbable that an accurate estimate of deforestation by random sampling of Landsat scenes will be achieved” (Townshend & Tucker, 2000). But this assertion was demonstrated only at a national level for the unique case of Bolivia with a total of 41 Landsat scenes where 75% of all deforestation was concentrated into five Landsat scenes in 1985. Czaplewski (2002) demonstrates that a 10% random sampling of Landsat scenes is capable of accurate estimates of deforestation at appropriate scales, i.e. pan-tropical, continental or sub-continental scales.

A dedicated stratified statistical sampling scheme was deemed indispensable for cost and effort effectiveness.

Requirements for an optimised sampling scheme

Starting from such considerations, a number of initial specific requirements were made in order to design an appropriate sampling scheme:

1. The scheme should be, as far as possible, sensor independent in order to be applicable in the future with different sensors.
2. An adaptation should be foreseen to optimise the use of fine spatial resolution satellite images which size is considered most convenient for forest area change estimation at a pan-tropical level, namely Landsat-TM or SPOT.

3. Unbiased estimators and error variance should be computed from the sample.
4. In order to reduce the variance of the parameter to be estimated (area change), a large part of the sample should be concentrated on areas where forest change is expected to be high. This can be achieved through a stratified sampling approach.
5. Adjacent sampling units are likely to give redundant information and should be generally avoided. Systematic sampling can be advantageous in this sense.
6. The scheme should also be pragmatic considering the image interpretation phase.

Background on grid systems for spatial sampling at global scale

A variety of different grid systems are available for spatial sampling purposes. Examples include rectilinear grids based on degrees of longitude and latitude, satellite based grids such as the Landsat WRS-2 system and Cartesian grids on map projections. Samples may be located on these grid systems in various ways according to standard sampling theory: random, systematic, stratified random etc. However, these systems run into problems when very large areas of the Earth are considered. These problems arise essentially from the classic map projection problem that it is not possible to maintain both shape and area on the projection plane and that gross distortions of either one or the other are inevitable when considering the entire globe.

The sample frame used by FAO for tropical forest resources assessment from Landsat imagery during the 1980’s (FAO, 1996) is based on the Landsat World Reference 2 System (WRS-2). The WRS-2 system is used to identify Landsat scenes based on a system of paths (orbits) and rows (an arbitrary along-track division of the data stream). The WRS-2 scenes overlap slightly (5%) at the equator to ensure complete global coverage. Because of the geometry of the satellite's sun-synchronous near polar orbit, the ground tracks of the satellite overlap increasingly towards the poles.

The WRS-2 grid provides a convenient sampling frame for a sample of Landsat scenes. However, we decided to use a sampling frame which is independent of any given satellite sensor and hence orbit geometry. It was also noticed that at high latitudes a WRS-2 based sampling frame, whilst possible (Czaplewski, 1997), becomes very complicated because of the irregularity of the WRS-2 grid. Alternative sample frames were therefore investigated.

Conventional alternatives include using a regular Cartesian grid overlaid on either a projected or un-projected map. Either of these approaches results in sample frames with grossly distorted sample units, either in shape and/or area.

Another alternative includes using a tessellation of geometric shapes either on the sphere or on a facet of a Platonic solid. However, the seemingly trivial task of creating a distribution of points on a sphere, such that they are all the same distance apart and which form the centre points of a network of polygons has not been solved. Approximations are available using polyhedral solids. Hexagonal grids have a number of advantages over both their Cartesian counterparts and WRS-2 for sampling applications, including:

- The grid elements do not have gaps or overlaps
- The cells have approximately equal areas
- The cells have the same shape
- The centre of each cell is the same distance from its neighbours

A sampling scheme based on such tessellated grid has been developed by Olsen *et al.* (1998).

5.2.2. Selection of a stratified sampling frame

Considering that a tessellated grid fulfils a number of the specific project requirements and also gives the opportunity to expand to a more general global sampling scheme, such a sampling grid was selected.

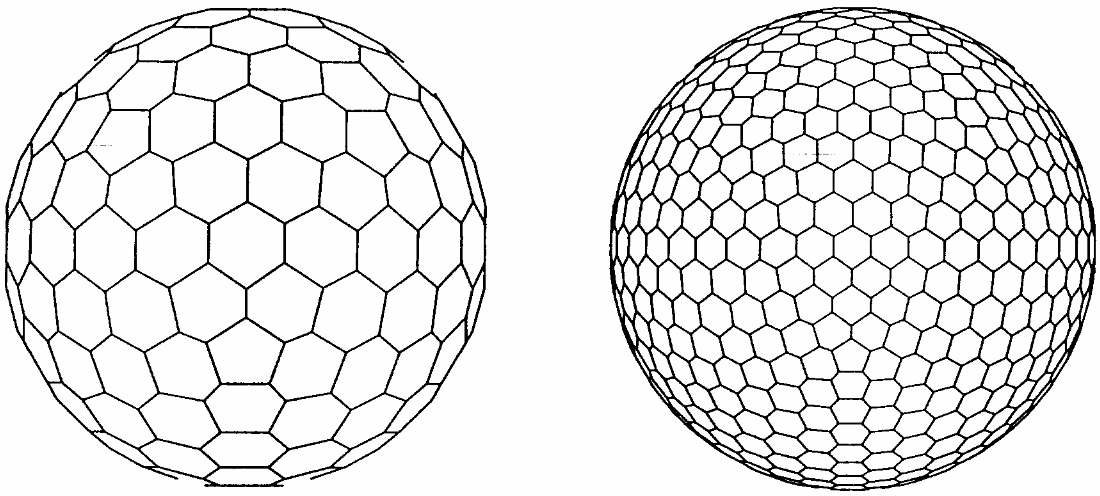
The sampling frame selected for our approach is based on hexagon tessellations on a sphere, derived from a spherical system developed by Thuburn in 1997 (Richards *et al.*, 2000).

The tessellation is constructed by inscribing a regular icosahedron inside a unit sphere. The triangular facets of the icosahedron are then bisected to form a denser network of triangles. Then if the centre of each triangle is taken as a vertex, a mesh of twelve pentagons and *n* hexagons can be formed. No matter how fine the tessellation is made the number of pentagons always remains the same. Figure 12 shows the first two levels of recursion of the tessellation.

This type of geometry has a number of useful characteristics, particularly that the sample frame is made up nominally equal area and equal shape units. A scheme with equal probabilities of sample unit selection can therefore be devised.

The distance between hexagons was set to approximately 60 km, i.e. the average size of the hexagons has been tuned to 3,600 km^2, which is comparable to the smallest size of available fine spatial resolution images (from SPOT satellites). The sampling frame is a finite set of 12532 points that are the centres of the hexagons, which intersect with the study area by more than 10 km^2.

Figure 12: Initial steps to create a spherical hexagonal tessellation



Stratification of the sampling frame

Stratification is aimed at reducing the variance of the statistical estimates if relevant variables are used in the stratification procedure. However the absence of adequate spatial information on forest cover change at the global level proved to be a major limitation for the desired stratification in strata of different deforestation intensity. Although FAO has published estimates of annual forest cover change between 1990 and 1995 (FAO, 1997), these statistics are available only at the country level and are therefore too general for use as the basis for a continuous spatial stratification.

Therefore the two TREES information layers produced in the previous steps, i.e. forest cover (1-km resolution forest cover baseline - chapter 3) and 'Deforestation Hot Spot' areas (chapter 4) have been used for the stratification.

For each hexagon of the sample frame the number of pixels classified as forest or non-forest in the forest map has been computed. All data processing has been performed in the Lambert Cylindrical Equal Area projection with a cell resolution of 1000m by 1000m and area calculation were therefore just a matter of counting the pixels in each land cover class. Furthermore the hot spot area in each hexagon has been also computed.

The output from this process is a database with a unique identifier for the hexagon followed by a series of fields containing the forest cover statistics for each forest class and the hot-spot area. Five broad strata of hexagons could then be defined, based on the percentage of forest cover and the hot spot area contained in each strata, as shown in Table 5.

As the information from the 'deforestation hot spot' layer contains to a certain extent a 'subjective' component, the variances of the estimates might be higher than if based on fully objectively defined spatial information only.

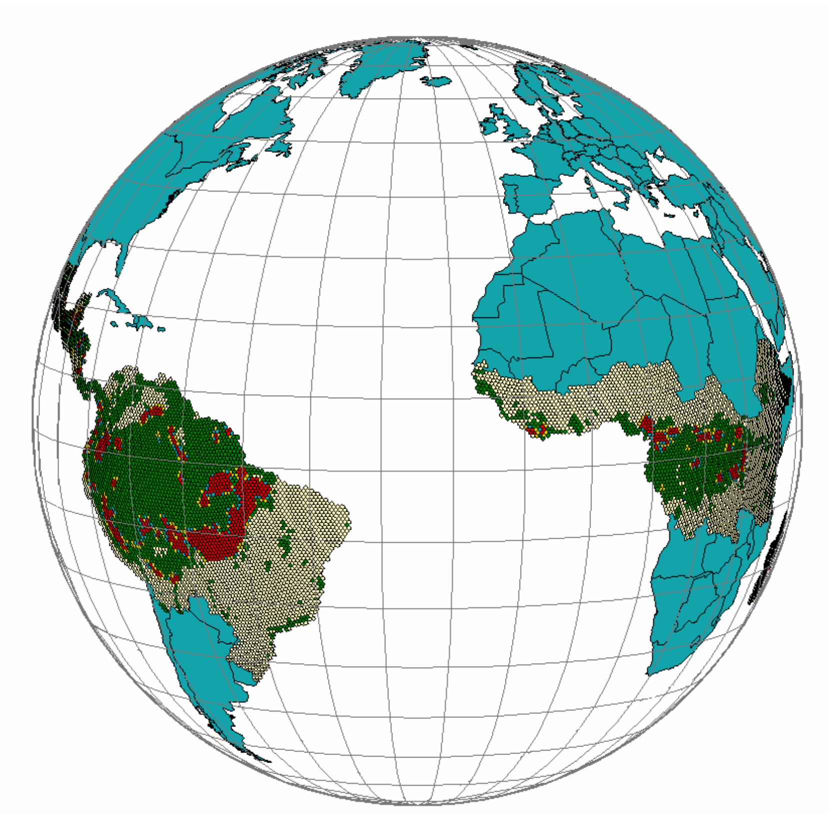
Table 5: Definition of the sampling strata

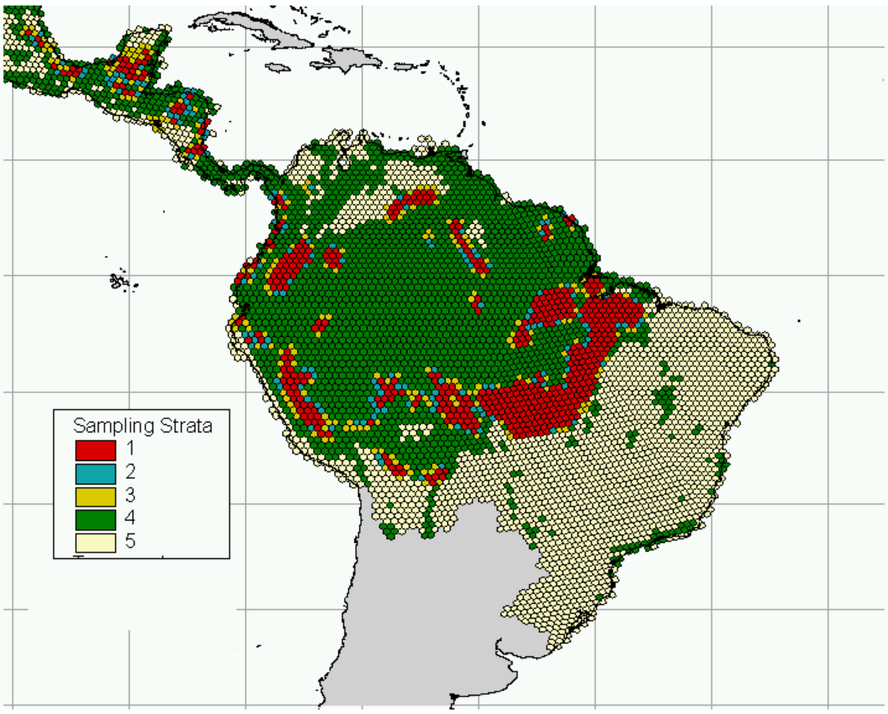
<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">% hot spot area in sample unit</td></tr>
<tr><td>No hot spot</td><td><20%</td><td>20-50%</td><td>>50%</td></tr>
<tr><td rowspan="3">% Forest cover (1km-res.) in sampling unit</td><td>No forest (0%)</td><td colspan="4" rowspan="1">Stratum 5</td></tr>
<tr><td><10%</td><td></td><td colspan="3">Stratum 3</td></tr>
<tr><td>>10%</td><td>Stratum 4</td><td>Stratum 3</td><td>Stratum 2</td><td>Stratum 1</td></tr>
</table>

As shown in the following eight sub-regions have been identified to be used for balancing the sample distribution. These sub-regions are: Pan-Amazon and Andes; Brazil and Guyanas; Insular South-East Asia; Continental South-East Asia; Central Africa; Madagascar; West Africa.

The spatial distribution of the strata in the sample frame is illustrated in Figure 13 over Latin America and Africa.

Figure 13: Stratified sample frame of the Latin America and African continents





5.2.3. Systematic sampling by points on a regular grid

To avoid adjacent sampling units to be selected, as they are likely to give redundant information, systematic sampling was considered advantageous. Furthermore, many examples can be found in the literature showing that systematic sampling improves results in practice with particular applications to remote sensing data (Schreuder *et al.*, 1995).

Depending on the rule adopted for the arrangement of units, a systematic sample is either aligned, aligned in one direction or unaligned. Here we only consider aligned samples in which the selected units have the same relative position in the block. If we take more than one element per block, we have a systematic sampling with multiple starting points (Thompson, 1992). The sub-samples generated by each of the starting points can be referred to as replicates.

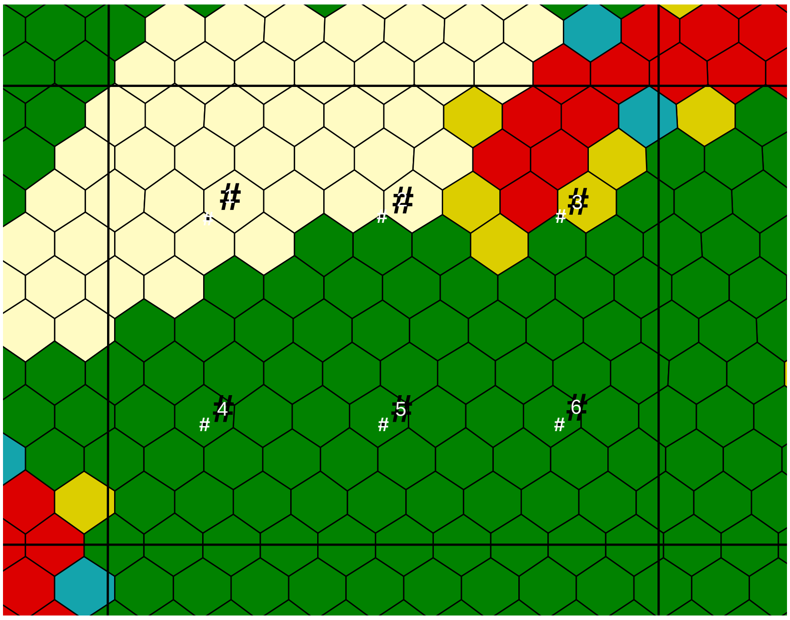
The issue of systematic sampling of a stratified population is generally not addressed in classical literature on sampling. It is normally assumed that each stratum is independently sampled. In our case the strata are made up of many irregular polygons, generally smaller than a reasonable sampling block; independent samples in different strata can lead to numerous contiguous sample units, highly correlated even if they belong to different strata, and the main advantage of systematic sampling (ensuring a certain distance between sample units) may be lost.

An easy approach for systematic sampling on an irregular stratification with different sampling rates for each stratum is using a common grid of sampling blocks and starting points and discarding some elements depending on the stratum to which they belong (Gallego, 1995 & 2000). We present here the way this approach has been selected and applied to the sample hexagons of the tessellation.

The steps involved in the systematic sampling are as follows:

- Selection of a sample grid: blocks of 600 km by 500 km.
- Selection of a fixed pattern of 6 points inside each block.
- Each point, numbered from 1 to 6, repeated across all blocks, generates a replicate of the sample. Each replicate is a systematic sample with sampling step 600 km (East-West) and 500 km (North-South), i.e. with a rate of 1 unit per 300,000 km^2, that we considered a priori suitable for strata 4 and 5. The 6 replicates together correspond to a sampling rate of 1 unit per 50,000 km^2, more suitable for stratum 1. The set of all replicates constitutes a pre-sample.
- Points falling outside the region under study are eliminated. This makes the sampling probability of an individual hexagon proportional to the part of that hexagon which lies within the study area.
- Decide on the number of replicates m_h to be retained for each stratum Ω_h. This determines the sampling intensity. Once the target sample size is determined, the number of replicates per stratum and region may be tuned in order to achieve the desired sample size.
- Select the final sample as a subset of the pre-sample. Each point of the pre-sample is labelled with the number of the replicate (1 to 6) to which it belongs, *rep(w)=k*. A point *w* in stratum Ω_h, is kept in the sample if $k \le m_h$, for example, if a point *w* corresponds to replicate number 3 (k=3), and it falls in stratum 4, for which we are keeping only one replicate (m_h =1), the corresponding hexagon will not be kept in the sample.
- The sampling probability p_i for the hexagon t_i in stratum Ω_h, will be proportional to the area inside the study region t_i and the number of replicates for the stratum m_h. This can be expressed as: $p_i \propto t_i \times m_h$.

Figure 14: Relationship between the stratified sample units, the sample grid and the replicates



Note: The sample units are the hexagons, the lines represent the sample grid, and the replicates are numbered

The size of the blocks (600 km x 500 km) and the 6 points repeated in the blocks correspond to a sampling rate of 1 unit per 50,000 km^2 in order to be in the same range as a full Landsat scene size (32,000 km^2).

In summary we selected a systematic sample of points based on a rectangular grid (600 km x 500 km) in equal area projection (Lambert Cylindrical) with several replicates. A hexagon is selected if a point of the sampling grid (pattern of 6 points in the grid cell) falls inside the hexagon and inside the study area.

5.3. Number and size of sample units

5.3.1. Target sample size and sampling intensity

Target sample size

Once the sampling approach has been selected, the next steps to define the sampling scheme are:

- To set up the total target sample size
- To decide the number of replicates that will be kept for each stratum and region (sampling intensity).

The total target sample size has been set up initially to around 100 as a feasible target linked to availability of resources.

Once the target sample size is determined, the number of replicates per stratum and region may be tuned in order to achieve the desired sample size.

Sampling intensity based on regional hotness index

Because the spatial patterns of both the forest cover and the size and shape of the identified hot-spot areas differ considerably between continents, it was found to be desirable to balance the sampling size at the regional level to facilitate this a *deforestation hotness index* was defined which provides an indication of the intensity or *hotness* of the hot-spot areas at the regional level. The index is defined as:

$$\text{Regional Hotness Index} = \frac{\text{Regional deforestation 1990 - 1995}}{\text{Regional hotspot area}}$$

The only regional deforestation estimates available for the period 1990 - 1995 were from FAO (1997). This measure was not considered to be useful for application at the country level because of the general nature of both information sources. The deforestation hotness index for each region is shown in Table 6.

Table 6: Regional Deforestation Hotness Index

Region	**Deforestation 1990-1995 (1000 ha)**	**Hot spot area Of region (1000 ha)**	**Hotness Index (%)**
Central America	4,794	18,400	**26.1**
Pan-Amazon and Andes	8,764	47,100	**18.6**
Brazil and Guyana’s	12,880	112,900	**11.4**
West Africa	2,459	3,600	**68.3**
Central Africa	5,699	31,500	**18.1**
Madagascar	650	6,000	**10.8**
Continental Southeast Asia	5,911	38,300	**15.4**
Insular South-East Asia	9,401	33,200	**28.3**

These measures (hotness index) are then used to balance the regional sampling. The number of replicates per stratum (in each block) has been tuned to be roughly proportional to the hotness index (Table 7).

The relative sampling intensity from one stratum to another (number of replicates in each block) is chosen subjectively, because available information is not enough to give a proper measure of the variance of deforestation per stratum.

In strata 4 and 5 the number of replicates was reduced to ½ and ¼ for most regions because experts considered that the sample size was unnecessarily large. This was achieved by selecting the first replicate only in every second or every fourth sampling block.

Table 7*:* Number of replicates per stratum in each region

	Hotness Index	Number of replicates per stratum (*h*)				
Region (*g*)		*1*	*2*	*3*	*4*	*5*
Central America	26.1	**6**	**3**	**2**	½	¼
Pan-Amazon and Andes	18.6	**6**	**3**	**2**	½	¼
Brazil and Guyana	11.4	**3**	**2**	**2**	½	¼
Continental South-East Asia	15.4	**6**	**3**	**2**	½	¼
Insular South-East Asia	28.3	**6**	**3**	**2**	½	¼
Central Africa	18.1	**6**	**3**	**2**	½	¼
Madagascar	10.8	**3**	**2**	**1**	**0**	**0**
West Africa	68.3	**12**	**6**	**4**	**2**	¼
Other Regions		0	0	0	0	0

Once the target sample size and the sampling intensity (number of replicates per stratum and region) are selected the final sample of hexagons is determined as a subset of the pre-sample.

5.3.2. Size and number of compulsory sample units

From clusters of hexagons to observation units

The area change estimation had to be made from Landsat TM images, that are provided as full scenes (180 km × 180 km) or quarter scenes (90 km × 90 km). A choice was first necessary on the most cost-effective size of images. An analysis was made on the comparison between use of full Landsat TM scenes and quarter Landsat TM scenes with the hypothesis that image acquisition and interpretation costs for a full scene are about twice the costs for a quarter scene.

The optimal size of the observation units is not constant, but varies with the land cover homogeneity (or forest cover fragmentation). Smaller observation units are suitable for homogeneous areas and larger observation units are suitable for heterogeneous areas; heterogeneity is measured through intracluster correlation (Cochran, 1977) of the possible sampling units seen as clusters of smaller units. Previous analysis of intracluster correlation of forest area in Eurasia has suggested that Eurasia can be divided into two types of regions for forest area estimation. Smaller sites are suitable for relatively homogeneous areas (high spatial correlation), and larger sites are preferable for more heterogeneous areas (Gallego *et al*, 1998).

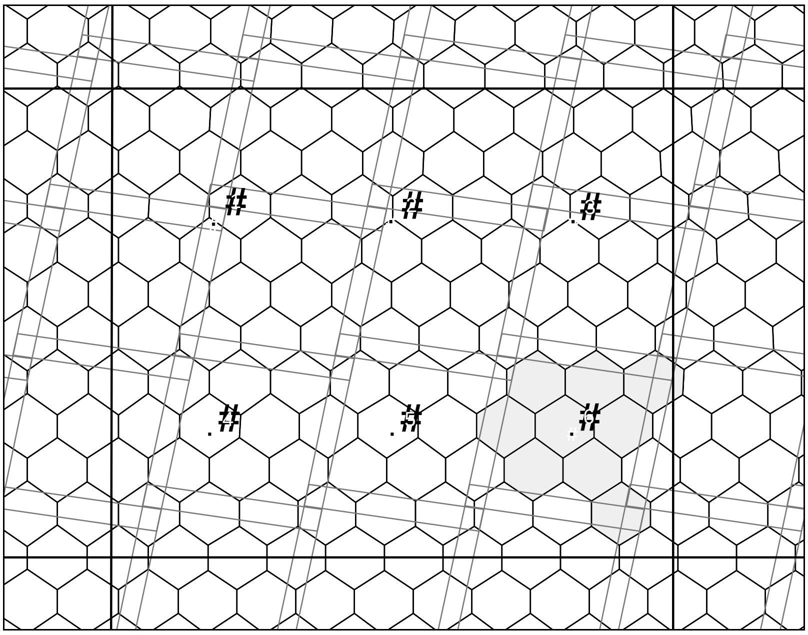
Available information did not allow an objective measurement of the spatial heterogeneity of deforestation at the pan-tropical scale. We adopted a site size rule based on two assumptions:

- Deforestation is more heterogeneous where forest pattern are more heterogeneous;
- Deforestation is more heterogeneous in hot spots.

To relate the hexagons to the Landsat TM full scenes we defined clusters of hexagons as follows. If the hexagon t_i is selected we looked for the Landsat TM scene A_j whose centre is closest to t_i. The Landsat TM scene defines a cluster T_j of hexagons that are closer to A_j than to any other Landsat TM scene. Figure 15 gives an example of cluster for one full Landsat scene.

$$f(t_i) = A_j \Leftrightarrow d(t_i, A_j) < d(t_i, A_{j'}) \;\; \forall j' \neq j$$

Figure 15: An example of one cluster of sample units



Note: The sample units are the hexagons, the sample grid is shown in bold, the replicates are numbered, the observation units are full Landsat frames and the sample unit cluster is shown as shaded hexagons.

For each cluster T_j we computed:

H_j = hot spot area in T_j (in km^2)
F_j = forest area in T_j according to the forest map used for stratification (in km^2)
s_j = standard deviation of the % of forest cover in each of the hexagons of the cluster.

$$s_j = stdev\left\{\frac{100 \times F_i}{D_i}\right\} t_i \in T_j \;,$$

where F_i is the “a priori forest area” in hexagon t_i
and D_i is the area of the hexagon (or the part of it inside the study region).

The rule selects a full Landsat TM scene if one of the two following conditions is valid:

1. **[Hot spot area H_j × hotness index of the region] > 250,000 ha, or**
2. **[standard deviation s_j × area of forest F_j] > 600,000 ha**

Otherwise a quarter Landsat scene is selected, again with a criterion of minimal distance between the center of the hexagon and the center of the quarter Landsat scene. This procedure defines another set of clusters for quarter Landsat TM scenes

The function linking the hexagons with the Landsat TM scenes was thus modified as follows:

$$f'(t_i) = f(t_i) = A_j \Leftrightarrow H_j \times Hotness > 250{,}000 \quad or \quad s_j \times F_j > 600{,}000$$
$$f'(t_i) = A_j^q \quad otherwise. \quad d\left(t_i, A_j^q\right) < d\left(t_i, A_j^{q'}\right) \quad q' \neq q \ (quarter\ TM)$$

These thresholds for the site size rule have been chosen after plotting both composite parameters to get a rough proportion of one full scene for two quarter scenes.

Number of compulsory sample units

The sample is obviously constrained by financial and practical limitations. An initial pre-sample of 95 sites was selected. A list of additional replicates was then produced to allow replacement of missing scenes (for example in the case of permanent cloud cover) or additional samples in Southeast Asia. From this list of additional replicates, 3 samples in Latin America and 3 samples in Africa were used as replacements and 7 samples were taken as additional samples in Southeast Asia.

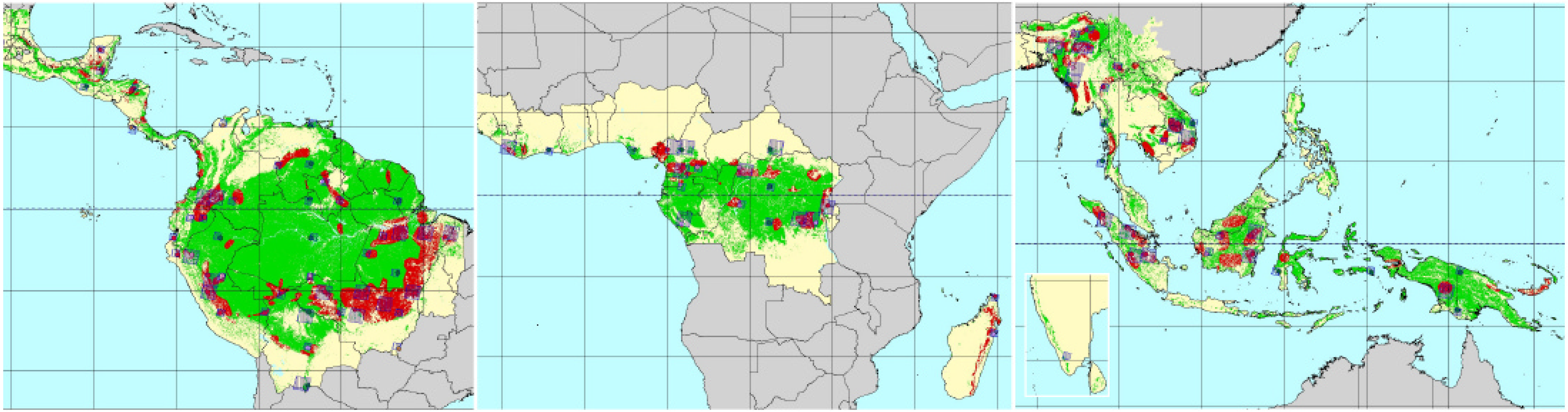
It leads to a total of 102 compulsory sample units.

The resulting number of full and quarter scenes that were selected as compulsory sample units, is given in Table 8 and displayed in Figure 16. It leads to a total of 41 full scenes and 61 quarter scenes.

Table 8: Number of observation units per stratum / region /size

	Total per Region (F/Q)	Number of sampling units per strata (Full/Quarter)				
Region		1	2	3	4	5
Central America	1/5	0/3	0/0	0/0	1/1	0/1
Pan-Amazon and Andes	7/15	4/8	1/1	0/2	2/3	0/1
Brazil and Guyanas	8/12	8/5	0/1	0/1	0/4	0/1
West Africa	1/2	0/0	0/0	1/0	0/2	0/0
Central Africa	8/5	3/0	1/3	2/0	2/2	0/0
Madagascar	1/2	1/1	0/0	0/0	0/0	0/1
Continental South-East Asia	7/11	5/5	1/3	1/0	0/3	0/0
Insular South-East Asia	8/9	8/1	0/1	0/0	0/7	0/0
Total per strata	41/61	29/23	3/9	4/3	5/22	0/4

Figure 16: Compulsory sample of observation units (full or quarter Landsat TM scenes)



Legend:

- All regions not considered in the analysis are shown in grey
- Humid forests derived from the TREES maps are shown as green
- Dry forests and other forest classes derived from Iremonger *et al.* (1997) are shown in yellow tones
- Deforestation hot-spot areas are depicted in red tones
- Sample hexagons are coloured from red (stratum 1) to green (stratum 5)
- Sample observation units (Landsat TM full or quarter scenes) are shown as blue frames.

6. Mapping forest cover changes within the TREES observation sites

Summary

***Forest cover* and *forest cover change* have been mapped over 104 observation sites, statistically distributed over the humid tropics. Mapping has been done by visual interpretation of the fine spatial resolution (20m to 30 m) satellite imagery from Landsat TM and SPOT HRV sensors, displayed on the screen.**

The best satellite images have been selected from the existing acquisitions and at two dates closest to our target years: 1990 and 1997

Satellite image interpretation has been carried out with a common standardised method by a network of 20 local experts or institutions having an extensive knowledge of the local forest conditions and change processes. The minimum mapping unit is 50 ha and the change has been mapped in an interdependent manner, i.e. using both dates together during the interpretation.

In order to verify the quality of the interpretations from the satellite images, an independent consistency assessment has been performed.

6.1. *Procedure for the interpretation of forest cover types from fine resolution satellite images*

A common strategy for the analysis of fine spatial resolution remote sensing satellite data has been developed, including a vegetation cover classification scheme. The strategy aimed at visual on-screen interpretation of forest cover from satellite images and, as far as possible, at local collaborators, who would be able to contribute their knowledge on local forest conditions to the monitoring procedure.

A standard version of technical specifications has been produced for collaborators in different countries as basis for the co-operation. A brief guideline for visual interpretation of different vegetation classes was prepared in order to assure interpretation standards and compatibility of the results provided. A standard cross-matrix for presentation of vegetation cover changes, and conventions for naming and structuring of the digital files were prepared.

The primary objective of image interpretation was to map for each sample site forest cover at the two dates of satellite image acquisition in order to assess changes from forest to non-forest or vice versa. The TREES forest and land cover classification scheme was defined mainly for this purpose. However, as far as possible from satellite images, forest and vegetation cover was mapped at more detail than required for an assessment of forest versus non-forest. This was done in order to provide a more complete view of land cover change within the individual test sites, but also to obtain indication on processes going on within the forest cover, forest namely degradation and fragmentation.

6.1.1. Thematic classification scheme for interpretation of high resolution data

Forest definition

Forest is defined in terms of *tree cover*, based on density and height thresholds that are compatible with those used by the FAO Forest Resources Assessment (FAO 1996, FAO 2001c).

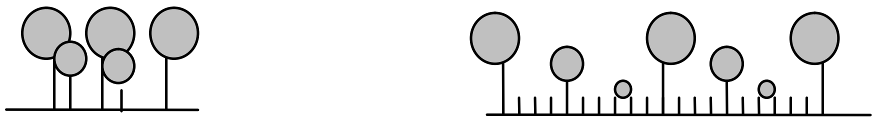
A tree layer is considered a forest when reaching a canopy or crown cover of at least 10% and a tree height of more than 5 meters. It was assumed that approximately such tree cover height in the tropics would be recognized as ‘forest’ from satellite images. It was understood that some variability would have to be accepted in applying these thresholds, because neither of them can be measured exactly from the satellite images used. Thresholds were therefore considered as useful guiding criteria for interpretation and fieldwork rather than exact separation boundaries.

The TREES forest definition does not consider aspects of land use and is therefore not fully compatible with the FAO forest definition or with the term *forest land*, usually used by national forest statistics. ‘Forest land’ may include permanent or temporarily un-stocked areas, not recognizable as ‘forest’ from satellite images. Similarly, very young, planted or natural tree cover of low height is considered by the TREES definition still as *Non-forest* cover. Furthermore, it would be difficult in most cases to differentiate very young tree cover from other vegetation on satellite images. Rubber and oil palm plantations as well as areas of bamboo were also not included in the forest class**.**

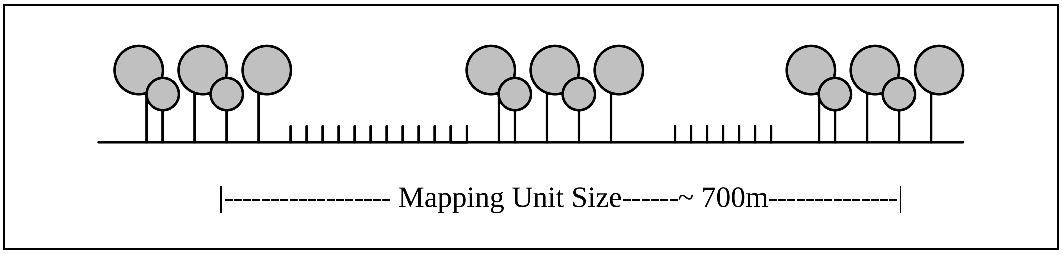
Closed, open, and fragmented forest cover

The classification of a forest cover as ‘closed’ or ‘open’ refers to its ‘canopy or crown cover' (cc). Thresholds established are compatible with those used by FAO. However, the assignment of a forest polygon to these sub-categories was again considered as being approximate and indicative. The use of supporting information from fieldwork and other sources was recommended.

A tree layer was classified as *closed forest* for crown cover percentages of at least 40 percent or higher; a tree layer with a crown cover ranging between 10% and 40% was classified as *open forest*. In both cases there should be a continuous tree layer.



A tree layer is considered *fragmented* when discontinued by spatially separated portions of non-forest. While the non-forest elements would be recognizable in most cases, they would be too small for individual mapping, i.e. below the minimum mapping unit. The portion covered by the tree layer is expected to be in the range of 40 to 70%, i.e. in average more than 50%. No further differentiation was made for canopy density of the forested portion, but a canopy cover of at least 10% is required.

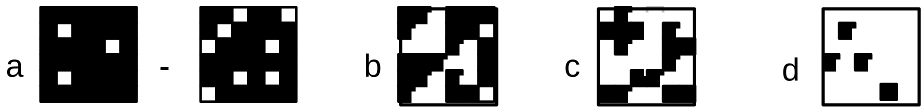


The assignment to forest cover classes is summarized in the following table.

Table 9: Summary of thresholds used in the legend

Estimated parameter / Forest class	Forest cover portion within mapping unit		Canopy density of tree layer		Assumed tree height
closed forest	>70%	&	>40%	&	>5m
open forest	>70 %	&	40% ≥ cc > 10%	&	>5m
fragmented forest	>40 and ≤ 70%	&	> 10	&	>5m
mosaics	>10 and ≤ 40%	&	> 10	&	>5m
Other ***non-forest cover***	≤10	and/or	≤ 10	and/or	< 5m

An example of the spatial appearance of different forest portions within a minimum mapping unit (forest proportion = black) is given below: type ‘a’ (90%) or ‘b’ (70%) would still be classified to *closed* or *open forest* depending on the crown canopy density present, type ‘c’ would be assigned to *fragmented forest cover*, type ‘d’ would be classified as a *mosaic*, and a mapping unit of type ‘d’ (forest portion < 10%) would be considered *non-forest*.

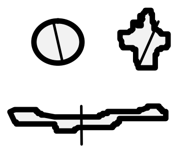


Minimum mapping unit

The minimum mapping unit was fixed at about 50 hectares, assuming that interpretation would be done at a scale of approximately 1: 100,000. A mapping unit of round or square shape would therefore be displayed with a diameter of approximately 7 mm. For linear features the smaller diameter should reach 3 mm to justify separate mapping of a feature on the satellite image.

Non-linear shapes: diameter ~7 mm (~700m x 700m, ~49ha, 0.5 km^2)

Linear shape, i.e. ‘gallery forests’: smaller diameter 3 mm (~300m)



Features recognizable as a specific land cover type but smaller than the minimum mapping unit were to be integrated in the appropriate mosaic or mixed, or in an alternative class.

The TREES thematic classification scheme

Based on the definitions mentioned above a classification scheme has been developed consisting of three main levels (Table 10). Level 1 of the scheme refers to land cover classes while level 2 includes broad forest types as well as some aspects of land use (plantation forest, shifting cultivation). Level 3 allows an indication of canopy density and fragmentation.

The forest and land cover classes of the first two levels were expected to be applicable for all tropical regions. The possibility to specify forest formations typical for different regions was provided at a fourth level (not displayed). However, mapping of detailed forest types was not expected to be achievable for all sites from the satellite images used and depended also on the interpreters’ knowledge of the local forest conditions.

Table 10: Vegetation classification scheme for interpretation of Landsat imagery

Level 1	Level 2		Level 3
1 Forest	***> 40 % forest cover* and > 10% canopy cover *****		
	1 Evergreen & Semi-evergreen Forest	-	A & B Closed, high density *> 70% forest cover* *> 70% canopy cover* Closed, medium density *> 70% forest cover* *70 - > 40% canopy cover*
	2 Deciduous Forest		C Open *>70% forest cover* *40 - >10 % canopy cover*
	3 Inundated Forest		D Fragmented *>40-70% forest cover* *> 10% canopy cover*
	4 Gallery-forest		
	5 Plantation		E Undefined
	6 Forest Regrowth		
	7 Mangrove		
	9 Other		
2 Mosaic	**>10% - 40 % forest cover (and > 10% canopy cover)**		
	1 Shifting Cultivation		
	2 Cropland & Forest		
	3 Other Vegetation & Forest		
	9 Other		
3 Other Natural Vegetation (Non-forest) ***£ 10% forest cover or £ 10% canopy cover***			
	1 Wood & shrubland		
	2 Grassland		
	3 Non-Forest Regrowth		
	9 Other		
4 Cropland (Agriculture) ***£ 10% forest cover or £ 10% canopy cover***			
5 Non-vegetated			
6 Water			
7 Sea			
8 Not visible			
9 No data			

* *forest cover = portion of forest area in a mapping unit*
** *canopy cover = density of tree canopy*

Comment to specific classes

Evergreen forests are expected to be multi-storied forests with an evergreen canopy during the whole year. They comprise lowland tropical rain forests, hill evergreen forests and dry evergreen forests. The following three forest types were specified separately if possible: (i) evergreen montane forests for altitudes above 900 meters; (ii) Heath Forests ('Kerangas' in SE-Asia, 'Caatingas' in Latin America), (iii) semi-evergreen forests of a more or less green appearance during the whole year and (iv) coniferous forests, if present as pure stands and recognizable as such from the satellite images.

The term semi-evergreen forest was not used in the very strict botanical way but for forest formations that contain a varying percentage of deciduous trees. This may include formations also referred to as 'moist mixed deciduous forests' or 'seasonal forests'. Natural pine forests can often not be separated from evergreen forests particularly if stands are very open and accompanied with a layer of other green vegetation. Such areas would remain in the class 'evergreen forest cover'.

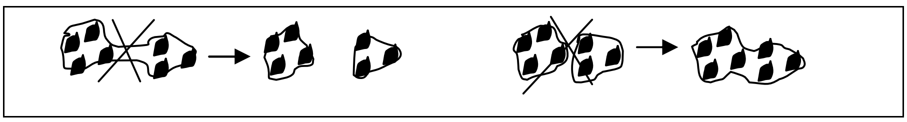
Deciduous forests refer to a tree layer that sheds more or less completely its leaves during the dry season, displaying the typical dry season signature of non-green vegetation. Deciduous forests include dry formations of the 'Mixed deciduous forests', 'Dry *Dipterocarpus* forests' (Asia), 'Dense dry forests' (Africa) and 'Miombo forest'. Dry deciduous forests are often characterized by 'open' forest canopy and the impact of the soil and the grass layer on spectral reflectance may be significant. The transition to woodland is often gradual and the differentiation of density classes remains difficult.

Inundated Forests include temporarily or periodically flooded forests, swamp and peat swamp forests, for Africa also a sub-class of 'swamp forest with palms'. ***Mangroves*** were mapped separately because of their specific importance for bio-diversity and their distinct spectral signature on the satellite images.

Forest re-growth refers to young forests (> 5 m height) and with a more or less dense layer of trees, without further differentiation of canopy density. Other re-growth of vegetation or smaller trees was considered 'Non-Forest re-growth'.

Forest plantations, visible due to their geometric shapes and texture, were mapped separately; information on species was provided if known.

The class ***mosaic*** was assigned for a mix of spatially separated portions of forest (<40%) and one or more of the following: cropping, natural re-growth, shrubs, grassland or other land cover. The delineation of mosaics allows quite some variability and the interpreters were asked therefore (i) not to include homogenous areas bigger than the minimum mapping unit and (ii) to base their decision on whether to delineate less bigger or more smaller polygons on minimizing the total boundary line.



Other natural ***non-forest vegetation*** includes:

(i) Wood & shrubland,
(ii) Grassland
(iii) Non-forest regrowth.

The ***wood and shrubland*** class contains vegetation formations of shrubs and trees below 10% canopy cover and/or 5 meters height. Sub-classes for Latin America are 'Cerrado' and 'Chaco'. For Africa a differentiation was made for 'woodland savanna', 'Tree savanna' and 'Shrub savanna'. Pure areas of bamboo were also included here.

A class of ***non-forest re-growth*** was added to cover stages of secondary vegetation including small trees, but where an assignment to the class 'wood & shrubland' would not have been considered appropriate. This class may occur on areas where cropping was abandoned and where a young tree cover has not yet developed to a forest in the sense of the TREES definition.

The class ***cropland*** (agriculture) includes cash-crop plantations not only for example of coffee, coca, cacao or cotton, but also of rubber and oil palm, as far as recognized as such.

Interpreters were asked to delineate ***roads***, particularly logging roads (indicator for forest disturbance) in a separate data layer.

6.1.2. Image processing and interpretation

Numerous detection algorithms exist based on the simultaneous analysis of multi-temporal imagery or comparative analysis of independent single date classifications (but for the latter methods, the bias and the resulting variance are unknown). Data transformations can consist of image differencing, band ratioing, vegetation index differencing, regression between bands or multi-temporal linear transformation. The analysis techniques are usually derived from thresholding, supervised or unsupervised spatial classification or temporal analysis (for a review see: Coppin & Bauer, 1996).

Digital image processing

Interpretation and mapping were done for each sampled site from two satellite images with acquisition dates close to the reference years 1990 and 1997. Images of the same season were selected in order to avoid misinterpretation caused by seasonal effects such as leaf shedding. In cases where the distinction of forest and non-forest was difficult (e.g. deciduous forest during the dry season) additional images of a different season were acquired. Additional images were also provided in cases of partial cloud cover or of extraordinary deforestation events (fire), not covered by the first acquisition. The additional images were to be used in support to the base images.

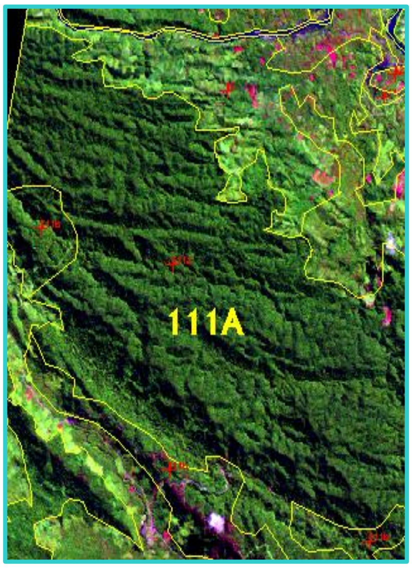
Digital image processing was limited to the geometric correction of the data. The TREES partners were asked to use ground control points (preferably about 20 GCPs and a polynomial function of 2^{nd} degree) taken from 1: 50,000 or 1:100,000 maps. The UTM projection was chosen as the preferred projection, projection parameters like spheroid and map datum varied depending on the country and national base maps available and had to be reported.

Visual interpretation

Visual interpretation was selected as the 'preferred' mapping approach, because it has been shown to provide the best results for mapping of the different forest types within the complex forest and land cover patterns in many parts of the tropics. The experienced interpreter would consider for his decisions not only image parameters, such as spectral signature, texture and patterns, but also make use of his knowledge of local forest cover types and land use practices.

Delineation and digitising was performed 'on-screen', i.e. while displaying the digital data sets on the monitor (Figure 17). The main advantage of this approach is due to the possibilities of digital contrast enhancement, zooming and different combination of spectral bands, allowing the most intensive use of digital satellite images. Standard software packages were used for this task, and for a few tasks additional software routines have been developed (Copilot ©JRC; ArcView © ESRI).

Figure 17: Example of delineation and field photo for Landsat scene 126/61 on Sumatra



Field work and reference data

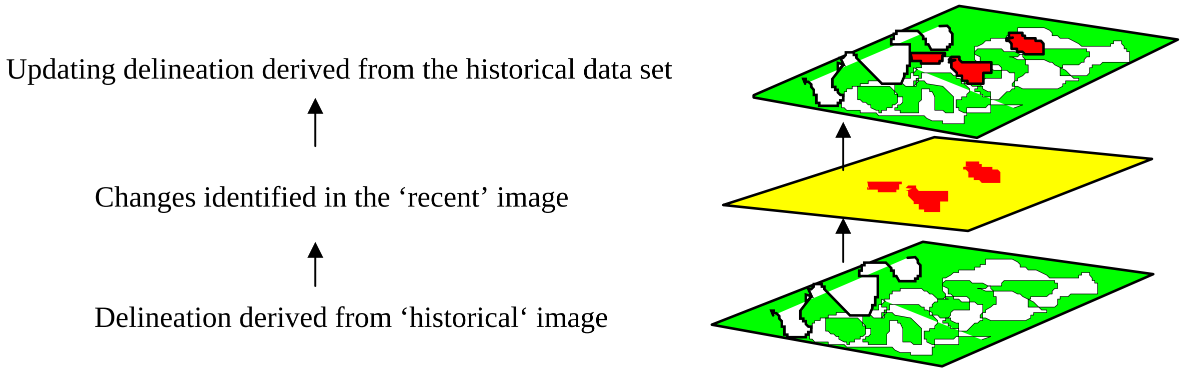
Fieldwork was performed for most of the sites by the TREES partner teams, with the main exception for Democratic Republic of Congo. Fieldwork was considered essential for obtaining ground-truth information on forest and other vegetation cover, for verifying the interpretation and mapping done, and for acquiring knowledge on ecological conditions of forests, human disturbance and socio-economic aspects of forest functions.

The TREES partners were asked to collect any reliable reference material available locally, such as aerial photography, forest or vegetation maps, and forest management or concession maps, and to make use of this information.

Change assessment

The mapping of changes in land cover was performed in an 'inter-dependant way', i.e. by overlaying the interpretation results of the historical image on the recent data set and by only updating the polygons that changed. Errors of interpretation were minimised by alternate comparison of the historical and the recent image during delineation: the introduction of 'slivers' can be avoided and at the same time corrections can be applied to those polygons wrongly assigned or delineated in the historical data set.

Figure 18: Image interpretation procedure



Results and analysis of forest cover change

For each site the TREES partners provided the following data sets: (i) the geo-referenced historical (~1990) and recent (~1997) satellite images, (ii) the geo-referenced digital maps (image interpretations) of two dates, (iii) the geo-referenced change map (change polygons), (v) a change matrix, (vi) a report and (vii) any additional data layers obtained.

The TREES partners performed a first quantitative assessment of the changes already. By comparing the historical and recent mapping results for each site, spatial and thematic changes were recorded within the overlapping area of the two satellite images. A change matrix could be established, displaying the different transitions from one land cover type to another.

Based on this the TREES partners performed an analysis of the changes and the responsible processes. The issues to be addressed were related to (i) the description of forest types and conditions in each site, (ii) the magnitude of forest cover changes, (iii) the main causes and actors responsible for deforestation, (iv) the underlying causes and driving forces, and (v) to the potential environmental impact.

All the spatial data that was delivered, was transformed to the UTM projection in order to be compiled in the TREES Tropical Forest Information System (TFIS).

6.2. Interpretation of satellite imagery over the observation sites

6.2.1. Selection of fine resolution satellite imagery

Selection of high resolution imagery

The location and size of the observation sites was determined by the statistical sampling procedure applied. For all selected sites, a pair of satellite images was acquired, close to the reference years 1990 and 1997. The vast majority of the images were acquired by the Landsat TM sensor (full or quarter scenes) at a spatial resolution of 30 by 30 meters. Full Landsat TM images cover a total area of 180 by 180 kilometres, quarter scenes only 90 by 90 kilometres. Images from the SPOT HRV sensor at a spatial resolution of 20 by 20 meters and covering a total area of about 60by 60 kilometres have been used for some sites, in cases of non-availability of cloud-free Landsat TM scenes.

The satellite data was selected from the catalogues of the providers or receiving stations: for Asia from Bangkok (Thailand), Jakarta (Indonesia), and Townsville (Australia), for Africa from EOSAT (Lanham, US) and Eurimage (Frascati, Italy), and for Latin America from EOSAT or Cuiaba (Brazil). The total number of images acquired amounts to more than 200 scenes from the Landsat satellites (TM sensor) and around 20 from the SPOT satellite (HRV sensor).

From the 102 compulsory sample units, one site in Brazil could not be covered by existing imagery, the two sites of Mexico were not used in the estimation phase due to processing issues and one site at the border Bolivia/Brazil was split in two parts (adding one observation unit in “Brazil and the Guyanas” region). Four extra sites (not part of the compulsory sample) were added in Southeast Asia.

The final statistical estimation of forest cover change in the tropics at the global level was based on a total of 104 observation units (next table and Figure 19 to Figure 21)

Table 11: Number of available observation units per region

Region	Number of compulsory observ. units	Sample units type (F/Q)	Number of extra units	Sample units type (F/Q)	**Number of available Observation units**
Central America	6	1/5	-2	-1/-1	**4**
Pan-Amazon and Andes	22	7/15			**22**
Brazil and Guyanas	20	8/13	-1 +1	-1/+1	**20**
West Africa	3	1/2			**3**
Central Africa	13	8/5			**13**
Madagascar	3	1/2			**3**
Continental South-East Asia	18	7/11	+1	0/1	**19**
Insular South-East Asia	17	8/9	+3	2/1	**20**
Total	102	41/61	+2	0/2	**104**

The list of used observation units with the reference satellite images for the recent and historical dates are given in the annexes. Complementary satellite images, which were used to fill cloudy parts or to complement for seasonal information, are not listed in these tables.

Figure 19: Location of observation units in Latin America

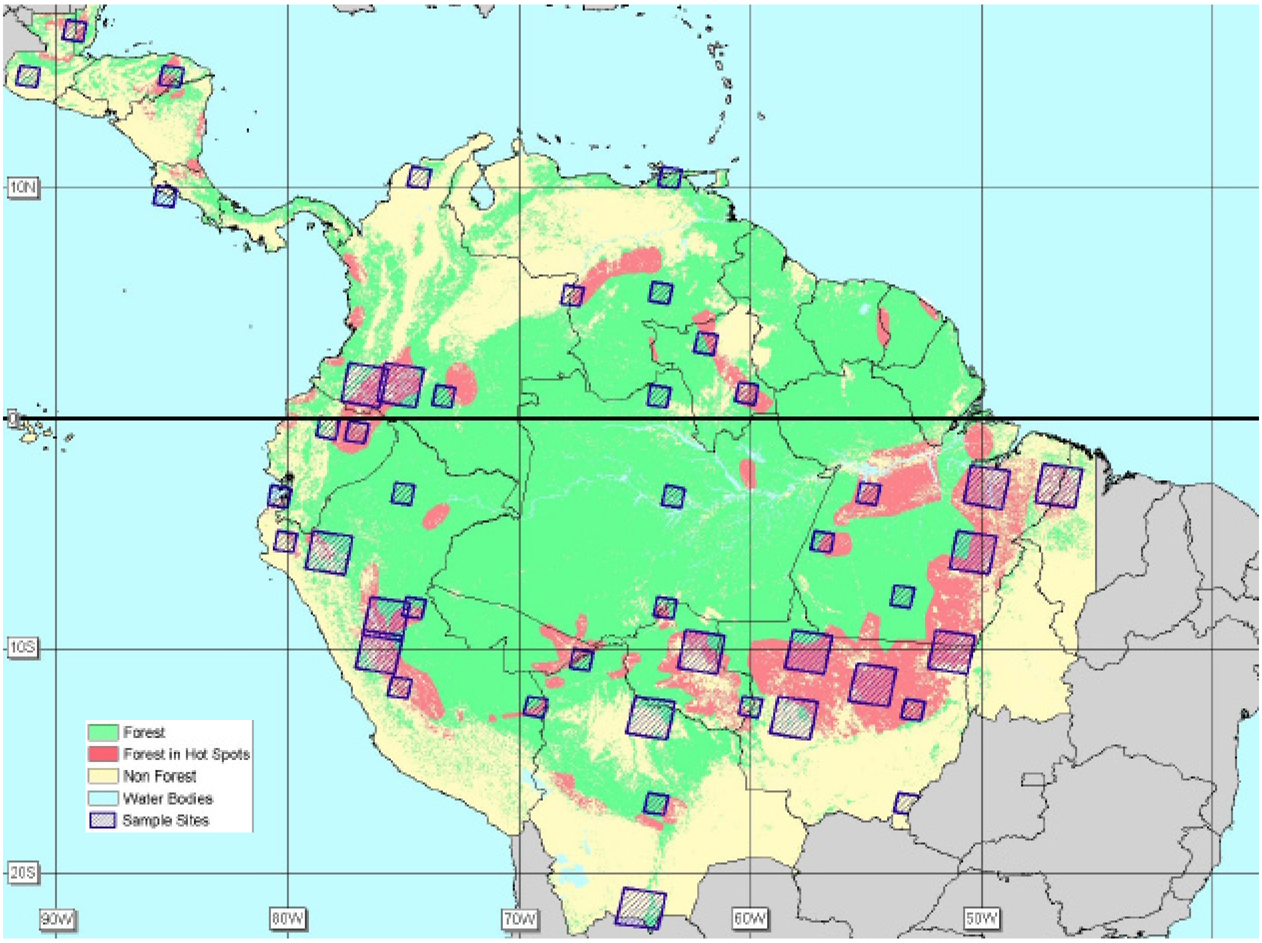


Figure 20: Location of observation units in Africa

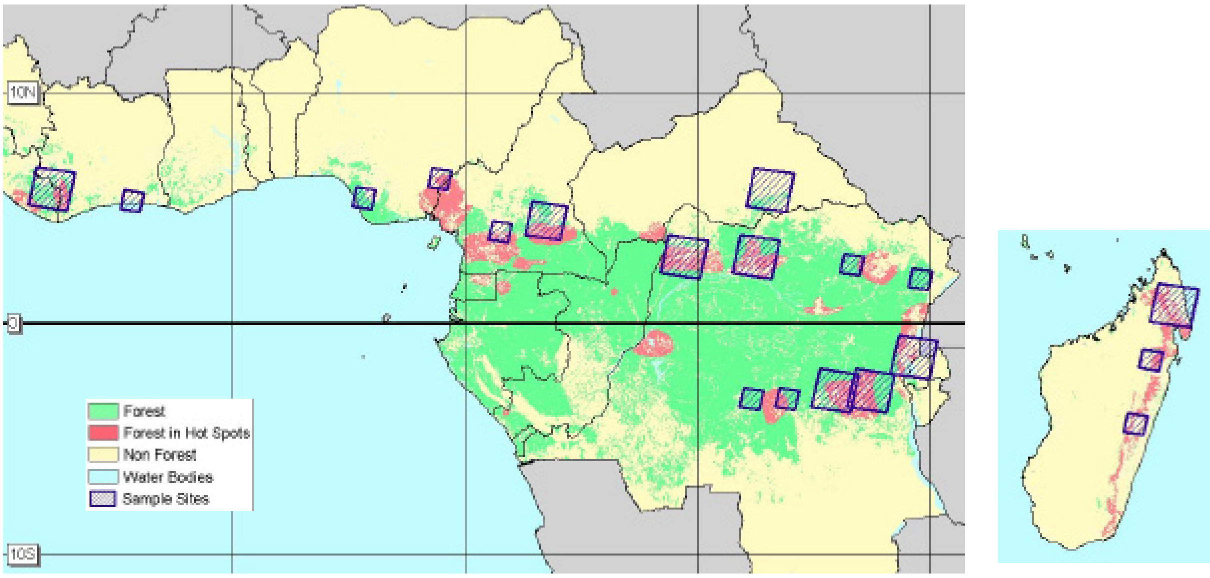
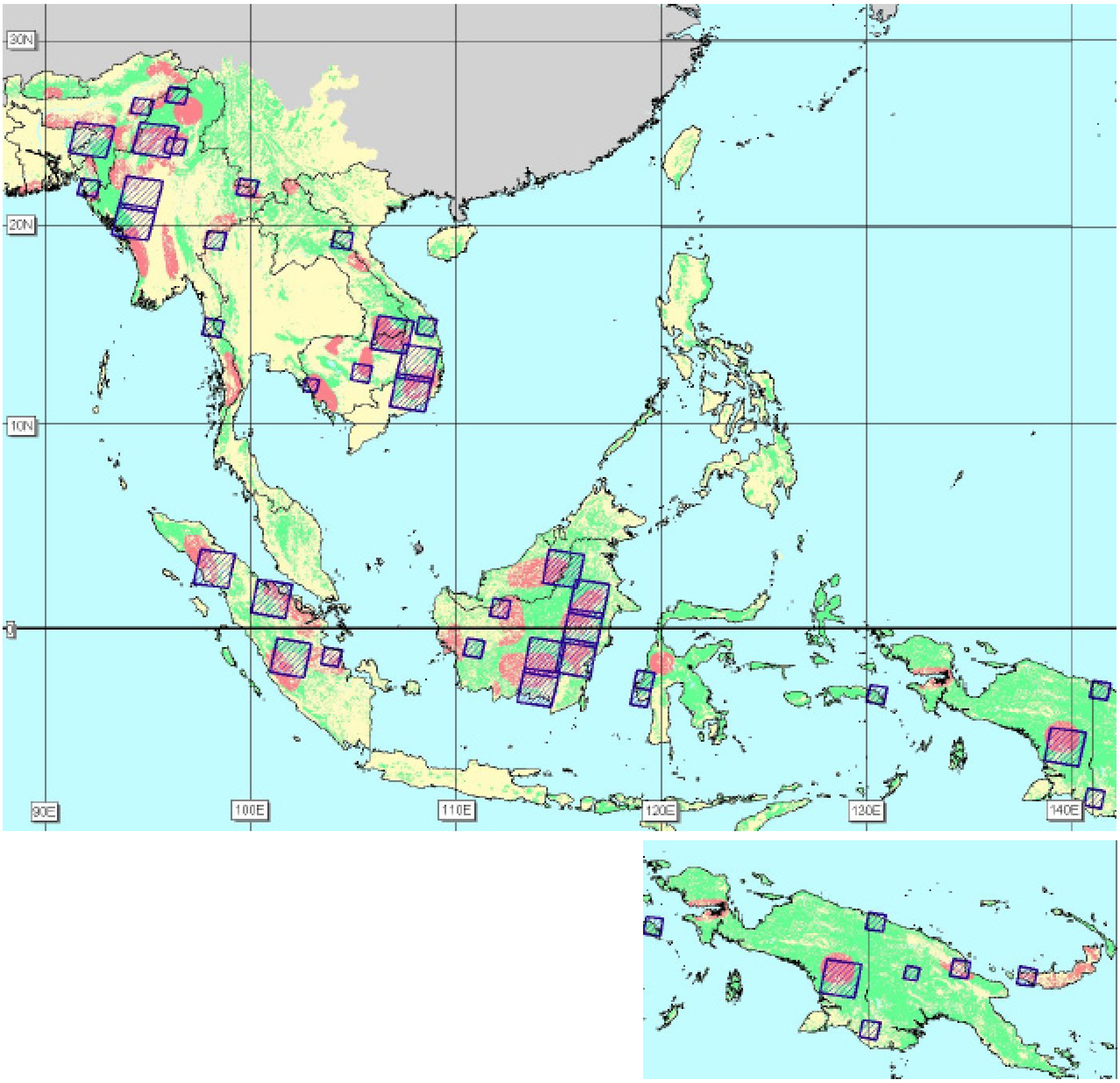


Figure 21: Location of observation units in Southeast Asia



Note: one site located in the Anamali mountains in southwest India is not displayed

6.2.2. The TREES network of regional and local partner institutions

The local partners

Local and regional partners performed all image interpretation and mapping work. The total network consists of twenty-six partners in South America, Africa and Southeast Asia. The partners engaged for the task have, apart from their technical skills, a profound knowledge on local forest conditions and land use practices of the observation sites concerned.

Partners were:

In Latin America:

- EPOMEX, Univ. of Campeche, Mexico
- ECOSUR, Chiapas, Mexico;
- CONABIO, Mexico City, Mexico;
- CATIE, Costa Rica
- CIAT, Cali, Colombia
- IIAP, Iquitos, Peru
- CPDI, University of Simon Bolivar, Caracas, Venezuela
- CLAS, Bolivia
- ECOFORÇA and EMBRAPA-CNPM, Campinas, Brazil
- IMAZON, Belem, Brazil
- PIXEL, São Jose Dos Campos, Brazil

In Africa:

- VITO, Belgium
- I-MAGE Consult, Belgium
- CETELCAF, Yaoundé, Cameroon
- FTM, Madagascar

In Southeast Asia:

South and continental part:

- Indian Institute of Remote Sensing, Dehra Dun, India
- SPARRSO Bangladesh & Dresden University, Germany
- UNEP-GRID, Bangkok, Thailand
- Royal Forest Department of Thailand, Bangkok
- Chinese Academy of Forestry, Beijing, China
- Department of Forestry and Wildlife, Phnom Penh , Cambodia
- CIAS, Hanoi, Vietnam

Insular part:

- SEAMEO-BIOTROP & IPB University, Bogor, Indonesia
- PUSPIC, University of Yogjakarta, Indonesia
- CIFOR, Bogor, Indonesia
- Max Plank Institute, Fire Ecology Group, Germany & IFFM Project, MoF/ GTZ, Samarinda, Indonesia,
- Remote Sensing Services, München, Germany
- Malaysian-German FOMISS Project , Forestry Department Sarawak / GTZ, Kuching, Malaysia
- UNITECH, University of Lae, Papua New Guinea

The establishment of regional and 'TREES' networks was on line with the projects objectives. The networks are meant as a forum for the exchange of information between forest and remote sensing experts of the different tropical countries, but also to support technology transfer, capacity building and the strengthening of forest mapping and monitoring capabilities in the countries.

Table 12: Number of observation sites per partner

Region / country	Nb of scenes (F: Full ; Q: Quarter)	Name of participant organisation
Highlands South America / Central America		
Colombia /Peru /Ecuador	4F / 9Q	CIAT/IIAP, Cali / Iquitos
Costa R/ Hondur/Guatem	3 Q	CATIE, Costa Rica
Mexico / Belize	2 Q	EPOMEX, Campeche
Lowlands South America		
Brazil	4 F / 8Q	Ecoforca, Campinas
Brazil	3F / 1Q	IMAZON, Belem
Brazil	3Q	Pixel, Sao Jose dos Campos
Venezuela	3 Q	CPDI, Caracas
Bolivia	2F / 1Q	CLAS Cochabamba, Bolivia
Africa		
West Africa	1 F / 2 Q	VITO, Belgium
Congo Dem Republic	5 F / 4Q	I-MAGE, Belgium
Cameroon	3 F / 1 Q	Cetelcaf, Yaounde
Madagascar	4 Q	FTM, Madagascar
South & continental southeast Asia		
India/Myanmar	1 F / 2 Q	IIRS, Dehra Dun
Bangladesh	1 Q	SPARRSO /Dresden University, Germany
Myanmar	3 F / 1Q	UNEP, Bangkok
China	2 Q	Forestry Academy, Beijing
Thailand	2 Q	Royal Forest Dep., Bangkok
Cambodia	1 F / 2 Q	Forest Dep., Phnom Penh
Vietnam	2 F / 2 Q	CIAS, Hanoi
Insular southeast Asia		
Indonesia	2 F / 5 Q	BIOTROP, Bogor, Indonesia
Eastern Kalimantan, Indonesia	2 Q	Max Planck Institute / IFFM, Samarinda
South Kalimantan, Indonesia	2 F	RSS, München
Eastern Indonesia	4 Q	PUSPIC, Yogjakarta
Sumatra, W Kalimantan, Ind.	2 F	CIFOR, Bogor
Sarawak, Malaysia	1 F	FOMISS project, Forest Dep., Kuching
Papua New Guinea	3Q	UNITECH, Morobe, PNG

The TREES-II partners in Latin America include the NGO ECOFORCA and the government research agency EMBRAPA-CNPM, both working on environmental monitoring. Collaboration was established in Central Africa with ECOFAC (an EU-funded conservation project running over 6 national parks), which gave access to information concerning deforestation processes. Except for the Philippines, the project established a complete network of partners in Southeast Asia: 14 TREES partners worked on 39 observation sites in the framework of co-operation contracts.

Training of local partners staff

A number of training sessions were organized for the TREES partners in the different regions. Training focused on the methodology for change assessment and the use of image analysis and mapping software.

Three training courses on the analysis 'Co-pilot' software (Perdigão & Annoni, 1997) were organised in 1999 at Caracas (Venezuela), Bangkok (Thailand) and Jakarta (Indonesia) for the TREES partners.

- Participants from IMAZON (Belem, Brazil), Ecoforca (Campina, Brazil), Embrapa-NMA (Campinas, Brazil), CIAT (Cali, Colombia) and IIAP (Iquitos, Peru) took part to the first course at CPDI (University of Simon Bolivar, Caracas).
- The second course was organised at AIT, Bangkok Thailand, with participants from RFD (Bangkok, Thailand), VTGEO (Hanoi, Vietnam), DFW (Pnom Penh, Cambodia) and UNEP-GRID (Bangkok, Thailand).
- The third course was organised at BIOTROP (Bogor, Indonesia) with participants from BIOTROP and PUSPICS (Yogyakarta), Indonesia.

Progress and quality control

The execution and quality of the work carried out by these partners was monitored on a continuous basis. All 12 partners who carried out the analysis in Latin America were visited on a regular basis. In particular, Professor O. Huber of the University of Simon Bolivar, Caracas, visited the three main contractors (Ecoforca, Brazil, CIAT, Colombia and CPDI, Venezuela) and assessed their capacities and complementarities.

An independent consultant (C. Feldkötter) was engaged in order to provide on the job support and training to all main TREES partners in Southeast-Asia, monitoring at the same time the progress and quality of work. The consultant reported on the status of work, on the compatibility of the products (interpretation and data formats), and provided assistance to the TREES project by recommending interactions required for ensuring compatibility and overall quality of the results.

Four regional meetings were organised: in Bogor, Indonesia, in Libreville, Gabon and in Caracas, Venezuela.

- The Latin American regional workshop was carried out in Caracas. The main partners (representing 75 % of the work being carried out) from Brazil, Colombia, Venezuela and Bolivia presented their results. Suggestions were made and collated for improvements in both the classification legend employed and the methods used to perform the change assessment.

- The Libreville regional workshop in the framework of the GOFC programme (Mayaux *et al.*, 2000c).

- A first regional workshop was held in Bogor, Indonesia. The main objectives of the workshop in Bogor were to discuss the deforestation results obtained for the sites in Southeast Asia and to achieve harmonization of methods and results between the partners in the region.

- A final regional workshop in Asia was organized at Dehra Dun, India in January 2002. TREES partners from South Asia, from Southeast Asia and a number of external partners from South and Central Asia participated in this workshop. Results of the TREES project as well as other remote sensing research studies from Central and South Asia were presented.

6.2.3. Compilation of results provided by the TREES partners

All data layers provided by the TREES local and regional partners were compiled and entered in the central TREES Tropical Forest Information System (TFIS) at the JRC.

All interpretation results were screened by TREES staff and checked for errors and for plausibility of the class assignments. In case of major discrepancies between the interpretation provided and the screening result by the regional coordinator at JRC, the local partner was contacted in order to clarify or to agree on necessary amendments.

The data sets for each observation site (recent and historical interpretation) were treated as follows:

- Correction of delineation errors and class labels
- Uniform projection of the image and map data to (a) geographical and (b) UTM coordinates
- Clipping of the edges of all data sets in order to select only the area non-overlapping with neighbouring scenes
- Uniform reproduction of change maps and change matrices for the clipped area only
- Input of the change matrix results the statistical calculation procedure for quantifying forest cover change at regional and global level
- Preparation of the results for presentation and display on the GVM website

Data volume

An estimate of the approximate volume of data received from the TREES partners is as follows:

- geometrically corrected satellite images (per scene):
  - Landsat TM full scene with 4 channels: 250 MB
  - Landsat TM (quarter) sub-scene with 4 channels: 80 MB
  - SPOT scene with 3 channels: 40 MB
- interpretations (per file)
  - In vector format
    Landsat TM full scene size: 10 MB
    Landsat TM sub-scene or SPOT scene size: 5 MB
  - In raster format
    Landsat TM full scene size: 50 MB (TIFF) – 2 MB (GRID)
    Landsat TM sub-scene / SPOT scene size: 13 MB (TIFF) – 1 MB (GRID)

Table 13: Overview of data volume

Input data type	Volume per scene (MB)	Number of files	Total volume per data type (MB)
TM full scene - 4 channels	250	100	25,000
TM sub-scene - 4 channels	80	120	9,600
SPOT scene (3 channels)	40	20	800
Interpretations	20	3 x 200	12,000
Total			41,000

Figure 22 to Figure 24 display examples for the summary information presented for the individual sites.

Figure 22: Example of interpretation results: sample site 224/67 in Brazil

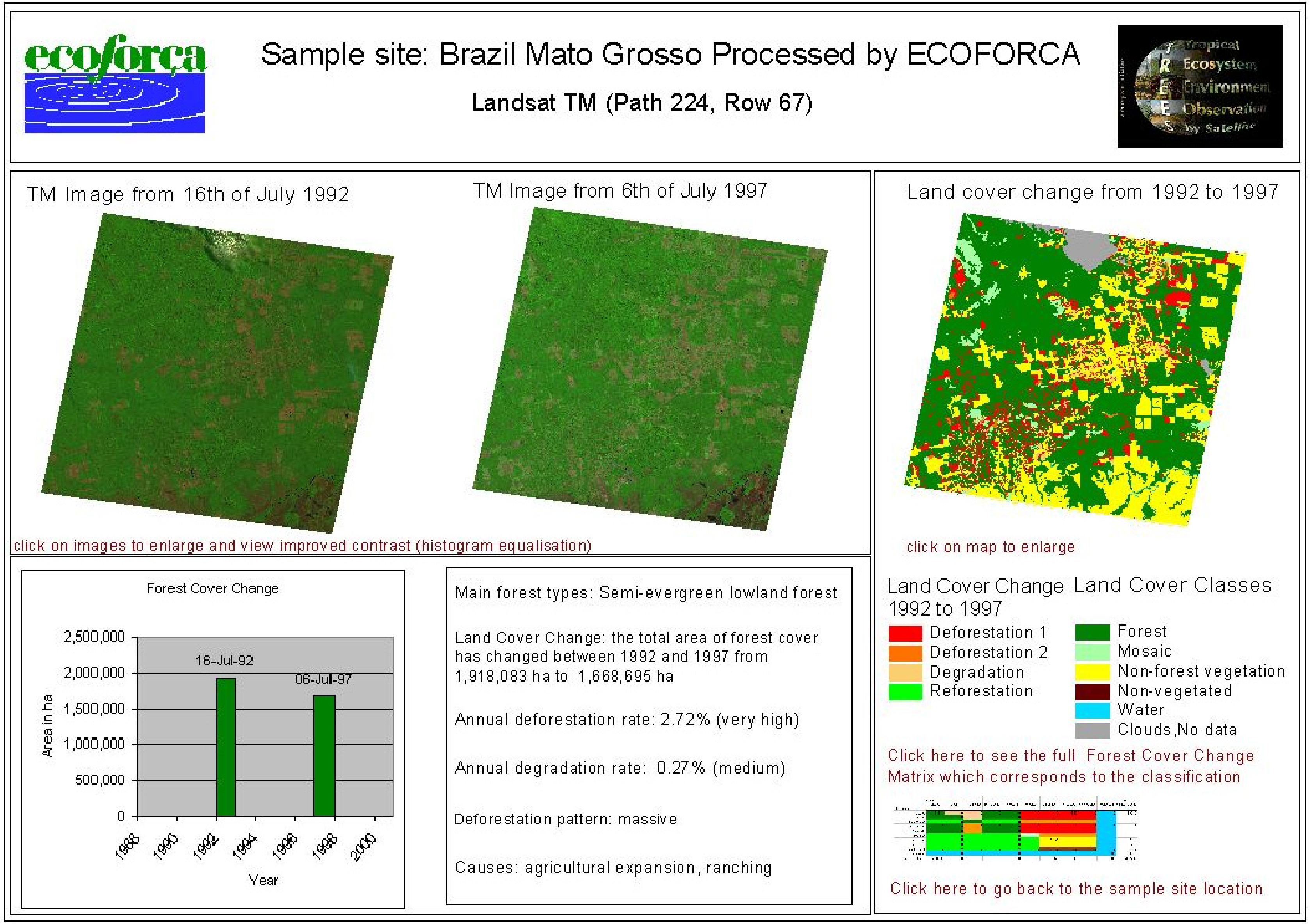


Figure 23: Example of interpretation results: site 180/58 in Democratic Republic of Congo

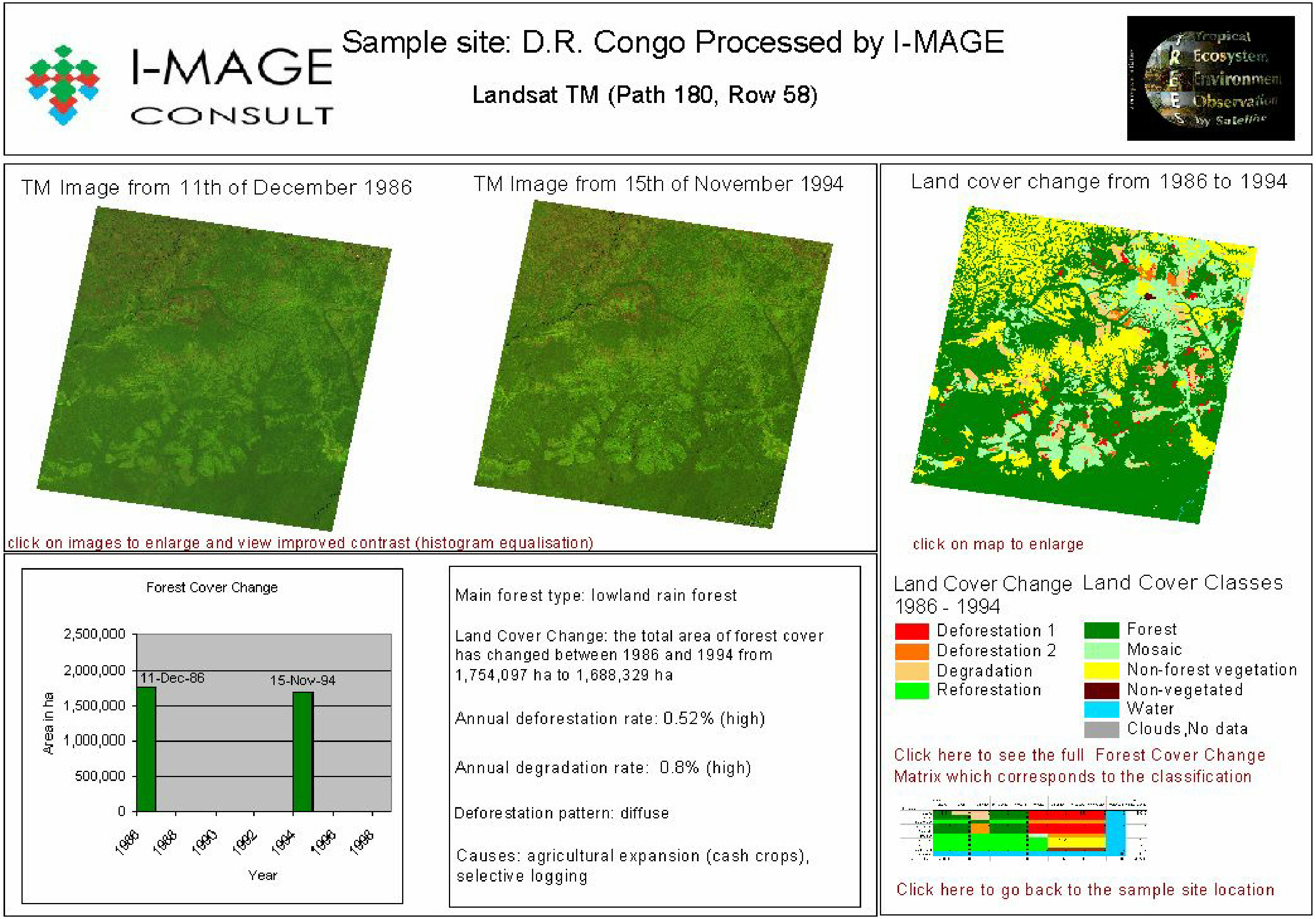
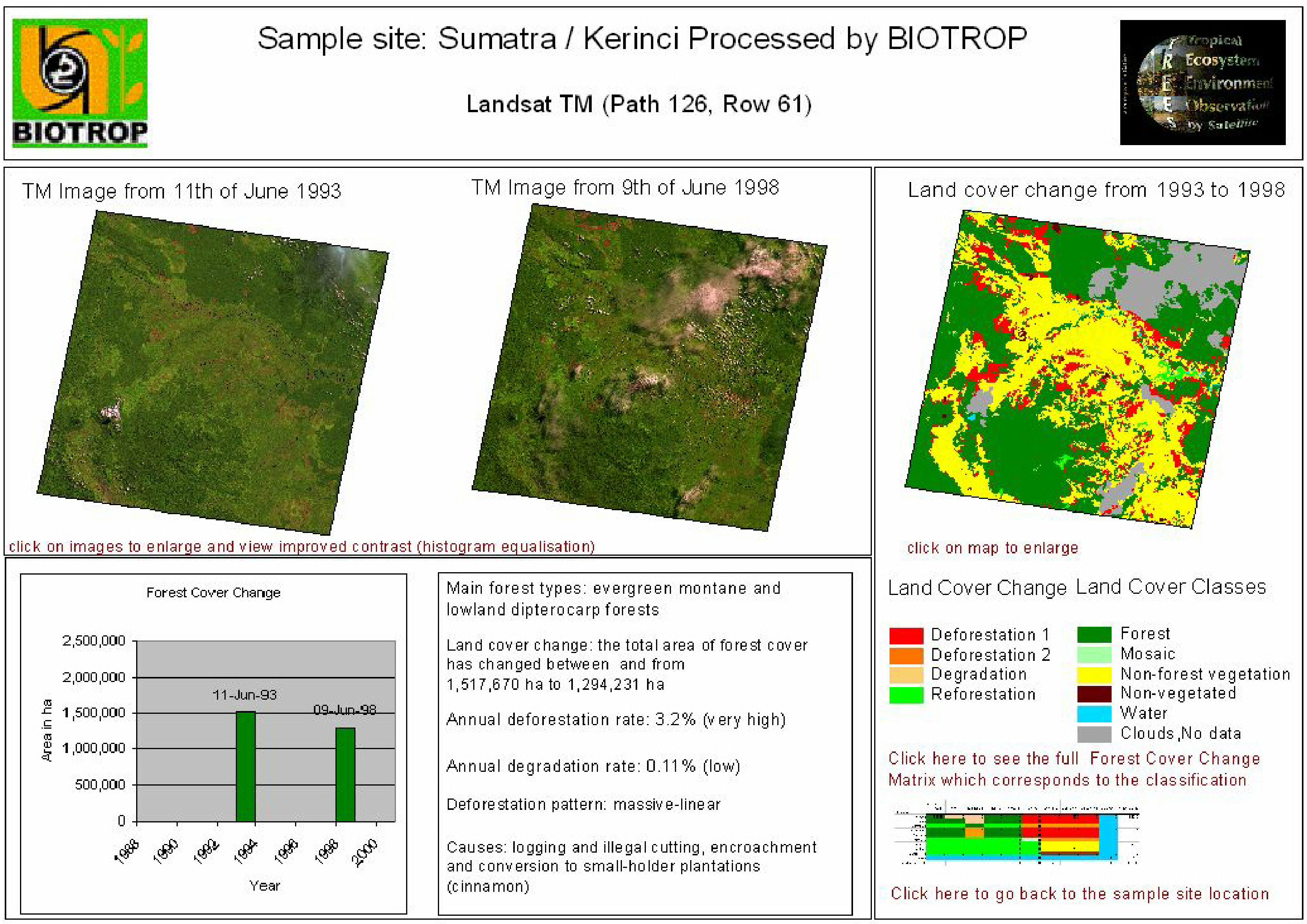


Figure 24: Example of interpretation results: sample site 126/61 in central Sumatra



6.3. Consistency assessment exercise

An independent consistency assessment was performed by the Istituto Agronomico per l'Oltremare, Florence, Italy (Drigo et al, 2001). The experienced team of IAO assessed the quality and the compatibility of the satellite image interpretations of the observation sites.

6.3.1. Objective and method

Objective

As various partners performed the satellite image interpretation, a study of the consistency of the classification and interpretation procedures implemented was considered necessary. Although a standard classification system and interpretation procedure had been proposed, some heterogeneity had to be expected. Heterogeneity is due to specific conditions of vegetation in various sites, but also due to the individual interpreter and his level of experience.

The scope of the study was therefore to assess the consistency of the thematic and geometric properties of the interpreted polygons. The scope was not to implement an accuracy assessment, since true reference data were not available.

Methodology

The consistency assessment was based on the re-interpretation of spatial subsets (blocks) extracted from the original data sets provided by the TREES partners.

For each full Landsat TM scene two blocks of 30 km x 30 km size were systematically selected and extracted, and for each Landsat quarter scene, one block of 20 km x 20 km size was systematically selected. A systematic dot grid was used for the reinterpretation within the blocks. The dot grids contained 225 (15x15) dots for the 30 km x 30 km sized blocks, and 100 (10x10) dots for the 20 km x 20 km sized blocks.

In total 127 blocks were extracted from the 94 sample sites available at the time of the consistency assessment. These subsets represented approximately 5 % of the total interpreted area. The input data sets for each block included (i) the digital subsets (blocks) of pairs of geometrically corrected satellite images and (ii) the digital subsets of land cover interpretation maps (one historical and one recent) produced from these satellite images.

The main task was to re-interpret the subsets (blocks) based on the dot grids and on a simplified legend. For each sub-sample the dots were re-interpreted in an independent and consistent way.

Each block was analysed in its specific geographic, ecological and floristic context. Systematic references (pan-tropical vegetation maps, TREES coarse resolution maps, ICIV Ecological and Eco-floristic zone maps, etc.) as well as location-specific references available at IAO were used to understand the characteristics of the study site. Previous IAO experience with the FAO FRA sample sites provided useful background information. Three of the four IAO team members had participated to the pan-tropical remote sensing survey carried out by FAO during the Forest Resource Assessments of 1990 (FAO, 1996) and 2000 (FAO, 2001a).

The reinterpretation was done in two separate steps:

(i) Assessing the vegetation class covered by a specific dot

(ii) Assessing the whole polygon a dot would fall in.

(i) Assessing the vegetation class covered by a specific dot:

For each dot of the grids a point interpretation was done on-screen, applying the simplified TREES classification scheme (10 aggregated land cover classes: closed, open or fragmented forests, plantations, regrowth, mosaics, natural non forest, agriculture, non vegetated, water), which privileged the physiognomic aspects since they are of high relevance in the analysis of change. In order to classify the land cover at point location below the minimum mapping level defined for the study, the scale of interpretation was generally larger than the standard 1:100,000. Being a point classification, composite classes were not used.

(ii) Assessing the whole polygon a dot would fall in:

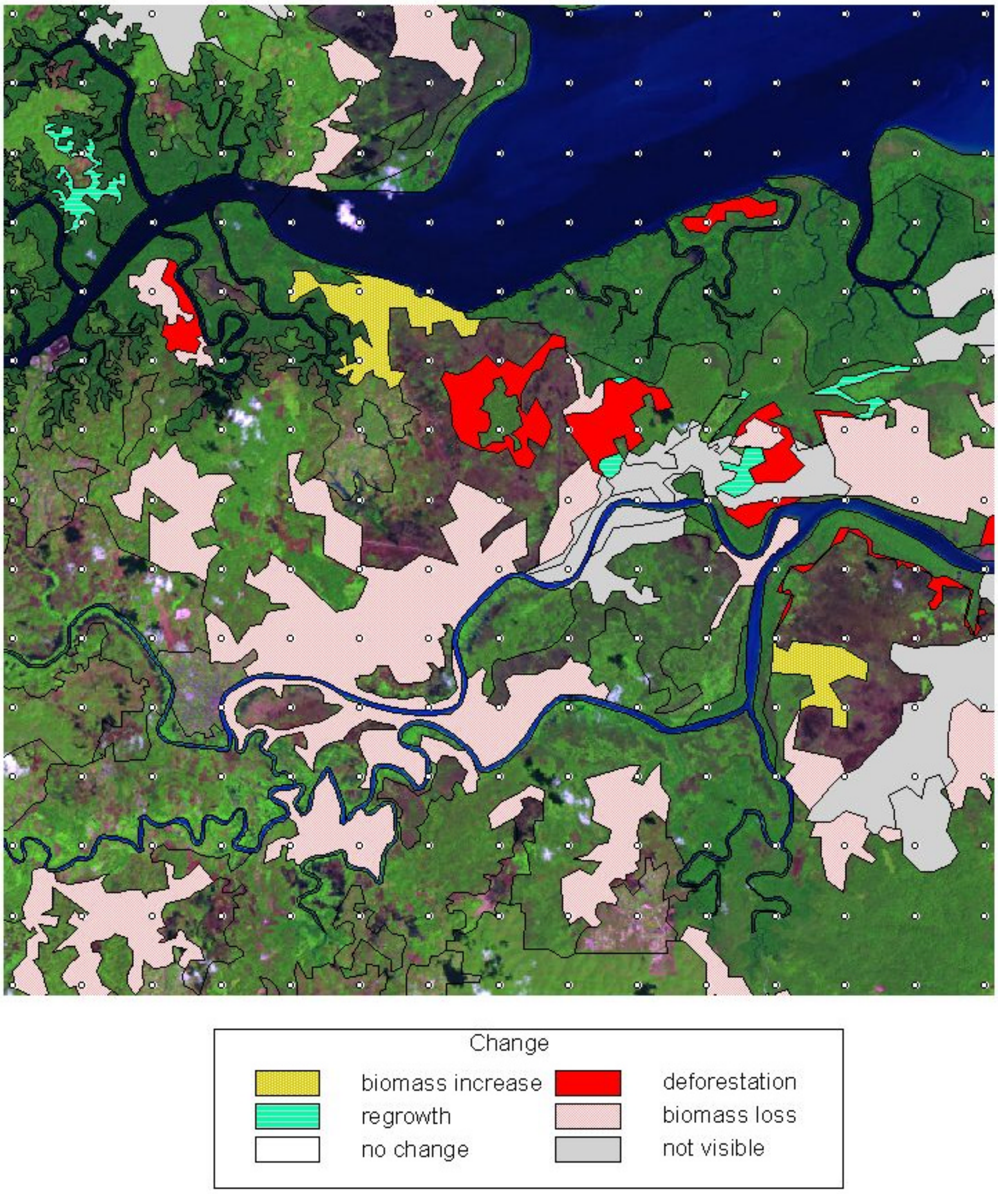
For all grid dots, the polygons that contained the dots were assessed thematically and geometrically. The assessment was done on-screen, using a 1:100,000 equivalent scale, and applying the simplified TREES classification scheme. Being an area classification, composite classes were also used.

The original class label and geometric accuracy of the ‘dot polygon’ (polygon containing the dot) were assessed and three ’accuracy’ codes were assigned per ’dot polygon’: agreement / debatable / disagreement.

The re-interpretations of the land cover class at each dot location were also used as reference data set for an assessment below the level of the TREES II minimum mapping unit. This analysis was based on the new codes assigned at each dot location. In order to remain free from the classification inconsistencies identified during polygon re-interpretation, the analysis was based exclusively on the dots for which there was an agreement with the original polygon class and for which no composite classes were used.

An example for one subset is displayed in Figure 25, in which change polygons are displayed in different colours.

Figure 25: Example for a grid of 15x15 dots within a 30 x 30 km block



6.3.2. Consistency assessment results

The resulting interpretation consistency has been estimated at 93% globally for the 10 aggregated land cover classes (closed, open or fragmented forests, plantations, regrowth, mosaics, natural non forest, agriculture, non vegetated, water) with the following continental distribution: 96% for Latin America, 88% for Africa and 92% for Southeast Asia.

For the forest cover change estimations, the global consistency was estimated at 91% with 96% for Latin America, 82% for Africa and 90% for Southeast Asia.

Consistency of the class interpretation

The consistency was measured as the fraction of agreed dot interpretations to the total number of dots.

Block by block results have been reviewed for major inconsistencies. A few blocks (7 blocks corresponding to 5 sample sites) included significant inconsistencies of classification particularly for the classes fragmented and open forests. These 5 inconsistent sample sites (called "outliers"), representing 6% of the total number of dots studied, were removed from the dataset for the further consistency assessment. From these 5 outliers, 3 were corrected before being used in the estimation phase (224/62 FS, 175/58 FS, 134/46 FS) and one was not used (20/46 Q4).

The exclusion of these out-layers, which carried major inconsistencies, improved the overall consistency from 90.5% to 93.1% (level 1 of Table 14). Most relevant, the consistency of *open* and *fragmented forest* classes considerably improved, with respective commission indices of 11.8% and 20.9%. At regional level the overall consistency indices are estimated at 96.1% for Latin America, 92.4% for Asia, and 88.2% for Africa.

A large part of the relatively low performance of Africa appeared to be due to the sample sites analysed through digital classification procedures rather than by applying the recommended interdependent visual method. The class 'regrowth', which has been used almost exclusively in this region, and the class 'mosaics', caused some weaknesses in Southeast Asia.

Table 14: Pan-tropical classification consistency matrices.

Level 1 aggregation

TRES interpretation	Polygon codes - IAO interpretation (dots): CL.Fo	OP.Fo	FR.Fo	Un.Fo	Plant.	Regr.	Mosai	Agric.	Water	NonVi	Total	Thematic disagreed (commission) %	Thematic debat. %	Geometric disagreed %	Geometric debat. %
Closed	20909	166	151	1		5	126	158	2	117	21635	**3.4**	0.3	**8.3**	0.6
Open For	92	1497	50				37	21		1	1698	**11.8**	2.8	**22.2**	2.0
Frag. For	96	80	965			1	37	36	4	1	1220	**20.9**	0.3	**29.9**	0.3
Undef. For				140			6				146	**4.1**		**12.3**	
Plantations	1				134						135	**0.7**	3.0	**7.4**	1.5
Regrowth	12	20	35		1	524	78	30		8	708	**26.0**	26.1	**26.8**	5.4
Mosaic	141	81	119				2391	236	5	4	2977	**19.7**	0.3	**25.2**	0.6
Agricult.	46	67	60		2	3	541	10616	7	66	11408	**6.9**	0.5	**13.4**	1.0
Water			9				5	1	359		374	**4.0**	0.3	**8.3**	0.5
NonVisible	34		1				2	17	1	394	449	**12.2**		**14.5**	0.4
Total	21331	1911	1390	141	137	533	3223	11115	378	591	40750	**6.9**	0.9	**12.6**	0.8
Omission %	**2.0**	**21.7**	**30.6**	**0.7**	**2.2**	**1.7**	**25.8**	**4.5**	**5.0**	**33.3**					

Level 2 aggregation

TREES interpretation		IAO interpretation: **Forest & plantations**	**Regrowth & mosaics**	**Agriculture & water**	**Total visible**	Thematic disagreement (commission) dots	%
Forest & plantations	%	**98.2**	**0.9**	**0.9**	**100**		**1.8**
	dots	24282	212	221	24715	433	
Regrowth & mosaics	%	**11.1**	**81.5**	**7.4**	**100**		**18.5**
	dots	409	2993	271	3673	680	
Agriculture & water	%	**1.6**	**4.7**	**93.7**	**100**		**6.3**
	dots	184	549	10983	11716	733	
Total visible		24875	3754	11475	40104		
Omission	**dots**	593	761	492		1846	**4.6**
%		**2.4**	**20.3**	**4.3**			

Consistency of the change estimation

The change matrices (Table 15) were produced by simple aggregation of the blocks studied with the objective to indicate the level of consistency of the change assessment at regional and pan-tropical level. Since they were not aggregated according to the original statistical sampling design, the land cover changes described by these matrices are not representative of the regions surveyed.

In order to allow for a comparison between the IAO and TREES change matrices, two parameters were used: (i) Number of dots classified as *closed forest* classes and (ii) number of dots classified as *closed forest* + *open forest.* + *fragmented forest* + *undefined forest* (Total Forest).

The consistency of change assessment improved after the exclusion of the same outliers identified during the classification consistency analysis. After their removal, the difference between the *closed forest* change rates estimated by IAO and those estimated by TREES became very small: -3.6% for net deforestation and -4.2% for degradation. Considering the Total Forest, the difference was -8.3% for net deforestation and -7.9% for degradation.

At regional level the differences of deforestation rates for *closed forest* were very small: -1% (Asia), -2% (Latin America) and -8% (Africa). Concerning the change of Total Forests, the differences with IAO estimates were found to be a bit higher: -4.4% (Latin America), -7.5% (Asia), -17.8% (Africa). Differences in the estimated forest degradation rates were higher in relative terms but quite small in absolute terms.

Considering the relatively small amount of change to be detected (approximately 1 % per year) and its uneven distribution, the values resulting from the "clean" data set confirm the good overall consistency of the study regarding the estimation of deforestation and degradation rates at pan-tropical level.

Table 15: Comparison of pan-tropical change matrices from TREES and IAO interpretations.

IAO Interpretation

	Recent image interpretation (dots)										Total historical	
Hist. interp.	**CL.For**	**OP.For**	**FR.For**	**Un.For**	**Plant.**	**Regr.**	**Mosaic**	**Agric.+**	**Water**	**NonVis.**	Total	**Visible**
Closed	**10012**	**120**	**191**	**4**	**74**	**5**	**166**	**443**	**2**	**149**	11166	**11017**
Open For	**39**	**697**	**54**		**5**	**3**	**48**	**70**		**14**	930	**916**
Frag. For	**5**	**36**	**477**			**6**	**68**	**55**		**4**	651	**647**
Undef. For		**3**	**7**	**61**				**5**			76	**76**
Plantations					**19**					**5**	24	**19**
Regrowth	**4**	**2**			**11**	**230**	**9**	**13**		**1**	270	**269**
Mosaic	**6**	**3**	**5**			**13**	**1340**	**157**	**6**	**12**	1542	**1530**
Agricult.	**2**	**1**	**4**		**4**	**3**	**59**	**5044**	**10**	**58**	5185	**5127**
Water	**2**						**3**	**19**	**168**		192	**192**
NonVisible	**187**	**9**	**11**			**3**	**34**	**88**		**7**	339	
Tot. recent	10257	871	749	65	113	263	1727	5894	186	250	20375	
Visible rec.	**10070**	**862**	**738**	**65**	**113**	**260**	**1693**	**5806**	**186**	**243**		**19793**
Change	-947	-54	91	-11	94	-9	163	679	-6			

TREES interpretation

	Recent image interpretation (dots)										Total historical	
Hist. interp.	**CL.For**	**OP.For**	**FR.For**	**Un.For**	**Plant.**	**Regr.**	**Mosaic**	**Agric.+**	**Water**	**NonVis.**	Total	**Visible**
Closed	**10219**	**150**	**164**	**3**	**74**	**11**	**139**	**463**	**4**	**115**	11342	**11227**
Open For	**33**	**586**	**44**		**5**		**34**	**74**		**13**	789	**776**
Frag. For	**20**	**41**	**405**				**50**	**43**	**8**	**2**	569	**567**
Undef. For		**9**	**7**	**61**				**5**			82	**82**
Plantations					**18**					**5**	23	**18**
Regrowth					**11**	**306**	**1**	**50**		**1**	369	**368**
Mosaic	**22**	**5**	**15**			**15**	**1174**	**144**	**7**	**3**	1385	**1382**
Agricult.	**3**	**7**	**7**		**4**	**6**	**100**	**5191**	**11**	**40**	5369	**5329**
Water	**1**						**2**	**15**	**163**		181	**181**
NonVisible	**152**	**11**	**2**			**1**	**22**	**73**		**5**	266	
Tot. recent	10450	809	644	64	112	339	1522	6058	193	184	20375	
Visible rec.	**10298**	**798**	**642**	**64**	**112**	**338**	**1500**	**5985**	**193**	**179**		**19930**
Change	-1044	22	75	-18	94	-30	118	656	12			

Comparison of estimated changes			**Nat. Forest change**		**Total Forest change**		**Nat.For. Degradation**	
(Clean data set)		total dots	dots	%	dots	%	dots	%
IAO	Closed Forest historical	11017	-676	-6.1	-582	-5.3	267	2.4
	Total Forest historical	12656	-921	-7.3	-827	-6.5	285	2.3
TREES	Closed Forest historical	11227	-665	-5.9	-571	-5.1	261	2.3
	Total Forest historical	12652	-850	-6.7	-756	-6.0	264	2.1
Difference	Closed Forest historical	1.9	**-1.7**	-3.6	**-1.9**	-3.9	**-2.3**	-4.2
(TREES-IAO / TREES %)	Total Forest historical	0.0	**-8.4**	-8.3	**-9.4**	-9.4	**-8.0**	-7.9

Analysis below minimum mapping level

This analysis at the dot level was done for documenting the content of the land cover classification at a higher level of resolution, i.e. below the standard minimum mapping level applied during the interpretation. The particular purpose was to define the land cover elements of the composite classes *fragmented forest* and *mosaics*.

The summary of results at the pan-tropical level, presented in
Table 16 shows that there is a considerable homogeneity within continuous (non-composite) classes, as stated by the high percentage values along the diagonal. The only exception is the *undefined forest* classes, which tells us that in 61.4 % of the cases this class contains *closed forest*, in 6.4 % of the cases *open forest* and that in only 2.1 % are represented by *non-forest* gaps. More important, are the results for the composite classes:

- *Fragmented forest* appears composed by 78.1% of forest (closed 22.4%, open 55.7%) and only by 21.9% of non-forest. The latter part being further divided into non-forest natural vegetation classes (approximately 2/3) and agriculture/non-vegetated (approximately 1/3). This testifies for an unbalanced use of this class. In fact the range of forest proportion for this class should have been between 40 and 70%. This further confirms the relatively poor consistency identified during the classification consistency analysis presented above where the *fragmented forest* class showed the highest commission index.

- *Mosaic* classes appear to be composed by 29.7 % of forest (8.3 percent closed and 21.4% open). The non-forest part (70.3%) being composed by non-forest natural vegetation classes and by agriculture/non-vegetated classes with a slight dominance of the former group. This composition well responds to the theoretical structure of mosaic classes for which the forest proportion was set between 10 and 40%.

Table 16: Comparison between IAO dot classification versus TREES polygon classification

	CL.For	OP.For	FR.For	Un.For	Plant.	Regr.	Mosaic	Agric.+	Water	NonVis.	Total Visible
	Dot codes - IAO Interpretation of agreed polygons Number of dots										
	21549	82				10		114	34	835	21789
Open For	43	1509						17	2	481	1571
Frag. For	210	521				4		198	3	1168	936
Undef. For	86	9		42				3		6	140
Plantations	3				129			2		1	134
Regrowth	6	17			2	484		11		188	520
Mosaic	202	520			1	21		1649	34	691	2427
	54	53				2		10526	24	1265	10659
Water								1	358	15	359
NonVisible	21	1						7	7	429	
	22153	2711		42	132	521		12521	455		38535

	CL.For	OP.For	FR.For	Un.For	Plant.	Regr.	Mosaic	Agric.+	Water	NonVis.	Total Visible
	Dot codes - IAO Interpretation of agreed polygons Percent of original TREES polygon classification										
	98.9	0.4				0.0		0.5	0.2		100
Open For	2.7	96.1						1.1	0.1		100
Fragment.	22.4	55.7				0.4		21.2	0.3		100
Undef. For	61.4	6.4		30.0				2.1			100
Plantations	2.2				96.3			1.5			100
Regrowth	1.2	3.3			0.4	93.1		2.1			100
Mosaic	8.3	21.4			0.0	0.9		67.9	1.4		100
	0.5	0.5				0.0		98.8	0.2		100
Water								0.3	99.7		100
NonVisible											

The consistency assessment dot classification was done below the mapping level.

7. Forest cover change estimation at continental level

Summary

The *forest cover* and other *land cover areas* measured from the digital on-screen interpretations of the 104 observation units (samples) were standardized and linearly interpolated to the two reference dates: 1st June 1990 and 1st June 1997.

***Forest cover change* and *land cover transitions* were then estimated statistically at continental level using the extrapolated data.**

The statistical sampling accuracy of the *forest cover* and the *forest cover change* estimations is estimated through a re-sampling (bootstrap) method.

The individual site measurements were integrated in a statistical calculation, which takes into account their selection probabilities. First we considered that each observation site (full TM scene or quarter TM scene) is linked to a unique relative cluster of hexagonal sampling units (as sum of probabilities of the corresponding hexagons).

As each observation site does not belong necessarily to a single sampling stratum, we fall in a situation of unequal probability sampling rather than stratified sampling. The traditional unbiased estimator for an unequal probability sample is the Horwitz-Thomson estimator, also called π-estimator (Cochran, 1977).

However in our case we had (i) observation units (Landsat images) slightly different from the sample units (cluster of hexagons) and (ii) partially missing information (mainly due to cloud coverage) and non-random location shifting or replacement of a few sites in the sample (4 replacement sites in total). This may introduce a bias in the estimator that must be corrected as far as possible.

Two correction steps were applied to handle this situation of unequal probability sampling: (i) correction of the initial probabilities of the clusters of hexagons to fit with the Landsat TM observation sites and (ii) calibration estimator using two proxies (or co-variables) available at regional scale.

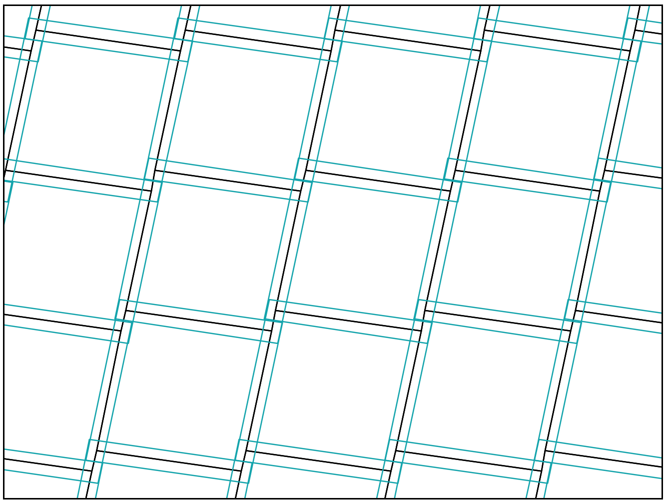
7.1. Standardization of the sample site interpretations

All interpretations from the TREES local partners were imported in the Tropical Forest Information System and processed in order to meet the TREES format and standards for integration in the statistical estimation phase. The processing procedure performs a number of standard processing steps described below.

7.1.1. Design of a simplified change matrix

Nominal area clipping

The Landsat WRS-2 (World Reference System) coverage (vector layer) was used to generate a new Landsat frame reference system with no overlapping zones. It is obtained by bisecting the overlapping area between the WRS-2 Landsat frames, so that all frames become contiguous units with no gaps and no overlaps. This is illustrated below with the actual TM frames shown in grey and the contiguous frames shown in black.

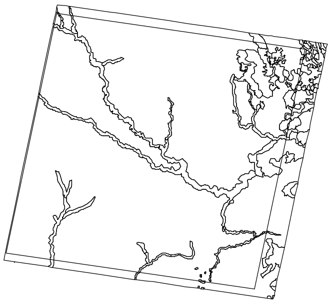


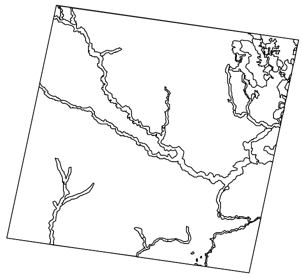
As the TREES sample is based mainly on full and quarter Landsat scenes the contiguous Landsat full frames have been further subdivided into quarter scenes. These quarters are numbered 1,2,3,4 following the order top-left, top-right, bottom-left, bottom-right. A Quarter value of zero in the database indicates a full scene.

As the interpretations are in UTM projection the TM frame coordinates (originally in geographic projection, i.e. latitude - longitude) were transformed into UTM in order to overlay the frames onto the interpretations. For each interpretation a UTM map projection is defined using the parameters from the database.

The "historical" T1 interpretation is first clipped to the boundary of the TM frame.

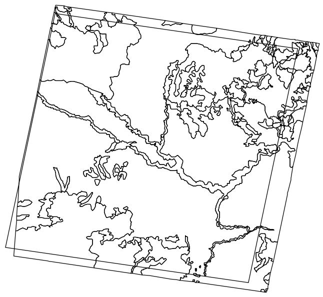
Figure 26: Nominal area clipping procedure for satellite imagery interpretation

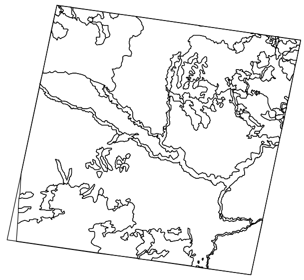




Original T1 interpretation T1 interpretation clipped to TM frame

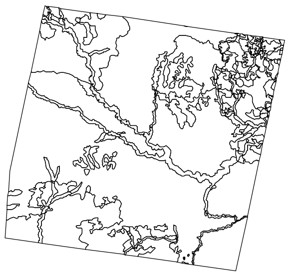
The “recent” T2 interpretation is then clipped to the boundary of the TM frame.





Original T2 interpretation T2 interpretation clipped to TM frame

The clipped T1 and T2 interpretations are finally intersected to generate an output change interpretation, which contains unique polygons with attributes for both T1 and T2. The area covered by the output is the common area between (T1) AND (T2) AND (the TM frame).



Change interpretation clipped to TM frame

Figure 22 to Figure 24 illustrate the results of the clipping procedure for the satellite imagery and change interpretation.

The areas of each polygon in the clipped change layer (in UTM projection units) are recalculated and an additional field is added which contains the class name for T1 followed by the class name for T2 - e.g. "13A -> 8". Following this a summary table is generated for each unique change class, summarising the number of polygons and area for each change class.

Simplified vegetation classification scheme and cross-tabulation change matrix

First the original vegetation classification scheme (Table 10) was simplified in order to reduce the number of classes for calculating the change matrices. Only 10 main forest and other land cover classes were kept. The forest cover percentages of these 10 classes were set up at the initial stage and have been confirmed from the consistency assessment exercise. This gives the correspondence between the original vegetation classification scheme and the simplified version.

Table 17: List of simplified vegetation classes

Interpretation classes	New code	Forest cover in %
Forest classes		
Closed	**11 A**	**100**
Open	**11 C**	**100**
Fragmented	**11 D**	**75**
Plantations	**15**	**100**
Regrowth	**16**	**100**
Non forest classes		
Mosaics	**2**	**25**
Natural vegetation	**3**	**0**
Agriculture	**4**	**0**
Non vegetated	**5**	**0**
Water or sea	**6**	**0**
Clouds	**8**	**0**

Table 18: Recoding of the vegetation scheme

Original label (levels 1 & 2)	Recoded label	Original label (level 3)	Recoded label
11	11	A	A
12	11	B	A
13	11	C	C
14	11	D	D
15	15	E	A
16	16		
17	11		
19	11		
21	4		
22	2		
23	2		
29	2		
31	3		
32	3		
33	3		
39	3		
41	4		
42	4		
43	4		
44	4		
49	4		
5	5		
50	5		
51	5		
52	5		
53	5		
54	5		
59	5		
6	6		
61	6		
62	6		
7	6		
81	8		
82	8		
9	8		

The simplified legend is then used to produce the change matrices from the two dates clipped change interpretation. An example of such a matrix is given in Figure 27.

Figure 27: Change matrix results over sample site 224/67 in Brazil (available on Web site)

ecoforça

Sample site: Brazil Mato Grosso Processed by ECOFORCA

Landsat TM (Path 224, Row 67)

Tropical Ecosystem Environment Observation by Satellite

Change matrix between historical and recent interpretations from **16-Jul-92** to **06-Jul-97**

	Recent Closed	Open	Fragmented	Plantations	Regrowth	Mosaics	Savannas	Agriculture	Unvegetated	Water/Sea	Total without Clouds
Historical											
Closed	1530650	21350	3216	0	0	13156	728	208764	37	0	1777901
Open	643	79875	349	0	0	3261	0	19610	0	0	103739
Fragmented	0	0	12530	0	0	961	0	4013	0	0	17503
Plantations	0	0	0	0	0	0	0	0	0	0	0
Regrowth	0	0	0	0	0	0	0	0	0	0	0
Mosaics	137	0	0	0	0	77842	0	15282	0	0	93261
Savannas	0	0	0	0	0	0	175262	1593	0	0	176855
Agriculture	37	105	28	0	0	0	0	461290	33	0	461492
Unvegetated	0	0	0	0	0	0	0	0	418	0	418
Water/Sea	0	0	0	0	0	0	0	0	0	3987	3987
Total withouth Clouds	1531468	101330	16122	0	0	95220	175990	710552	488	3987	2635156

Historical forest cover	**16-Jul-92**	**1,918,083 ha**	Annual deforestation rate	-2.72 %
Recent forest cover	**06-Jul-97**	**1,668,695 ha**	Annual degradation rate	-0.27 %

Note1: forest cover = closed + open forests + forest plantations + forest regrowth + 75% fragmented forest + 25% mosaics

Note2: all figures are in hectares

Back to sample site

7.1.2. Interpolation to a reference period: 1st June 1990 to 1st June 1997

The change matrices of all sample sites were then linearly adjusted (interpolated or extrapolated) to two reference dates: **1st June 1990 and 1st June 1997**. These reference dates have been selected in relation to the average dates of selected satellite imagery.

	Average historical date	Average recent date
Latin America	25-Feb-91	08-May-97
Africa	25-Feb-89	24-Mar-96
Southeast Asia	27-May-90	29-Jun-97
Global	**16-Jun-90**	**22-Mar-97**
Reference dates	***01-Jun-90***	***01-Jun-97***

Considering the forest change matrix between date t_1 and date t_2

$$CM(t_1,t_2)=\begin{array}{|c:c:c:c|c}
 & & & & \sum_k C_{i\to k} \\ \hdashline
 & C_{i\to i}(t_1\to t_2) & C_{i\to j}(t_1\to t_2) & & TA_i(t_1) \\ \hdashline
 & C_{j\to i}(t_1\to t_2) & C_{j\to j}(t_1\to t_2) & & TA_j(t_1) \\ \hdashline
 & & & & \\ \hline
\sum_k C_{k\to i} & TA_i(t_2) & TA_j(t_2) & &
\end{array}$$

We used the following formulas for the linear adjustment of the change matrices:

$$C_{i\to j}(90\to 97)=C_{i\to j}(t_1\to t_2)\times\frac{no.\_days(90\to 97)}{no.\_days(t_1\to t_2)}$$

$$C_{i\to i}(90\to 97)=TA_i(t_1)+\left[(TA_i(t_1)-TA_i(t_2))\times\frac{no.\_days(t_1\to 90)}{no.\_days(t_1\to t_2)}\right]-\sum_{k\neq i}C_{i\to k}(90\to 97)$$

An example of result of the linear adjustment process is given in the following table.

Table 19: Interpolation of change matrix of sample 224 / 67

a) Change matrix between historical (16 July 1992) and recent (06 July 1997) interpretations

	06 July 1997										Total
	Closed	Open	Fragment	Plantat.	Regrow.	Mosaics	Savannas	Agricult.	Unveget.	Water	
16 July 1992											
Closed	1530650	21350	3216	0	0	13156	728	208764	37	0	1777901
Open	643	79875	349	0	0	3261	0	19610	0	0	103738
Fragmented	0	0	12530	0	0	961	0	4013	0	0	17504
Plantations	0	0	0	0	0	0	0	0	0	0	0
Regrowth	0	0	0	0	0	0	0	0	0	0	0
Mosaics	137	0	0	0	0	77842	0	15282	0	0	93261
Savannas	0	0	0	0	0	0	175262	1593	0	0	176855
Agriculture	37	105	28	0	0	0	0	461290	33	0	461493
Unvegetated	0	0	0	0	0	0	0	0	418	0	418
Water/Sea	0	0	0	0	0	0	0	0	0	3987	3987
Total	1531468	101330	16122	0	0	95220	175990	710552	488	3987	2635157

b) Adjusted change matrix between 01 June 1990 and 01 June 1997

	01 June 1997										Total
	Closed	Open	Fragment	Plantat.	Regrow	Mosaics	Savannas	Agricult.	Unveget.	Water	
01 June 1990											
Closed	1535135	30057	4527	0	0	18522	1025	293902	53	0	1883220
Open	906	71172	492	0	0	4591	1	27608	0	0	104769
Fragmented	0	0	11092	0	0	1352	0	5649	0	0	18093
Plantations	0	0	0	0	0	0	0	0	0	0	0
Regrowth	0	0	0	0	0	0	0	0	0	0	0
Mosaics	193	0	0	0	0	70717	0	21514	0	0	92424
Savannas	0	0	0	0	0	0	174981	2243	0	0	177225
Agriculture	53	147	39	0	0	0	0	354765	46	0	355051
Unvegetated	0	0	0	0	0	0	0	0	388	0	388
Water/Sea	0	0	0	0	0	0	0	0	0	3987	3987
Total	1536287	101377	16149	0	0	95181	176007	705682	487	3987	2635156

7.2. Estimation phase

To derive continental and global estimates, it was necessary to expand the area estimates upon the data from the 102 individual sample measurements, which are covering only 6.5% of the study area. This is done by statistical calculation which takes into account the selection probabilities and variances per stratum.

7.2.1. Selection of a statistical estimator

Selection probabilities of the observation units

In the estimation phase the selection probability of an observation unit is considered. Although the sampling units are tessellation hexagons, observation units are full or quarter Landsat TM scenes. Applying the site size rule, for each hexagon there is a linked observation unit (full Landsat scene or quarter Landsat scene) and a relative cluster of hexagons. The probability that a specific observation unit is selected is the sum of probability that the corresponding hexagons are selected. Each observation unit does not belong necessarily to a single sampling stratum, but its sampling probability is known (this leads to an estimation with unequal probability sampling rather than stratified sampling).

For each site we have the sampling probability p_k, the total geographical area D_k (excluding sea and area outside the study region), although only an area D_k^* was cloud free and could be photo-interpreted. The targeted variable in the site (deforested area) is z_k.

Selection of a non classical estimator

The probabilities p_k do not behave like in a stratified sampling, where they have to be constant inside each stratum, and standard estimators for stratified sampling cannot be used. The traditional unbiased estimator for an unequal probability sample is the Horwitz-Thomson estimator (Cochran, 1977), also called π-estimator (Särndal et al, 1992). For any variable Y (any particular *land cover transition area*), the formula for the estimation of the total of Y is:

$$\hat{Y}_p = \sum_i \frac{y_i}{p_i} = \sum_i d_i y_i$$

where y_i = Measured value of variable Y in sample site i

d_i = Weight of sample site i (inverse of the sampling probability p_i).

However in our case we have observation units (Landsat images) slightly different from the sample units (cluster of hexagons) and partially missing information (mainly due to cloud coverage). We have also non-random location shifting or replacement of a few sites in the sample (4 replacement sites in total). The average proportion of missing data (mainly clouds) inside the observed sites is 9%. This may introduce a bias in the estimator that must be corrected as far as possible. In consequence, the Horwitz-Thomson estimator cannot be applied straightforward. It cannot be applied either to the area proportion $z_k = \frac{y_k}{D_k^*}$, because it is not additive (the sum of area proportion for all the sites in the population has no meaning).

An adapted statistical estimator was derived from the Horwitz-Thompson estimator. Two correction steps were applied to the probabilities to handle the situation of unequal probability sampling:

(i) Correction of the initial probabilities of the clusters of hexagons to fit with the Landsat TM observation sites

(ii) Calibration estimator using two proxies (or co-variables) available at regional scale (Deville & Särndal, 1992).

7.2.2. Determination of the estimator (sample weights)

First correction step: fitting to clipped areas

Due to the particular sampling method used, the sampling probability of each image was proportional to the total land area of the tessellation hexagons that were associated to the image (cluster of hexagons), and depended on the proportion of forest area (from the 1 km resolution maps) and hot spot area in these hexagons. The total area and the proportion of forest area and hot spot area in the clipped observation units (high resolution image frames) are sometimes quite different from these initial parameters. These differences have to be taken into account in particular to reduce the impact of influential observations, especially in the cases in which an image has been sampled with a low probability (high extrapolation weight), and the image size has been changed/shifted to cover a larger forest area.

The first step allows correcting the initial sampling probabilities for such effects by applying the following linear 'fitting' model for each continent:

$$\frac{10^6 \times p_k}{XL_k} = a + b\frac{XF_k}{XL_k} + c\frac{XH_k}{XL_k}$$

where : p_k = *Selection probability* of site k
XL_k = *Total land area* in site k
XF_k = *Forest area from the 1km resolution map* in site k
XH_k = *Hot spot area* in site k

The parameters of the model (a, b and c) were determined for each continent from the data of the sample sites (clusters of hexagons), and then applied to the data of the observation sites (high resolution image frames).

The resulting estimated model parameters are the following:

Region \ Parameter	a	b	c	correl (p_k, p_k^*)
Pan-Amazon & Cent. America	1.52	0.94	29.94	0.994
Brazil & Guyanas	1.65	1.94	7.39	0.962
Africa	0.00	5.50	19.02	0.965
Southeast Asia	2.22	3.47	26.95	0.995

Applying these coefficients to:

XLk^{*} = *Total land area* in clipped observation unit k
XFk^{*} = *Forest area from the 1 km resolution map* in clipped observation unit k
XHk^{*} = *Hot spot area* in clipped observation unit k

We obtain new "estimated" probabilities $p0_k$ that can be used as starting point for calibration. As expected the impact of influential observations is reduced. The non-sampled images that have been added in Asia were not used for estimating the model parameters.

Second correction step: calibration using co-variables

Calibration estimators with the help of one or more proxies (co-variables) provide a way to correct potential biases and to improve precision. Actually we have two additional co-variables, which are available everywhere (for all sites and for the total population) and which are similar to the variables to be estimated (*forest area* and *forest area change from fine spatial resolution maps*):

- F_k = *forest area according to the 1km resolution forest maps*
- DF_k = *deforested area* = FHS_k *x regional hotness index*

Where FHS_k = *forested hot spot area* in site k

$$regional.hotness.index = \frac{regional.deforestation.1990-1995}{regional.forested.hotspot.area}$$

The *regional hotness index* was previously defined in 5.3.1 (Richards *et al.*, 2000) and was used in the sampling phase in order to balance the sampling size at the regional level (the number of replicates per stratum have been tuned to be roughly proportional to the hotness index). This index provides an indication of the intensity of the hot-spot areas at the regional level. A slightly modified index has been used here. The only regional deforestation estimates available for the period 1990 - 1995 were from FAO (1997). The deforestation hotness index defined for each region is shown in Table 20

Table 20: Regional hotness index used in the estimation phase

	Sub-region	*Deforestation 1990-1995* (1000 ha)	*Forest area In hot spots* (1000 ha)	*hotness Index*
1	Central America - Mexico	2,294	3,800	0.594
2	Pan-Amazon and Andes	8,764	30,900	0.283
3	Brazil and Guyanas	12,880	80,900	0.159
7	West Africa	2,459	2,200	1.091
6	Central Africa	5,699	22,000	0.258
8	Madagascar	650	4,500	0.144
4	Continental Southeast Asia	5,911	26,100	0.227
5	Insular South-East Asia	9,401	32,700	0.288

We selected the following approach (Deville & Särndal, 1992): Starting from the Horwitz-Thompson estimator, the calibration computes new weights w_k as close as possible to first step correction weights $d0_k$ ($1/p0_k$), such that the estimator applied to the two co-variables X_j (known for the whole population) gives a result that coincides with the known total of the co-variables. The new calibrated weights are obtained through an optimisation process.

If x_k and $y_{k\ are}$ the values of co-variable *forest area* and *deforested area* in sample element k , with the fitted weights we get estimates for the totals of the co-variables:

$$\sum_k w0_k\, x_k = TX^* \qquad \text{and} \qquad \sum_k w0_k\, y_k = TY^*$$

where: x_k and y_k = Values of the co-variables X and Y in site k respectively
$w0_k$ = *corrected weight* of observation site k

TX^* and TY^* can be compared with TX and TY, the known totals of the co-variables X and Y respectively.

Table 21: Known totals of the co-variables at continental level

	Total Area (1000 ha)	*TX* *Forest area* (1000 ha)	*TY* *Deforestation* (1000 ha)
C Amer. + Pan-Amazon	333,201	239,034	11,058
Brazil+Guyanas	530,324	391,388	12,880
Africa	680,529	202,291	8,808
Southeast Asia	865,523	276,740	15,312

The usual weight calibration is searching for weights $w1_k$ as close as possible to $w0_k$ for which the estimated totals of the co-variables coincide with the known totals:

$$\min\left(\sum_k (w1_k - w0_k)^2\right) \qquad \text{with} \qquad \sum_k w1_k\, x_k = TX \;\text{ and }\; \sum_k w1_k\, y_k = TY$$

where: TX and TY = Totals of the co-variables X and Y respectively
x_k and y_k = Values of the co-variables X and Y in site k respectively
$w0_k$ = *corrected weight* of observation site k
$w1_k$ = *calibrated weight* of observation site k

A few modifications are added to this usual weight calibration:

- The extra sites (i.e. not in the sample), which have been added in Asia, are removed from population for this calibration step. Both $w0_k$ and $w1_k$ are forced to be 1, so that they only represent themselves in the extrapolation.
- In order to limit the difference between fitted weight and calibrated weight for sites with large forest and hot spot areas (i.e. low weight subject to large potential change), we apply a factor in the minimisation function: Sum of the *forest area* and *hot spot area* of the site ($F_k + HS_k$)

- We apply a few restrictions to the calibrated weights:
  - To allow each scene to represent at least itself, single weight contributions can not be lower than 1: $w1_k \geq 1$
  - To avoid single weight contributions to be higher than 4 times the average weight contribution: $(w1_k \times y_k) \leq 4 \times \overline{(w1_k \times y_k)}$

The final weight calibration is searching for weights $w1_k$ with the following conditions and restrictions:

Searching for $\min\left(\sum_k (w1_k - w0_k)^2 \times (F_k + HS_k)\right)$

with the following conditions:

$$\sum_k w1_k \ x_k = TX \qquad \text{and} \qquad \sum_k w1_k \ y_k = TY$$

and with the following restrictions:

- for all sample sites: $w1_k \geq 1$ and $(w1_k \times y_k) \leq 4 \times \overline{(w1_k \times y_k)}$
- for the 4 extra (not in sample) observation sites: $w1_k = 1$

The calibration of weights has been applied separately for the four continents/regions listed in Table 21. The list of resulting calibrated weights is given in annex.

Selection of an variance estimator

The classical unbiased variance estimator (Cochran, 1977) is known to have stability problems; in fact it can even yield negative estimates for the variance (Thompson, 1992). Conservative estimators for the variance exist but an alternative bootstrap approach (Efron & Tibshirani, 1993) has been used.

For the variance estimator, as the usual estimator is not applicable for this calibration, we adopted a re-sampling (bootstrap) approach to overcome this problem. For each bootstrap replicate, the calibration is re-computed and the variance of the obtained estimations gives an estimate of the calibration variance.

The variance estimation has been applied separately for the four regions.

7.2.3. Considerations about potential bias

Risks of bias can come from the sampling and estimation scheme or from the procedure to measure the transition matrix in each sampling site (image-interpretation). For the statistical part, the main risk of bias is the existence of missing or replacement sites and missing data for specific areas inside the sample sites with persistent cloud cover. For partially missing data inside a site, we assume that the change rate in the missing areas is similar to the change rate in the areas with data of the same site. To reduce the bias due to replacement sites (4 sites in total), we have applied the calibration estimator described above. Possible inaccuracy in the 1 km forest map or in the hot spot areas make the sampling and the calibration less efficient (higher variance in the estimates), but do not introduce any significant bias in the area change estimates.

The possible bias from the image-interpretation of the satellite images over the 104 observation sites has been monitored in the following manner: an independent image-interpretation 'consistency assessment' was performed on a sub-sample (Drigo *et al.*, 2001). The re-examination of one or two sub-samples covering (in total) 5 % of the interpreted area in each sample site was carried out by a single expert. For each sub-sample the polygons covering 100 dots were re-interpreted in an independent and homogeneous way.

The consistency represents the fraction of agreed polygon interpretations to the total number of polygons. The resulting interpretation consistency has been estimated to some 93% globally for the 10 aggregated land cover classes (closed, open or fragmented forests, plantations, regrowth, mosaics, natural non forest, agriculture, non vegetated, water) with the following continental distribution: 96% for Latin America, 88% for Africa and 92% for Southeast Asia. For the forest cover change estimations, the global consistency was estimated to some 91% with 96% for Latin America, 82% for Africa and 90% for Southeast Asia. A comparison of the *forest area* and *forest area change* has been made between the two interpretations (original and re-interpreted) using the sum of entire sub-sample dataset, which gives an indication of a possible source of bias. The relative difference in the *forest area* ranges from -1.9% to 0.0% for dense forest or total forest classes respectively. The relative difference in the *forest area change* ranges from –1.7% to –8.4% depending of two different definitions used.

The same independent consistency assessment allowed an assessment of the thematic accuracy by re-interpretation over the 100 dots (i.e. not polygons). The re-interpreted results show that 89.7% of the sample dots correspond to the class of the polygon and 9.7% are from the composite classes, fragmented forest and mosaic. The assessment shows that fragmented forest is 78% forest with 22 % non-forest, while the mosaic class contains 30% forest, which corresponds well to its definition 10 – 40% forest. Hence together with pure class assignments there is a 99.4 % correspondence between dot interpretation and polygon assignment.

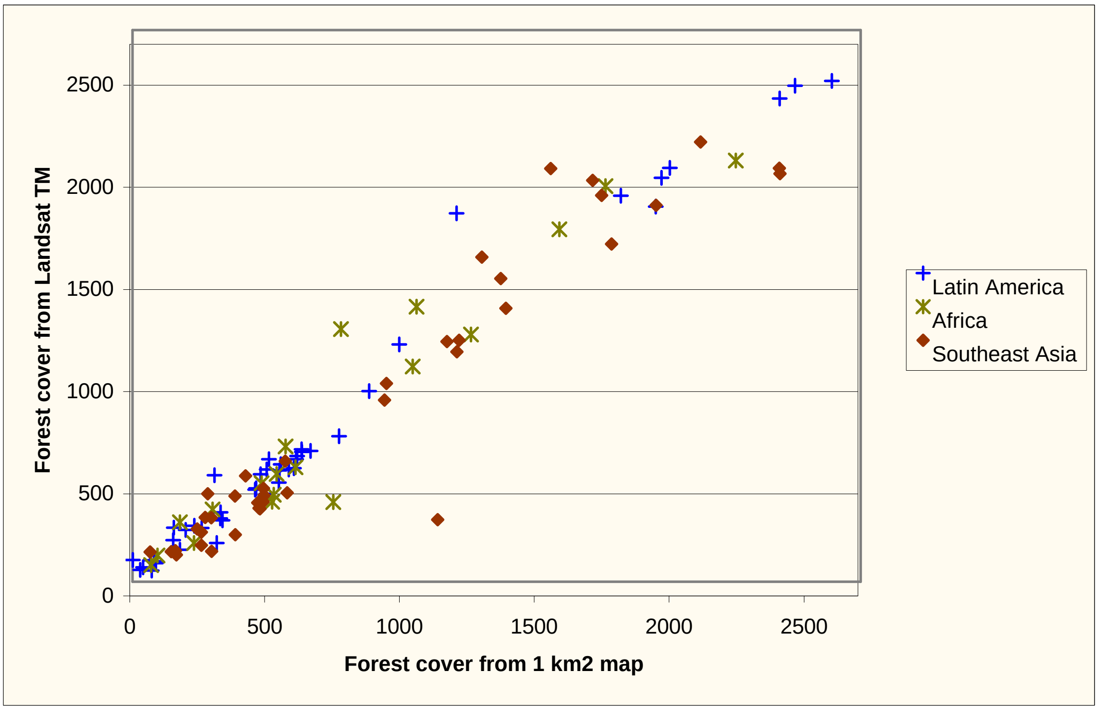
The confidence intervals presented in the results (in chapter 8.1) represent the statistical sampling accuracy. The consistency assessment accuracy is not included as it does not correspond to a real ground truth validation and is only indicative. The confidence range corresponds to two standard deviations to the mean (standard error) and represents therefore 95% of the confidence range. The relative variances (standard deviation) are then 2.4% for the global forest cover estimate (from 3.3% to 5.5% for continental estimates) and 13% for the global forest cover change estimate (from 19% to 28% for continental estimates).

7.2.4. Confidence intervals

The confidence intervals presented in Table 22 represent the statistical sampling accuracy. The consistency assessment accuracy is not included as it does not correspond to a real ground truth validation. The statistical sampling accuracy of the area and change estimations is estimated through a re-sampling (bootstrap) method. The confidence range corresponds to two standard deviations to the mean and represents therefore 95% of the confidence range. The relative variances are then 2.4% for the global forest cover estimate (from 3.3% to 5.5% for continental estimates) and 13% for the global forest cover change estimate (from 19% to 28% for continental estimates).

Figure 28 shows the correlation between one of the sampling co-variables, *forest area according to the 1km resolution forest maps*, against one of the estimation variables, *forest cover from 30m resolution maps*.

Figure 28: Relationship between forest cover from 30 m and 1km resolution classifications for the 102 sample sites



Note 1: the graph displays the measurements over the 104 samples for the year 1990
Note 2: Scales are in thousand hectares (10^3 ha).

8. Discussion of the change estimates

Summary

The three continents reveal considerable differences in change rates (Table 22). Southeast Asia has the highest annual rate of deforestation and Africa is loosing its forests at about half this rate. Latin America shows the lowest deforestation rate but with 2.5 10^6 ha yr^{-1} the annual loss 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 the degradation proportion, which can be identified from satellite imagery and do not include processes such as selective removal of trees.

Reforestation is dominant in Southeast Asia, however mainly through the transition of former mosaics and woodland cover to forest. It is found to a lesser extent in Latin America and limited in Africa.

These statistical estimates were finally compared to estimates from other existing sources.

8.1. *Forest area change estimates for the period 1990 - 1997*

This study shows that in 1990 (the Kyoto Protocol baseline year) there were some 1,150 ±54 million hectares of humid tropical forest. The estimation of global tropical humid forest cover change for the period 1990–97 shows a marked reduction of natural dense and open forests: the annual deforestation rate for the humid tropics is estimated at 5.8 ±1.4 million hectares with a further 2.3 ±0.7 million hectares of forest with degradation measurable from satellite imagery. Large non-forest areas were also re-occupied by forests. But this is mainly young re-growth on abandoned land and partly plantations, both very different from natural forests in ecological, biophysical and economic terms, and therefore not appropriate to counterbalance for the loss of old growth forests.

Globally, the main forest conversion process in the humid tropics (Table 23) is the transformation from closed, open or fragmented forests to agriculture with 3.09 10^6 ha yr^{-1} with specific situations for each continent (Table 24). Indeed, deforestation within the three regions is not uniformly distributed but the actual changes are confined to a number of 'hot spot' areas where change rates are alarmingly high. We documented annual rates of change of more than 3% in various sample sites.

For the calculation of the change figures (deforestation and degradation):

- Forest cover was calculated as 100% [closed forests + open forests + forest plantations/regrowth] + 75 % [fragmented forests] + 25% [mosaics]
- Degradation includes all areas from closed forests to open or fragmented and from open to fragmented forest.

A first analysis shows that for most of the sample sites belonging to the defined stratum of ‘Deforestation Hot Spot’, deforestation rates are high. In addition, there is indication of degradation for a significant area. This refers to degradation processes visible or at least 'interpretable' from satellite images. A more detailed analysis is carried out in the following chapter.

Table 22: Humid tropical forest cover estimates for the years 1990 and 1997 and mean annual change estimates during the 1990 to 1997 period.

	Latin America (10^6 ha)	Africa (10^6 ha)	Southeast Asia (10^6 ha)	Global (10^6 ha)
Total study area	**1,155**	**337**	**446**	**1,937**
Forest cover in 1990	**669 ±57**	**198 ±13**	**283 ±31**	**1,150 ±54**
Forest cover in 1997	**653 ±56**	**193 ±13**	**270 ±30**	**1,116 ±53**
Annual deforested area	**2.5 ±1.4**	**0.85 ±0.30**	**2.5 ±0.8**	**5.8 ±1.4**
rate	**0.38%**	**0.43%**	**0.91%**	**0.52%**
Annual regrowth area	**0.28 ±0.22**	**0.14 ±0.11**	**0.53 ±0.25**	**1.0 ±0.32**
rate	**0.04%**	**0.07%**	**0.19%**	**0.08%**
Annual net cover change	**- 2.2 ±1.2**	**- 0.71 ±0.31**	**- 2.0 ±0.8**	**- 4.9 ±1.3**
rate	**0.33%**	**0.36%**	**0.71%**	**0.43%**
Annual degraded area	**0.83 ±0.67**	**0.39 ±0.19**	**1.1 ±0.44**	**2.3 ±0.71**
rate	**0.13%**	**0.21%**	**0.42%**	**0.20%**

Note 1: sample figures were extrapolated linearly to the dates 1st June 1990 and 1st June 1997. Average observation dates are February 1991 and May 1997 for Latin America, February 1989 and March 1996 for Africa and May 1990 and June 1997 for Southeast Asia.
Note 2: Estimation ranges are at 95% confidence.

Table 23: Forest cover changes in the humid tropics from June 1990 to June 1997

		1997	Forest classes				Non-forest classes				Forest cover in 1990	
			Closed	Open	Fragmented	Plant/regrow	Mosaics	Natural	Agriculture	Unvegetated		
1990		*cover weight*	*100*	*100*	*75*	*100*	*25*	*0*	*0*	*0*	*per class*	*total*
Forest classes	Closed	*100*	902.3	11.2	4.1	1.1	4.6	3.4	16.3	1.1	*944*	
	Open	*100*	1.7	120.6	2.4	0.1	1.2	1.6	2.3	0.2	*130*	
	Fragmented	*75*	1.8	1.0	37.8	0.1	3.0	1.0	3.1	0.2	*36*	
	Plant/regrow	*100*	0.0	0.1	0.0	7.2	0.1	0.3	1.2	0.1	*9*	
Non forest classes	Mosaics	*25*	0.9	0.1	0.5	0.1	108.5	3.2	10.4	0.6	*31*	
	Natural	*0*	1.0	0.4	0.2	0.3	4.1	377.1	21.6	1.4	*0*	
	Agriculture	*0*	0.6	0.3	0.3	0.3	2.6	3.6	232.9	0.6	*0*	
	Unvegetated	*0*	0.0	0.0	0.0	0.1	0.0	0.8	0.5	33.7	*0*	***1150***
Forest cover	***in 1997***	*per class*	*908*	*134*	*34*	*9*	*31*	*0*	*0*	*0*		
		total								***1116***		

Note 1: All area figures are in million hectares.

Note 2: The forest class definitions were made according to those applied by the FAO Forest Resource Assessment Exercise (*11*) using two parameters: *tree cover* (canopy density within a forest stand) and *forest proportion* (forest stand density within the mapping unit). An area assigned to one of the forest classes has a *forest proportion* of more than 40% in which the forest stands have a *tree cover* of more than 10%. When the *forest proportion* is at least 70 %, the area is considered "closed forest" if the *tree cover* is more than 40%, and "open forest" if between 10 and 40%. When the *forest proportion* is between 40 and 70%, the area is defined as "fragmented forest". "Plantations / Forest regrowth" are grouped as non-natural forest. Referring to the non-forest classes: "Mosaics" are defined as containing a *forest proportion* between 10 and 40%. Other "Natural Vegetation" such as shrub or grassland, but also "agriculture" land may still contain a *forest proportion* or a *tree cover* up to 10 %.

Note 3: For *forest cover* calculation we applied forest cover "*weights*" per class as determined by an independent post-assessment of the observation site results (*8*). The "*Total forest cover*" estimates in 1990 and in 1997 are derived by the addition per class of the weighted forest cover areas.

Table 24: Forest cover changes in the humid tropics from 1990 to 1997 by continent

Pan-Amazon & Central America

		1997	Forest classes				Non-forest classes				Forest cover in 1990	
			Closed	Open	Fragmented	Plant/regrow	Mosaics	Natural	Agriculture	Unvegetated		
1990		*cover weight*	*100*	*100*	*75*	*100*	*25*	*0*	*0*	*0*	*per class*	*total*
Forest classes	Closed	*100*	199.6	2.7	0.7	0.0	1.1	0.3	3.2	0.0	*208*	
	Open	*100*	0.1	16.9	1.3	0.0	0.1	0.1	0.6	0.0	*19*	
	Fragmented	*75*	0.6	0.2	16.7	0.0	0.8	0.1	1.1	0.1	*15*	
	Plant/regrow	*100*	0.0	0.0	0.0	0.5	0.0	0.1	0.2	0.0	*1*	
Non forest classes	Mosaics	*25*	0.1	0.0	0.0	0.0	24.8	0.3	1.1	0.0	*7*	
	Natural	*0*	0.2	0.0	0.1	0.1	1.1	195.4	7.5	0.3	*0*	
	Agriculture	*0*	0.1	0.0	0.1	0.0	0.9	0.6	69.5	0.2	*0*	
	Unvegetated	*0*	0.0	0.0	0.0	0.0	0.0	0.5	0.0	28.1	*0*	***249***
Forest cover	***in 1997***	*per class*	*201*	*20*	*14*	*1*	*7*	*0*	*0*	*0*		
		total								***243***		

Brazil & Guyanas

		1997	Forest classes				Non-forest classes				Forest cover in 1990	
			Closed	Open	Fragmented	Plant/regrow	Mosaics	Natural	Agriculture	Unvegetated		
1990		*cover weight*	*100*	*100*	*75*	*100*	*25*	*0*	*0*	*0*	*per class*	*total*
Forest classes	Closed	*100*	336.0	1.2	0.4	0.1	0.3	0.1	6.2	0.0	*344*	
	Open	*100*	0.1	53.7	0.1	0.0	0.0	0.0	0.5	0.0	*54*	
	Fragmented	*75*	0.2	0.0	4.7	0.0	0.1	0.0	0.5	0.0	*4*	
	Plant/regrow	*100*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*0*	
Non forest classes	Mosaics	*25*	0.0	0.0	0.0	0.0	59.9	0.4	8.0	0.0	*17*	
	Natural	*0*	0.0	0.0	0.0	0.0	0.7	44.5	8.7	0.0	*0*	
	Agriculture	*0*	0.0	0.0	0.0	0.0	0.9	0.3	48.9	0.1	*0*	
	Unvegetated	*0*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	*0*	***420***
Forest cover	***in 1997***	*per class*	*336*	*55*	*4*	*0*	*15*	*0*	*0*	*0*		
		total								***411***		

Africa

		1997	Forest classes				Non-forest classes				Forest cover in 1990	
			Closed	Open	Fragmented	Plant/regrow	Mosaics	Natural	Agriculture	Unvegetated		
1990		*cover weight*	*100*	*100*	*75*	*100*	*25*	*0*	*0*	*0*	*per class*	*total*
Forest classes	Closed	*100*	154.8	1.9	0.8	0.3	1.5	0.9	1.4	0.0	*162*	
	Open	*100*	0.6	26.7	0.3	0.0	0.4	0.2	0.2	0.0	*28*	
	Fragmented	*75*	0.2	0.0	5.1	0.0	0.1	0.3	0.5	0.0	*5*	
	Plant/regrow	*100*	0.0	0.0	0.0	0.4	0.0	0.0	0.1	0.0	*1*	
Non forest classes	Mosaics	*25*	0.1	0.1	0.0	0.0	8.9	1.8	0.7	0.1	*3*	
	Natural	*0*	0.0	0.0	0.0	0.0	1.3	89.7	1.5	0.5	*0*	
	Agriculture	*0*	0.2	0.0	0.0	0.0	0.2	0.2	30.4	0.0	*0*	
	Unvegetated	*0*	0.0	0.0	0.0	0.0	0.0	0.3	0.1	3.6	*0*	***198***
Forest cover	***in 1997***	*per class*	*156*	*29*	*5*	*1*	*3*	*0*	*0*	*0*		
		total								***193***		

Southeast Asia

		1997	Forest classes				Non-forest classes				Forest cover in 1990	
			Closed	Open	Fragmented	Plant/regrow	Mosaics	Natural	Agriculture	Unvegetated		
1990		*cover weight*	*100*	*100*	*75*	*100*	*25*	*0*	*0*	*0*	*per class*	*total*
Forest classes	Closed	*100*	211.8	5.4	2.2	0.8	1.8	2.0	5.4	1.1	*231*	
	Open	*100*	0.9	23.3	0.6	0.1	0.7	1.3	1.0	0.1	*28*	
	Fragmented	*75*	0.8	0.8	11.3	0.1	2.0	0.5	1.0	0.2	*13*	
	Plant/regrow	*100*	0.0	0.1	0.0	6.3	0.1	0.2	0.9	0.1	*8*	
Non forest classes	Mosaics	*25*	0.6	0.0	0.4	0.1	15.0	0.6	0.7	0.5	*5*	
	Natural	*0*	0.7	0.3	0.1	0.2	0.9	47.5	3.9	0.6	*0*	
	Agriculture	*0*	0.2	0.2	0.2	0.3	0.6	2.4	84.1	0.4	*0*	
	Unvegetated	*0*	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.7	*0*	***283***
Forest cover	***in 1997***	*per class*	*215*	*30*	*11*	*8*	*5*	*0*	*0*	*0*		
		total								***270***		

8.2. Analysis of deforestation estimates by continent

8.2.1. Comparison between continents

The main global land cover change process is the transformation from closed, open or fragmented forests to agriculture with 21.6 million hectares deforested over the 1990-1997 period (Table 23). Deforestation within the three regions is not uniformly distributed but the actual changes are confined to a number of 'hot spot' areas where change rates are alarming high in particular when located in high biodiversity zones. We documented annual rates of change of more than 3% per sample site in various hot spots around the world.

The spatial detail and ability to compare different geographical regions provided by this work reveals considerable variation around the world. Southeast Asia has the highest annual rate of deforestation at 0.91%, Africa is loosing its forests at about half this rate, at 0.43% and at 0.37% Latin America shows the lowest deforestation rate but at 2.5 million hectares per year the annual loss is almost the same as that loss in Southeast Asia. Forest degradation shows a similar overall pattern. It is most prominent in Southeast Asia: 0.42%, intermediate in Africa: 0.21% and lowest in Latin America: 0.12%. But these estimates represent only the degradation proportion that can be identified from satellite imagery and does not contain processes such as selective removal of trees. Reforestation is dominant in Southeast Asia, however mainly through the contribution of former mosaics and woodland cover now interpreted as forest (Table 24), to a lesser extent in Latin America (0.28 million hectares/year) and limited in Africa (0.14 million hectares/year).

8.2.2. Latin America

Whilst the net regional forest change rate for Latin America is relatively low (0.33%), the overall annual gross deforestation of humid forests is significant (2.5 10^6 ha yr^{-1}).

Deforestation in Latin America is confined to several 'hot spots' (Table 25) where remaining forests are increasingly fragmented or are already heavily logged and burnt. The prognosis is that such forest remnants will soon disappear. It is then expected that new hot spots will appear. Large areas of forest are also becoming isolated at the regional level, highlighting the urgent need for establishing biological corridors.

The average annual net change rate over the 46 observation sites is -1.19% with one site at -4.77% in Colombia, one site at -4.41% in Acre and another at -3.2% in Rondonia, Brazil, 3 sites between -3% and -2%, 9 sites between -2% and -1%, 24 sites between -1% and 0%, 4 sites at 0%.

In Brazilian Amazonia, the hot spot areas covering Rondonia, Acre and the eastern part of the forest belt (around-2.3%) are under very high pressure. The southern hot spot area of the belt is also under high pressure but with a more heterogeneous pattern (between -0.4% and -2.7%). Rates are also high in the bordering hot spot area between Colombia and Ecuador (around-1.5%) and to a lesser extent in the Peru hot spot along the Andes (from -0.5% to –1.0%). The pattern of rates seems also heterogeneous in Central America hot spot areas (from -0.8% to -1.5%).

The transformation from closed, open or fragmented forests to agriculture by clear-cutting is a predominant factor. Moreover 3.61 10^6 ha yr^{-1} of mosaics or savannas -woodlands were transformed into agriculture. Increase of the agriculture land is the major cause of deforestation in this continent. Two third of these transformations are happening in the Brazilian Amazon region.

8.2.3. Africa

The estimated rate of deforestation for Africa is higher than Latin America (0.43%) with very high local rates for Madagascar and Côte d'Ivoire, which are not compensated by re-growth.

The average annual net change rate over the 19 observation sites is –0.59% with: one site at -4.5% in Madagascar, five sites between -2% and -1%, twelve sites between -1% and 0%, one site at 0.1%. Rates are very high in Madagascar (average -1.8%), high in West Africa (average -1.1%), in eastern Democratic Republic of Congo (-1.2%) and in Central Cameroon (average -0.8%).

On this continent 310,000 ha yr^{-1} of forests were transformed to agriculture with a further 280,000 ha yr^{-1} into mosaics and 200,000 ha yr^{-1} into savannas or woodlands.

The causes of deforestation are manifold from agricultural encroachment and illegal logging in Cameroon, urban expansion in the Democratic Republic of Congo (DRC) or refugees' migrations in Liberia and eastern DRC. Shifting cultivation mainly occurs in the mosaics of secondary forests and affects only partially the closed primary forests. Agricultural colonisation follows a diffuse spatial pattern, with a particular population pressure in eastern DRC. Selective forest logging plays an indirect role allowing the opening of the forest cover by exploitation roads. The hunting pressure from poachers, which is the main environmental problem in Central Africa, is then increased.

8.2.4. Southeast Asia

The overall trend of continuing deforestation appears almost unchanged for Southeast Asia. The forest cover change estimate for Southeast Asia indicates a high annual deforestation rate (0.91%) for the humid forest domain and in addition a substantial annual rate of 'visible' degradation.

The importance of separate estimates for deforestation and reforestation could be seen for individual countries as for example for Vietnam. Country net figures of forest change including reforestation of fast growing forest plantations mask easily ongoing deforestation of old growth as apparent in the individual sample sites.

The average annual net change rate over the 35 observation sites is -1.25% with one site at -5.6% and another at -3.8% in Sumatra, 5 sites between -3% and -2%, 8 sites between -2% and -1%, 17 sites between -1% and 0%, 3 sites over 0%.

In particular rates are very high in central Sumatra (from -3.0% to -5.6%) and in central Myanmar (around -3%). They are high in most regions of Vietnam, southeastern Kalimantan and Bangladesh (from -1.6% to -2.4%). Papua New Guinea and Irian Jaya appear "cool " (rate less than 0.25%), also because in the eastern Papua New Guinea and New Britain heavy logging occurred already before the observation period. The few sites that did not show high change rates may suffer from degradation processes, which are not visible from satellite imagery.

In total, 1.06 10^6 ha yr^{-1} of forests were converted into agriculture and 650,000 ha yr^{-1} into mosaics. A further 550,000 ha yr^{-1} were degraded into savannah or woodlands. At the same time some 650,000 ha yr^{-1} of mosaics or savannah-woodlands changed to agriculture.

Among others, the main factors for deforestation in Southeast Asia are unsustainable and illegal logging, the conversion of old-growth forests to plantations for pulp and paper and the conversion of forests to agriculture and cash crop production, particularly in the insular part of the continent. Shifting cultivation plays a more important role in the continental part. However, as shifting cultivation has existed there for a long time it mostly does not occur in primary forests anymore, and also large parts of the shifting cultivation mosaics do not contain high forests anymore, but instead, relative young re-growths.

Table 25: Annual deforestation rates in hot spot areas.

Hot spot areas by continent	Annual deforestation rate of sample sites
Latin America	***0.38%***
Central America	0.8% to 1.5%
Brazilian Amazonian belt	
Acre	4.4%
Rondonia	3.2%
Mato Grosso	1.4% - 2.7%
Para	2.4%
Colombia / Ecuador border	around 1.5%
Peruvian Andes	0.5% to 1.0%
Africa	***0.43%***
Madagascar	1.4% to 4.7%
Côte d'Ivoire	1.1% to 2.9%
Southeast Asia	***0.91%***
South-eastern Bangladesh	2.0%
Central Myanmar	around 3.0%
Central Sumatra	3.2% to 5.9%
Southern Vietnam	1.2% to 3.2%
South-eastern Kalimantan	1.0% to 2.7%

Note 1: continental averages are given in bold.

8.3. Comparison with FAO estimates

Our estimates of *forest cover change* can be compared to those of the United Nations' Food and Agricultural Organisation (FAO, 2001a) which are generally considered as reference figures, in spite of highlighted internal inconsistencies (chapter 46 in FAO, 2001b), which might be due to the difficulties to standardize country level data obtained from official intergovernmental processes (Matthews, 2001).

The FAO Global Forest Resources Assessment of 2000 (FAO, 2001a) provides estimates separately through two methodological approaches:

(i) The Country Survey (CS), which is based on the compilation and standardization of national data

(ii) The Remote Sensing Survey (RSS), which is a statistical estimate from a 10% sample of 30 m resolution satellite imagery over the dry and humid Tropics.

The FAO CS estimates can be compared to our estimates when adjusting to the common humid area. The FAO RSS estimates can not be directly compared to our estimates as they are meaningful only at the continental level including all the dry domain, which leads to much higher figures that our estimates.

For the comparison we adjusted the FAO CS estimates to the humid domain for the countries included in our survey. The FAO CS estimates were extracted for the corresponding countries, restricted to the humid domain (using the FAO definition of rain and mountain ecofloristic zones) and aggregated to the continental level.

8.3.1. Comparison of forest cover area estimates

Our forest cover estimates (indicated as TREES-II in Table 26) are relatively close to the FAO CS forest area estimates, with a 1.9% relative difference at the global level (+3% for Latin America, -9% for Africa and -6% for Southeast Asia). The use of secondary information, expert opinions and old country data by FAO may explain these differences. As "in many countries, primary information on forest area was not available or was not reliable", FAO "had to rely on secondary information and/or expert estimates". In particular the average reference years for latest area data are 1991 for Africa and South America and 1995 for Asia and Central America (Matthews, 2001). Furthermore "a high proportion of developing countries had to rely on expert opinion for the latest area estimates". Comparisons may suffer because of the expert extrapolation to the 1990 – 2000 period.

These FAO CS forest area estimates produced in 2001 for the baseline year 1990 (FAO, 2001a) were already found to be much higher than previous FAO CS estimates for the same baseline year (FAO, 1993) with the exception of South America (Matthews, 2001). Furthermore our TREES-II forest cover estimates for 1990 are very close to our TREES-I estimates from a previous study (Mayaux et al, 1998) using coarse spatial resolution maps calibrated with a sample of high spatial resolution maps. In this previous method (Mayaux & Lambin, 1997) the 1 km resolution baseline forest continental input maps were the same for the present study, but (i) the set of high resolution imagery was different (30 sites were selected instead of 100 sites, and on different locations) and (ii) the baseline maps were used in a different way (to derive two 'calibration co-variables' – forest area and fragmentation - for all 100 km^2 grid cells of the humid tropical zone on one hand, to derive 'sampling co-variables' - forest and hot spot areas - for the sample frame and for the regions on the other hand).

8.3.2. Comparison of forest cover net change estimates

Our forest cover net change estimates are lower than the FAO CS estimates adjusted to the humid domain with a difference of 0.5 10^6 ha yr^{-1} in each continent[2].

- In Southeast Asia the difference can not be explained by the exceptional fire event in Indonesia in 1997-98 which burned 2.6 million hectares in East Kalimantan alone (Siegert et al, 2001) and which are not accounted for in our estimate, because also the FAO estimate for Indonesia is based largely on remote sensing - derived information for earlier years (1985 and 1997).

- In Africa the difference can be explained by very low monitoring capacities of most forested countries.

- In Latin America our estimates refer to two sub-regions: the Brazilian Amazon and Guyanas region and the pan-Amazon and Central America region. Our Brazilian Amazon and Guyanas region estimates (420 ±37 10^6 ha of forest area in 1990 and -1.32 ±0.74 10^6 ha yr^{-1} of net change) are closer to estimates from other sources (401 10^6 ha and -1.43 10^6 ha yr^{-1})[3] with small relative differences (5% and 9%). The latter regional estimates being considered as reference figures. This confirms that our method allows for a determination of global tropical humid forest cover change in a more reliable way than previously available.

Furthermore our net change estimate for Southeast Asia is very similar to the FAO RSS estimate (-2.0±1.2 million hectares), which includes only a low contribution from non-considered countries and is based on the same time period (chapter 46 in FAO, 2001b).

Our global estimate of annual net change in the humid Tropics during the 1990-1997 period is 23% lower than the FAO CS estimate.

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[2] The FAO CS net change estimate for Africa before adjustment (-1.9 10^6 ha yr^{-1}) is mainly made from contributions of a few countries which include a large proportion of dry forests (Cameroon, Côte d'Ivoire, Democratic Republic of Congo and Nigeria). The Latin America FAO CS net change estimate before adjustment (-3.6 10^6 ha yr^{-1}) includes contributions of deciduous forests from Bolivia, Colombia, Peru, Venezuela and Brazil.

[3] We used two other estimates for Legal Amazonia: the Landsat Pathfinder 1988 forest area estimate (Skole &. Tucker, 1993) normalized to 1990 (362 10^6 ha) and the Brazilian average estimate of net change (INPE, 1997) corrected for deciduous forests contribution (-1.38 10^6 ha yr^{-1}). For the Guyanas the FAO estimates were used.

Table 26: Comparison of TREES humid tropical forest cover with FAO country estimates for year 1990 and 2000

Region	Forest cover for year 1990				Forest cover for year 2000		
	TREES-II (10^6 ha)	TREES-I (10^6 ha)	FAO CS (10^6 ha)	FAO RSS f2 (10^6 ha)	TREES-II (10^6 ha)	FAO CS (10^6 ha)	FAO RSS f2 (10^6 ha)
Southeast Asia	283 ±31	281	302	244 ±41	264 ±29	278	224 ±38
Africa	198 ±13	207	218	506 ±72	191 ±12	207	484 ±69
Latin America	669 ±57	671	652	808 ±102	649 ±46	624	767 ±96
Global	1,150 ±54	1,158	1,172	1,558 ±131	1,103 ±52	1,109	1,475 ±124

Note 1: TREES-II = this study. TREES-I = previous study (Mayaux *et al.*, 1998)

Note 2: FAO CS (Country Survey) estimates are derived from the country tables (FAO, 2001b). India is included with Southeast Asia but excluding 41 10^6 ha of dry forest for India. For Africa and Latin America we corrected the country estimates to the humid domain by multiplying the forest area by the proportion of rain and mountain forests, excluding the moist and dry forests (appendix 3 in FAO, 2001a). Mexico is excluded from Latin America.

Note 3: FAO RSS (Remote Sensing Survey) f2 definition of forest "comprises the closed and open forest classes, and a fraction (two-ninths) of the fragmented forest class"; it was constructed to match the forest definition used in the country reporting (FAO, 2001a, p 308). These figures are available only at continental level including all types of tropical forests.

Note 4: TREES-II forest cover estimates were extrapolated linearly to the year 2000

Note 5: Estimation intervals are at 95% confidence (two standard errors).

Table 27: Comparison of TREES humid tropical forest cover net change estimates with FAO estimates for period 1990-1997

Region	Annual net change 1990 – 1997		
	TREES-II (10^6 ha yr^{-1})	FAO CS (10^6 ha yr^{-1})	FAO RSS f2 (10^6 ha yr^{-1})
Southeast Asia	-2.0 ±0.8	-2.5	-2.0 ±1.2
Africa	-0.7 ±0.3	-1.2	-2.2 ±0.8
Latin America	-2.2 ±1.2	-2.7	-4.1 ±2.2
Global	-4.9 ±1.3	-6.4	-8.3 ±2.6

Note 1: TREES forest cover net change estimates are interpolated to the June 1990 – June 1997 period. Average observation dates are June 1990 - March 1997 for the TREES-II study and December 1988 – July 1997 for FAO RS survey. FAO Country forest cover net change estimates are reported for the 1990 – 2000 period. The average reference years for latest national area data used by FAO are 1991 for Africa and South America and 1995 for Asia and Central America ” (FAO, 2001b).

Note 2: FAO CS (Country Survey) estimates are derived from the country tables (FAO, 2001b). India is included with Southeast Asia. For Africa and Latin America we corrected the country estimates to the humid domain by multiplying the forest area by the proportion of rain and mountain forests, excluding the moist and dry forests (appendix 3 in FAO, 2001a). Mexico is excluded from Latin America.

Note 3: FAO RSS (Remote Sensing Survey) f2 definition of forest “comprises the closed and open forest classes, and a fraction (two-ninths) of the fragmented forest class”; it was constructed to match the forest definition used in the country reporting (FAO, 2001a, p 308). These figures are available only at continental level including all types of tropical forests.

Note 4: Estimation ranges are at 95% confidence (two standard errors).

8.4. Implications for the Global Carbon budget

Our new estimates can contribute to further reduce uncertainties in carbon net flux from deforestation (Scholes & Noble, 1993) and re-growth in the humid tropics. In the debate related to Global CO_2 budgets, "there remain large uncertainties associated with estimating the CO_2 release due to land-use change (mainly tropical deforestation)" (Albritton *et al*., 2001). These scientific uncertainties can be grouped into three main categories: i) the true level of tropical deforestation, ii) the amount of biomass for different forest types and iii) the spatial distribution of these forest types. Our contribution to this debate is related to points i) and iii). Until now the current deforestation figures used by IPCC were considered to be as much as ±50% in error (Watson *et al.*, 2000). To calculate net Carbon emissions, we apply the findings of our survey on tropical deforestation to existing published and refereed data on biomass and methods.

To estimate such net carbon flux, we considered as a starting point existing regional estimates of total carbon vegetation biomass estimates derived from the actual biomass density without roots (Brown, 1997) as 1990 forest area weighted average and considering an additional 20% for below-ground vegetation (roots) biomass, knowing that biomass of roots varies considerably among tropical forests. The purpose of Brown (2000) was not only to "(i) present methods that are available for estimating biomass density", but also to "(iv) present biomass density estimates for many tropical countries using the methodologies given". The error range of such biomass estimates is suggested to be as high as from ±30% to ±60%. Biomass is assumed to be 50% carbon (Watson *et al.*, 2000). These regional estimates are:

- 129 t C ha^{-1} for the Pan Amazon and Central America region;
- 190 t C ha^{-1} for the forests of the Brazilian Amazon[4];
- 179 t C ha^{-1} for tropical moist Africa;
- 151 t C ha^{-1} for Southeast Asia.

A more recent article by Houghton *et al*. (2001) reviews the estimates of biomass for the Brazilian Amazon and clearly points to the remaining uncertainty in forest biomass. In this article (Houghton, 2001), the highest of seven surveys is 232 t C ha^{-1} (Fearnside, 1997) with the mean at 177 t C ha^{-1}. In this study work we opted for 190 t C ha^{-1}.

Carbon fluxes can be then computed using conversion factors associated with deforestation and regrowth carbon rates proportional to initial forest biomass (Houghton *et al*., 2000). The conversion factors are:

(i) 0.2 from initial forest biomass burned,
(ii) 0.008 annual rate over a 10 year period from decay of wood removed from site
(iii) 0.07 initial annual rate with an exponential decrease in time from decay of biomass left as slash.

[4] For the Brazilian Amazon region, in the absence of undisputed reference figures for biomass, we have opted for the average of Brown (1997) and Houghton *et al.* (2000): 186 t C ha^{-1} and 195 t C ha^{-1}, first being derived from 310 t ha^{-1} of actual biomass density without roots (Brown, 1997), second being average of three estimates: 145, 210 and 232 t C ha^{-1} (Houghton, 2000). The paper by Houghton *et al.* in *Nature* (2000) is one of the most recent publications on the Amazon. Their biomass estimate is the average of three estimates, the highest being Fearnside's estimate (1997).

The initial (first year) conversion factor of 0.28 increases to 0.72 when including future sources embodied in first year decay pools over a 10 year period and to 0.97 over a 75 year period.

The accumulation of carbon on abandoned lands reverted to forests is taken at 2.8, 5.5, 5.0 and 3.8 t C ha^{-1} yr^{-1} for Pan Amazon, Brazilian, Africa and Southeast Asia regions respectively (Houghton *et al*., 2000) with a maximum accumulation of 129, 190, 179 and 151 t C ha^{-1}. "The assumption that forests are fully regrown after as little as 75 years is probably not valid, but this analysis was largely concerned with human-induced changes over the past 10-40 years" (Houghton *et al*., 2000). Our study is only concerned with human-induced changes over the 1990s.

From our annual deforestation and regrowth estimates we computed three estimates of carbon fluxes:
Initial flux of first year
'Committed' flux for the next 10 year (including future sources and sinks)
'Committed' flux for the next 75 years.

At the global level and for one year of forest cover change these three estimates of net fluxes amount respectively to:

- 0.26 ±0.08 Gt C
- 0.64 ±0.21 Gt C
- 0.76 ±0.32 Gt C

We aim to compute the *actual* carbon flux for the mid- 1990s. As such we must make assumptions of what has happened in previous years, not in future years. The first year flux will obviously underestimate the impact of the land-cover change. To use the 75-year committed flux would imply that the deforestation and regrowth rates we have measured have been constant for the *past* 75 years. The 10-year committed flux has therefore been assumed to be more representative than the 75-year committed flux. It means that for our final estimate we only assume regrowth and deforestation rates at the same level for the previous decade, i.e. over a period of 10 years.

In order to further validate the use of the 10-year committed flux as best estimate of the actual annual net flux of carbon, the following existing estimates over Brazilian Amazonia served as references: 0.18 Gt C yr^{-1} of annual net flux over the period 1989 to 1998 (Houghton *et al*., 2000) and 0.26 Gt C yr^{-1} of annual 'total committed' flux (Fearnside, 1997). As our three 'committed' flux estimates for this region range from 0.07 ±0.05 Gt C over 0.19 ±0.12 Gt C to 0.24 ±0.18 Gt C, this comparison suggests to use our 'committed over 10 years' net flux estimate as best actual annual net flux estimate.

Considering our 10-year committed flux figure as a good estimate of the actual annual net flux, it leads to a global estimate of 0.64 ±0.21 Gt C yr^{-1} for the period 1990 to 1997. This estimate is far lower than the estimate of total annual net emission from land-use change, "primarily in the tropics" for the period 1989 to 1998 reported by IPCC (1.6 ±0.8 Gt C yr^{-1}) (Watson *et al.*, 2000).

To provide an estimate of global net emissions from land-use change in the tropics, we add to our humid forest deforestation figure, an estimate to account for the dry forests. We consider a net forest area change in the dry tropics of the same magnitude as in the humid tropics

(FAO, 2001a), i.e. we add 100% of deforested area in the dry tropics. Considering that vegetation biomass in the dry tropics is less than half magnitude than in the humid domain (Brown, 1997; Zhang, & Justice, 2001), a maximum estimate of global net emissions from land-use change in the tropics would be about 0.96 Gt C yr^{-1}. Even if this latter figure does not include loss of carbon from forest degradation, which is much more difficult to estimate[5], it leads us to believe that the residual terrestrial uptake must be smaller than previously inferred.

These results can be used for carbon flux models in the humid tropics (Schimel *et al*., 2001). The lower deforestation rate found by us, evidently, has a major impact, reducing significantly the estimated carbon emission. The purpose of this chapter is to demonstrate this impact.

[5] The reason is that selective logging and a part of forest fragmentation are happening at scales below our minimum mapping unit and therefore these processes can not accounted for in our change estimates. However:

(i) The impact of selective logging on carbon emissions may not be very significant because there is no burning, the damage to soils can be expected smaller than in the case of forest conversion and there will be regrowth in the openings.

(ii) Often, selective logging is an initial phase in the transformation of "pristine" forest to non-forest. When such logged forests are transformed to pasture or degraded forests to mosaics, we counted 100% of the forest area as deforested with a 100% biomass content. A certain percentage of biomass lost through selective logging and non-visible degradation may be therefore already accounted in our deforestation statistics.

9. Conclusions

Since the 1970s it has been realized that forest monitoring is required not only at the national but also at the regional and global levels. Regional and sub-regional organizations rely on consistent information on the 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 Biodiversity) and most recently for global climate modelling.

For a number of tropical countries reliable information is not available at all. Furthermore, the aggregation of national statistics has proved to be extremely difficult, due to incompatible definitions and inventory methods, often completely outdated. This is why FAO, charged with providing global forest statistics, had to rely on national data partly from the 1980ties and sometimes on expert estimates. Reliable information on forest cover *change* is even more difficult to obtain. As a consequence, IPCC (Watson, 2001) stated that deforestation figures for tropical countries could be in error as much as 50 percent.

With satellite remote sensing technology, one can produce independent and up to date estimates. For this reason, the EU Directorate General for Environment decided to support this Research and Development initiative. The second phase of the TREES project (TREES-II) was a 4-years project supported through the Support to the Commission programme.

The project focused on tropical humid forests because they are heavily threatened, and they contain the highest biodiversity and much higher biomass than in the temperate forests or in the dry tropical forests.

The TREES achievements are:

- **A contribution to global environmental monitoring research** in the perspective of international conventions

  TREES was the only European global monitoring programme of the tropical forests and was a major contribution to global environmental monitoring research. Our aim was to make a contribution for improving current practices, both in terms of reliability and in terms of efficiency. The developed methods are complementary to United Nations FAO’s methods and demonstrate the benefit of use of advanced Earth observation by providing an independent view with a far richer spatial detail.

- **The development of a methodology for global and continental monitoring of forest cover change** mainly based on remote sensing data of different scales.

  There was no consensus amongst the scientific community about the best method to monitor forests globally. Remote sensing technology was the only way to get an independent and synoptic view over large areas (especially in remote areas such as Amazonia, the Congo Basin or Kalimantan) and a detailed view for mapping our sample areas.

The project demonstrated that a dedicated statistical sampling allows for the calculation of deforestation from conventional satellite imagery in a more reliable way than previous methods. This is a major contribution to global observation. This prototype method for global forest monitoring may be appropriate also for regional studies and for other land cover types.

- **The establishment of regional networks of scientists**.

  The integration of information on forests from three regional networks of local scientists and experts has proved to be efficient and exploitable in a statistical scheme. We contributed also to technology transfer (through software development) and capacity building in tropical countries, which is an essential ingredient of European Union cooperation with these countries.

<u>The project was characterised as:</u>

Science oriented

The method proposed by TREES is based on state of the art scientific methods and represents an independent, repeatable and reliable approach to estimating global forest change.

Independent from any national or organisational perspectives

The project was not designed to provide national estimates but to provide complementary knowledge to national, regional, or global operational assessment as done by UN FAO for example. We are supporting FAO's efforts (which has the mandate to implement regularly these assessments) by carrying out advanced research.

The project provided also supportive information for DGs involved in issues of land cover change in tropical countries, e.g. up-to-date spatial knowledge on active deforestation zones and on extent and change of tropical forest. Such spatially available information is invaluable for locating new projects and targeting initiatives.

The TREES project reduced one of the major uncertainties in the determination of global deforestation rates. The estimates of change rates were published in *Science* Magazine on August 09, 2002.

<u>The main TREES results are:</u>

Deforestation is 23% lower than previously estimated from other sources

The TREES project reduced one of the major uncertainties in the determination of global deforestation rates. Even if total deforestation rates in the tropics might be a bit lower than expected, the impact of the present rate may be even more severe than in previous decades, because these resources have become a 'limited' asset.

Gross global deforestation of humid forests is at 5.8 million hectares per year

The magnitude of forest destruction remains enormous: the annual gross deforestation is twice the size of Belgium, twice the size of Maryland, or nearly three times the size of Wales.

Degradation is also very large (2.3 million hectares per year)

The magnitude of forest degradation indicates that the process of deforestation will continue. We can assume that forest degradation affects in total much larger areas than the ones detected by our method (selective logging, non-sustainable management).

Carbon emissions from land use change in the Tropics are lower than reported until now (~1 Gt C yr^{-1}).

A significant advance was made towards reducing one of the major scientific uncertainties in estimating carbon emissions from the loss of humid forests. If the general assumption on the role of tropical forests for the carbon cycle is valid, less deforestation releases less carbon. Conversely, this means that terrestrial uptake is lower than assumed up to now.

Main lesson and recommendations:

The main lesson of the project for future operational assessments of forest cover change in the Tropics is to make use of a similar approach with the following recommendations:

- To orient the sampling procedure towards 'change' *i.e.* make use of stratified sampling;
- To integrate coarse resolution satellite results in the stratification procedure as a priory information on broad forest distribution and fragmentation;
- To integrate knowledge on deforestation hot spots in order to make sampling and stratification more efficient;
- To use a higher number of observations in order to increase the confidence significance when addressing the tropical humid forests;
- To expand over the dry domain. We have looked only at humid forest domain. Major uncertainty remains for the changes in dry forest domain;
- To expand over time, i.e. during the 1980's and after 1997 to estimate accurately the trends of the deforestation processes.

Forest inventory, accounting and statistical work to improve the quality of environmental data and environmental indicators and the building up of compatible public data banks are a necessary step towards the sustainable development and environmental protection of the world's forest resources.

Through this study important new findings demonstrate that deforestation in the humid tropics is still a major global environmental issue and one deserving of sustained attention.

The expertise and the political will exist to continue these research issues and to further develop and test global and regional monitoring possibilities. Within the next research period, the focus of the Joint Research Centre will be on land cover change issues and sustainable environment, at regional levels, with priorities on EU aid-development areas (e.g. Africa and Russia).

10. Annexes

10.1. References

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10.2. List of the 104 observation Units

Notes for Latin America:

- sample 28/46 FS (Mexico) was not processed by local partner
- sample 20/46 Q4 (Mexico) was not used in the estimation phase
- sample 1/67 Q3 (Bolivia / Brazil border) initially considered in the Pan-Amazon region was split in two parts (because at the border between two sub-regions). That adds one sample in the Brazil & Guyanas region
- sample 226/62 FS was not processed due to missing satellite imagery
- sample 227/59 Q4 was replaced by observation unit 1/59 Q4 because of missing satellite imagery on original sample.

Notes for Southeast Asia:

- observation units 127/47 Q1 in continental Southeast Asia and 188/61 FS, 117/60 FS and 97/64 Q1 in insular Southeast Asia are extra added sites which are not in the original sample. They were considered with a weight of 1.

Latin America

Requested Sample		Landsat TM selected scene path	row	quarter	Localisation	historical date	recent date	Interpretation Partner
28/46 FS		*28*	*46*	*Full*	*Mexico Central*	*09-Apr-93*	*07-Apr-98*	*not processed*
20/46 Q4		*20*	*46*	*Q4*	*Mexico Yucatan*	*17-Apr-93*	*17-Mar-99*	*Not used*
20/50 Q1		20	49	FQ1	Guatemala	16-Mar-90	30-Mar-98	CATIE
19/48 Q3		19	48	Q3	Guatemala/Belize	20-Mar-91	08-Apr-98	EPOMEX
16/50 Q1		16	50	Q1	Honduras	20-Mar-93	28-Dec-97	CATIE
16/53 Q4		16	53	FQ	Costa Rica	25-Mar-92	14-Feb-98	CATIE
231/72 Q1		231	72	Q1	Bolivia	26-Feb-90	21-Jun-97	CLAS
231/75 FS		231	75	Full	Bolivia South	05-Aug-90	21-Jun-97	CLAS
232/69 FS		232	69	Full	Bolivia - Rondonia	22-Jun-92	15-Aug-97	CLAS
1/56 Q3		1	56	Q3	Venezuela - Amazon	09-Apr-89	11-Sep-96	CPDI
1/67 Q3		1	67	Q3	Bolivia / Brazil - Acre	20-Jun-92	15-Jul-98	Ecoforca
2/69 FS		2	69	Full	Colombia - Florensa	08-Jan-90	17-Aug-96	FAO
4/56 Q4		4	56	Q4	Venezuela - Amazon	23-Oct-89	05-Oct-97	CPDI
6/66 Q1		6	66	Q1	Peru - Central	13-Aug-90	18-Jul-98	CIAT
6/69 Q2		6	68	FQ2	Peru - South Andes	20-Apr-92	16-Oct-96	CIAT
7/59 Q4		7	59	Q4	Colombia - Amazon	01-Apr-91	08-Sep-97	CIAT
7/62 Q3		7	62	Q3	Peru - Iquitos	18-Sep-92	10-Oct-97	CIAT
7/66 FS		7	66	Full	Peru - Ucayali	24-Jul-89	08-Sep-97	CIAT
7/67 FS		7	67	Full	Peru - Andes	24-Jul-89	08-Sep-97	CIAT
8/59 FS		8	59	Full	Peru - P. Maldonado	02-Feb-91	11-Aug-96	FAO
9/53 Q2		9	52	FQ2	Colombia - Coast	06-Jan-90	21-Aug-97	CIAT
9/59 FS		9	59	Full	Colombia - Andes	07-Aug-89	24-Oct-97	CIAT
9/61 Q2		9	60	FQ2	Ecuador - Amazon	07-Feb-90	03-Sep-96	CIAT
9/64 FS		9	64	Full	Peru - Andes	11-Nov-89	21-Oct-96	CIAT
10/61 Q2		10	60	Q4	Ecuador - Andes	15-Oct-91	24-Jul-96	CIAT
10/63 Q1		10	63	Q1	Peru - North West	28-Dec-89	28-Oct-96	CIAT
11/62 Q4		11	62	FQ2	Ecuador - Tumbes	19-Aug-91	06-Oct-97	CIAT
1/59 Q4		1	59	Q4	Brazil - Amazonas	01-Nov-91	13-Oct-96	Ecoforca
1/67 Q3		*1*	*67*	*Q3*	*Bolivia / Brazil- Acre*	*20-Jun-92*	*15-Jul-98*	*Ecoforca*
222/62 FS		222	62	Full	Brazil – Para Belem	27-Jul-91	06-Mar-96	IMAZON
224/62 FS		224	62	Full	Brazil – Para Tucur	01-Aug-92	18-Aug-95	IMAZON
224/67 FS		224	67	Full	Brazil - Mato Grosso	16-Jul-92	06-Jul-97	Ecoforca
224/72 Q1		224	72	Q1	Brazil - Mato G. del Sul	17-Aug-92	06-Jul-97	Ecoforca
225/69 Q2		225	69	Q2	Brazil - Mato Grosso	07-Jul-89	28-Aug-97	Ecoforca
226/62 FS					*Brazil – Para*	*Missing*	*data*	*missing*
226/65 Q4		226	65	Q4	Brazil - South Para	04-Jun-92	18-Jun-97	PIXEL
226/68 FS		226	68	Full	Brazil - Mato G. Cuiab	19-May-92	05-Jun-98	Ecoforca
227/59 Q4		*1*	*59*	*Q4*	*Brazil- Amazonas*	*01-Nov-91*	*13-Oct-96*	*Ecoforca*
227/62 Q3		227	62	Q3	Brazil – Para Santar	11-Jul-91	27-Jul-97	IMAZON
228/64 Q1		228	64	Q1	Brazil - Para Itaitu.	26-Jun-92	19-Aug-97	PIXEL
228/67 FS		228	67	Full	Brazil - Mato Grosso	09-Jan-90	31-Jul-96	FAO
228/69 FS		228	69	Full	Brazil - Mato Grosso	18-Jun-92	03-Jun-98	Ecoforca
229/69 Q1		229	69	Q1	Brazil - Mato Grosso	25-Jun-92	13-Oct-97	Ecoforca
231/59 Q3		231	59	Q3	Brazil - Roraima	22-Sep-90	27-Oct-97	Ecoforca
231/67 FS		231	67	Full	Brazil - Rondonia	14-Mar-90	21-Jun-97	Ecoforca
232/66 Q1		232	66	Q1	Brazil - Rondon. Porto V.	24-Jul-92	14-Jul-97	Ecoforca
233/58 Q2		233	57	Q2	Brazil - Roraima	11-Feb-91	05-May-98	Ecoforca
233/62 Q4		233	62	Q4	Brazil - Amazonas	24-Feb-90	19-Jun-97	PIXEL

Africa

Requested Sample		Landsat TM selected scene path	row	quarter	Localisation	historical date	recent date	Interpretation Partner
198/56 FS		198	56	Full	Cote d'Ivoire / Liberia	07-Jan-89	29-Mar-98	VITO
196/56 Q4		196	56	Q4	Cote d'Ivoire - Abidjan	30-Dec-90	15-Mar-98	VITO
189/56 Q3		189	56	Q3	Nigeria	21-Dec-87	24-Dec-91	Cetelcaf
187/57 Q1		187	56	Q1	Nigeria / Cameroon	12-Dec-86		Cetelcaf
185/57 Q3		85	342	SPOT	Cameroon	07-Feb-92	10-Dec-94	Cetelcaf
185/59 Q4		184	57	Full	Cameroon - Bertoua	23-Dec-86	00-Jan-00	Cetelcaf
180/58 FS		180	58	Full	Rep Dem Congo - Gemena	11-Dec-86	15-Nov-94	I-Mage
178/56 FS		178	56	Full	CAR - Bangassou	19-Dec-94	07-Nov-99	Cetelcaf
178/58 FS		178	58	Full	Rep Dem Congo - Bumba	14-Jan-90	19-Dec-94	I-Mage
177/62 Q3		177	62	Q3	Rep Dem Congo	10-Jan-91	15-Sep-97	I-Mage
176/62 Q3		176	62	Q3	Rep Dem Congo	02-Mar-92	21-Sep-96	I-Mage
175/58 FS		175	58	Q3	Rep Dem Congo	20-Feb-85	19-Dec-94	I-Mage
175/62 FS		175	62	Full	Rep Dem Congo - Kindu	25-Nov-90	10-Apr-97	I-Mage
174/62 FS		174	62	Full	Rep Dem Congo - Shabunda	08-Apr-90	21-Nov-94	I-Mage
173/59 FS		173	59	Q1	Rep Dem Congo	07-Aug-87	17-Jan-95	I-Mage
173/61 FS		173	61	Full	Rep Dem Congo / Rwanda	07-Aug-87	17-Jan-95	I-Mage
158/70 FS		158	70	Full	Madagascar North	23-Sep-90	22-Aug-96	FTM
158/72 Q1		158	72	Q1	Madagascar	07-Sep-90	26-Sep-97	FTM
158/74 Q1		158	74	Q1	Madagascar Antananarivo	30-Aug-93	08-May-97	FTM

Southeast Asia

Requested Sample	Landsat TM selected scene path	row	quarter	Localisation	historical date	recent date	Interpretation Partner
144/53 Q2	144	53	Q2	India - Anaimalai	18-Mar-92	19-Mar-98	IIRS
136/43 FS	136	43	Full	India - Maghalaya-Manipur	20-Feb-91	02-Feb-96	IIRS
136/45 Q2	136	45	Q2	Bangladesh	31-Oct-90	03-Nov-97	Dresden U
135/42 Q2	135	42	Q2	India - Naga Hills	28-Jan-91	11-Feb-96	IIRS
134/41 Q4	134	41	Q4	India / Myanmar - Tirap	18-Nov-90	15-Sep-96	IIRS
134/43 FS	134	43	Full	India / Myanmar - Kachin	22-Feb-91	25-Feb-98	UNEP
134/45 FS	134	45	Full	Myanmar - Sagain	08-Feb-89	25-Feb-98	UNEP
134/46 FS	134	46	Full	Myanmar - Rakhine Yoma	08-Feb-89	20-Dec-96	UNEP
133/43 Q3	133	43	Q3	Myanmar - Kachin East	16-Jan-89	02-Feb-98	UNEP
131/45 Q2	131	45	Q2	China - Yunnan	03-Feb-89	04-Feb-98	AOF
131/47 Q1	131	47	Q1	Thailand - Chiang Mai	02-Jan-89	03-Jan-98	RFD
131/50 Q2	131	50	Q2	Thailand - Kao Lem	02-Jan-89	16-Jan-97	RFD
127/52 Q1	127	52	Q10	Cambodia	20-Nov-91	07-Jan-98	DFW
	127	*47*	*Q1*	*Vietnam*	*04-Apr-89*	*25-Jun-95*	*VTGEO*
126/51 Q4	126	51	Q4	Cambodia	29-Nov-91	15-Dec-97	DFW
125/50 FS	125	50	FS	Cambodia	08-Jan-89	06-Jan-97	DFW
124/50 Q2	124	50	Q8	Vietnam - Quang Nai	30-Dec-90	05-Apr-97	FIPI
124/51 FS	124	51	Full	Vietnam - Dac Lac	30-Dec-90	15-Nov-97	FIPI
124/52 FS	124	52	Full	Vietnam	30-Dec-90	13-Jan-96	FIPI
129/58 FS	129	58	Full	Indonesia - Sumatra	13-Jun-89	26-Mar-98	BIOTROP
127/59 FS	127	59	Full	Indonesia - Sumatra	23-Apr-90	29-Apr-98	BIOTROP
126/61 FS	126	61	Q11	Indonesia - Sumatra	11-Jun-93	09-Jun-98	BIOTROP
125/61 FS	125	61	FS	Indonesia - Sumatra-Jambi	09-Jun-89	18-Aug-97	CIFOR
120/61 Q1	120	61	Q1	Indonesia - Kalimantan	24-May-90	27-May-97	BIOTROP
120/59 Q4	120	59	Q4	Indon. – Kalim / Malaysia	25-Apr-91	11-Jun-97	CIFOR
118/58 FS	118	58	Full	Indon. – Kalim / Malaysia	12-Mar-92	29-Mar-98	FOMISS
	118	*61*	*Full*	*Indonesia – Kalimant. Palank*	*30-Jun-91*	*29-May-97*	*RSS*
118/62 FS	118	62	Full	Indonesia - Kalimantan Palank	24-Apr-90	29-May-97	RSS
117/59 FS	117	59	Full	Indonesia - Kalimantan	12-Feb-90	18-Feb-98	MPI
	117	*60*	*Full*	*Indonesia - Kalimantan*	*28-Aug-92*	*02-Feb-98*	*MPI*
117/61 FS	117	61	Full	Indonesia - Kalimantan	02-Aug-94	16-Dec-97	BIOTROP
115/62 Q4	115	62	Q4	Indonesia - Sulawesi	30-Aug-83	26-Sep-96	PUSPICS
107/62 Q3	107	62	Q3+Q2	Indonesia - Seram Maluku	24-Jan-79	28-Feb-98	PUSPICS
101/64 FS	101	64	FS	Indonesia - Irian Jaya	21-Mar-83	27-Jan-96	BIOTROP
100/62 Q3	100	62	Q9	Papua New Guinea	04-May-90	19-Aug-97	PUSPICS
100/66 Q2	100	66	Q2	Indonesia /Papua New Guinea	12-Nov-90	31-May-97	PUSPICS
99/64 Q2	99	64	Q2	Papua New Guinea	20-Nov-90	28-Aug-97	UNITECH
	97	*64*	*Q1*	*Papua New Guinea*	*22-May-90*	*05-Jun-95*	*UNITECH*
95/64 Q1	95	64	Q9	Papua New Guinea	14-Jun-89	15-Sep-97	UNITECH

10.3. Table of estimation probabilities and weights

Latin America

Samples							**Observation Units**			
Contin.	Region	**path**	**row**	NbHex	p_k	w_k	Clouds	$p0_k$	$w0_k$	$w1_k$
1	2	1	56	1	0.005	203.1	2.0	0.012	86.5	62.4
1	2	1	67-1	3	0.203	4.9	1.0	0.052	19.4	16.3
1	2	2	53	3	0.010	102.6	1.3	0.006	169.0	93.8
1	2	2	69	6	0.167	6.0	1.0	0.205	4.9	1.5
1	2	4	56	2	0.098	10.2	1.0	0.127	7.9	6.8
1	2	6	66	1	0.050	20.2	1.0	0.148	6.7	5.7
1	2	6	69	1	0.099	10.1	1.5	0.335	3.0	1.0
1	2	7	59	3	0.105	9.6	1.5	0.030	33.4	27.5
1	2	7	62	2	0.012	85.3	1.2	0.011	87.8	57.3
1	2	7	66	8	0.705	1.4	1.2	0.642	1.6	1.0
1	2	7	67	9	0.692	1.4	1.2	0.590	1.7	4.8
1	2	8	59	9	0.668	1.5	1.1	0.636	1.6	2.6
1	2	9	53	3	0.010	98.6	1.0	0.007	144.6	152.1
1	2	9	59	11	0.618	1.6	1.3	0.190	5.3	12.2
1	2	9	61	3	0.234	4.3	1.5	0.181	5.5	9.0
1	2	9	64	7	0.248	4.0	1.0	0.088	11.3	14.6
1	2	10	61	2	0.029	34.1	1.3	0.026	38.2	39.3
1	2	10	63	3	0.035	28.3	1.0	0.104	9.6	6.5
1	2	11	62	1	0.069	14.6	1.0	0.049	20.3	34.9
1	1	16	50	4	0.168	6.0	1.1	0.084	11.9	12.9
1	1	16	53	3	0.003	327.6	1.0	0.016	61.1	54.9
1	1	19	48	2	0.123	8.1	1.0	0.166	6.0	14.8
1	1	20	49	3	0.204	4.9	1.1	0.023	44.1	47.6
1	2	231	72	2	0.047	21.4	1.0	0.052	19.3	21.2
1	2	231	75	9	0.035	28.3	1.0	0.033	30.6	27.0
1	2	232	69	8	0.039	25.6	1.0	0.036	27.6	23.9
4	3	1	59	2	0.010	101.7	1.2	0.011	89.9	102.7
4	3	1	67-2	3	0.171	5.9	1.0	0.045	22.4	20.6
4	3	222	62	10	0.295	3.4	1.0	0.304	3.3	1.6
4	3	224	62	9	0.256	3.9	1.1	0.274	3.6	1.6
4	3	224	67	9	0.265	3.8	1.0	0.275	3.6	1.8
4	3	224	72	2	0.005	194.6	1.0	0.005	184.4	199.5
4	3	225	69	3	0.089	11.3	1.0	0.070	14.3	12.4
4	3	226	65	3	0.015	67.6	1.0	0.011	90.8	101.6
4	3	226	68	9	0.267	3.7	1.0	0.275	3.6	1.8
4	3	227	59	2	0.011	88.8	1.2	0.011	92.2	105.0
4	3	227	62	2	0.052	19.4	1.0	0.063	15.9	14.0
4	3	228	64	2	0.043	23.3	1.1	0.051	19.5	20.0
4	3	228	67	9	0.240	4.2	1.0	0.246	4.1	3.3
4	3	228	69	9	0.101	9.9	1.0	0.085	11.8	13.9
4	3	229	69	2	0.042	23.8	1.1	0.034	29.2	36.0
4	3	231	59	3	0.088	11.3	1.0	0.070	14.4	12.8
4	3	231	67	9	0.257	3.9	1.1	0.215	4.6	4.7
4	3	232	66	2	0.059	17.0	1.0	0.058	17.2	19.3
4	3	233	58	3	0.049	20.3	1.1	0.042	23.7	27.5
4	3	233	62	3	0.016	61.5	1.8	0.010	98.9	118.0

Africa

Samples							Observation Units			
Contin.	Region	**path**	**row**	NbHex	$\boldsymbol{p_k}$	w_k	Clouds	$\boldsymbol{p0_k}$	$w0_k$	$\boldsymbol{w1_k}$
3	7	**158**	**70**	10	**0.449**	2.2	1.1	**0.254**	3.9	**7.9**
3	7	**158**	**72**	2	**0.072**	14.0	1.0	**0.029**	34.8	**22.4**
3	7	**158**	**74**	2	**0.118**	8.5	1.1	**0.118**	8.5	**12.5**
3	6	**173**	**59**	3	**0.053**	18.9	1.3	**0.022**	45.8	**45.1**
3	6	**173**	**61**	8	**0.455**	2.2	1.1	**0.433**	2.3	**1.0**
3	6	**174**	**62**	9	**0.518**	1.9	1.1	**0.532**	1.9	**1.0**
3	6	**175**	**58**	8	**0.318**	3.1	1.2	**0.072**	13.8	**12.2**
3	6	**175**	**62**	9	**0.463**	2.2	1.4	**0.495**	2.0	**1.0**
3	6	**176**	**62**	3	**0.064**	15.7	1.2	**0.065**	15.3	**14.2**
3	6	**177**	**62**	2	**0.015**	67.9	1.1	**0.016**	64.1	**62.4**
3	6	**178**	**56**	8	**0.041**	24.4	1.0	**0.045**	22.2	**21.4**
3	6	**178**	**58**	8	**0.527**	1.9	1.1	**0.529**	1.9	**2.1**
3	6	**180**	**58**	9	**0.585**	1.7	1.0	**0.566**	1.8	**1.1**
3	6	**185**	**57**	3	**0.098**	10.2	1.8	**0.056**	17.8	**21.4**
3	6	**185**	**59**	3	**0.039**	25.5	1.7	**0.130**	7.7	**6.0**
3	6	**187**	**57**	3	**0.158**	6.3	1.7	**0.135**	7.4	**4.3**
3	8	**189**	**56**	2	**0.009**	111.5	1.1	**0.009**	114.9	**93.0**
3	8	**196**	**56**	3	**0.006**	181.1	1.3	**0.032**	31.0	**31.4**
3	8	**198**	**56**	9	**0.258**	3.9	1.5	**0.243**	4.1	**1.4**

Southeast Asia

Samples							**Observation Units**			
Contin.	Region	**path**	**row**	NbHex	$\boldsymbol{p_k}$	w_k	Clouds	$\boldsymbol{p0_k}$	$w0_k$	$\boldsymbol{w1_k}$
2	5	**95**	**64**	2	**0.010**	98.8	1.2	**0.060**	16.5	**16.3**
2	5	**99**	**64**	1	**0.012**	81.2	1.2	**0.008**	121.7	**122.9**
2	5	**100**	**62**	3	**0.033**	30.4	1.8	**0.021**	48.8	**50.5**
2	5	**100**	**66**	3	**0.036**	27.7	1.0	**0.021**	47.0	**48.0**
2	5	**101**	**64**	8	**0.596**	1.7	1.1	**0.612**	1.6	**1.7**
2	5	**107**	**62**	2	**0.014**	71.9	1.0	**0.012**	86.5	**87.5**
2	5	**115**	**62**	2	**0.012**	85.3	1.3	**0.041**	24.2	**25.5**
2	5	**117**	**59**	8	**0.505**	2.0	1.1	**0.474**	2.1	**2.2**
2	5	**117**	**61**	10	**0.500**	2.0	1.3	**0.537**	1.9	**1.9**
2	5	**118**	**58**	9	**0.446**	2.2	1.9	**0.569**	1.8	**1.7**
2	5	**118**	**62**	7	**0.270**	3.7	1.0	**0.420**	2.4	**2.5**
2	5	**120**	**59**	2	**0.179**	5.6	1.0	**0.105**	9.5	**9.4**
2	5	**120**	**61**	3	**0.059**	17.1	1.0	**0.037**	27.2	**28.2**
2	4	**124**	**50**	1	**0.009**	110.8	1.0	**0.024**	41.1	**42.2**
2	4	**124**	**51**	9	**0.448**	2.2	1.1	**0.301**	3.3	**4.0**
2	4	**124**	**52**	8	**0.472**	2.1	1.1	**0.529**	1.9	**2.1**
2	4	**125**	**50**	8	**0.682**	1.5	1.0	**0.688**	1.5	**1.5**
2	5	**125**	**61**	10	**0.569**	1.8	1.0	**0.189**	5.3	**5.1**
2	4	**126**	**51**	1	**0.099**	10.2	1.0	**0.169**	5.9	**6.1**
2	5	**126**	**61**	11	**0.471**	2.1	1.1	**0.460**	2.2	**2.5**
2	4	**127**	**52**	9	**0.458**	2.2	1.0	**0.049**	20.4	**20.4**
2	5	**127**	**59**	9	**0.388**	2.6	1.0	**0.346**	2.9	**3.0**
2	5	**129**	**58**	7	**0.412**	2.4	1.1	**0.450**	2.2	**2.3**
2	4	**131**	**45**	2	**0.156**	6.4	1.0	**0.173**	5.8	**5.8**
2	4	**131**	**47**	3	**0.137**	7.3	1.0	**0.102**	9.8	**10.5**
2	4	**131**	**50**	2	**0.019**	51.3	1.0	**0.017**	57.4	**58.4**
2	4	**133**	**43**	3	**0.237**	4.2	1.0	**0.206**	4.9	**4.8**
2	4	**134**	**41**	3	**0.147**	6.8	1.1	**0.069**	14.5	**15.2**
2	4	**134**	**43**	9	**0.671**	1.5	1.0	**0.702**	1.4	**1.4**
2	4	**134**	**45**	8	**0.221**	4.5	1.0	**0.178**	5.6	**6.2**
2	4	**134**	**46**	9	**0.202**	5.0	1.0	**0.185**	5.4	**5.8**
2	4	**135**	**42**	2	**0.116**	8.6	1.0	**0.142**	7.1	**7.2**
2	4	**136**	**43**	9	**0.242**	4.1	1.0	**0.187**	5.3	**6.0**
2	4	**136**	**45**	2	**0.084**	11.9	1.0	**0.037**	27.1	**27.7**
2	4	**144**	**53**	3	**0.015**	65.2	1.0	**0.009**	114.6	**115.5**
2	5	**97**	**64**	2	**1**	1.0	1.1	**1.302**	0.8	**1.0**
2	5	**117**	**60**	8	**1**	1.0	1.1	**0.737**	1.4	**1.0**
2	5	**118**	**61**	11	**1**	1.0	1.1	**0.923**	1.1	**1.0**
2	4	**127**	**47**	2	**1**	1.0	1.2	**1.171**	0.9	**1.0**

10.4. Table of forest cover measurements per observation site

Latin America

Sample site			Total	Forest area	Deforestation		Degradation		Regrowth	
Path	Row	Type	**site area in ha**	**in 1990 in ha**	1990-1997 in ha	**rate in %**	1990-1997 in ha	**rate in %**	1990-97 in ha	rate in %
1	**56**	**Q3**	335,809	300,049	-601	**-0.03**	0	**0.00**	970	0.05
1	**59**	**Q4**	576,423	573,674	0	**0.00**	0	**0.00**	0	0.00
1	**59**	**Q4**	576,423	573,674	0	**0.00**	0	**0.00**	0	0.00
1	**67**	**Q3**	457,110	451,155	-3,500	**-0.11**	-9,195	**-0.29**	0	0.00
1	**67**	**Q3**	212,700	156,565	-41,889	**-4.41**	-30,298	**-3.30**	0	0.00
2	**53**	**Q2**	536,768	99,495	-9,348	**-1.40**	-3,492	**-0.65**	1,349	0.20
2	**69**	**FS**	2,658,543	2,365,040	-14,494	**-0.09**	-259	**0.00**	738	0.00
4	**56**	**Q4**	603,307	274,004	-7,136	**-0.38**	0	**0.00**	131	0.01
6	**66**	**Q1**	660,957	429,891	-22,801	**-0.77**	-10,566	**-0.40**	4,171	0.14
6	**68**	**FQ2**	735,502	90,654	-2,129	**-0.34**	-2,039	**-0.34**	0	0.00
7	**59**	**Q4**	460,722	456,563	0	**0.00**	0	**0.00**	0	0.00
7	**62**	**Q3**	556,434	544,374	-526	**-0.01**	0	**0.00**	0	0.00
7	**66**	**FS**	2,179,658	1,889,370	-87,680	**-0.67**	-49,472	**-0.41**	20,551	0.16
7	**67**	**FS**	2,297,047	599,088	-48,091	**-1.19**	-6,191	**-0.17**	3,961	0.10
8	**59**	**FS**	2,396,727	1,161,864	-341,450	**-4.90**	0	**0.00**	8,936	0.13
9	**52**	**FQ2**	683,185	57,133	-3,458	**-0.88**	-4,514	**-2.66**	1,760	0.45
9	**59**	**FS**	495,067	253,378	-28,754	**-1.71**	-8,795	**-0.59**	1,943	0.12
9	**60**	**FQ2**	353,277	263,279	-25,547	**-1.45**	-15,579	**-0.94**	1,547	0.09
9	**64**	**FS**	636,595	263,993	-18,135	**-1.00**	-10,292	**-0.82**	9,682	0.53
10	**60**	**Q4**	519,018	104,868	-2,023	**-0.28**	-28,687	**-4.68**	404	0.06
10	**63**	**Q1**	684,194	54,639	-1,321	**-0.35**	-4,033	**-1.90**	259	0.07
11	**62**	**FQ2**	610,152	71,064	-7,490	**-1.58**	-3,910	**-1.05**	388	0.08
16	**50**	**Q1**	583,350	525,982	-30,654	**-0.86**	-3,984	**-0.12**	2,046	0.06
16	**53**	**FQ**	783,515	190,105	-85	**-0.01**	-2,495	**-0.24**	1,127	0.08
19	**48**	**Q3**	647,560	521,261	-55,021	**-1.59**	-19,452	**-0.60**	2,267	0.07
20	**49**	**FQ1**	593,538	203,600	-10,090	**-0.72**	0	**0.00**	3,159	0.23
222	**62**	**FS**	2,735,536	1,976,500	-311,505	**-2.44**	-121,824	**-1.02**	11,765	0.09
224	**62**	**FS**	2,535,581	1,835,712	-290,105	**-2.44**	-65,290	**-0.78**	20,705	0.17
224	**67**	**FS**	2,635,156	2,024,665	-351,468	**-2.72**	-33,821	**-0.27**	374	0.00
224	**72**	**Q1**	656,708	106,392	-9,998	**-1.39**	0	**0.00**	2,413	0.34
225	**69**	**Q2**	668,825	635,805	-22,661	**-0.52**	-1,547	**-0.04**	0	0.00
226	**65**	**Q4**	657,713	639,764	-33	**0.00**	-101	**0.00**	2	0.00
226	**68**	**FS**	2,705,055	2,427,109	-245,819	**-1.52**	-103,025	**-0.65**	25	0.00
227	**62**	**Q3**	683,099	549,158	-34,695	**-0.93**	-1,442	**-0.04**	1,134	0.03
228	**64**	**Q1**	649,876	615,284	-2,000	**-0.05**	0	**0.00**	44	0.00
228	**67**	**FS**	2,704,647	2,450,525	-232,313	**-1.42**	-526	**0.00**	1,494	0.01
228	**69**	**FS**	1,969,355	647,426	-15,228	**-0.34**	-14,419	**-0.35**	0	0.00
229	**69**	**Q1**	623,797	310,251	-11,950	**-0.56**	-116	**-0.01**	149	0.01
231	**59**	**Q3**	659,643	548,969	-24,874	**-0.66**	-803	**-0.02**	261	0.01
231	**67**	**FS**	2,458,488	1,803,232	-361,595	**-3.18**	-11,830	**-0.10**	713	0.01
231	**72**	**Q1**	654,655	485,215	-33,496	**-1.02**	-3,463	**-0.11**	2,091	0.06
231	**75**	**FS**	2,300,466	712,617	-1,732	**-0.03**	-4,552	**-0.09**	387	0.01
232	**66**	**Q1**	679,679	554,927	-11,073	**-0.29**	-2,654	**-0.07**	2	0.00
232	**69**	**FS**	2,669,389	933,016	-7,178	**-0.11**	-737	**-0.01**	7,513	0.12
233	**57**	**Q2**	610,553	599,962	-2,505	**-0.06**	0	**0.00**	59	0.00
233	**62**	**Q4**	382,241	339,184	-796	**-0.03**	0	**0.00**	11	0.00

Africa

Sample site			**Total**	**Forest** area	**Deforestation**		**Degradation**		**Regrowth**	
Path	Row	Type	**site area in ha**	**in 1990 in ha**	1990-1997 in ha	**rate in %**	1990-1997 in ha	**rate in %**	1990-97 in ha	rate in %
158	**70**	**FS**	2,489,164	1,236,875	-112,955	**-1.37**	-34,700	**-0.57**	1,346	0.02
158	**72**	**Q1**	625,893	353,488	-44,962	**-1.94**	0	**0.00**	85	0.00
158	**74**	**Q1**	614,634	291,061	-83,180	**-4.73**	0	**0.00**	3,606	0.20
173	**59**	**Q1**	529,368	482,761	-3,839	**-0.11**	-6,435	**-0.19**	452	0.01
173	**61**	**FS**	2,443,483	389,631	-37,235	**-1.42**	-40,111	**-1.90**	5,088	0.19
174	**62**	**FS**	2,505,474	2,060,818	-29,549	**-0.21**	-13,778	**-0.10**	2,399	0.02
185	**57**	**X**	231,404	128,193	-9,964	**-1.15**	-19,812	**-2.79**	1,015	0.12
175	**58**	**Q3**	579,721	527,056	-671	**-0.02**	-15,501	**-0.44**	266	0.01
175	**62**	**FS**	1,669,865	1,209,522	-38,516	**-0.46**	-10,870	**-0.13**	5,460	0.07
176	**62**	**Q3**	576,692	391,625	-21,760	**-0.81**	-5,122	**-0.19**	1,672	0.06
177	**62**	**Q3**	621,802	560,271	-177	**0.00**	-5	**0.00**	3,119	0.08
178	**56**	**FS**	2,728,000	1,053,945	-752	**-0.01**	-150	**0.00**	632	0.01
178	**58**	**FS**	2,421,259	1,935,828	-102,821	**-0.78**	-4,844	**-0.04**	51	0.00
180	**58**	**FS**	2,737,258	1,725,292	-61,482	**-0.52**	-88,409	**-0.80**	3,412	0.03
184	**57**	**FS**	952,004	661,757	-9,569	**-0.21**	-1,222	**-0.03**	2,064	0.04
187	**56**	**Q1**	297,213	189,134	-10,617	**-0.82**	-944	**-0.08**	2,894	0.22
189	**56**	**Q3**	1,051,623	426,335	-3,212	**-0.11**	-4,607	**-0.15**	410	0.01
196	**56**	**Q4**	434,283	81,771	-15,987	**-2.91**	-6,394	**-1.66**	9,498	1.73
198	**56**	**FS**	1,799,533	1,345,813	-97,920	**-1.07**	-26,539	**-0.35**	29,063	0.32

Southeast Asia

Sample site			Total	Forest area	Deforestation		Degradation		Regrowth	
Path	Row	Type	site area in ha	in 1990 in ha	1990-1997 in ha	rate in %	1990-1997 in ha	rate in %	1990-97 in ha	rate in %
95	**64**	**Q9**	515,321	147,887	-15,148	**-1.52**	-10,694	**-1.20**	3,338	0.34
97	**64**	**Q1**	622,204	360,755	-26,540	**-1.07**	-99	**0.00**	12,553	0.51
99	**64**	**Q2**	178,888	131,305	-7,556	**-0.83**	-1,416	**-0.21**	6,129	0.67
100	**62**	**Q9**	318,117	313,058	-3,411	**-0.16**	-7,756	**-0.36**	1,865	0.09
100	**66**	**Q2**	643,448	258,771	-5,569	**-0.30**	-6,628	**-0.41**	13,504	0.73
101	**64**	**FS**	2,489,816	2,151,529	-13,120	**-0.09**	0	**0.00**	2,555	0.02
107	**62**	**Q3**	333,544	314,570	-5,956	**-0.27**	-1,810	**-0.08**	398	0.02
115	**62**	**Q4**	627,735	422,524	-40,220	**-1.41**	-1,565	**-0.06**	9,785	0.34
117	**59**	**FS**	2,052,107	1,890,621	-100,197	**-0.77**	-215,718	**-1.88**	19,065	0.15
117	**60**	**FS**	1,563,213	970,595	-92,410	**-1.40**	-166,756	**-4.12**	33,775	0.51
117	**61**	**FS**	2,172,813	2,022,247	-348,202	**-2.67**	-376,145	**-3.71**	30,861	0.24
118	**58**	**FS**	1,239,773	1,125,670	-62,301	**-0.81**	-298,235	**-4.07**	13,207	0.17
118	**61**	**FS**	2,426,721	1,841,755	-126,274	**-1.01**	-47,359	**-0.42**	9,431	0.08
118	**62**	**FS**	2,210,994	1,484,414	-178,954	**-1.83**	-88,956	**-1.06**	9,874	0.10
120	**59**	**Q4**	381,370	243,111	-13,731	**-0.83**	-17,207	**-1.15**	2,105	0.13
120	**61**	**Q1**	655,977	589,878	-12,888	**-0.32**	-16,067	**-0.42**	0	0.00
124	**50**	**Q8**	698,525	391,702	-17,961	**-0.67**	-5,163	**-0.20**	1,917	0.07
124	**51**	**FS**	2,345,792	1,589,316	-126,573	**-1.18**	-12,315	**-0.12**	3,260	0.03
124	**52**	**FS**	2,420,886	1,181,376	-246,171	**-3.18**	-125,508	**-1.62**	94,204	1.22
125	**50**	**FS**	2,652,819	2,023,991	-32,147	**-0.23**	-1,641	**-0.01**	15,072	0.11
125	**61**	**FS**	650,533	418,792	-145,116	**-5.93**	-38,683	**-1.88**	6,376	0.26
126	**51**	**Q4**	618,025	356,858	-32,241	**-1.34**	-2,772	**-0.15**	4,814	0.20
126	**61**	**Q11**	2,473,718	1,653,124	-334,763	**-3.20**	-9,319	**-0.11**	21,602	0.21
127	**47**	**Q1**	658,258	230,171	-27,083	**-1.77**	0	**0.00**	3,156	0.21
127	**52**	**Q10**	177,976	151,533	-2,650	**-0.25**	-2,201	**-0.21**	0	0.00
127	**59**	**FS**	2,690,097	1,964,302	-475,740	**-3.92**	-41,318	**-0.41**	10,875	0.09
129	**58**	**FS**	2,419,498	1,175,640	-56,736	**-0.70**	-8,517	**-0.13**	5,613	0.07
131	**45**	**Q2**	613,264	387,300	-23,610	**-0.85**	-38,834	**-2.33**	42,634	1.53
131	**47**	**Q1**	628,771	517,690	-10,002	**-0.28**	-3,529	**-0.10**	0	0.00
131	**50**	**Q2**	661,054	430,312	-18,405	**-0.62**	-1,337	**-0.05**	90	0.00
133	**43**	**Q3**	626,444	435,252	-45,772	**-1.58**	-4,881	**-0.17**	3,097	0.11
134	**41**	**Q4**	485,503	457,109	-14,723	**-0.47**	0	**0.00**	993	0.03
134	**43**	**FS**	2,460,752	1,997,699	-26,834	**-0.19**	-11,555	**-0.08**	43,183	0.31
134	**45**	**FS**	2,549,007	888,632	-171,636	**-3.05**	-107,402	**-1.96**	315	0.01
134	**46**	**FS**	2,582,022	1,337,783	-250,377	**-2.94**	-18,283	**-0.24**	5,706	0.07
135	**42**	**Q2**	570,469	149,412	-44,702	**-4.61**	-10,856	**-1.45**	22,921	2.36
136	**43**	**FS**	1,704,937	304,027	-22,115	**-1.06**	-1,123	**-0.07**	8,699	0.42
136	**45**	**Q2**	598,600	177,743	-23,873	**-2.03**	-5,192	**-0.68**	4,745	0.40
144	**53**	**Q2**	553,799	144,947	-1,501	**-0.15**	-37	**0.00**	411	0.04

European Commission

EUR 20523 EN – Determination of the World’s Humid Tropical Deforestation Rates During the 1990’s
Frédéric Achard, Hugh D. Eva, Hans-Jürgen Stibig, Philippe Mayaux, Javier Gallego, Timothy Richards, Jean-Paul Malingreau
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Abstract

In spite of the importance of the world’s humid tropical forests our knowledge concerning their rates of change remains limited (IPCC, 2000). The second phase of a research programme (TREES-II) exploiting the global imaging capabilities of Earth observing satellites has just been completed to provide the latest information on the status of these forests.
The results of the TREES II programme show that in 1990 (the Kyoto Protocol baseline year) there were some 1,150 ±54 million hectares of humid tropical forest. Furthermore the 1990–97 period showed a marked reduction of dense and open natural forests: the annual deforestation rate for the humid tropics is estimated at 5.8 ±1.4 million hectares with a further 2.3 ±0.7 million hectares of forest degradation visible from satellite imagery. Large non-forest areas were also re-occupied by forests. But this consists mainly of young re-growth on abandoned land and partly of new plantations, both of which are very different from natural forests in ecological, biophysical and economic terms, and therefore not appropriate in counterbalancing the loss of old growth forests.
These new figures are the most consistent currently available. They show that Southeast Asia is the continent where forests are under the highest threat (0.91% annual deforestation rate). The annual area deforested in Latin America is similarly large, but the rate (0.37%) is lower, due to the vast Amazonian forest. The humid forests of Africa are being depleted at a similar rate to that of Latin America.
At the global level, these figures indicate a 23% lower net forest cover change rate for the tropical humid forests than was generally accepted until now. This has major repercussions on the calculation of carbon fluxes in the global budget resulting in a terrestrial sink smaller than previously inferred.

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