LAND USE CHANGE MONITORING IN THE FRAMEWORK OF THE UNFCCC AND ITS KYOTO PROTOCOL

Report on CURRENT CAPABILITIES OF SATELLITE REMOTE SENSING TECHNOLOGY

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Cover page figure: Remote sensing image time series (Landsat satellites) over a farm in Brazilian Amazon (10 x 12 km size)
Land Use Change Monitoring in the framework of the UNFCCC and its Kyoto Protocol

Report on Current Capabilities of Satellite Remote Sensing Technology

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Context

This report on current capabilities of satellite remote sensing technology documents presentations made at the side-event on “Land Use Change Monitoring in the framework of the UNFCCC and its Kyoto Protocol” held at the 19th meeting of the Subsidiary Body for Scientific and Technological Advice (SBSTA19) and the 9th Conference of Parties (COP 9) of United Nations Framework Convention on Climate Change (UNFCCC) on December 3rd 2003 in Milan, Italy.

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Preface

By the end of the 20th Century, scientific advances had unequivocally influenced the political agenda concerning climate change. From the pioneering efforts of scientists such as John Tyndall and Svante Arrhenius more than 100 years ago to the collected inputs of hundreds of world-class experts working with the Intergovernmental Panel on Climate Change (IPCC) today, the scientific community has amassed a growing body of reliable scientific evidence concerning our climate and the way in which it functions. Our governments use this evidence as the base for the conception, development, implementation and monitoring of climate change policy.

Scientific evidence has been a key driver behind the United Nations Framework Convention on Climate Change (UNFCCC), and sound science remains a cornerstone on which the implementation of many policy decisions related to the Convention rest. The reports by the IPCC to the 185 member governments of the UNFCCC have shown that the biosphere is a strong determinant of the chemical composition of the atmosphere, and as a consequence human activities that change the way land is used are included in the calculations of greenhouse gas emissions and sinks made by the Parties. These inventories are very necessary if the Parties are to judge progress towards the Convention’s objective of “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”.

To achieve this objective all Parties shall promote the development of practises and processes that control, reduce or prevent anthropogenic emissions, and promote the conservation and enhancement of greenhouse gas sinks and reservoirs. Governments now need to develop and implement appropriate national climate change policies. These policies can be built around a variety of instruments, including the land-use, land-use change and forestry (LULUCF) activities, to meet commitments. The rules surrounding the implementation of these tools are being established, with key definitions being agreed upon at the 7th Conference of the Parties (COP 7). Science is helping this process and will help LULUCF activities to be monitored and measured in a consistent and exhaustive manner.

This report confirms that operational methods exist which can help monitor the development of mitigation activities in the field of LULUCF according to the presently defined time rules and over the specified reference periods. This report provides a summary of the most up-to-date findings of the scientific community concerning land-use change monitoring from satellite remote sensing technology and describes their relevance to the Convention and Protocol, according to the definitions agreed upon at COP 7.

The involvement of science in the political arena considerably raises the expectations on science to be an accurate and reliable information provider. We believe this to be the case for monitoring our planet’s land-cover, and we hope you will find this report useful in your own work.

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Executive Summary

This report presents a synthesis of the most up to date techniques on monitoring land-use, land-use change and forestry (LULUCF) activities from satellite data, along with its relevance to the United Nations Framework Convention on Climate Change and its Kyoto Protocol.

The aim of the report is to describe the technical potential of satellite remote sensing for independent verification, certification and documentation of the actual land-cover state of any region of the world. In particular the report shows that the technical capacity already exists to ascertain with a high degree of certainty the cover state for the year 1990 at both the required spatial scale and at low cost.

Policies relating to Climate change issues operate at multiple scales, from local projects to global impacts, and this report is structured accordingly.

Chapter 1 provides background issues over potential land use change and forestry activities in the framework of the flexible mechanisms of the Protocol, in particular the afforestation and reforestation activities.

In chapter 2 we report on the current capabilities of satellite remote sensing technology for project monitoring at local scale. Determining the land-use category at the project scale in the past (up to the point in time specified in the definition of reforestation as agreed by the Parties to the UNFCCC) can help ensure that the reforestation time limit is respected. Earth observation derived products can also contribute to the verification process (gains) as the only means of instantaneous assessments of all projects at the same time even if ground-based information is needed for the assessment of carbon stocks.

Chapter 3 outlines the current capabilities of satellite remote sensing technology for monitoring of forest cover change at regional scale. Two operational projects for assessing forest cover change over large regions in the tropics are presented: the PRODES project of the Brazilian Space Agency and the TREES project of the Joint Research Centre. Such monitoring is particularly relevant for monitoring leakage effects (displacement of deforestation) and for providing a baseline reference against which project activities are checked (baseline scenario).

In chapter 4 we consider assessments of global vegetation resources at global scale from satellite remote sensing technology. Such assessments are relevant at the UNFCCC level by contributing to the determination of LULUCF trends and contribute to reducing uncertainty concerning climate change.

This report confirms that operational tools exist now to monitor the development of mitigation activities in the field of land-use change and forestry with the presently defined time rules and over the specified reference periods.

Legally binding contexts increase requirements for full accountability. The science to support this is mature, appropriate sensors are currently flying, but robust, long-term institutional commitments and frameworks to ensure continuity of satellite observations and to deliver products in a guaranteed manner are indispensable and still need to be served.
1. Rules for LULUCF activities in the Kyoto Protocol

The reports published by the Intergovernmental Panel on Climate Change (IPCC) have shown that the biosphere is a strong determinant of the chemical composition of the atmosphere. IPCC includes human activities that change the way land is used, in national calculations of greenhouse gas emissions required for compliance with the United Nations Framework Convention on Climate Change (UNFCCC) under its Article 4.

In 1997, the Parties to the Convention agreed by consensus through the Kyoto Protocol (KP) that developed Countries ('Annex I') should accept a legally binding commitment to reduce their collective emissions of six greenhouse gases by at least 5.2% compared to 1990 levels by the period 2008-2012.

The Protocol makes provision for the use of biological sources and sinks to meet commitments. Annex-I Parties to the Protocol are thus required to monitor and measure changes in carbon stocks and in GHG emissions resulting from human-induced land use, land-use change and forestry project activities under Article 3, Article 6 (Joint Implementation) and Article 12 (Clean Development Mechanism). Moreover, Countries can transfer the issued carbon credits.

1.1. Background on LULUCF activities

Land use, land-use change and forestry (LULUCF) activities can provide a relatively cost-effective way of combating climate change, either by increasing the removals by sinks of greenhouse gases from the atmosphere (e.g. by planting trees or managing forests), or by reducing emissions (e.g. by curbing deforestation). There are drawbacks, however, since it may be often difficult to calculate greenhouse gas removals and emissions from LULUCF.

LULUCF activities in the Kyoto Protocol

Under Article 3.3 of the Protocol, the Parties decided that greenhouse gas removals and emissions through certain activities - namely, afforestation, reforestation and deforestation since 1990 - are accounted for in meeting the Protocol's emission targets. Conversely, activities that deplete forests, namely deforestation, will be subtracted from the amount of emissions that an Annex I Party may emit over its commitment period. Through Article 3.4 of the Protocol the Parties decided that supplementary activities can be added to this list.

A number of issues remain unresolved in the Kyoto Protocol. Nevertheless, the definitions for "forest" and for all the LULUCF activities to be considered under Article 3.3 (afforestation, reforestation and deforestation) and under Article 3.4 (forest management, revegetation, cropland management and grazing land management) have been agreed and most rules for the accounting of these activities were developed as part of the Marrakesh Accords (UNFCCC, 2002b).

The Kyoto Protocol also establishes “flexible mechanisms” including emissions trading regime and the so-called Joint Implementation (JI) under Article 6 and Clean Development Mechanism (CDM) under Article 12. Developed Countries which signed the Protocol may reach their greenhouse gas reductions commitments not only by decreasing national emissions but also by implementing projects through these flexible mechanisms, including ones that increasing increase sinks of carbon. The JI is a mechanism under which the cooperative production and transfer of carbon credits between Annex-I Parties is encouraged. The CDM is a mechanism under which the cooperative production and transfer of carbon credits between Annex I Parties and non-Annex I Parties is encouraged. Annex I Parties will be credited for carbon sequestered in approved projects, and the credits will count towards their national emission targets.
Definitions of forestry terminology for LULUCF activities

For the purposes of forestry activities in the Protocol, it was agreed at COP 7 (annex to decision 11/CP.7) that forest is defined by the respective host country within the ranges of “an area of at least 0.05-1 hectares of trees, with a canopy cover of at least 10-30%, and with trees capable of reaching 2-5 m”; and that afforestation should mean that the site “has not been forested for a period of at least 50 years”; and that reforestation refers to the conversion of lands that “did not contain forest on 31 December 1989”.

Although these definitions are accepted for application in Articles 3.3 and 3.4 and, consequently, for Article 6 activities, they have been challenged for use in Article 12 (CDM activities). The justification for the challenge is that official records in non-Annex I Parties are imperfect and may not be available for that date (31 December 1989).

1.2. Sinks in the Clean Development Mechanism

According to the Bonn Agreements in June 2001 (UNFCCC, 2001a) and the subsequent Marrakesh Accords in November 2001 (UNFCCC, 2002a), it was agreed that some LULUCF activities can be carried out as CDM but, for the first commitment period (2008-2012), those will be limited to afforestation and reforestation project activities (AR-CDM). Even capped at 1% of the emission reduction target, the quantity of carbon that might be involved worldwide is potentially significant in relation to national emission reduction targets, and is equal to 137,3 Mt CO₂ equivalent per year.

The development modalities and procedures for including afforestation and reforestation project activities under the CDM in the first commitment period is one of the last outstanding issues relating to the Kyoto Protocol. Work on this issue started with the adoption of the terms of reference and agenda at the end of the sixteenth session of the SBSTA.

At the eighteenth session of the SBSTA, delegates agreed on a draft negotiating text which will be the basis for an annex on modalities and procedures for including afforestation and reforestation project activities under Article 12 of the Kyoto Protocol in the first commitment period. The negotiating text was produced on the basis of several documents which were considered by the SBSTA, namely, three options papers on modalities for addressing non-permanence, baseline, additionality and leakage, and socio economic and environmental impacts, including impacts on biodiversity and natural ecosystems. The negotiating text should be further considered in pre-sessional consultations, which has to be held in Milan, prior to the nineteenth session of the SBSTA. It is expected that SBSTA 19 will make a recommendation to COP 9 on these matters.

Presently, to meet the temporal criteria of the Protocol, a reforestation project must respect two dates: the reforestation time limit and the Project Activities time limit. The latter has been fixed for CDM at 1st January 2000 (UNFCCC, 2001c). In 2001, within the Marrakech Accords (UNFCCC, 2002b), it was agreed that reforestation activities eligible for carbon credits would be limited to activity occurring on lands that did not contain forest on 31st December 1989. However, in the forthcoming discussions on CDM some Parties are requested modifications on the reforestation time limit. Canada and Indonesia have requested a 10-year extension of the reforestation time limit from 31st December 1989 to 31st December 1999. Colombia and Japan have also asked for more flexible reforestation definitions (UNFCCC, 2002b). In the case of Colombia, a ten-year shifting window has been proposed. One possible approach suggested by Japan would be to ‘tune’ the reforestation time limit for developing Countries, according to the availability of reliable data sources, including satellite imagery (UNFCCC, 2002b).
2. Current capabilities for monitoring of afforestation and reforestation activities at the project scale

This chapter demonstrates that satellite remote sensing data and applications are powerful tools for assessing land-use change processes and for monitoring LULUCF projects development since the late 1970’s. The wider potentials and limitations of current Global climate observing systems are addressed by the Second Report on the Adequacy of the Global Observing Systems for Climate in support of the UNFCCC, prepared under the guidance of the Global Climate Observing System steering Committee (GCOS, 2003).

2.1. Land resource observation from satellite

By the late 1960s, the first satellites specifically dedicated to land resource monitoring entered the planning stages. NASA (National Aeronautics and Space Administration of the US) designed and launched a satellite sensor which was able to collect land information at a landscape scale. ERTS-1 (Earth Resources Technology Satellite) was launched on July 23, 1972. This satellite, renamed ‘Landsat’, was the first in a series (seven to date) of Earth-observing satellites that have permitted almost continuous global coverage since 1972. Subsequent satellites have been launched every 2-3 years. Landsats 1-3 were making 14 full orbits every day and they were repeating their previous tracks after 18 days. Landsats 4-5-7, from a lower altitude (705 km), cover the same ground track again every 16 days. It takes about 11,000 scenes to fully image the entire Earth's land surface (excluding the Polar Regions).

The operational success and the obvious value of the information which was delivered by the first Landsat satellites have prompted many countries to set up direct-readout receiving stations so as to download the raw data in near real time without depending on the NASA processing centres.

Figure 1. Map of current receiving stations for data acquired by Landsat satellites.
Since 1986 with the launch of the first French SPOT satellite, a number of other multi-spectral satellite sensors have been launched. From the SPOT series alone, there were five satellites, three of them are still operating, and more than ten millions images have been acquired up to date.

Today a wide range of Earth observation satellite sensors, designed to collect multi-spectral images at landscape scale, are available (see annex II). And in recent years very high resolution satellite sensors (less than 5 m pixel size) have come into service and can be used to monitor land activities at stand-project scale.

While remote sensing techniques are now very well developed for vegetation cover assessments, especially from optical remote sensing data, further developments are expected from techniques using radar imagery (active remote sensing). It is likely that in few years time, biomass stock changes in LULUCF project areas will be measured with good accuracy using a combination of both these types of remote sensing data (optical and radar). In the next sections, we focus our attention upon the current operational methods developed from remote sensing imagery in the optical domain.
2.2. Satellite imagery availability

Since 1975 global coverage of multispectral satellite images has been achieved by NASA through the Landsat MSS sensors. Since this date, the Earth’s surface has been observed many times by multispectral satellite sensors. Today it is even possible to run a data search from a number of Websites. These allow one to obtain information on the availability of all satellite imagery at any time and location (e.g. http://edcnsn17.cr.usgs.gov/EarthExplorer/) within a few minutes. Some of these Websites, such as http://www.landsat.org/ and http://bsrsc.msu.edu/trfic/LBA_E/, allow the searcher to view full resolution satellite images.

Satellite images can be considered as a unique source to document the Earth’s recent land history reliably. For milestone events, such as the start of the 3rd Millennium, NASA has exerted considerable effort to achieve global data coverage. As a result, a global land mosaic from the Landsat ETM+ sensor for the year 2000 will soon be available. A global land mosaic has already been assembled for the year 1990 from the Landsat TM sensor and the data are freely available from NASA’s web site: https://zulu.ssc.nasa.gov/mrsid.

**Figure 2.** Data coverage of the global geo-referenced mosaic of TM-sensor imagery from Landsat satellites for the year 1990

Moreover it is possible to download thousands of satellite images at low or even no cost from some of these Websites. A notable open source for archived imagery from the sensors MSS, TM and ETM+ of the Landsat satellites is the University of Maryland's Global Land Cover Facility (available at: http://glcflapp.umi.acs.umd.edu/). This data archive includes 7,910 Landsat TM, 6,332 Landsat MSS, and 5,440 Landsat ETM+ images.
Figure 3. Coverage of the Landsat imagery data which are freely available from the University of Maryland's Global Land Cover Facility by type of sensor (MSS, TM and ETM+).

Available at: http://glcfapp.umiacs.umd.edu/

Historical information on land cover, and in particular that related to the year 1990 (which is the UNFCCC base year and is also linked to the reforestation time limit), may be retrieved from other “high resolution” satellite images such as imagery from the SPOT satellites (available at http://www.spotimage.fr) (fig. 4), and the Indian IRS satellites (available at http://www.csre.iitb.ac.in/isro/irs-l1d.html).
Since early 2000, companies such as Spacimaging, Digitalglobe, Spotimage and Orbital have launched commercial satellites providing very high spatial resolution (between 1 and 5 meters). These satellites also have the technical capability to acquire images of any area in the world within a scheduling time of few days. This technical aspect increases the opportunities for the acquisition of images in spite of cloud coverage within a short period (by repeating the acquisitions until a cloud-free image is obtained). Thanks in particular to the high ground spatial resolution, these images can be used to help ascertain the area extension and type of LULUCF activities throughout the life of an Afforestation / Reforestation (AR) project. The following image (Figure 5) shows an example of what it is possible to monitor with these kind of data.
Figure 5. Forest Depletion as viewed by the 1-meter resolution IKONOS sensor (available at http://www.spaceimaging.com/solutions/forestry_ecosystems/index.htm)

Selected Web sites of satellite remote sensing data catalogues

- French SPOT-Image distributor:
  http://sirius.spotimage.fr/francais/Welcome.htm
- Earth Observing System Data Gateway of the US Space Agency (NASA):
- Center for Global Change and Earth Observations of the US Michigan State University:
  http://www.landsat.org/
- EROS Data Center of the US Geological Survey:
  http://glovis.usgs.gov/
- Official query interface to the European Space Agency remote sensing catalogues:
  http://odisseo.esrin.esa.it/
- Indian National Remote Sensing Agency:
  http://www.nrsla.gov.in/engnrsla/imagesearch/dataavailability.html
2.3. Methods for monitoring and measuring LUC activities

Introduction on existing methods

Remotely sensed data provide the basis for a tried and tested method for monitoring LUC activities at the project level. It is important to note that such methods have been employed on an operational scale by a number of national, international and EU projects, and can therefore be considered as ‘routine’ technology. Such projects include, for example (see Table 1), the European Commission’s Monitoring Agriculture by Remote Sensing project (MARS) and the Brazilian government’s annual deforestation monitoring project PRODES (see Chapter 3.1). Such data engender a traceable and repeatable process which is documented and based on an objective, independent source data. As most of the data are publicly available, the process is open to wide scrutiny from national and local government, from internal project control, from external (NGOs) and Intergovernmental bodies (IPCC, UNFCCC Secretariat). In remote areas or regions with limited access, the acquisition of remotely sensed data can provide a rapid, quantitative and objective assessment of LUC activities, without involving costly, difficult and sometimes subjective field surveys. In the event that historical evidence is required (as in monitoring a specific time limit) remotely sensed data may be the only objective and so certifiable data available.

Table 1. Examples of large-scale projects using remote sensing data in an operational manner

<table>
<thead>
<tr>
<th>Project</th>
<th>Project level</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODES (INPE-Brazil)</td>
<td>National</td>
<td>Forest changes</td>
</tr>
<tr>
<td>CORINE (EU)</td>
<td>European</td>
<td>Land-cover mapping</td>
</tr>
<tr>
<td>MARS (EU)</td>
<td>European</td>
<td>Monitoring agriculture</td>
</tr>
<tr>
<td>AFRICOVER (FAO)</td>
<td>African continent</td>
<td>Land-cover</td>
</tr>
<tr>
<td>PATHFINDER (US)</td>
<td>Pan-tropical</td>
<td>Forest cover change</td>
</tr>
<tr>
<td>TREES (EU)</td>
<td>Pan-tropical</td>
<td>Forest cover change</td>
</tr>
<tr>
<td>FRA (FAO)</td>
<td>Pan-tropical</td>
<td>Forest cover change</td>
</tr>
</tbody>
</table>

Image acquisition and pre-treatment

As presented in the previous section, several Web-based catalogues exist for searching for images in selected geographic areas and for selected dates. In recent years the data come with the information required to automatically geo-reference the data into a map projection. This means they can be rapidly ingested into a Geographic Information System (GIS) for the elaboration of cartographic products. At the same time, images from different dates can be easily overlaid on top of each other to follow the development of a project baseline.

Figure 6. Web interface of University of Maryland, US, Global Land Cover Facility Project: a) selecting the required area / dates; b) screening, selecting and downloading the required images
Available at [http://glcfapp.umd.edu/index.shtml](http://glcfapp.umd.edu/index.shtml)
Project identification and delineation

Once the satellite data are ingested into a GIS, a particular project can be easily located by its geographic co-ordinates. On-screen digitising can then be employed to delineate its extent. Spatial cadastral data can also be read into the GIS to identify the project’s boundaries. Further geospatial data, such as roads, settlements, administrate boundaries, etc. can be displayed in relation to the project. This means that in the first instance the general location of the project can be mapped (Figure 8), in the second case the specific extent, boundaries and area of the project can be mapped (Figure 9). Both these are essential for the verification of boundaries and area extent. The location of the project at the regional level, allows a broader analysis as to the implications of leakage and ‘Business as usual’.

Figure 7. Satellite image (left) and its location on Sumatra Island (right)

Once the satellite data are geospatially registered, general location maps can be made, adding other geospatial data, such as roads towns and rivers.

Figure 8. Example of geospatially referenced remote sensing imagery (Landsat TM sensor). (Box is representing location of project area as illustrated in Figure 9)
Monitoring project development

The availability of historical and current satellite data, allow land-use change activities to be monitored throughout the life of the project, both for controlling eligibility (see below) and for measuring the extent and nature of land-use changes. The delineation of a project allows the area of each land parcel to be calculated and for subsequent changes to be tracked. The land cover ‘history’ of a parcel can be followed through time. In figure 9 we show a hypothetical project and its development from 1989 through 1992 to 1997. During this period an area of natural forest has been progressively converted to oil palm plantations.

Figure 9. Example of development of agriculture and plantations in Sumatra
Top: three Landsat TM images including the delineation of hypothetical project outline (yellow line).
Bottom: maps of forest cover (green), new deforestation (red) and plantations (ochre) derived from the satellite images.

Once a sequence of images is acquired, the land-use changes sequence of the project can be outlined, with each change quantified. Each parcel’s area, land cover and land cover history can be registered in a Geographical Information System, thus providing an important tool for monitoring eligibility.

Figure 10. Cadastral representation of a project derived from the satellite imagery (left) with table of the land cover changes between 1992 and 1997 in ha (on right side).

<table>
<thead>
<tr>
<th></th>
<th>1992</th>
<th>1997</th>
<th>Total 1992 (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forest</td>
<td>Bare soil (deforested)</td>
<td>Tree Plantation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>158</td>
<td>1.116</td>
<td>249</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0</td>
<td>1.074</td>
<td>5,323</td>
</tr>
<tr>
<td>(def.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree plant.</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>plantation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total 1997 (ha)</strong></td>
<td>158</td>
<td>2,190</td>
<td>5,572</td>
</tr>
</tbody>
</table>
If more detailed information is required then very high resolution data can be obtained. In Figure 11 consecutive zooms from Landsat TM (A,B,C) show an area of ‘regrowth’ on the north west edge of the primary forest. It is unclear from the final zoom (C) as to the actual nature of the regrowth. The acquisition of one IKONOS satellite 1-metre resolution image clearly shows the presence of a new forest plantation (note the uniform arrangement of the vegetation).

**Figure 11.** Forest plantation as viewed by the 30-meter resolution Landsat TM sensor (consecutive zooms in A, B and C with full resolution in C) and 1-meter resolution IKONOS sensor (D)

IKONOS Image courtesy of "Doxiadis Geoimaging"

High-resolution imagery from the IKONOS satellite were found to be a valuable resource for many resource management applications, including mapping of tree cover in the mid-Atlantic region of the US (Goetz et al., 2003) and land-use change and ecosystem dynamics in Brazilian Amazonia (Hurt et al., 2003). For these applications map accuracies comparable to manual aerial photo interpretation were achieved.
Example of cost estimation for monitoring a project

A major concern of monitoring projects with ‘high tech’ methods may be the associated costs. However, such costs are low in comparison with conventional field survey. An indicative cost can be seen in Table 2 where for a normal project monitoring exercise, i.e. the ‘low’ scenario, the costs are around the same as an economy class inter-continental airfare. There are obvious advantages to be had in economies of scale, where both the overhead charges, archiving and training costs all fall rapidly as the number of sites monitored increases.

Table 2. Indicative costs for monitoring a project with remote sensing data and methods. Example taken from project illustrated in Figures 9 and 10.

<table>
<thead>
<tr>
<th>Operating Costs</th>
<th>Euro</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Image acquisition</strong></td>
<td></td>
</tr>
<tr>
<td>Archive data (3 images)</td>
<td>0 - 1200</td>
</tr>
<tr>
<td>Recent data</td>
<td>100 - 600</td>
</tr>
<tr>
<td>Exceptional data (e.g. very high resolution)</td>
<td>1,000 - 3,000</td>
</tr>
<tr>
<td><strong>Manpower</strong></td>
<td></td>
</tr>
<tr>
<td>Image search</td>
<td>300</td>
</tr>
<tr>
<td>Pre-treatment</td>
<td>150</td>
</tr>
<tr>
<td>Project delineation</td>
<td>150</td>
</tr>
<tr>
<td>Cartography</td>
<td>150</td>
</tr>
</tbody>
</table>

| Overheads                        |          |
| Computer equipment               | 2,000    |
| Image processing software        | 6,000    |
| Cartographic software            | 1,000    |

Overheads distributed over 10 monitoring exercises: 9,000 / 10 = 900

<table>
<thead>
<tr>
<th>Total costs**</th>
<th>Cost for project</th>
<th>Cost per ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>(total area: 7,900 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Low scenario</strong></td>
<td>€ 1,750 to 2,250</td>
<td>€ 0.22 to 0.28</td>
</tr>
<tr>
<td><strong>High scenario</strong></td>
<td>€ 2,750 to 6,450</td>
<td>€ 0.35 to 0.81</td>
</tr>
</tbody>
</table>

* Manpower costs are based on using an European service company charging 300 Euro/diem. These can be assumed to be at the higher end of the market.

** “Low scenario” totals assumes no costs for archive data, and no exceptional image data. The opposite is assumed for the “high scenario” totals.
2.4. Relevance for the Kyoto Protocol

Using remote sensing satellite imagery for consistent representation of land areas

As first step, any Party wishing to carry out a reforestation activity under the Kyoto Protocol terms should provide proof that the land under reforestation was not forest on 31st December 1989, regardless of the location. This requirement could represent a serious obstacle if a legal certificate of land-cover use is to be issued by a national institution. In fact it is possible to rely on national geographical land-cover databases which satisfy the Kyoto Protocol provisions (reforestation time limit, forest definition, minimum mapping unit, etc.) only in a few countries. Arguably the easiest and most reliable way to guarantee the reforestation time limit criteria is to use the satellite or aerial (when existing) remote sensing data.

An example of such an application of remote sensing techniques to a Kyoto reforestation project comes from the action that the STMicroelectronics Company is undertaking in the Agricultural Park of South Milan. In this case, one Landsat TM image, acquired on 31st August 1989 (Figure 12) has been used by this company to prove that there was no forest on the project area (circa 13 ha) at the reforestation time limit date. This example shows that remote sensing data, which are often the only available historical sources of data, even in countries with highly developed infra-structures and cadastral databases, can guarantee reliable reference information on land-cover.

Figure 12. Landsat TM false-colour image acquired on 31st August 1989 over a Kyoto reforestation project in the Agricultural Park in Southern Milan City, Italy. Courtesy of STMicroelectronics.

Any Party with obligations to report under the Kyoto Protocol Articles 3.3 and 3.4 will have to develop a detailed national land-use database. Also in that case the easiest and most reliable way to guarantee consistent verifiable reference datasets to measure land-use changes is the use of regular periodic national wall-to-wall coverages of remote sensing data. Two good examples of such on-going projects at national level are the Brazilian PRODES project (see part 3.1 of the report) and the New Zealand land-use / cover database (available at: www.mfe.govt.nz/issue/land-land-cover-dbase/index.html).
**Ensuring the reforestation time limit**

Under the current Protocol definition reforestation is: the direct human-induced conversion of non-forested land to forest. A reforestation activity should therefore be characterized by a land-use change. Ensuring by remote sensing that a land use change did occur could have some temporal constraint from a technical point of view. In spite of the availability of global satellite coverage since 1975, monitoring fast and subsequent land use change processes could be still difficult. This is because often during a short time period only one or two satellite images are available.

During deforestation or reforestation processes vegetation canopy properties (such as leaf area index, tree coverage, etc.) can have similar characteristics, thus if only one satellite image is available to certify a land use change process, large uncertainties on process discrimination are expected, in particular when the observation time period is short. Figure 13 shows a subset of a satellite image from the year 2000, where both reforestation and deforestation processes are occurring. These two areas have very similar spectral properties (as shown on the spectral plot in the same figure) which make them almost inseparable if land cover change analysis has to be based only on this single date satellite image.

**Figure 13.** Landsat ETM+ image of year 2000 (left) and spectral signatures of land-cover classes (right panel)

The longer the time period for monitoring forest-use change the higher the number of satellite images that can be available and the easier it is to understand the land use change processes. Such a scenario is depicted in Figure 14 (next page), where the same area is imaged at different dates from Landsat satellites. The area indicated as ‘A’ was bare soil in 1999, but shows vegetation regrowth in 2001. The area indicated as ‘B’, was forested in 1996, and by 1999 it has been substantially cleared. The following year, 2000, the area was bare soil, and in 2001 partly re-vegetated.

This clearly demonstrates that a multi-temporal analysis significantly reduces uncertainties on land use and forest change processes, and therefore the longer the window of opportunity to acquire images the higher the confidence in the resulting analysis.
Figure 14. Sequence of Landsat TM images from 1996 to 2001, showing the development of deforestation and reforestation processes in South America (the intact forest appears in red tones).

It was agreed within the Marrakech accords (UNFCCC, 2002b) that reforestation activities eligible for carbon credits would be limited to activities occurring on lands that did not contain forest on 31st December 1989. A change in this reforestation time limit would have some technical implications for project monitoring by remote sensing. As a result of a minimum 10-years time window, the current limit of 31st December 1989 allows a multi-temporal analysis of the land-use change process and a more reliable detection of the forest land use changes. A shift of the reforestation time limit to 31st December 1999, which is practically coincident with the carbon account time limit of the first commitment period, could represent a severe technical constraint for applying an independent and accurate verification of the land-use change process by remote sensing, especially if the 'non-forest' land-use period is so short that only a few or, worse, no satellite images may be available in this time window (Figure 15).

Figure 15. Effect on satellite image availability when moving the reforestation time limit forward: A short time window may not allow to identify the land-use change process (e.g. cattle ranching).

Technical capabilities exist now to ascertain at a satisfying spatial resolution and at a low cost, the land-cover for the beginning of the year 1990 for virtually any place on the face of the Earth and to
understand the land-use processes by using time-series of satellite imagery during the 1990's.

*Establishing baseline*

Any emission reducing or carbon absorbing project should refer to a baseline situation. In the case of LULUCF activities, the project should be additional to what would have happened under a ‘business as usual’ scenario. For example a reforestation activity should be characterized by a specific human-induced land-use change, which must be compared to what would have happened naturally. Ensuring additionality is only possible by comparison with the baseline scenario in neighboring areas. Figure 16 shows a case in a semi-arid region, in which reforestation activities are easily referred to the baseline scenario. Indeed the reforestation activities are taking place along a sandy dune which shows no vegetation cover increase outside the reforestation sites.

**Figure 16.** Subsets of Landsat MSS and TM images for years 1980 (left) and 1992 (right) showing a reforestation site in the Inner Mongolia region of China. The two white circles on the 1992 image highlight the areas of tree plantations (*Pinus sylvestris* L.) over a large sandy dune (white tones).
3. Monitoring of forest cover change and carbon fluxes at regional scale

This chapter presents two examples of the most up-to-date findings by the scientific community on land-use change monitoring from satellite remote sensing technology at the regional and continental scales. The examples presented here are two projects dealing with on-going (or recent) assessments of forest cover change (deforestation and forest regrowth) over large regions or continents in the tropics: the PRODES project (Projeto de Estimativa do Desflorestamento Bruto da Amazônia) of the Brazilian Space Agency and the TREES project (Tropical Ecosystem Environment observations by Satellites) of the Joint Research Centre.

Such operational monitoring over large regions is relevant for providing baseline reference assessments (Business as usual activities) and for assessing leakage effects. It can also contribute in the future to the definition of some of the LULUCF actions for the second commitment period.

3.1. Monitoring of forest cover change

**Monitoring of the Brazilian Amazon by the Brazilian National Space Agency**

The Brazilian National Space Agency (INPE) produces annual estimates of deforestation from a comprehensive annual national monitoring program called PRODES.

The Brazilian Amazon covers an area of approximately 5 million km², large enough to cover all of Western Europe. Around 4 million km² of the Brazilian Amazon is covered by forests. The Government of Brazil decided to generate periodic estimates of the extent and rate of gross deforestation in the Amazon, “a task which could never be conducted without the use of space technology” (INPE, 2002).

The first complete assessment by INPE was undertaken in 1978. Annual assessments have been conducted by INPE since 1988. For each assessment 229 Landsat satellite images (180 km x 180 km size each) are acquired around August and analysed (Figure 17). Results of the analysis of the satellite imagery are published every year (see Table 3 concerning mean rate of gross deforestation in Legal Amazonia from 1988 to 2001 on next page).

PRODES also provides the spatial distribution of critical areas (in terms of deforestation) in the Amazon. For the period August 1999 to August 2000, more than 80% of the deforestation was concentrated in 49 of the 229 satellite images analysed.

A new methodological approach based on digital processing is now in operational phase. A geo-referenced multi-temporal database is produced including a mosaic of deforested areas by States of Brazilian federation. All results for the period 2000 to 2002 are accessible and can be downloaded from the INPE web site at: http://www.dpi.inpe.br/prodesdigital.
**Figure 17** Mosaic of Landsat Satellite images from years 1999/2000 over Brazilian Amazon


<table>
<thead>
<tr>
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<td>ACRE</td>
<td>620</td>
<td>540</td>
<td>550</td>
<td>380</td>
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<td>482</td>
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<td>358</td>
<td>536</td>
<td>441</td>
<td>547</td>
<td>419</td>
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<tr>
<td>AMAPA</td>
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<td>130</td>
<td>250</td>
<td>410</td>
<td>36</td>
<td>...</td>
<td>...</td>
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<td>30</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>7</td>
</tr>
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<td>AMAZONAS</td>
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<td>1180</td>
<td>520</td>
<td>980</td>
<td>799</td>
<td>370</td>
<td>2114</td>
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<td>589</td>
<td>670</td>
<td>72</td>
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<td>1100</td>
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<td>1230</td>
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<td>958</td>
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<td>5960</td>
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<td>2840</td>
<td>4674</td>
<td>6220</td>
<td>10391</td>
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<td>6466</td>
<td>6959</td>
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<td>PARA</td>
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<td>4890</td>
<td>3780</td>
<td>3787</td>
<td>4284</td>
<td>7845</td>
<td>6135</td>
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<td>5829</td>
<td>5111</td>
<td>6571</td>
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<tr>
<td>RONDÔNIA</td>
<td>2340</td>
<td>1430</td>
<td>1670</td>
<td>1110</td>
<td>2265</td>
<td>2595</td>
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<td>1986</td>
<td>2041</td>
<td>2358</td>
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<td>2473</td>
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<td>RORAIMA</td>
<td>290</td>
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<td>150</td>
<td>420</td>
<td>281</td>
<td>240</td>
<td>220</td>
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<td>184</td>
<td>223</td>
<td>220</td>
<td>253</td>
<td>145</td>
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<tr>
<td>TOCANTINS</td>
<td>1650</td>
<td>730</td>
<td>560</td>
<td>440</td>
<td>409</td>
<td>333</td>
<td>797</td>
<td>320</td>
<td>273</td>
<td>576</td>
<td>216</td>
<td>244</td>
<td>189</td>
</tr>
</tbody>
</table>

* Decade Mean  
+ Biennium Mean

**Table 3.** Mean rate of gross deforestation (km² / year) in Legal Amazonia 1988 to 2001 (INPE, 2002 & 2003)
Monitoring deforestation and forest regrowths in the tropics: the TREES project

A recently completed research programme exploiting the global imaging capabilities of Earth observing satellites (TREES) provides updated information on the status of the world’s humid tropical forest cover. The project developed a statistical sampling strategy using satellite imagery with 100 sample observation sites (Figure 18) covering 6.5% of the humid tropical domain, which was designed for change assessment by higher sampling probabilities in deforestation hot spot areas. This provided a reliable measurement of tropical forest cover change in a uniform, independent and repeatable manner.

Figure 18. Location of the sample of 100 observation sites around the tropics

Between 1990 and 1997, 5.8 ±1.4 million hectares of humid tropical forest were lost each year with a further 2.3 ±0.7 million hectares of forest visibly degraded. The three continents revealed considerable differences in change rates (Table 4). Latin America shows the lowest deforestation percentage rate, but with 2.5 ×10⁶ ha yr⁻¹ the annual forest area loss is almost the same as that estimated for Southeast Asia. Forest regrowth is dominant in Southeast Asia (0.53 million hectares/year), however mainly through the contribution of former mosaics and woodland cover now interpreted as forest, to a lesser extent in Latin America (0.28 million hectares/year) and limited in Africa (0.14 million hectares/year).

Table 4. Humid tropical forest cover estimates for the year 1990 and mean annual change estimates during the 1990 to 1997 period (from Achard et al., 2002).

<table>
<thead>
<tr>
<th></th>
<th>Latin America (10⁶ ha)</th>
<th>Africa (10⁶ ha)</th>
<th>Southeast Asia (10⁶ ha)</th>
<th>Global (10⁶ ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest cover in 1990</td>
<td>669 ±57</td>
<td>198 ±13</td>
<td>283 ±31</td>
<td>1,150 ±54</td>
</tr>
<tr>
<td>Annual deforested area rate</td>
<td>2.5 ±1.4</td>
<td>0.85 ±0.30</td>
<td>2.5 ±0.8</td>
<td>5.8 ±1.4</td>
</tr>
<tr>
<td>Annual regrowth area rate</td>
<td>0.38%</td>
<td>0.43%</td>
<td>0.91%</td>
<td>0.52%</td>
</tr>
<tr>
<td>Annual degraded area rate</td>
<td>0.28 ±0.22</td>
<td>0.14 ±0.11</td>
<td>0.53 ±0.25</td>
<td>1.0 ±0.32</td>
</tr>
<tr>
<td></td>
<td>0.04%</td>
<td>0.07%</td>
<td>0.19%</td>
<td>0.08%</td>
</tr>
<tr>
<td></td>
<td>0.83 ±0.67</td>
<td>0.39 ±0.19</td>
<td>1.1 ±0.44</td>
<td>2.3 ±0.71</td>
</tr>
<tr>
<td></td>
<td>0.13%</td>
<td>0.21%</td>
<td>0.42%</td>
<td>0.20%</td>
</tr>
</tbody>
</table>
Relevance of the two monitoring systems (PRODES and TREES)

In Latin America, for the Brazilian Amazon and Guyanas region the TREES estimate can be compared with the sum of estimates of (1) Brazilian Amazon from PRODES (INPE, 2002) adjusted to humid forests and (2) the Guyanas from FAO (FAO, 2001). From the PRODES estimate of gross deforestation in Legal Amazonia there is a proportion of the dry forest types. Breaking down the deforestation estimates of INPE by forest physiognomy it appears that around 16% of the annual deforestation in Legal Amazonia occurs in these dry forests cerrado and non-forest areas. By subtraction of 16% from INPE's estimate, the following value is obtained: $-1.38 \times 10^6$ ha yr$^{-1}$ for the period 1990-1997. By adding the contribution of Guyanas, the resulting estimate of gross deforestation for humid forests of the Brazilian Amazon and Guyanas region is: $-1.43 \times 10^6$ ha yr$^{-1}$. The TREES estimate $-1.40 \pm 0.74 \times 10^6$ ha yr$^{-1}$ is exceptionally close to this latter estimate. This provides a confirmation that a statistical sampling method allows for a determination of continental humid tropical forest cover change in reliable, cheap and quick ways.

The PRODES operational monitoring system provides the answer to a basic question: what area was deforested before 12/31/1989? In August 1989 there were already more than 40 million hectares of deforested land in the Brazilian Legal Amazon (INPE, 2002). This demonstrates that large areas can be used for reforestation activities under the CDM.

The PRODES operational monitoring system is carried out at local scale using satellite imagery at 30m resolution. These results are assembled at state and national scales as the project conducts wall-to-wall assessments using such high-resolution satellite images. This demonstrates the relevance of satellite remote sensing for project monitoring at local scale and carbon inventory at national scale over very large areas. The PRODES project is carried out in an operational manner and on a yearly basis since 1988 over an area of approximately 5 million km$^2$.

Figure 19. Detailed example of the products of PRODES.

The TREES monitoring system is also carried out at local scale, as derived from satellite imagery at 30m resolution. But results can only be assembled at regional and global scales as the system is based on a statistical sample of such high-resolution satellite images. The TREES project was carried out over an area of approximately 19 million km$^2$ (full tropical belt). The accurate estimation of forest cover change over regions, continents or the globe, and along regular time periods is relevant for assessing the evolution and trends in forest cover. Such information can contribute in the definition of future activities to be encouraged or supported under the Convention and/or its Protocol.
3.2. Estimation of carbon fluxes due to forest cover change

In the debate related to the global carbon budget there remain large uncertainties associated with estimating the CO₂ release due to land-use change (mainly tropical deforestation) (Prentice 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 knowledge concerning the rates of change of the tropical forests remains limited. The uncertainty of these rates has implications on the estimation of global carbon emissions due to land-use change. The IPCC has pointed out that “the uncertainty ranges – in average annual budget of CO₂ perturbations for 1980 to 1998 – result partly from our limited ability to determine accurately the gradual changes in the carbon balance resulting from human-induced emissions” (Bolin and Sukamar, 2000). Global carbon emissions from land-use change are estimated to fall within the range of +0.5 to +3.0 GtCyr⁻¹ for the 1990s (Houghton, 2003) with errors estimated to be approximately ±50% for tropical regions.

The present contribution of satellite remote sensing imagery to quantifying the global carbon budget issue is related to the true level of humid tropical deforestation, and not yet to the amount of forest biomass. Here we apply the findings of the TREES survey on tropical deforestation and forest regrowth in the 1990’s (chapter 3.1) to existing published and refereed data on biomass and methods, for the calculation of net carbon emissions. By applying the TREES estimates to refereed data on biomass and adding the contribution of the emissions due to the exceptional peat fire event in Indonesia in 1997-1998, new estimates of net carbon emissions were produced (Achard et al., submitted). The estimate of global net emissions from land-use change in the tropics during the 1990’s amounts to 0.8 ±0.24 Gt C yr⁻¹ (intermediate estimate) with an upper estimate at 1.1 ±0.35 Gt C yr⁻¹. These estimates are supported by recent, independent estimations of net carbon emissions over Brazilian Amazon and globally (DeFries et al., 2002), and observations of atmospheric CO₂ emissions over Southeast Asia (Schimel and Baker, 2002).

<table>
<thead>
<tr>
<th>Flux estimates</th>
<th>Humid domain</th>
<th>Dry domain</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross emissions from deforestation (10⁶ tC yr⁻¹)</td>
<td>559 ±193</td>
<td>84 ±24</td>
<td>743 ±217</td>
</tr>
<tr>
<td>Sinks from regrowth (10⁶ tC yr⁻¹)</td>
<td>35 ±18</td>
<td>Not signific.</td>
<td>35 ±18</td>
</tr>
<tr>
<td>Net emissions (10⁶ tC yr⁻¹)</td>
<td>624 ±211</td>
<td>84 ±24</td>
<td>708 ±235</td>
</tr>
</tbody>
</table>

A main conclusion is that the source of atmospheric carbon from tropical deforestation could be substantially smaller than the 1.6 ±0.8 Gt C yr⁻¹ previously reported by the IPCC (Watson et al., 2000) or the 2.2 ±0.8 Gt C yr⁻¹ more recently estimates by Houghton (2003), even if this estimate does not include loss of carbon from forest degradation.

These results demonstrate the potential of remote sensing based methods for quantifying emissions at regional scale. They should help reduce uncertainties in the global carbon budget, as well as contributing to planning activities or strategies under the Protocol or the Convention, even if the current remote sensing techniques do not allow estimating biomass at project level with the required accuracy.
4. Assessment of global vegetation resources at global scale

4.1. Land-cover mapping at the global level

Although 70% of our Planet’s surface is covered by water it has long been known that land cover affects our climate by influencing energy, water and gas exchanges with the atmosphere, and through acting as a source and sink in biogeochemical cycles. Accurate land surface parameterisation is therefore needed to improve our understanding of the state of the global climate system and its variability, and to monitor the forcing of the climate system. These requirements call for a land cover classification where divisions between cover types are determined for use in biogeochemical models (Running et al. 1994).

There are several scientific communities involved in making terrestrial observations, and many use different protocols for making even measurements of the same land cover variables. The resulting lack of homogeneous and complementary data sets limits our capacity to monitor the changes in the terrestrial domain relevant to climate and to investigate the causes of observed land-surface changes. Furthermore, the fact that data are collected and/or processed independently by different parts of the community leads to unnecessary duplication of effort and a waste of resources.

Humans have mapped their immediate environment throughout history. The advent of suitable Earth Observing (EO) satellites in the early 1970’s provided a means of uniform observation, but globally consistent maps treating all parts of the world equally and representing actual land cover over a fixed, contiguous period of time only became available in the 1990’s. The first of these was begun in 1990 to meet the scientific needs of the International Geosphere Biosphere Programme (IGBP). The IGBP’s land cover mapping activities were based on data from the AVHRR sensor with a nominal 1 km resolution, collected between 1992 and 1993 and the validated data set was published towards the end of the decade (Loveland et al., 1999). The final IGBP legend mapped global land cover into 17 classes and continues to be used for global land cover maps destined for the modelling communities today; for example, the Moderate Resolution Imaging Spectro-radiometer Land Discipline Group currently provides land cover map updates at 1 km resolution using the same land cover legend as IGBP (Friedl et al., 2002). The AVHRR archive has also subsequently been used by the University of Maryland, US, to create other global land cover products (Hansen et al., 2000). These products have been well received by the global change science community (e.g. Kucharik et al., 2000).

It has also to be noted that global products at high spatial resolution (ground resolution of 0.1 or 1.4 ha) are under development. These products are commercially distributed by Earthsat and are derived from satellite remote sensing imagery, in particular from the two available global Landsat mosaics produced by NASA, the 1990 and 2000 ‘GeoCover’ mosaics. These products, called ‘Geocover-LandCover’, features a standard 13-class land cover legend designed to provide a basic understanding of the landscape. Two datasets (global land cover maps) at two dates (1990 and 2000) are under production with a ground resolution of 0.08 and 1.4 ha, respectively for raster and vector maps. They are already partially available at http://www.geocover.com/ge_1e/.

There are now several instantaneous assessments of land-cover based on data collected by EO satellites (research missions). Some land-cover products are being produced on a routine basis (e.g. Friedl et al., 2002 but the currently available global land-cover data sets vary significantly, are of uncertain accuracy and use different land-cover-type characterization systems. The lack of compatibility between the products means that there are significant difficulties in using them to measure and monitor climate-induced or anthropogenic changes in land cover.). The second report on the adequacy of the global observing systems for climate in support of the Convention highlights this shortcoming and indeed
calls for the establishment of an international body to advise on standards for the production of land-cover maps, specifically in terms of the resolution and land-type characterization to be employed and finds that new land-cover maps should be produced every five years. This section of the report describes one such global database.


New Earth observing capabilities have given rise to an improved global land cover mapping exercise. A new land-cover database for the year 2000 has been produced by an international partnership of 30 research groups co-ordinated by the Joint Research Centre (Bartholomé et al., 2002). The database contains land-cover maps with detailed, regionally relevant map legends and a global product that combines all regional classes in one consistent legend. Each continent is dealt with as a separate region. The database is designed to serve users from science programmes, policy makers, environmental convention secretariats, international and non-governmental organisations and development-aid projects.

The land-cover maps are derived from the analysis of one year of daily satellite imagery from the VEGETATION sensor on-board SPOT 4 satellite. In addition data from other sensors (ATSR sensor onboard ERS satellite, radar sensors onboard JERS and ERS satellites, and DMSP sensor) have been used to solve specific problems, in particular in regions with persistent cloud cover, especially in equatorial regions and for identification of urban areas. Detailed legend definition, image classification and map quality assurance are carried out region-by-region. A statistically valid accuracy assessment is being performed on the final global product.

The regional maps have been published individually (Bartalev et al., 2003; Eva et al., 2003; Stibig et al., 2003) and the global data set is being published by the JRC in association with FAO and UNEP. The database has been adopted by Millennium Ecosystem Assessment as the baseline for 2000 and is being used the World Conservation Monitoring Centre in their report on the State of the World’s protected areas.

Analysis of the GLC2000 data base is just beginning. The globally consistent nature of the data set means that comparisons between different continents can be made.

Such exercise of global land cover mapping can now be repeated on a regular manner in the future. There are already programmes in Europe and in the US to develop new land cover data bases for 2005 and beyond with an improved detail (at 300m resolution).

The GLC2000 database and the more detailed regional products are freely available to science and policy users. Results may be found at: http://www.gvm.sai.jrc.it/glc2000/defaultGLC2000.htm
Table 6. The legend of the Global Land-Cover map for the year 2000

<table>
<thead>
<tr>
<th>Class</th>
<th>Land Cover Type</th>
<th>Area (in km²)</th>
<th>% of total area</th>
</tr>
</thead>
<tbody>
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<td>Tree Cover, broadleaved, evergreen</td>
<td>12,259,348</td>
<td>9.4</td>
</tr>
<tr>
<td>2</td>
<td>Tree Cover, broadleaved, deciduous, closed</td>
<td>6,361,682</td>
<td>4.9</td>
</tr>
<tr>
<td>3</td>
<td>Tree Cover, broadleaved, deciduous, open</td>
<td>3,977,810</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>Tree Cover, needle-leaved, evergreen</td>
<td>9,323,796</td>
<td>7.1</td>
</tr>
<tr>
<td>5</td>
<td>Tree Cover, needle-leaved, deciduous</td>
<td>3,863,697</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>Tree Cover, mixed leaf type</td>
<td>3,271,984</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>Tree Cover, regularly flooded, fresh</td>
<td>570,489</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>Tree Cover, regularly flooded, saline</td>
<td>112,019</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>Mosaic: Tree cover / Other natural vegetation</td>
<td>2,466,656</td>
<td>1.9</td>
</tr>
<tr>
<td>10</td>
<td>Tree Cover, burnt</td>
<td>307,086</td>
<td>0.2</td>
</tr>
<tr>
<td>11</td>
<td>Shrub Cover, closed-open, evergreen</td>
<td>1,661,956</td>
<td>1.3</td>
</tr>
<tr>
<td>12</td>
<td>Shrub Cover, closed-open, deciduous</td>
<td>10,072,046</td>
<td>7.7</td>
</tr>
<tr>
<td>13</td>
<td>Herbaceous Cover, closed-open</td>
<td>14,581,389</td>
<td>11.1</td>
</tr>
<tr>
<td>14</td>
<td>Sparse Herbaceous or sparse shrub cover</td>
<td>14,056,379</td>
<td>10.7</td>
</tr>
<tr>
<td>15</td>
<td>Regularly flooded shrub or herbaceous cover</td>
<td>1,755,253</td>
<td>1.3</td>
</tr>
<tr>
<td>16</td>
<td>Cultivated and managed areas</td>
<td>17,534,440</td>
<td>13.4</td>
</tr>
<tr>
<td>17</td>
<td>Mosaic: Cropland / Tree Cover / Other nat. veg.</td>
<td>3,910,480</td>
<td>3.0</td>
</tr>
<tr>
<td>18</td>
<td>Mosaic: Cropland / Shrub or grass cover</td>
<td>3,020,347</td>
<td>2.3</td>
</tr>
<tr>
<td>19</td>
<td>Bare Areas</td>
<td>19,136,285</td>
<td>14.6</td>
</tr>
<tr>
<td>20</td>
<td>Snow and Ice (natural &amp; artificial)</td>
<td>1,430,236</td>
<td>1.1</td>
</tr>
<tr>
<td>21</td>
<td>Artificial surfaces and associated areas</td>
<td>274,681</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: the regional levels are not being considered in this table

Figure 20. Zoom of the GLC-2000 map over Brazilian Amazonia - full resolution
Figure 21. The global land cover map for the year 2000 at 1 km resolution (GLC-2000 map) - full extent
4.3. Relevance for international agreements

The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC highlights the importance of sustained land cover information because the spatial pattern of land cover is critical information for determining the capacity of biodiversity to adapt to climate change, because changes in land cover force climate and because land cover is used as a surrogate for other important climate variables. The report recommends that existing land-cover data should be analyzed and/or reprocessed, wherever possible, to ensure the compatibility of maps produced for the last decade and that new land cover maps should be produced every five years.

Eleven years ago the Rio Earth Summit’s Agenda 21 stated, “Relevant international organisations should develop practical recommendations for co-ordinated, harmonised collection and assessment of data at the national and international levels.” Ten years later the Plan of Implementation arising from the Johannesburg World Summit on Sustainable Development reaffirmed the need for the nations of the world to work together, calling for “international joint observation and research, through improved surface-based monitoring and increased use of satellite data”. The need for international co-operation was reaffirmed in June 2003 at Evian, France where the G-8 Heads of State set themselves the objective of developing close co-ordination of their respective global observation strategies for the next ten years and identifying new observations to minimize data gaps. Plans to advance such co-operation were confirmed and supported by 34 nations and the European Commission at the first Earth Observation Summit, Washington, DC USA in July 2003. Global land cover observations feature heavily and repeatedly as requirements to be satisfied by these processes.

Global land cover information has tremendous value beyond the “climate change agenda”. The sustainable management and use of forests and other land resources in developing countries, forest conservation and restoration, environmental impact assessments, trans-boundary issues such as desertification and watershed degradation are all subjects of internationally funded development aid projects. Policy users need information on the state of the World’s land cover to develop sustainable development policies and strategies at different levels and to measure the impact and effectiveness of management actions associated with these. This is also the case for the work of international institutions, including the United Nations Environment Programme and Food and Agriculture Organisation.

Global mapping, global monitoring and global measurements should follow commonly agreed standards. Working with established programmes such at the Global Terrestrial Observing System’s science panel dealing with Global Observations of Forest Cover can only facilitate this process.
5. Conclusions

5.1. Relevance of Earth observation monitoring systems for the Protocol

Remote sensing monitoring systems provide information on the drivers of climate change, principally through measurements of land-cover change (including cover type and biophysical parameters) and disturbance due to fire. By using the repeat coverage of the Earth observation (EO) satellites it has been possible to monitor land-cover change in an operational mode since the mid 1970’s.

Independent verification should be prerequisite before projects are accepted for generating carbon credits through the Kyoto Protocol. In this respect EO products can contribute to the verification process and can also help the Parties to meet their obligations arising from the Protocol.

Information centres (at global, regional or national levels) linked to a network of local partner institutions could carry out the tasks of keeping up an operational monitoring system and geo-referenced spatial database management. The impartial nature of a centralised control using independent and objective observations would deliver accurate information which may reduce opportunities for fraud and ensure homogeneous quality control.

Several outstanding questions regarding the feasibility of verification and review of project-based LULUCF activities under the Kyoto Protocol and in particular its Clean Development Mechanism could be solved through the use of satellite remote sensing monitoring systems. In particular, technical capabilities exist now to ascertain with a high degree of certainty (forest versus non-forest), at a satisfactory spatial resolution (20 to 30m), and at a low cost (most of the data are freely accessible from the Web), the land use for the beginning of the year 1990 for virtually any place on the face of the Earth and any following land-use change.

International initiatives, such as those introduced in section 4.3, give every reason to suppose that space technologies for Earth Observation are set to continue long into the future.

Within the present IPCC proposed Good Practice Guidance for LULUCF (IPCC, 2003), remote sensing is presented as an optional tool for data provision and for verification, while indeed current operational capacities show that it could be presented as a viable approach for testing eligibility, monitoring baseline, estimating leakage and verifying time scale.
5.2. Perspectives

The European Union (EU) shows international leadership on global environmental issues, especially those linked to multilateral environmental agreements (MEAs), such as the UNFCCC or the Convention to Combat Desertification. The establishment of operational monitoring systems is highly relevant to the “Global Monitoring for Environment and Security” initiative (GMES), one of the main pillars of the nascent European Space Policy. The EU’s increasing willingness to act collectively on environmental issues should help to provide more operational monitoring capabilities. GMES will support the European Union in meeting its strategic goals on the global environmental stage. GMES would also allow the EU to measure the impact and effectiveness of management actions associated with these Conventions through regular observations of the Earth.

As legally binding commitments will mean requirements for full accountability, this may entail that land cover maps be accompanied by statements of accuracy (and quantified) product descriptions. The science to support this is mature, appropriate sensors are currently flying, but robust, long-term institutional commitments and frameworks to ensure continuity of satellite observations and to deliver products in such a guaranteed manner will be needed.
6. References


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- UNFCCC (2001b) *Activities Implemented jointly: list of projects*. UNFCCC, Bonn, Germany. Available at: unfccc.int/program/coop/aij/aijact01/bolusa-01-01.html

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- UNFCCC (2002a) *The Marrakech Accords*. UNFCCC, Bonn, Germany. Available at: unfccc.int/resource/docs/cop7/13a01.pdf


Appendix I
- Agenda of the side-event

13.00 – 13.10: “Welcome address”
Dr. Corrado Clini, Director General, Ministry for the Environment and Territory

“Overview of technical presentations”
Dr. Alan Belward, Head of the Global Vegetation Monitoring Unit, JRC

13.10 – 13.30: “Current capabilities for monitoring of afforestation and reforestation activities at the project scale”
Dr. Danilo Mollicone & Dr. Hugh Eva, Joint Research Centre

13.30 – 13.45: “Monitoring of forest cover change at regional scale and Estimation of carbon fluxes from LCC activities”
Dr. Frédéric Achard, Joint Research Centre

13.45 – 14.00: “Assessment of global vegetation resources at global scale. Perspectives for future negotiations”
Dr. Alan Belward, Head of the Global Vegetation Monitoring Unit, JRC
Appendix II
Time life of Earth observation satellites
Appendix III

Example of operational methodology: the TRESs project
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Determination of Deforestation Rates of the World's Humid Tropical Forests

Frédéric Achard,1* Hugh D. Eva,1 Hans-Jürgen Stibig,1 Philippe Mayaux,2 Javier Gallego,2 Timothy Richards,3 Jean-Paul Malineau4

A recently completed research program (TREES) employing the global imaging capabilities of Earth-observing satellites provides updated information on the status of the world's humid tropical forest cover. Between 1990 and 1997, 5.8 ± 1.4 million hectares of humid tropical forest were lost each year, with a further 2.3 ± 0.7 million hectares of forest visibly degraded. These figures indicate that the global net rate of change in forest cover for the humid tropics is 23% lower than the generally accepted rate. This result affects the calculation of carbon fluxes in the global budget and means that the terrestrial sink is smaller than previously inferred.

Loss of forest cover affects climate. Global forest assessments such as those undertaken by the Food and Agriculture Organization (FAO) (1) are designed to measure the area of and the trends in the extent of the world's forests. The humid tropical forests deserve our special attention because demographic, economic, and social changes continue to exert considerable influence on forest cover and conditions in this region (2), and our knowledge concerning their distribution and rates of change remains surprisingly limited. The Intergovernmental Panel on Climate Change (IPCC) has pointed out that "for tropical countries, deforestation estimates are very uncertain and could be in error by as much as ±50%" (3).

The uncertainty of such estimates suggests that total global deforestation rates vary from year to year and that the number of hectares from land-use changes fall within the range of +0.8 to +2.4 gigatons of carbon (GtC) per year for the 1990s (4, 5). Here we estimate the changes in humid tropical forest cover from satellite remote sensing imagery, with better global consistency and with greater accuracy than previously available, in order to understand their implications for the global carbon budget.

The evergreen and seasonal forests of the humid tropical bioclimatic zone covered by our work correspond closely to those forests defined by the FAO as closed broadleaved forests (6) and by the World Conservation Union as closed forests (7). We do not document the woodlands or the forests of the dry tropics, except for continental Southeast Asia, where the seasonal forests are intermixed with the humid forests (table S1). All figures reported here refer to the humid tropical forest biome of Latin America, excluding Mexico and the Atlantic forests of Brazil; the humid tropical forest biome of Africa (Guinea-Congolian zone and Madagascar); and the humid tropical forest biome of Southeast Asia and India, including the dry biome of continental Southeast Asia.

We developed a statistical sampling strategy using satellite imagery to provide a reliable measurement of change in tropical forest cover in a uniform, independent, and repeatable manner. The method is based on (i) the establishment of subcontinental forest distribution maps for the early 1990s at 1:5,000,000 scale derived from 1-km 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 (8); (iii) the definition of five states as 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 (Fig. 1) covering 6.9% of the humid tropical domain, which was designed for change assessment by including higher sampling probabilities in deforestation hot-spot areas; (v) the change assessment for each site, based on the interpretation of fine spatial resolution (20 to 30 m) satellite imagery acquired at dates closest to our target years, 1990 and 1997, and performed by local partners using a common approach; and (vi) the statistical evaluation of the results and estimation of the deforestation rates at the continental level using the data that were obtained by linearly interpolating between the two reference dates. Because we applied an unequal probability sampling scheme, a nonclassical statistical estimator (derived from the Horvitz-Thomson estimator) was used (9). The sampling accuracy (standard error) was estimated with a resampling (bootstrap) method.

The results of our study show that in 1990 (the Kyoto Protocol baseline year) there were about 1150 ± 24 ± 10% hectares (ha) of humid tropical forest (Table 1). The estimated change in global humid tropical forest area for the period from 1990 to 1997 is 1.7% of a marked reduction of closed and open natural forests: The annual deforested (lo) area for the humid tropics is estimated at 5.8 ± 1.4 ± 10% ha, plus a further 2.3 ± 0.7 ± 10% ha of forest where degradation could be visually inferred from satellite imagery. Large nonforest areas were also recouped by forests, but these areas were not located in the most degraded regions. The abandonment of land, along with some forest plantations. Both are very different from natural forests in ecological, biophysical, and economic terms and therefore are not an appropriate counterbalance to the loss of mature forests.

The three continents we examined revealed considerable differences in percentage change rates (Table 1). Southeast Asia had the highest percentage deforestation rate, and Africa lost its forests at about half the rate of Southeast Asia. Latin America showed the lowest percentage rate, but at a rate of 2.5 ± 1.0 ± 10% ha year-1, the annual loss of forest area was almost as severe as in Southeast Asia. Forest degradation shows a similar overall pattern most prominent in Southeast Asia, intermediate

Table 1. Humid tropical forest cover estimates for the years 1990 and 1997 and mean annual change estimates during the 1990-1997 period. All figures are ± 10% ha. Sample figures were extrapolated linearly to the dates 1 June 1990 and 1 June 1997. Average observation dates were February 1991 and May 1997 for Latin America, February 1993 and March 1996 for Africa, and May 1990 and June 1997 for Southeast Asia. Estimated ranges are at the 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>Latin America</th>
<th>Africa</th>
<th>Southeast Asia</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total study area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest cover in 1990</td>
<td>1155</td>
<td>337</td>
<td>446</td>
<td>1937</td>
</tr>
<tr>
<td>Forest cover in 1997</td>
<td>669 ± 57</td>
<td>198 ± 13</td>
<td>283 ± 31</td>
<td>1150 ± 54</td>
</tr>
<tr>
<td>Annual deforested area</td>
<td>536 ± 56</td>
<td>193 ± 13</td>
<td>270 ± 30</td>
<td>1156 ± 53</td>
</tr>
<tr>
<td>Rate</td>
<td></td>
<td></td>
<td>0.85 ± 0.30</td>
<td>0.25 ± 0.18</td>
</tr>
<tr>
<td>Annual regrowth area</td>
<td>2.3 ± 1.4</td>
<td></td>
<td></td>
<td>1.0 ± 0.32</td>
</tr>
<tr>
<td>Rate</td>
<td>0.38%</td>
<td></td>
<td>0.91%</td>
<td></td>
</tr>
<tr>
<td>Annual net cover change</td>
<td>0.28 ± 0.22</td>
<td></td>
<td>0.14 ± 0.11</td>
<td>0.53 ± 0.25</td>
</tr>
<tr>
<td>Rate</td>
<td>0.04%</td>
<td></td>
<td>0.07%</td>
<td></td>
</tr>
<tr>
<td>Annual degraded area</td>
<td>-2.2 ± 1.2</td>
<td></td>
<td>-0.71 ± 0.31</td>
<td>-2.0 ± 0.8</td>
</tr>
<tr>
<td>Rate</td>
<td>0.3%</td>
<td></td>
<td>0.36%</td>
<td>0.71%</td>
</tr>
<tr>
<td></td>
<td>0.83 ± 0.67</td>
<td>0.39 ± 0.19</td>
<td>1.1 ± 0.44</td>
<td>2.3 ± 0.71</td>
</tr>
<tr>
<td></td>
<td>0.13%</td>
<td>0.21%</td>
<td>0.42%</td>
<td>0.20%</td>
</tr>
</tbody>
</table>
in Africa, and lowest in Latin America. These estimates represent only the portion of degradation identifiable using our methodology, which does not include processes such as selective logging. Reforestation was dominant in Southeast Asia, but it occurred mainly through the transition of former mosaic and woodlands to forest. Reforestation occurred less frequently in Latin America as compared with Southeast Asia and was very limited in Africa.

Globally, the main forest conversion process in the humid tropical zone was the transformation of closed, open, or fragmented forests to agriculture at a rate of $3.09 \times 10^9$ ha year$^{-1}$ (Table 2). The major forest changes were largely confined to a number of hot-spot areas where change rates were alarmingly high. Annual transformation rates of more than 2.5% were measured at 16 sample sites. In Latin America, the transformation from closed, open, or fragmented forests to agriculture by clear-cutting dominated ($1.72 \times 10^9$ ha year$^{-1}$) (Table 2). This process is concentrated in hot spots (Table 3), where forests are increasingly fragmented, heavily logged, or burned. In addition, $3.61 \times 10^6$ ha year$^{-1}$ of mosaic or savanna-woodlands were transformed into agriculture in Latin America. Surprisingly the estimated percentage rate of deforestation for Africa was higher than that for Latin America, with very high local rates in Madagascar and Côte d’Ivoire. In Africa, $310,000$ ha year$^{-1}$ of forests were transformed to agriculture, with a further $280,000$ ha year$^{-1}$ into mosaics and $200,000$ ha year$^{-1}$ into savannas or woodlands. For Southeast Asia, the change estimate indicates a high annual deforestation rate and a substantial annual rate of detectable degradation. In total, $1.06 \times 10^9$ ha year$^{-1}$ of forests were converted into agriculture and $650,000$ ha year$^{-1}$ into mosaics. A further $50,000$ ha year$^{-1}$ of forests were degraded into savanna or woodlands. At the same time, about $650,000$ ha year$^{-1}$ of mosaic or savanna-woodlands changed to agriculture.

How do our estimates of forest area and forest area change compare to the FAO figures (1)? The latter are widely used in spite of the highlighted internal inconsistencies (chapter 4.6 in (11)) arising from the difficulties in standardizing national data obtained from different countries (12). For comparison, we adjusted the FAO figures to the humid tropical domain for the countries included in our survey (13). Our 1990 global forest area estimate (indicated as TREES-II in Table 4) shows only a 1.9% relative difference as compared with the FAO estimate (+3% for Latin America, −9% for Africa, and −6% for Southeast Asia). More striking, our global estimate of net forest area change during the 1990–1997 period is 23% lower than the FAO estimate.

The use of secondary information, expert opinions, and outdated country data by the FAO may explain these differences (14). Already, the FAO forest area estimates for the year 1990 (1)
Table 2. Forest cover changes in the humid tropics from January 1990 to June 1997. All area figures are × 10^4 ha. The forest class definitions were made according to those applied by the FAO Forest Resource Assessment Exercise (17) 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 had a forest proportion of more than 40%, in which the forest stands have a tree cover of more than 10%. When the forest proportion was at least 70%, the area was considered closed forest if the tree cover was more than 40% and open forest if the tree cover was between 10 and 40%. When the forest proportion was between 40 and 70%, the area was defined as fragmented forest. Plantations and forest regrowth are grouped as nonnatural forest. Referring to the nonforest classes, mosaics were defined as containing a forest proportion between 10 and 40%. Other natural vegetation such as shrub or grassland, but also agricultural land, may have still contained a forest proportion or a tree cover up to 10%. For forest cover calculations, we applied forest cover weights per class as determined by an independent postassessment of the observation site results (8). The total forest cover estimates in 1990 and 1997 were derived by the addition per class of the weighted forest cover areas. Bold figures indicate the total forest cover in 1990 and 1997; underlined figures indicate the unchanged area for each land cover class between the two dates.

<table>
<thead>
<tr>
<th>1997</th>
<th>Forest classes</th>
<th>Nonforest classes</th>
<th>Forest cover in 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Closed</td>
<td>Open</td>
<td>Fragmented</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Forest classes</td>
<td>100</td>
<td>17</td>
<td>1296</td>
</tr>
<tr>
<td></td>
<td>Fragmented</td>
<td>75</td>
<td>1.8</td>
</tr>
<tr>
<td>Plant/regrow</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Nonforest classes</td>
<td>25</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Mosaics</td>
<td>0</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Natural</td>
<td>0.6</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Unvegetated</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Forest cover in 1997</td>
<td>908</td>
<td>134</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 3. Annual deforestation rates, as a percentage of the 1990 forest cover, for selected areas of rapid forest cover change (hot spots) within each continent.

<table>
<thead>
<tr>
<th>Hot-spot areas by continent</th>
<th>Annual deforestation rate of sample sites within hot-spot area (% range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latin America</td>
<td>0.38%</td>
</tr>
<tr>
<td>Central America</td>
<td>0.8–15%</td>
</tr>
<tr>
<td>Brazilian Amazonian belt</td>
<td>4.4%</td>
</tr>
<tr>
<td>Acne</td>
<td>3.2%</td>
</tr>
<tr>
<td>Rondônia</td>
<td>14.2–27%</td>
</tr>
<tr>
<td>Mato Grosso</td>
<td>0.9–2.4%</td>
</tr>
<tr>
<td>Para</td>
<td>1.5%</td>
</tr>
<tr>
<td>Colombia-Ecuador border</td>
<td>0.5–5.0%</td>
</tr>
<tr>
<td>Peru-Venezuela</td>
<td>0.4%</td>
</tr>
<tr>
<td>Africa</td>
<td>0.4%</td>
</tr>
<tr>
<td>Madagascar</td>
<td>1.4–4.7%</td>
</tr>
<tr>
<td>Côte d’Ivoire</td>
<td>1.1–2.9%</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>0.91%</td>
</tr>
<tr>
<td>Southeastern Bangladesh</td>
<td>2.0%</td>
</tr>
<tr>
<td>Central Myanmar</td>
<td>3.0%</td>
</tr>
<tr>
<td>Central Sumatra</td>
<td>2.3–5.3%</td>
</tr>
<tr>
<td>Southern Vietnam</td>
<td>1.2–3.2%</td>
</tr>
<tr>
<td>Southeast Kalimantan</td>
<td>1.0–2.7%</td>
</tr>
</tbody>
</table>

were found to be much higher than the previous FAO estimates for the same year (6), with the exception of South America (12). Furthermore, our TREES-II forest area estimates for 1990 are very close to our estimates from a previous TREES-I study (15) that used coarse-spatial-resolution maps calibrated with a sample of high-spatial-resolution maps (16). Our forest area change estimates are lower than the FAO estimates that were adjusted to the humid domain (17) by an amount of ~0.5 × 10^4 ha/year for each continent, the FAO estimate for Indonesia (which represents 39% of the forest area of this region) is largely based on national remote-sensing-derived information for earlier years (1985 and 1997) and does not include the exceptional fire event in Indonesia in 1997–1998 (18, 19) (neither does our survey). In Africa, the difference can be explained by the very low in-country forest monitoring capacities of most countries.

In Latin America, our estimates refer to two subregions: the Brazilian Amazon and Guyanas subregion and the pan-Amazon and Central America subregion. Our Brazilian Amazon and Guyanas subregion estimates (420 × 37 × 10^4 ha) of forest area in 1990 and 132 ± 0.74 × 10^4 ha/year of forest area change are close to estimates from other sources (401 × 10^4 ha and 1.43 ± 10^4 ha/year) with small relative differences (5 and 9%). Because the latter regional estimates were derived from wall-to-wall assessments using high-resolution satellite images, the similarity in estimates provides an independent confirmation that our method allows for a determination of total humid tropical forest cover change in a more reliable way than was previously available and highlights the importance of this new estimate of forest area change in the humid tropics.

Our data can help reduce the amount of uncertainty in calculating net carbon flux from deforestation (22) and regrowth in the humid tropics. To estimate net carbon flux, we considered existing regional figures of total carbon vegetation biomass derived from the actual biomass density without roots (22) as a starting point. These figures are weighted by the 1990 forest area, and we added 20% for belowground vegetation (root) biomass, accepting that root biomass varies considerably in tropical forests (22). The error range of such biomass estimates is suggested to be as high as ±30 to ±60%. Carbon was assumed to be 50% of biomass (3). The resulting regional estimates are 129 tons of carbon (tC ha^-1) for the pan-Amazon and Central America region, 100 tC ha^-1 for the Brazilian Amazon forests (23), 179 tC ha^-1 for tropical moist Africa, and 151 tC ha^-1 for Southeast Asia. Carbon fluxes can then be computed using the fractions of biomass (fbb) that are assumed to be converted to CO₂ as a result of the deforestation and regrowth carbon rates, which are proportional to initial forest biomass (24). The fractions of biomass converted are 0.2 from initial forest biomass burned, 0.008 annual...
Table 4. Comparison of TREES humid tropical forest cover estimates with FAO estimates. TREES II: this study; TREES I: previous study (15). FAO country estimates are derived from the country tables (7). India was included with Southeast Asia but not 41 \times 10^6 ha of India's dry forest. For Africa and Latin America, we refer to 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 (7)]. Mexico was excluded from Latin America. The TREES estimates of net change in forest cover were interpolated to the June 1990–June 1997 period. Average observation dates were June 1990 and March 1997 for the TREES study and June 1990 and March 1998 for the FAO forest cover change estimators are reported for the 1990–2000 period. The average reference years for the latest data area used by the FAO are 1991 for Africa and South America and 1995 for Asia and Central America. Estimated intervals are at the 95% confidence level.

<table>
<thead>
<tr>
<th>Forest area for the year 1990 (10^6 ha)</th>
<th>Annual forest area change, 1990–1997 (10^6 ha year^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TREES II</strong></td>
<td><strong>TREES I</strong></td>
</tr>
<tr>
<td><strong>FAO country</strong></td>
<td></td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>283 ± 31</td>
</tr>
<tr>
<td>Africa</td>
<td>198 ± 13</td>
</tr>
<tr>
<td>Latin America</td>
<td>669 ± 57</td>
</tr>
<tr>
<td>Global</td>
<td>1150 ± 54</td>
</tr>
</tbody>
</table>

rate from decay of wood removed from the site for a 10-year period, and 0.07 initial annual rate with an exponential decrease in time from the decay of biomass left as slash. The initial (first-year) fraction of 0.28 increases to 0.72 over a 10-year period, when including future sources embodied in first-year decay pools and to 0.97 over a 75-year period. The accumulation of carbon on abandoned lands that reverted to forests (24) is taken as 5.5, 5.0, and 3.8 1C ha⁻¹ year⁻¹ for the pan-Amazon, Brazilian, African, and Southeast Asian regions, respectively, with a maximum accumulation of 129, 190, 170, and 151 1C ha⁻¹ year⁻¹.

From our annual deforestation and regrowth estimates, we can compute three estimates of carbon flux: an initial flux for the first year, a "committed" flux for the next 10 years (including future sources and sink), and a "committed" flux for the next 75 years. The first-year flux will obviously underestimate the impact of the land-cover change. The 75-year committed flux implies that the deforestation and regrowth rates that 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. For the Brazilian Amazon, comparison with other studies supports this assumption: Our 10-year and 75-year committed flux estimates for this region are 0.19 ± 0.12 1C year⁻¹ and 0.24 ± 0.18 1C year⁻¹, which correspond well with the estimates of 0.18 1C year⁻¹ of annual net flux over the period from 1989 to 1998 and 0.26 1C year⁻¹ of annual 100-year committed flux (25).

Using our 10-year committed flux figure as a good estimate of the actual annual net flux leads to a global estimate of 0.64 ± 0.21 1C year⁻¹ for the period from 1990 to 1997. This estimate is lower than the estimate of annual net emissions from land-use changes primarily in the tropics, for the period from 1980 to 1998 as reported by the IPCC (1.6 ± 0.8 1C year⁻¹) (3). Considering that the net change in forest area is lower in the dry tropics than in the humid tropics (11) and that the biomass of dry tropical forests is less than half of that of humid tropical forests (22, 26), a maximum estimate of global net emissions from land-use change in the tropics would be about 0.64 1C year⁻¹. Even if this figure does not include loss of carbon from forest degradation, which is much more difficult to estimate, this result leads us to believe that the residual terrestrial uptake must be smaller than previously inferred.

References and Notes
2. H. J. Geist, E. F. Lambin, What Do Tropical Deforesta-
tion in Indonesia, (Louvain, Louvain-De-Neuve, Belgium, 1993).
6. Forest Inventory Assessment 1990 (Asian Forests (FAO, Rome, 1993)).
9. Materials and methods are available on supporting material at SCIENCE ONLINE.
10. Deforestation is defined as the conversion non forest (closed, open, or fragmented forests; plantations; and forest regrowth) to non forest lands (mosses, natural forest such as shrubs or savannas, agriculture, and non-regrowth). Deforestation (or re- growth) is the conversion of non forest lands to for-
ests. Degradation is defined as a process within for-
ests that leads to a significant reduction in either tree density or proportion of forest cover (from closed forests to open or fragmented forests).
11. Global Forest Resources Assessment 2000 Main Re-
tort (FAO, Rome, 2000).
12. E. Matthews, Understanding the FAO (World Resources Institute, Washington, DC, 2001).
13. The FAO estimates were extracted for the corresponding countries, restricted to the humid domain using the FAO definitions and recent vegetation types, and aggregated to the continental level.
14. All primary sources of information on forest area were not available, so we used recalculated 1990 B.S.D. "100 years ago data (secondary information and expert estimates)" (13).

In particular, the average reference years for the latest data area 1993 for Africa and South America and 1995 for Asia and Central America (11). Furthermore, "1 high proportion of developing countries had to rely on expert opinion for the latest area estimates" (11). Comparisons may be less informative because of the expert prop lapulations to the 1990–2000 period.

16. In the previous method (27), the 1-km resolution base-
line-based maximum inputs were the same as the present study, but the set of high-resolution imagery was different (30 sites were selected instead of 100, and at different locations). Also, the baseline maps were used in a random fashion to derive the two-calibration coefficients and regression for all 1-km grid cells of the humid tropical forests, rather than to focus on forest and non-forest areas and hotspot areas for the sample flatten and expert for the region.
17. The FAO net change estimates for Africa before ad-
justment, mainly from the contributions of a few countries that include large areas of savanna transi-
ests, added up to 1.3 1C year⁻¹ (27). The Latin American FAO net change estimates were only corrected, including contributions of decision making, from Brazil, Panama, and Argentina, 0.5 ± 1C year⁻¹ (27). The Latin American FAO net change estimates were only considered to be adjusted, including contributions of decision making, from Brazil, Panama, and Argentina, 0.5 ± 1C year⁻¹ (27).
19. We used two other estimates for the Brazilian Amazo-
nia: the LANDSAT Pathfinder Methodology net change estimate (28) normalized to 1990 (626 ± 10 1C ha⁻¹) and the expert average maximum net change (29) corrected for decision making contribution (1.38 ± 10 1C year⁻¹ for the Cuyana region, the FAO used maximum net change estimate).
21. The Brazilian Amazon estimate in the per capita is the average of two estimates: 186 ± 100 1C ha⁻¹ and 195 ± 100 1C ha⁻¹. The first estimate was derived from 310 ± 100 1C ha⁻¹ of actual biomass density without removing 100 1C ha⁻¹ of biomass anecotric 1C ha⁻¹ was an average of three estimates: 145, 210, and 232 ± 100 1C ha⁻¹.
28. World Forest, Environment, and Development in the Meno Ambiente and the Nordic Countries, 1970–1993. Data were obtained byWorld Bank helps for assistance with the GIS representations of Fig. 1 and A. Bandit, P. N. Elyady, C. Romero, M. Villalobos, and anonymous reviewers for their constructive comments on the manuscript.
29. Supporting Online Material www.sciencemag.org/cgi/content/abstract/t972/5583/999/DC1

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Appendix IV
Example of remote sensing capabilities for project monitoring

Making Deforestation Pay Under the Kyoto Protocol?
Ernst-Detlef Schulze,1 Danilo Molincon,2 Frédéric Achard,2,∗ Giorgio Matteucci,2
Sandro Federici,1 Hugh D. Eva,3 Riccardo Valentini1

The Kyoto Protocol of the Framework Convention on Climate Change (UNFCCC) (1) has laid down goals for greenhouse gas reductions. However, from the beginning of the negotiations, there were concerns (2) that the protocol might lead to a perverse incentive to increase the logging of pristine forests, which are large carbon pools and reported to be carbon sinks (3). The industrialized countries that signed the Kyoto Protocol may reach their greenhouse gas reduction commitments either by decreasing emissions or by promoting sinks of carbon. Land use, land use change, and forestry (LULUCF) activities such as afforestation (4), reforestation, and land management are agreed ways to create such sinks.

In 2001 (5,6), it was agreed that reforestation activities eligible for carbon credits would be limited to activity occurring on lands that did not contain forest on 31 December 1989. As the agreements leave room for renegotiation of this time limit, some countries are already requesting its modification under the Clean Development Mechanism (CDM) (7). In particular, Canada and Indonesia requested a 10-year extension of the reforestation time limit from 31 December 1989 to 31 December 1999, and Colombia and Japan asked for even more flexible reforestation definitions (8). To look at the practical implications of such changes for pristine forests, we will use two well-documented and publicized examples of ongoing projects related to CDM: the Green Marathon project in Brazil (9) and the Noel Kempff Mercado Climate Action project in Bolivia (10).

Since 1999, the Carbon Sink project, based at the São Nicolau fazenda in Mato Grosso, has been feeding a reforest 2200 ha of pasture land to make "a positive contribution to the process launched by the Kyoto protocol" (9). The analysis of Landsat satellite images (acquired in 1992 and 1999) of the São Nicolau fazenda provides a basis for the estimation of land cover changes occurring over this period. Although in 1992 only 1200 ha of the fazenda's 10000 ha was forested, 7 years later an additional 1300 ha had been deforested (Fig. S1). If the reforestation time limit were to be extended by 10 years, then the project would become eligible for carbon credits without accounting for the deforestation that had taken place in a region where annual deforestation rates are above 2.7% (11). The Noel Kempff Mercado Climate Action project, said to be the "largest forest-based carbon project in the world" (approximately 634,000 ha area) (10), is located in the state of Santa Cruz. The project's beneficial carbon offsets would have been obtained from the prevention of logging or the conversion of forested lands to agriculture (12). This project has been submitted to the UNFCCC (13) and, in the Intergovernmental Panel on Climate Change Special Report on LULUCF, it has been presented as an example "to help policymakers develop internationally agreed rules" (14). As reported by the project, "in 2001, the time of the initiation of the project, most of the forest expansion area had been high-graded over a period of about 15 years for several commercial tree species" (12). High-grading is a harvesting technique that removes only the biggest and most valuable trees from a stand. In this case, analysis of Landsat satellite images confirms that high-grading was in progress in the project area in 1994 (Fig. S2).

These two projects were carried out in areas where deforestation or forest degradation occurred after 31 December 1989. At present, even if the deforestation and degradation were not carried out under their guidance, these projects would not be eligible for carbon sink credits because they do not meet the provisions of the Kyoto Protocol. However, a shift of the reforestation time limit may bring them into line for carbon credits. Although one must recognize the efforts of the reported projects in setting up activities aimed at absorbing carbon, a change in the reforestation time limit would set two dangerous precedents. First, all pristine forest sites, ranging from boreal to tropical regions, that were deforested or degraded later than 1989 up to a new reforestation time limit would become eligible to receive carbon credits without accounting for the relevant carbon losses due to biomass harvest and the subsequent decomposition of soil organic matter (15). Second, and more important, a shift in the reforestation time limit may lead to expectations that it may change again. This could stimulate a speculative round of deforestation or degradation in pristine forests in the hope of obtaining carbon credits from reforestation carried out later on.

In a climate of changing rules, particularly relating to the Kyoto Protocol, one of the underlying principles of the Kyoto Protocol—that of preserving pristine forests—would be severely compromised. Prevention of deforestation should be clearly established within the context of the Kyoto Protocol implementation. It would be paramount for climate change mitigation if the Kyoto Protocol mechanisms had the effect of paying for the destruction of pristine forests, which are one of the few genuine actors in climate change mitigation (16).

References and Notes
4. Afforestation is the conversion of land that has not been forested for a period of at least 50 years.
7. The CDM is one of the Kyoto Protocol flexible mechanisms. For the Kyoto Protocol first commitment period (2000–2012), the LULUCF activities that can be carried out as CDM will be limited to afforestation and reforestation.
16. We thank A. Belward from the Joint Research Centre, M.-J. Sáz from Centro de Estudios Ambientalesdel Mediterraneo, and J. S. Matiar, for contributions and comments.

Supporting Online Material
www.sciencemag.org/cgi/content/full/295/5561/1669/DC1
Figs S1 and S2
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