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ENRIC

A Source Book on:

TROPICAL FOREST MAPPING AND MONITORING THROUGH SATELLITE IMAGERY:

The Status of Current International Efforts

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Tropical Forest Mapping and Monitoring through Satellite Imagery: The Status of Current International Efforts

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This is a thematic mapper (TM) false color composite image from southern Rondonia, Brazil acquired using the Landsat 4 and 5 satellites on June 5, 1988. The size of the area identified as isolated forest is nearly 2 by 9 miles (3 by 15 kilometers). The viewed area is a segment from the full Landsat satellite image footprint corresponding to path 230, row 69.

By Alex Tait/Equator Graphics. Produced for USAID by the Environment and Natural Resources Information Center (ENRIC). ENRIC is a project of Datex, Inc., Arlington, Va.

INTRODUCTION

Recent efforts to map and measure the world's tropical forests from space employ the latest advances in remote sensing, geographic information systems, and myriad computerized applications. Images of tropical forest around the world were captured by Multi-Spectral Scanner sensors on board NASA's Landsat satellites from 1972 until 1993. In the 1980's low resolution imagery from NOAA's TIROS satellite as well as high resolution imagery from the French SPOT satellite became available for forest mapping. Global scale mapping of forest change with this imagery, spurred by global warming concerns, began in the late 1980's in Europe and in 1992 in the USA.

The results of these global surveys are crucial to humanity's understanding of what has happened to tropical forests during a period of unprecedented commercial and demographic pressures on tropical forests. The maps and statistics already flowing from these efforts will be extremely useful in planning and prioritizing actions to manage forested ecosystems and conserve their biodiversity, as well as model the carbon cycle and reduce greenhouse gas emissions through tree planting or conservation.

However, forest mapping from space is characterized by technological complexity as well as innovative solutions to problems of data management, image interpretation and analysis. Also, diverse institutional actors are taking part beyond the traditional forest management agencies.

Those who plan and manage programs aimed at conserving forested tropical ecosystems and their biological diversity need a basic grasp of the technologies involved, and they must be prepared to make maximum use of the information generated by these efforts over the next two to three years.

This source book brings under one cover landmark articles and findings on tropical forest monitoring from space in a presentation that guides the new-comer to the field through the complexities inherent to the work. The principal audience is USAID program and project managers who are planning and managing efforts to conserve biodiversity and avert global warming.

ACKNOWLEDGEMENTS

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Appreciation is expressed to a number of people who provided materials and guided our research through technical thickets in order to gain an understanding of satellite imagery and current applications to tropical forest assessments. They are: Sandra Brown (Department of Forestry, University of Illinois), Chris Elvidge (Desert Research Institute), Paul Howard (USDA Forest Service seconded to the FAO FRA1990 project), Chris Justice (Univ. of Maryland/NASA Goddard Space Flight Center), William Lawrence (Univ. of Maryland Geography Department), Gyde Lund (USDA Forest Service), Ross Lunetta and Dorsey Worthy (EPA, North American Land Characterization study), Susan Eggen McIntosh (USDA Forest Service), Jean-Paul Malingreau (Institute for Remote Sensing Applications, Ispra, Italy), Max Miller (Earth Satellite Corporation), Steve Miller (SPOT Image), Jeffery Sayer (World Conservation Monitoring Centre), K.D. Singh (FAO, Forest Resources Assessment), David Skole (Univ. of New Hampshire, Institute for the Study of Earth, Oceans and Space), Compton J. Tucker (NASA, Goddard Space Flight Center) and numerous individuals from the Earth Observation Satellite Corporation (EOSAT).

Primary overall research, as well as analysis and design of FAO tables (section III) for this sourcebook was carried out during 1993 by Dr. Robert Fox, Senior consultant to ENRIC. Index maps of mapping projects were designed by ENRIC's GIS programmer, Steve Davis. Studio Grafik, Arlington VA designed the overall presentation format for the Sourcebook. Editing of text was performed by Barbara Bever, ENRIC Research Assistant. Development of the Sourcebook was managed by Peter H. Freeman, Director, ENRIC, who also provided research, editorial, design, and production guidance.

Environment and Natural Resource Information Center.
Datex Inc., Arlington VA. June, 1994.

ENRIC SECTION I

The State of the Art

"Satellite Based Forest Monitoring: A Review of Current Issues," *J.P. Malingreau*

"Satellite Monitoring of Tropical Forests: A Commentary on Current Status and International Roles," *Chris Justice*

THE STATE OF THE ART

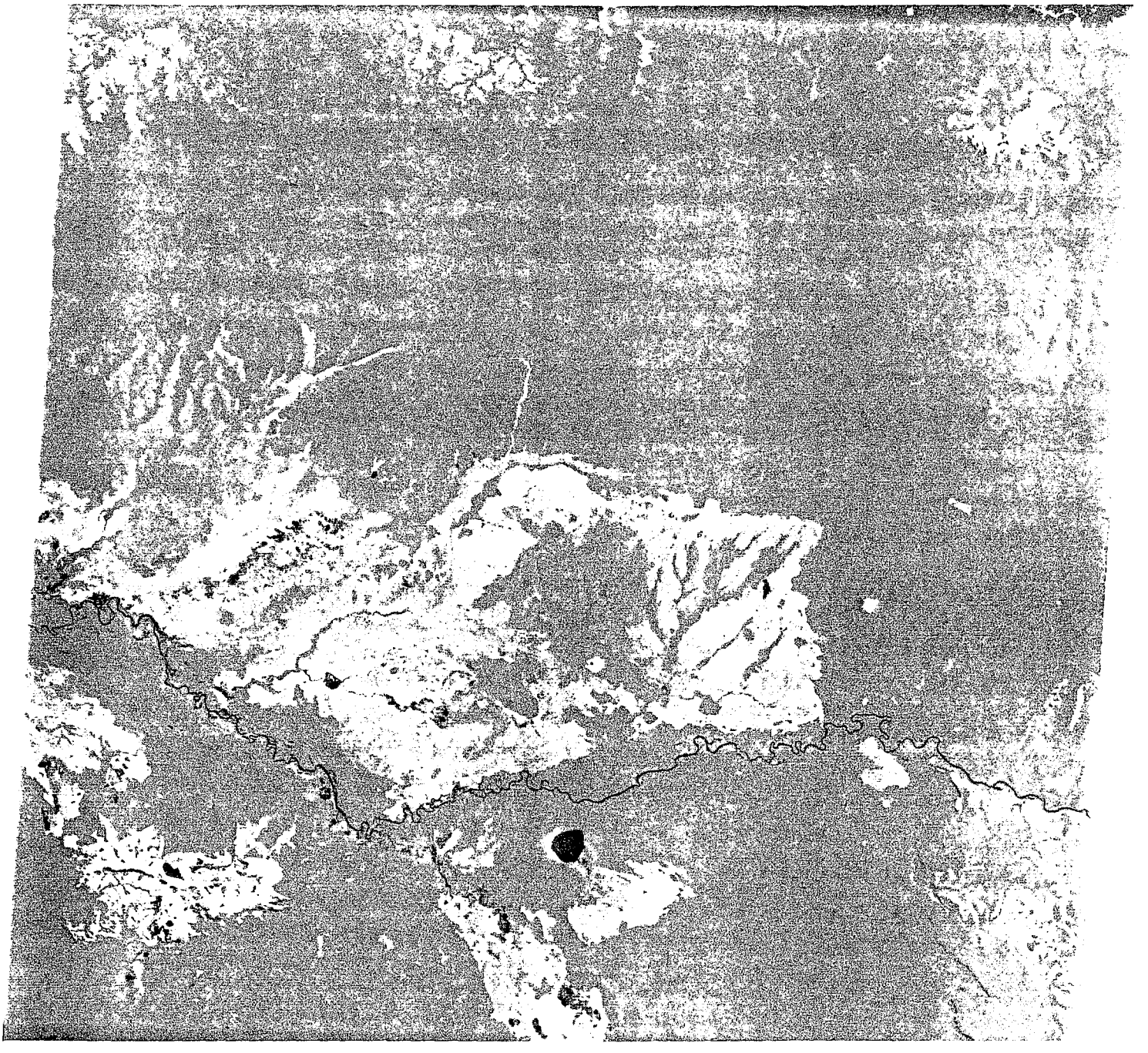
Two papers contained in the proceedings of the 1992 World Forest Watch Conference in São José dos Campos, Brazil[1] captured the state-of-the-art of mapping forests and monitoring change in forest cover from space. Incremental progress since 1992 has not altered the substance or conclusions of these landmark contributions.

In the first paper, J.P. Malingreau of the Commission of the European Community's Joint Research Center evaluates the roles of high and low resolution remote sensors in forest monitoring, the requirements of vegetation mapping, and the approaches used to monitor condition and change in forest cover. He concludes with a proposal for global forest monitoring with remote sensors of low to high resolution that includes an "alarm function" that can rapidly focus on areas of active change. Malingreau's proposals are built into the TREES project that he directs out of Ispra, Italy and have been generally adopted as a practical approach to global forest monitoring.

Impediments to global forest monitoring are analyzed in the second paper by Dr. Chris Justice, Goddard Space Flight Center. He noted that despite the availability for two decades of high resolution satellite imagery, a comprehensive global assessment of the world's tropical forests and their rates of change was still lacking. He lists numerous obstacles to progress, including data, institutional and technical problems, but observed these were not insurmountable. Progress since 1992 bears him out, but institutional constraints at all levels remain the most difficult to overcome. Many national agencies charged with managing forests resources remain ill equipped to assess or monitor these resources, whether from space or from the ground. Much more work remains to be done to coordinate global efforts.

1. Malingreau, J.P., R. da Cunha and C. Justice (eds.), "Proceedings of the World Forest Watch Conference." São José dos Campos, Brazil, May, 1992. ISPRA, Italy: Joint Research Council. The meeting was organized by Brazil's space research institute – the Instituto Nacional de Pesquisas Espaciais (INPE) – and by the Institute for Remote Sensing Applications of the Commission of the European Community, ISPRA, Italy.

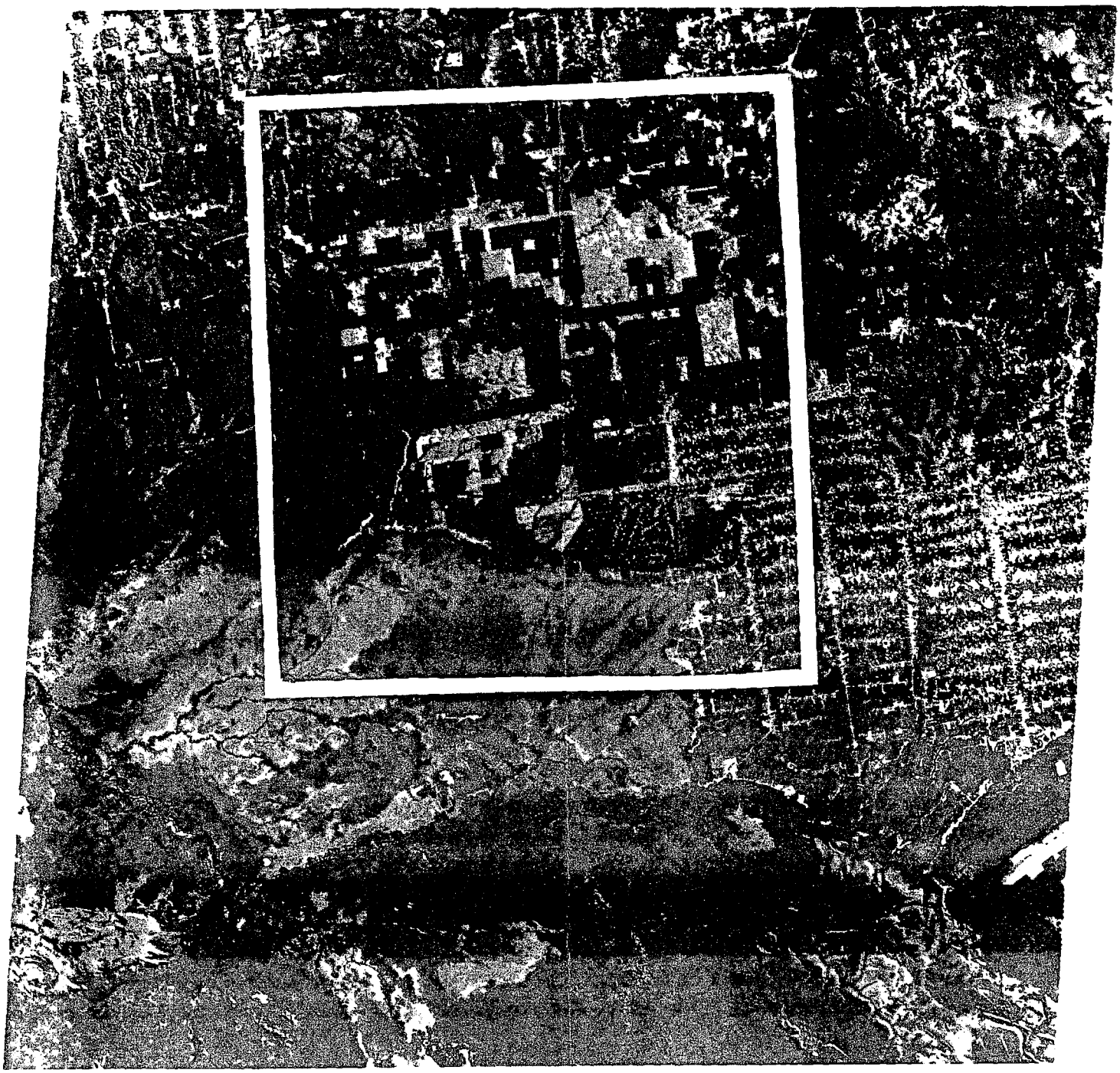
Destruction of the Brazilian Rainforest



1975

Undisturbed rainforest (magenta) in western Brazil's Rondonia state is shown in this false color composite of a Landsat satellite MSS image taken in 1975 (path 230, row 69). The light areas (cen represent natural clearings. The area covered by a single image is 185 x 185 kilometers—34,000 k roughly equal to the combined area of Maryland and Delaware.

By Alex Tait/Equator Graphics. Produced for USAID by the Environment and Natural Resources Information Center (ENRIC). ENRIC is a project of Datex, Inc., Arlington, Va.



1990

This second Landsat image (TM) of the same area taken in 1990 reveals the dramatic conversion to agricultural landuse that occurred in just 15 years and the accompanying deforestation. One field alone (top, center) measures 30 kilometers on its longest side. Great numbers of smaller holdings are seen adjoining local roads at center right. The area framed in white corresponds to the enlarged scene shown inside the front cover.

Satellite Based Forest Monitoring: A Review of Current Issues

J.P. Malingreau, Institute for Remote Sensing Applications, Joint Research Centre, (Va), Italy

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Satellite Based Forest Monitoring: A Review of Current Issues[1]

J.P. Malingreau, Institute for Remote Sensing Applications Joint Research Centre, ISPRA (Va), Italy

Introduction

Rapid changes in the forests of the world and the increased awareness of the critical environmental role played by those ecosystems have made urgent the development of an improved understanding of the nature, distribution, and functioning of the forest cover of the world. Forests are important natural resources which provide for the daily needs, sometimes survival and well being of large populations; their sustainable exploitation requires at the very least a good assessment of their potential for providing the required services without undergoing an irreversible degradation process. The need for establishing better accounting procedures for monitoring ongoing changes in vegetation canopies and for evaluating their impacts at various scales is thus considered as a major requirement in support to long-term economic policy as well as to the emerging science of global change. Space observation techniques have contributed for close to twenty years to local and national forest inventories. They are now increasingly called on to provide regular assessments of changes in forested areas at scales ranging from national to global. Despite obvious limitations, they are now expected to provide the main data source for regular monitoring of the world forests.

Regular monitoring of world forests will be by means of space observation techniques.

The International Space Year 1992 provides a good opportunity to take stock and better chart the future of earth observations from space to the service of mankind. The World Forest Watch Conference will give ample opportunity to discuss and evaluate current achievements and shortcomings. This paper will therefore not be an exhaustive technical review of the proposed approaches; these will hopefully be forthcoming from the individual paper presentations. Here, the intention is mainly to identify and discuss the main issues related to the use of remote sensing technologies for forest monitoring. The institutional aspects of this particular application of remote sensing are discussed in a companion paper (Justice, 1992).

Man has always shown an ambivalent historical relationship with the forest; conservation and exploitation, the two extreme ends of the spectrum continue to strongly colour the appreciation of the role of the forest in local economies, national development, environmental protection, global change studies, etc. It follows that requirements for facts and figure about the forests are as varied as opinions and positions on the issues. Needs are as complex as the forests resources themselves, "bewildering in their extent and complexity." Suffice it to mention here the imprecision surrounding the term "deforestation" or even the disagreement as to what constitutes a "forest cover." Furthermore, these requirements do not necessarily follow the classical division between site specific and global needs. Turning to space data collection platforms, we have to ask ourselves how these much-

1. Published in Proceedings of the International Space Year 1992 World Forest Watch Conference, May 27-29, 1992, São José dos Campos, Brazil.

vaunted techniques of today and tomorrow can support an information system capable of answering such a spectrum of needs. The question is especially relevant if one keeps in mind that remote sensing techniques can only measure the spatial distribution of a few simple surface physical parameters and changes thereof.

An additional complexity is attached to any attempt at defining needs for data in the field of forest monitoring; it is related to the fact that most information requirements are naturally expressed at "human scales," that is, those which correspond most directly to visual observations or measurements on the ground. Forest classifications schemes reflect such perspective as they are based upon criteria such as privileged composition and vertical structure. These parameters are obviously not directly measurable from space sensors, *a fortiori* from those working at coarse ground resolutions. One can thus, at the outset, question the relevance of orienting remote sensing analysis only toward the search, by inversion of a spectral signal or otherwise, for known ground features (i.e., a known forest class). There may be, instead, novel information on the nature and dynamics of the forest cover imbedded in the data set, information linked to the spectral and spatially integrating nature of the measurement. Research should obviously find here a privileged field of investigation. Today, most of the "common" needs expressed with respect to forest cover form a limited group of basic information items. Increasingly, however, sophisticated users, like those investigating problems related to sustainable forestry practices or the role of forest biomass in biogeochemical cycles, will address more complex questions which have to be examined with novel data analysis approaches.

The present review will thus start with an summary description of the spectrum of remote sensing instruments currently available, followed by an examination of the current approaches used in vegetation classification and parameterisation. The main characteristics of what could constitute a global forest information system are then described.

The Technology

Space based earth observation technology applicable to forest inventory and monitoring is fairly well known and there is no need to dwell here on the characteristics of the current sensors. The Landsat Multispectral Scanner, Thematic Mapper, the SPOT Multispectral and Panchromatic instruments, the Japanese Marine Observation Satellite , and the NOAA-AVHRR (Advanced Very High Resolution Radiometer) sensors form the nearly complete list of so-called operational earth observation instruments. The Synthetic Aperture Radar of the ERS-1 satellite has been recently added to the panoply, although its application to vegetation studies is still at a development stage. Extensive literature on the use of satellite for forest surveys exists (for a review, see Photogrammetric Engineering, Special Issue, 1990). The presentations made at the present conference testify again to the enormous vitality of this particular sector of remote sensing applications. A series of' issues regarding current and future use of those sensors is now discussed; see also Table 1.

High resolution sensors

Landsat MSS, Thematic Mapper, and SPOT Multispectral instruments, the high resolution instruments (10-80 m resolution), are among the most commonly used data sources for forest mapping and change detection at the local to national level. Many countries have, therefore, embarked upon intensive analysis of such products. Most of the analyses, outside research, are carried out visually on enhanced photographic products. Increasingly, wall-to-wall acquisition of high resolution data sets are being assembled and the activities of Brazil are noteworthy in this respect. By combining a relatively cheap reproduction technique (i.e., colour composite or even black and white single channel prints) with labor-intensive analysis, exhaustive inventories of the forest domain of large regions can be covered. Proposals are now made to cover the tropical forest portions of other continents such as Africa and Southeast Asia with "historical" MSS data in the framework of the NASA Landsat Pathfinder activity. The Forest Image Catalogue of Europe presented in this Conference is another application of the extensive use of high resolution data.

Landsat MSS, Thematic Mapper and SPOT multi-spectral instruments are principal high-resolution sensors (10 meters to 80 meters).

This trend—namely, large scale applications of high resolution data sets—has several implications for the future: 1) It implies that classification schemes will be progressively imposed via the exercises themselves. If, indeed, the use of high resolution data is the practical way to progress toward a regular monitoring of the world forest at regional scales, the classification will have to take into account not only the information needs (see section below), but also the capabilities of the remote sensing technique in terms of class or attribute identification. 2) If the high resolution is to become a norm in vegetation monitoring, the pricing of the data themselves will have to be such that the exercise can be affordable with an adequate frequency. The role of remote sensing in providing forest information as a public good, is to be reemphasized at this point because it should impinge upon the controversy surrounding commercialization trends. Pricing questions will be even more critical when the large scale exercises move from an approach based on visual analysis of photographic products to one relying upon a computer supported digital analysis. 3) Systematic and exhaustive coverage of large forested areas require that special attention be given at the satellite management level to maximize the probability of acquiring the full data set at the required frequency.

Complete wall-to-wall coverage with high-resolution imagery is expensive.

High resolution data are also used as mapping base for inventories since cartographic accuracies can now be obtained to satisfy mapping requirements down to 1/50,000 scale. Change detection through the use of multidate imagery is another important field of application of the high resolution data sets. Change detection capabilities depends upon 1) the relative positioning accuracy of the images taken at two different dates, 2) the radiometric contrast between the pre- and post-change features and 3) the size of the transformation taking place. Since change detection using low resolution data set is limited to situations where drastic and large scale transformation are taking place, high resolution data—with a resolution similar to Landsat MSS or better will always be needed for measuring more diffuse and complex transformations.

High resolution data will always be needed for measuring diffuse and complex changes in forest cover.

The high resolution data also play an important role in the interpretation and validation of low resolution data. The scale difference between low resolution data and field observations requires this intermediate level of analysis. At regional or global levels, field verification is most difficult and the high resolution data then becomes the reference. This point is discussed further with reference to the low resolution data analysis.

The high resolution data images are also used as part of a multilevel sampling strategy. For example, in the method proposed by the FAO, Landsat data are used as units of analysis in a worldwide change assessment exercise based upon a combined stratified and proportional to size random sampling (see table).

Low resolution sensors

Low resolution data, such as those provided by the NOAA-AVHRR instrument (1.1 km resolution), have found an increasing field of application in forest monitoring in the last few years. Indeed, they appear to provide a unique compromise between ground resolving power, vegetation related information content, frequency of acquisition, and breadth of geographical coverage. Currently, the AVHRR data appear to be the immediate and short term solution to the generation of a comprehensive global land coverage. Several applications presented in this Conference are directly based upon the analysis of the low resolution AVHRR data. While a number of problems still plague such application, it appears clearly that, although poorly suited for forest monitoring, the AVHRR will provide the main operational source of data on forest cover at continental to global scales for several years to come. Several large scale projects have, therefore embarked upon the acquisition and analysis of "wall-to-wall" AVHRR data sets. The TREES Project (Myers, TREES, 1991) is currently collecting a suitable AVHRR data set (1989-1992) for forest analysis over the entire tropical forest belt of the world; the completion of the first phase of the exercise is planned for mid-1993. Regional exercises of similar nature are under progress in various national or international institutions (UNEP-GRID, NASA-GSFC, Woods Hole Research Institute, etc.). The IGBP-Data and Information System has initiated the collection of a global AVHRR 1 km data base for land applications (IGBP,1992). The work is progressing under the technical leadership of NASA, NOAA, USGS-EDC, and ESA. The experience gained in the analysis of AVHRR data for forest monitoring and in the preparation of the above mentioned large-scale projects bring about a series of important issues:

AVHRR 1 km resolution data are the immediate solution for global land coverage.

- AVHRR 1 km full resolution data come from local receiving stations with the exception of limited on-board recorded data sets; a global coverage therefore requires the networking of stations distributed around the world. Truly global data sets already exist under the sampled format at a nominal resolution of 4 km (GAC product). This coarser resolution is considered insufficient for the need of forest mapping and inventory (see, however, remarks on seasonality analysis in the section below).

- Substantial efforts are required to preprocess AVHRR data sets for geometric and radiometric correction and calibration. With respect to forest

mapping and monitoring where the accurate measurement of canopy physical parameters are not required, this preprocessing can be somewhat reduced but still bears heavily on the logistics of AVHRR analysis. The five channels of the AVHRR are to be exploited for optimizing the analysis (NDVI alone does not provide adequate information).

- For most forest mapping applications, a major operation in the AVHRR methodology is the search for acceptable images through a screening process. This burdensome activity involves the painstaking display and evaluation of every daily orbit pass. It is only through mosaicking that large areas can be covered; cloud cover, haze, smoke, and other acquisition problems can make the search for suitable AVHRR passes a time consuming task. An assessment of the usefulness of the AVHRR approach for forest monitoring should not be made before this screening exercise has been fully conducted. Quick looks as produced by space agencies or GAC time series of individual channel images can facilitate the screening.

- The analysis consists essentially in the local search for contrasts between vegetation forms in one or more spectral channels. There is obviously no methodology which can be applied across the board since the reflectance characteristics, spatial mosaics of vegetation, atmospheric effects, seasonality effects, etc., introduce considerable variability across regions.

Seasonal variations in vegetation can be captured by AVHRR.

- The seasonality of tropical vegetation is an important classification criteria and a fundamental ecological characteristic. When captured by time series of AVHRR data, seasonal variations are useful keys to the identification of the vegetation formations. This approach can be based upon sets of AVHRR 1 km data obtained at crucial time windows during the season or upon more continuous time-series of vegetation index data such as those derived from the GAC product (see section 3).

- Additional clues to the detection and identification of deforestation processes can be obtained via the use of thermal channels which can detect the presence of fire. Burning is a common way to clear the land after the cutting of vegetation in many parts of the world. Burning patterns as shown be satellite data (active fires or burn scars) are apparent on the middle infrared AVHRR channels.

Burning patterns as shown be satellite data (active fires or burn scars) are apparent on the middle infrared AVHRR channels

- The high resolution data play an important role in the validation of low resolution data. Given the scale disparity between the AVHRR resolution and coverage and that of field verification, it is useful to start with a comparison with the high resolution data sets provided by the Landsat MSS, TM, or SPOT. Inversely, the global perspective afforded by the AVHRR can help in the sampling design used for the selection of sites for higher resolution analysis (stratification and purposive sampling). The AVHRR analysis is considered "validated" not only if the classification information is confirmed (or infirmed) but also if a coefficient is applied to the low resolution measurement to take into account the effective forest cover in the 1 km pixel (mixed cover). This type of analysis is usually difficult to perform on a pixel basis and, usually, one has to resort to a regional validation (using, for example, concepts

of disturbance areas, fragmentation, regional forest/nonforest patterns). Clearly, there are still significant methodological gaps in combining the information derived from sources operating at different resolutions and geographic coverages.

Remote Sensing Measurement of Forest Parameters

Three groups of forest parameters form the core of current requirements: they pertain to the vegetation classification, to the changes in vegetation cover, and to surface physical parameterisation.

Mapping vegetation by remote sensing

Remote sensing classification of vegetation is based on spectral measurements only.

This represents the most common operation using remote sensing observations; it consists in separating spectral data provided by the sensors into groups which can be associated with physiognomic vegetation classes. While the classes are often identified on the base of floristic composition, structure, and ecoclimatic zone (i.e., ombrophilous evergreen rainforest), remote sensing classification will be based upon a set of spectral measurements only. The classification will be accurate insofar as those measurements are unambiguously associated with a particular vegetation class. While this may be possible for the most contrasted classes (i.e., forest cover and clearings), the level of classification accuracy will vary depending upon the complexity of a particular association of vegetation forms (as for example in successional stages). Given the enormous spatial variability of spectral characteristics of surfaces, and the unique ability of the human brain to integrate spatial patterns of spectral features, visual analysis of spectral data appears to be the most reliable, if not the fastest, approach to the analysis. The vegetation cover of large areas is therefore often studied through a visual analysis of adequate photographic representations of the data (e.g., red channel image and color composites for deforestation measurement of the Brazilian Amazon basin). Internal consistency is usually maintained by using the same individuals or teams of interpreters. Outputs from such analyses are then incorporated in geographical information systems in which they are integrated with other information layers. There is currently a large demand for the products derived from such analyses and several country surveys proceed in such manner. There is, to our knowledge, no proposal for standardizing or automatizing the procedure.

Compatibility of vegetation classification schemes is essential.

A standardization of classification schemes or a least attempts at assuring compatibility between them at the higher level of the hierarchy of classes are essential. There is thus a need for a classification framework with local and national classifications compatible with the requirements at global scales.

Classification problems are quite different when one deals with low resolution data. In this case, there are fewer landscape clues which can be obtained to guide the analysis which relies more on the reflectance or emittance values in a few spectral channels. Questions of contrast between a forest canopy and other cover types determines the easiness with which a formation will be identified. Furthermore, given the large variability associated with spectral characteristics of vegetation cover, there is often a lim-

ited possibility of defining spectral signatures; spectral contrasts alone are used. Some spectral channels will work better in some situations than others. For example, large forest blocks isolated in the middle of an agricultural area will be well identified using brightness temperature contrasts, while primary forest blocks in the middle of secondary and less structured vegetation will be seen as area of lower near-infrared reflectance. The question of resolution arises with respect to the accuracy of positioning the boundary between two cover classes; the impact of the low resolution pixels upon the accuracy of measurements of surfaces depends obviously upon the perimeter/surface ratio of the unit to be identified. High perimeter to surface ratios lead to a thicker boundary zone of mixed pixels and thus reduces the accuracy.

With increasing population pressure on forest resources, growing proportions of "forested" landscapes will be occupied by mosaics of cover types in various proportions and not as in a more recent past by "pure" formations.

It is worth noting that with the increasing population pressure on forest resources, growing proportions of "forested" landscapes will be occupied by mosaics of cover types in various proportions and not as in a more recent past by "pure" formations (which by the year 2000 may be found mainly in plantations and natural reserves). Classifications have not properly addressed the identification of such degraded ecosystems; the problems associated with the classification of woodlands and tree savannah illustrate such difficulties.

Detecting and measuring changes by remote sensing

The transformation of the forest cover into another cover type is the result of the deforestation process. Such transformation can assume many forms, and again the accuracy of change measurement will depend upon the ground resolution and the spectral discrimination between surface features. In theory, change detection using spectral data does not require the preliminary identification of the constituting land cover types. However, the interpretation of changes in ecological or other terms requires that the characteristics of the beginning and end terms are known. Relative evaluation of change can be attempted if one only searches for the disappearance of one class without addressing the problem of identifying the replacement class. This is the case in forest/nonforest classification exercises.

Among the most pressing issues is the definition and examination of the concept of forest degradation.

Changes can be clear or diffuse, slow or fast, creeping or catastrophic. An effective monitoring requires that instruments and procedures be designed with those characteristics in mind. Even so, it will be difficult to ensure that all types of changes will be measured or even detected. Among the most pressing issues is the definition and examination of the concept of forest degradation. The urgency of the topic is driven by field observations around the tropical belt which show that there is a wide variety of deforestation patterns leading to degradation and that some of those patterns are more environmentally damaging than others. Work must now proceed with some urgency on a better characterization of spatial patterns of change at various scales (stand, regional, subcontinental, etc.) and under the examination of observation instruments of various resolutions. A typology of forest/nonforest patterns and of the mechanisms and features of their transformation through time would be highly valuable to better assess parameters related to impacts, sustainability, productivity, biomass, and the like. A

common and structured typology would, in addition, present the advantage of offering a common framework for inventory and analysis.

The FAO Forest Resource Assessment Project has based its change detection methodology upon a stratified random sampling using Landsat TM or MSS data at two dates interval (ten years). The sample covers one tenth of the forest domain. If suitable satellite data are available the entire forested area will be covered in the course of ten years. This approach which does not lead to a spatial characterization of change leads to the production of aggregated statistics on rates. Other approaches to change detection using global AVHRR data set, and a range of ancillary data have also been proposed. They are based on the stratification of the whole tropical forest domain and a focussing on "hot spots" or active deforestation areas in priority for the measurement of change, using higher resolution data sets for those selected areas only (TREES, 1991).

Remote sensing information is greatly enhanced by information on soils, climate, and field observations integrated through GIS.

As is usually the case, the value of any information derived from remote sensing data will be greatly enhanced if its is integrated into a spatially explicit geographical information system. This latter will bring information related to other landscape (i.e., soils, climate, river network, field measurements of biomass, and timber volumes, etc.) or societal characteristics (roads, population densities, migration patterns, etc.) important to understand patterns of deforestation and at some stage to develop capabilities to predict spatio-temporal trends. Geographical information systems are also useful tools for testing hypotheses with respect to possible scenarios of change in the determinants of deforestation. The experience in the use of such integrated GIS Remote Sensing systems is growing and applications will be reported at all levels of analyses during the Conference.

Forest seasonality

Seasonality is a character explicitly used in tropical forest classification; it is mainly related to rainfall patterns (by opposition to temperature-controlled seasonality in temperate areas). While such classification is often binary in the sense that it considers that a forest is seasonal (or semi-seasonal) or not, it avoids the question of intensity or even "facultativeness" of the seasonality character. Seasonality in spectral signal is also an important mapping criteria; yet, time series of satellite data will usually show gradients of seasonality more than a clear-cut distinction between evergreen and deciduous classes. Furthermore, satellite data taken over a long period of time show that interannual variability must also be taken into account in the classification.The enormous spatio-temporal variability of the satellite signals is more particularly seen in parts of southeast Asia or Africa where altitudinal and latitudinal gradients control the distribution of seasonal formations. The spectral distinction between a dry dipterocarp and a mixed deciduous forest of northern Thailand and Myanmar is, for example, notoriously difficult even with high resolution data sets.

Seasonal change and disturbance affect the spectral "behavior" of vegetation.

Time series of satellite derived vegetation index data are now available for over ten years from the GAC product; they show a continuum of signal amplitudes as ones goes from the typical "evergreen" to the more sea-

sonal formations (Malingreau, 1990). Such canopy related information is relevant for a series of analyses: seasonal flushes affect evapotranspiration, primary productivity, and geochemical cycles. Drought and stress related to seasonal effects are also an indication of forest susceptibility to fire, a common agent of land conversion in the tropics. Clearly, there is a host of information in time series of remote sensing data on forest canopies which has been little exploited so far, be it for classification or process studies.

The study of the woodlands and seasonal forests has received less attention from the research community than temperate or closed rainforest.

The detection of changes in the forest canopies, such as those associated with climate change or degradation will be possible only if the anomalies can be detected in a typical spectral "behavior" of the particular vegetation class. For example, preliminary indications are that the transformation of an evergreen forest cover into a mixed mosaic of regrowth vegetation types will affect the seasonal vegetation index signal in the direction of higher amplitude and higher sensitivity to weather conditions. Such hypothesis, if confirmed, offer a useful way to study forest degradation. Understanding the seasonality and fragmentation of vegetation cover is, therefore, indispensable to progress in the study of the woodlands and seasonal forests which have received less attention from the research community than temperate or closed rainforest. Yet, most of the exploitation of woody biomass is taking place in those mixed tree-shrub-grass ecosystems.

The application of these methods to the continuous monitoring of forest cover can only be achieved if a continuous data acquisition and processing system is established. As already indicated this seems currently possible, albeit with appreciable logistic difficulties, using the AVHRR 4 km GAC data sets. The TREES project will integrate the map results from the 1 km AVHRR analysis with the seasonal information derived from the GAC time-series analysis.

Toward an Operational System of Forest Monitoring

The development of remote sensing techniques for forest monitoring shows various levels of maturity, depending upon the instrumentation and the scale of application. While some aspects of high resolution image analysis are fairly straightforward, those related to large-scale coverage or low resolution image exploitation arc in the development stage. The last five years have shown, however, that prospects are broader than what had been foreseen only a few years ago. New dimensions are clearly brought into the analyses by the growing availability of extensive coverage with high resolution data sets (Landsat and SPOT) and by the extensive and repetitive coverage with low resolution data sets (AVHRR). The temporal dimension of those analyses has been radically revised by the appearance of projects willing to invest in the processing and analysis of historical data sets (for example, NASA Landsat Land Cover Change Pathfinder Project) and in the collection and handling of long-term frequent measurements over large areas (for example, IGBP improved and global land cover data sets).

These activities must be sustained and expanded in order to move towards an effective satellite-based global monitoring system. The main features of such a system can be summarized as follows:

- it must incorporate global and national objectives, analyses and results must be amenable to "nesting" at different scales,

- validation must be a constant concern and built in the operational procedure,
- results of the remote sensing analysis must feed into a more comprehensive forest information system,
- the system must support forest planning and management as well as scientific objectives,
- it must include a continuous monitoring system component providing an "alarm function" as well as capabilities to rapidly focus on areas of active change (hot spots, active fronts, pressure areas, etc.), and
- it must include a regular extensive coverage of all forest areas by high resolution instruments for measuring change within an accuracy of ten percent.

An "Advanced Forest Information System" would include a continuous low resolution monitoring component that would signal 'hot spots' to be observed with high resolution sensors.

The remote sensing components of such a forest assessment system are summarized in Figure 1 and briefly described below:

Low resolution component

1. Continuous and wall-to-wall coverage of all land surfaces with appropriate spectral channels (at a minimum red, nir and thermal), at a medium to coarse resolution (250 to 1 000 m) for a general monitoring of vegetation distribution and conditions.

2. This global system should be capable to distribute data to local users for the area in range of a station and to assemble in a central location a complete archive of all acquisitions (non-sampled). The AVHRR experience can be used as a model.

3. This global analysis is to be validated by high resolution data and field verification, the design of which should be established via statistical procedures. Research and development can contribute to the drawing of specifications for improved information extraction procedures at low resolutions (modeling).

4. High resolution systems should be on standby to focus on area of active deforestation as detected by a so-called alarm system based upon low resolution satellite and other, more conventional, data sources.

High resolution component

1. A regular (every three to five years) comprehensive assessment of forest cover is to be made using high resolution data sets such as Landsat TM. National and local mapping and monitoring activities contribute to such an objective by being integrated into the global assessment (for example, via regional centers). This requires a level of agreement on a hierarchical classification amenable to progressive generalization.

2. High resolution data sets should be made increasingly available in a distributed fashion; if commercialization can contribute to such dissemination it must established a price structure which makes it possible. Better access also means financial conditions facilitating the access.

3. A geographical information system is a major component of the exercise leading to what we have labeled here an Advanced Forest Information System.

Conclusion

The urgency of acquiring precise and up-to-date assessments of forest conditions around the world is clearly exerting a strong pull on remote sensing techniques. Forests are widely dispersed, complex and dynamic systems which are amenable to the kind of observations provided by orbital sensors. Remote sensing techniques have already contributed to improving our knowledge of those ecosystems. Efforts must now concentrate on the integration of the experience and results into truly global and multilevel exercises. The joint availability of low and high resolution sensors, each with their particular technical characteristics and mode of operation is a fundamental requirement for establishing operational observation systems. Furthermore, the level of sophistication of the applications should progressively match the complexity of the host of problems raised by defining a sustainable path toward the exploitation of the world forests. If technology and applications must continuously be improved, enhancing institutional support and developing adequate scientific expertise are also high on the priority list.

The International Space Year World Forest Watch has stimulated a renewal of interest around the world in issues surrounding the continuous assessment of forest resources. The ISY-WFW programme should now continue.

Acknowledgements

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Figure 1: Remote Sensing Components of a Forest Assessment Information System

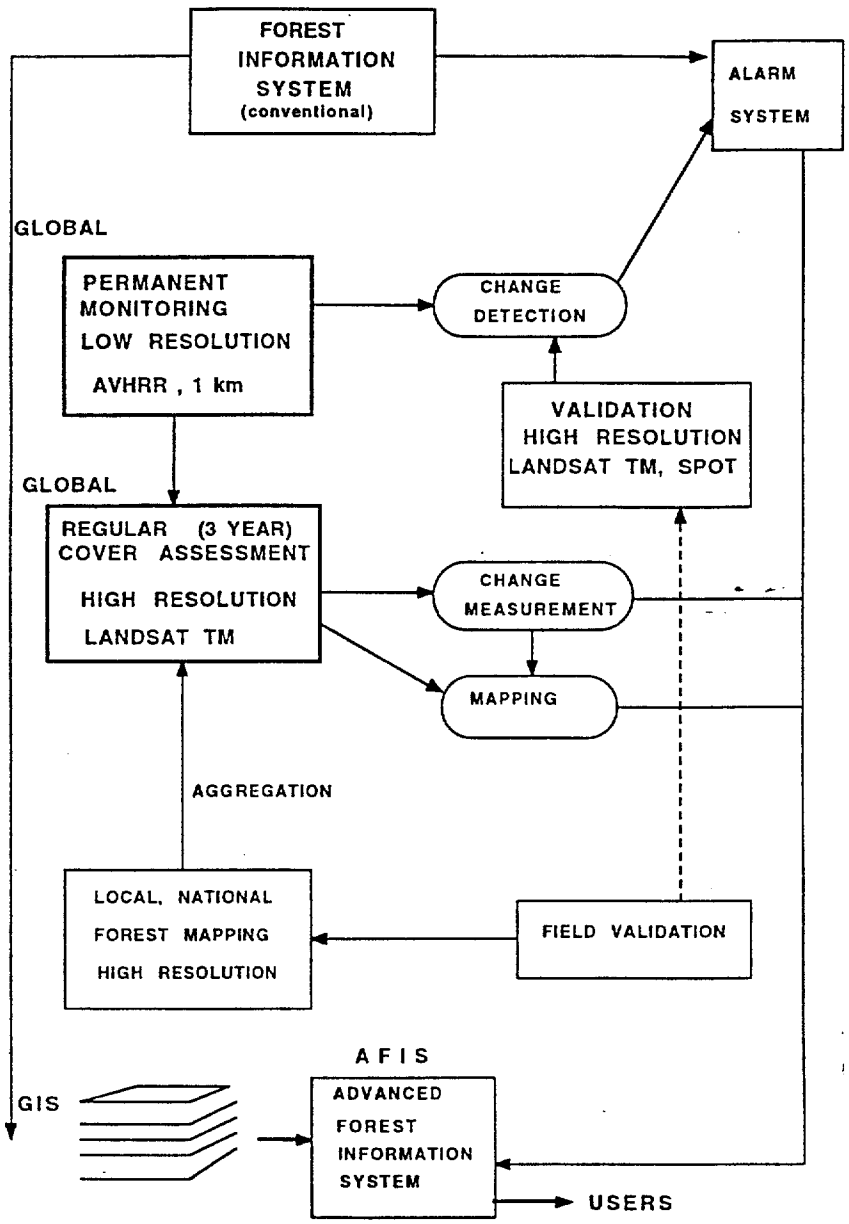

Table 1: Current Technology and a Summary Assessment of Its Relevance for Forest Monitoring

Available Technology:

1. **High resolution sensors (< 100 m resolution) (essentially landsat mss, tm, spot, mos) four functions**
   - local to national forest inventories
   - validation of low resolution analyses
   - sampling for change detection
   - trend toward wall-to-wall coverage

2. **Low resolution sensors (> 1000 m resolution) (essentially noaa - avhrr 1 km lac/hrpt) three functions**
   - wall-to-wall mapping, basic classes
   - stratification frame for sampling
   - change detection, "alert system" annual and interannual (directly or through indicators)

3. **Microwave (spaceborne sar) applications to vegetation monitoring under development**

Assessment:

1. **High resolution**

Advantages
- coordinated reception network
- adequate spectral range for classification of major vegetation forms with limitations in secondary vegetation identification
- may provide key cover parameters such as fractional cover
- lend themselves to digital and visual analysis on photographic products
- adequate ground resolution for local to national mapping requirements (1/25 to 250,000 scales); topographic mapping capabilities (spot)
- allows identification of major deforestation patterns
- good registration and radiometric normalization is feasible allowing change detection. long-term studies are possible (1972-92)
- coverage is in principle global

Drawbacks
- volume of data is very large
- level of detail may be excessive for intended application: need for synthesis, generalization
- there is no systematic acquisition policy for adequate forest coverage (comprehensiveness and frequency)
- acquisition frequency cannot be guaranteed for change detection over large or dispersed areas
- cost is prohibitive for large area coverage (data acquisition and analysis)
- developments are needed in middle infrared and thermal spectral range for process studies

Table 1 cont.:

Current Technology and a Summary Assessment of Its Relevance for Forest Monitoring

2. Low resolution

Advantages

- coverage is truly global (4 km gac, and in near future 1 km hrpt/lac), wall-to- wall can be attempted
- reception, archiving is distributed and centralized
- high frequency of acquisition increases probability of clear coverage and allow the establishment of time series
- use is regional and global
- long-term studies are possible (1982-92)
- spectral channels are appropriate for generalized radiance measurements relevant to vegetation characteristics (photosynthetic activity, structure)
- thermal channels are available for biomass burning identification and canopy brightness temperature measurement.
- unique exploration material; experience in its use is growing
- relatively cheap

Drawbacks

- spectral bands selection can be improved
- classification must be compatible with low resolution information
- distributed reception is still necessary for forming a 1 km global product, networking is a must
- large volumes of data to screen
- heavy preprocessing requirements
- poor calibration of instruments
- not suitable for spatial change detection in many cases
- shortage of experienced manpower for handling large data sets and scientific expertise to analyze vegetation at those scales

Satellite Monitoring of Tropical Forests: a Commentary on Current Status and Institutional Roles

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Satellite Monitoring of Tropical Forests: a Commentary on Current Status and Institutional Roles[1]

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Introduction

The International Space Year (ISY) provides an opportunity to review the successes of space technology to monitor the environment and provide information for improved management of global resources and the science of global change. The significance of tropical deforestation in terms of the carbon budget, biodiversity, ecosystem fragmentation, and environmental degradation is now well recognized. Space technology has an important contribution to make to the study and monitoring of tropical forests.

When in the context of the ISY, we assess the contribution of space technology, we can, for example, identify the recent success of the Brazilian Instituto Nacional de Pesquisas Espacias (INPE) in developing a national satellite-based forest monitoring program. We can identify the success of the ISY World Forest Watch (WFW) in providing a forum for discussion of remote sensing forest monitoring methodologies and results. We can identify the development of remote sensing based national forest monitoring programs by the Thai and Indian forest services. We can recognize the integration of remote sensing in a global tropical forest assessment by the United Nations Food and Agricultural Organization (UN/FAO). We could even point to the recent progress in the development of satellite-based microwave systems. However, it would be incorrect to acclaim satellite-based tropical forest monitoring as an unequivocal success. After twenty years of high resolution satellite data we still do not have a comprehensive global assessment of the real extent of the world's tropical forests or their rates of change, that can be used by the science and forest management communities.

Various satellite-based techniques for tropical forest monitoring are available and will be discussed during the WFW Conference. However, most of the national forest agencies within the tropics do not have the means to undertake operational satellite monitoring at a national scale. Although the technology has been available for almost two decades, until recently there has been no concerted effort to undertake comprehensive tropical forest monitoring on regional or global scales. There has been no initiative to coordinate the various agencies needed to implement a comprehensive program with sufficient resources to be effective. There are several major obstacles to achieving the objective of a global tropical forest assessment. With the current international focus on the global environment and development, it is time to review the previous experience and current status, identify the major obstacles to advancement, and to design and implement a strategy to provide an effective operational satellite-based global tropical forest monitoring program.

Until recently there has been no concerted effort to undertake comprehensive tropical forest monitoring on regional or global scales.

1. Published in "Proceedings of International Space Year 1992", World Forest Watch Conference, May 27-29, 1992, São José dos Campos, Brazil.

Information Needs

It would be naive to imagine that satellite data can satisfy all our information needs associated with tropical forests; clearly they cannot. There is a range of information needs from different communities and at different spatial scales from local to global.

At the local scale the needs of the global change science community differ from the forest management community. Forest managers require timber inventories, for example, before and after logging, and are concerned largely with the commercial assessment of the forests. At this scale, the science community is concerned, for example, with obtaining data on biomass density, gas fluxes, species composition, soil erosion, and ecosystem processes. Satellite data have little to offer at this scale and the data needs are met usually by a combination of field data and large- scale aerial photography. There is some possibility that the highest resolution satellite data such as the 10m data available from the System Probatoire pour l'Observation de la Terre (SPOT) may provide useful information but the contribution will be limited, as compared to the overall information needs.

At the national and global scale there is considerable overlap between the information needs of both forest managers and scientists. At the national scale forest managers are concerned for example, with forest type mapping, forest resource planning and forest reserve monitoring. They are also mandated with providing regular national assessments of forest area and estimation of rates of deforestation. The international forest community is interested in information on the state of national forests in a development assistance and commercial trading context. At this scale, the science community is concerned for example with carbon budget analyses incorporating the extent and rates of deforestation and regrowth, the extent of ecosystem fragmentation, the impact on biodiversity and regional hydrological modeling.

High-resolution remotely-sensed data can be used to augment the conventional methods for forest assessment.

High resolution remotely-sensed data can be used to augment the conventional methods for forest assessment at the national scale and, in many cases, may be the only way to derive a timely estimate of forest real extent and rates of deforestation. Similarly, they can be used to assist in the mapping of broad forest types. It should be noted, however, that when using optical sensors, there are limitations to using high resolution data to detect selective logging or forest degradation which does not significantly alter the appearance of canopy cover.

There are limitations to using high resolution data to detect selective logging or forest degradation.

At the global scale the international community is concerned with global trends in an economic and, more recently, an environmental policy context, and the interest of the national level forest management community is less obvious. The United Nations Food and Agricultural Organization (UN/FAO) has the mandate to conduct a global forest assessment every ten years. To date, the FAO assessment has been the source most commonly used for obtaining global forest information. The approach adopted by FAO has been to aggregate the available national information.

At the global scale, the science community is concerned for example with the role of tropical forests in global climate and biogeochemical cycle modeling and global biodiversity assessment. They are also concerned with the evolution of tropical forests as a result of different types and intensities of land use and the potential impact of climate change on the tropical forest ecosystems. In summary, at the national and global scales both science and management communities need an accurate assessment of the real extent and spatial distribution of forest, a description of forest type, the rates and spatial distribution of deforestation, and future trends.

At the national and global scales both scientists and forest managers need an accurate assessment of the areal extent and spatial distribution of forests, a description of forest type, the rates and distribution of deforestation, and future trends.

The general sparsity of information has resulted in the science community using the only available data, which are often out-of-date, summarized by political units and largely inadequate for their purposes. For example, a recent study used the FAO 1980 forest statistics to estimate regional trace gas fluxes from the tropics (Hao, et. al., 1990). The FAO data had neither the geographic specificity or the accuracy statements to permit reliable estimates to be derived.

If we are to go beyond a simple tracking of the progress of deforestation and move towards effective regional planning or predictions of future carbon fluxes, we need to develop models which are spatially explicit. A series of regional base maps of the forest area with the spatial extent of deforestation and regrowth taken at three successive time periods would provide the starting point for such modeling. However, the modeling of future trends in deforestation is a major challenge, requiring an interdisciplinary approach. Socioeconomic data, including population dynamics, macroeconomics and infrastructure are required inputs to more sophisticated predictive models. Unfortunately, the spatial data sets needed to develop such an information system are also very poor for the tropics.

Past Experience and Current Status

In the following commentary only tropical forest monitoring at national and global scales which can be addressed using satellite data are discussed.

National scale

Estimates of the real extent of tropical forests and the rates of deforestation are currently being made by a number of different groups resulting in statistics which range from wild or educated guesses with no error estimate to satellite-based estimates with a known error. The different approaches and classification schemes result in conflicting or incomparable estimates and confusion in the literature.

Conflicting or incomparable estimates exist for the extent of forest cover and the rates of deforestation in different countries...

In some cases national forest services are able to provide timely estimates of known accuracy. In other cases the task is taken up by those with the means to access and interpret the satellite data. In some cases there is duplication of the work with little or no collaboration. For some countries there is no reliable current assessment.

The process of developing and implementing a satellite-based monitoring system involves several interrelated steps (Figure 1). Effective monitoring of the tropical forests will require several organizations and agencies performing the different steps and working in concert. Difficulties in communication and funding and differences in institutional capability and objectives have resulted in very few concerted efforts. In some cases national space agencies are undertaking the complete sequence of data acquisition, analysis, interpretation, and evaluation. Although this may provide the most direct means of generating the data, the interpretation could benefit from the local expertise of the forestry community. The resulting data may serve some of the immediate needs of the science community but does not necessarily help to transfer the technology into the hands of the forest management agencies which ultimately must undertake the task of timely national forest monitoring and improved resource management. A more satisfactory approach is to have the space agencies working in close collaboration with the forest services taking responsibility for different components of the monitoring program.

There have been very few concerted national efforts to monitor and assess forests with satellite sensors.

Global scale

As part of the 1980 Tropical Forest Assessment, a small pilot study was undertaken by the FAO in conjunction with the United Nations Environmental Program (UNEP) Global Environment Monitoring System (GEMS) using Landsat data to map the forest cover of Togo, Benin, and Cameroon. The study provided new primary spatial data on forest extent but was not extended to cover other regions of the tropics with poor forest statistics. A decade later, the FAO 1990 Tropical Forest Resource Assessment Project reviewed the role of satellite data and decided to incorporate satellite data interpretation as an integral part of their methodology. Both wall-to-wall mapping using the National Oceanographic and Atmospheric Administration-Advanced Very High Resolution Radiometer (AVHRR) 1 km data and a global sampling of deforestation rates using Landsat image pairs were adopted by the project. The 1990 Assessment, in cooperation with other organizations, has supported AVHRR 1 km forest mapping for West and Central Africa and is currently in the process of coordinating the interpretation of 117 sample Landsat image pairs by selected national forest agencies. The 1990 Assessment consists of a compilation of national statistics supported by sample satellite analyses. Considerable effort was given to designing a global methodology and a sampling strategy using Landsat to provide representative global statistics. It is expected that this approach will provide considerably improved global estimates over the 1980 Assessment. It will not, however, generate the comprehensive spatial assessment needed for national forest management purposes or for such science analyses as regional carbon modeling.

The FAO 1990 Tropical Forest Resource Assessment Project reviewed the role of satellite data and decided to incorporate satellite data interpretation as an integral part of their methodology.

The 1990 Assessment Project has recently submitted a proposal to FAO to expand the project to a Continuous Forest Assessment. The proposal adopts the current methodology, sampling one tenth of the tropical forests each year, with the additional support of three regional centers. The proposal has been accepted by FAO and is currently seeking donor support.

In the absence of a complete wall-to-wall assessment, the Joint Research Centre (JRC) at Ispra of the Commission of the European Community (CEC) has initiated a global AVHRR 1 km forest mapping project for the tropics. The project called TREES will analyze data from a number of AVHFRR ground receiving stations and is planned for completion in 1993.

Recently, the United States National Aeronautics and Space Agency (NASA) has initiated a Landsat Land Cover Change Pathfinder Tropical Deforestation project which will provide multiple wall-to-wall Landsat analysis for the humid forests of South America, Central Africa, and Southeast Asia. Historical data will be compiled and new data will be collected providing an assessment for three epochs (1972-73, 1985-86, 1990-92). One of the objectives of this project is to make these data widely available as part of the EOS Pathfinder activity.

The primary obstacle to the use of high-resolution satellite data for national-scale monitoring is cost.

Current Obstacles to Progress

The current obstacles to developing a comprehensive satellite-based tropical forest monitoring program can be divided into three categories: data problems, institutional obstacles, and technological limitations.

Data problems

The primary obstacle to the use of high resolution satellite data for national-scale monitoring is cost. Commercialization of high resolution data in the mid-1980s, and the associated increase in data cost and acquisition fees, has effectively prohibited extensive use of these data. This is particularly the case for the forest management community of the developing world which is severely constrained in terms of funding.

For large areas of the tropics, historical data coverage is sparse.

Data availability is also a problem for large parts of the tropics. In the early 1970s, the United States Geological Survey (USGS), which was managing the Landsat program, attempted to provide complete one-time, global cloud-free coverage. Following commercialization, images were acquired by Earth Observation Satellite Company (EOSAT) and SPOT Image, in answer to specific data orders. The small number of requests has meant that for large areas of the tropics, historical data coverage is sparse. In regions with ground receiving stations, data coverage is better and the acquisition policies have commonly resulted in systematic and comprehensive coverage. With the proposed changes in the satellite access charges this systematic coverage by the ground stations may be reduced. Access to, and quality of the Landsat Multispectral Scanner System (MSS) from the early 1970s, are also problematic. The early MSS data were stored by the United States Geological Survey Eros Data Center (USGS/EDC) on wide-band video tapes. Although part of that archive was transcribed onto a newer format, EDC no longer supports the equipment to read these early data and some are now inaccessible in digital form. Those requiring data from this part of the archive are obliged to use photographic products. In addition, the quality of the Landsat 1 and 2 MSS data can present problems for interpretation. These data exhibit

detector banding and dropped lines which were removed in subsequent missions by improvements to the detector.

The problem of data availability is compounded by persistent cloud cover in some parts of the tropics. The combination of infrequent acquisition and persistent cloud cover makes the historical archives in some areas very patchy. Microwave imaging systems could provide some improvement over optical sensors but currently their data availability is limited. There have been a few successful airborne radar campaigns and the remote sensing community has some experience with microwave data for some parts of the tropics. However, in general, the forest services have had little exposure to microwave imagery.

The European Resource Satellite (ERS-1) and the Japanese Earth Resources Satellite (JERS-1) will provide microwave data for parts of the tropics but will require a significant amount of research and development to use them for operational forest monitoring. The digital preprocessing of microwave data is computer intensive and at least for the near future will have to be undertaken at specialized facilities. These data will also be distributed through commercial channels and the cost of processing will be prohibitive for large area analyses.

It is still difficult to obtain a complete picture of data availability for some areas of the tropics.

Access to the metadata on satellite data availability has improved over the last five years through the activities of such groups as the Committee on Earth Observation Systems (CEOS), the Landsat Ground Receiving Station Working Group (LGSWG), and development of user- oriented personal computer-based inquiry systems such as the USGS Global Land Information System (GLIS). However, determining data availability for large areas over from the entire historical record remains a labor-intensive task. EDC has taken the initiative of compiling a complete global metadata archive of all available Landsat data. Participation in this project by ground receiving stations has been incomplete and there is often a considerable time lag in the receipt of information on data availability from some stations.

It is still difficult to obtain a complete picture of data availability for some areas of the tropics. Individual ground stations need to be contacted for metadata and the data are not always in digital form. It is not always obvious to those wanting information on satellite data availability as to where they should address their requests.

Cloud cover estimates provided in the metadata can be misleading and different ground receiving stations have different quick-look products and quality. From the author's experience, the quality of SPOT quick-look products, for example, can be inadequate to determine data utility for tropical forest monitoring.

Data formats from the various satellite systems and receiving stations are often different causing unnecessary problems for the user community. The Committee on Earth Observing Systems is currently addressing data format questions and needs to be made aware of the range of format problems facing the user community.

The last link in the data distribution chain can also present an obstacle to rapid receipt of the data. Quite often data delivery is delayed by inefficiencies in the global network of postal or courier services. Customs regulations have been known to add a considerable delay to the distribution of satellite data.

Institutional obstacles

Institutional obstacles prevent the implementation of a concerted effort between agencies. Agencies with the mandate for forest monitoring are in some cases incapable of implementing the task. Sometimes there is direct competition for funding for satellite-based resource monitoring which results in an unwillingness for different ministries or agencies to cooperate. One of the biggest problems is that the national forest agencies often do not have the capacity to provide timely, comprehensive mapping and monitoring of their forests. They are severely limited in funding and the resources needed to fulfill the task. The satellite data are too expensive to acquire complete coverage and forest agencies do not always have the necessary GIS or remote sensing data processing and analysis capability.

Agencies with the mandate for forest monitoring are in some cases incapable of implementing the task.

For some of the tropical countries with large expanses of forest, the field experience of the forest services may be limited only to those areas where they have undertaken detailed inventories. In some cases they do not have the staff with the necessary training to interpret satellite data.

The means for a coordinated and sustained institutional underpinning for the national forest agencies in the tropics is unclear. In the late 1980s the World Bank and FAO developed the Tropical Forest Action Plan (TFAP) which was to provide the necessary long-term support for the forestry sector. Now the Bank has abandoned TFAP and has embarked on its own program of forestry sector loans. The newly created Global Environmental Facility (GEF) also has a series of country projects in the tropics in various stages of design and implementation. Donor coordination is still a major challenge.

In some cases the national forest services and national remote sensing agencies limit access to the aerial survey imagery used in the creation of forest maps. Forest agencies in the tropics are currently receiving support from a variety of development agencies and international sources. Development agencies are often territorial and unwilling to distribute information on their current and planned projects or the resulting data and information. In some cases the technical support is contracted to private companies with no long-term commitment beyond the duration of their contracts. Development agency contracts often cycle on a two- to three-year period and there is often no institutional funding mechanism for ensuring project support over longer periods. Without long-term institutional underpinning to include staffing, competitive salaries, vehicles, and equipment as well as specific project funding, the national forest agencies will be unable to provide operational satellite monitoring.

One of the roles of regional remote sensing centers has been to provide technical backstopping to national agencies. At least in Africa, the success of these regional centers in supporting the national forest services to establish operational monitoring has been very limited. The continuity of funding and support for these centers has also been difficult to secure.

The operational aspect of regional and global monitoring has, in the past, led to some resistance by research organizations and agencies to address or support a tropical forest monitoring activity. Recent establishment of a tropical deforestation program by NASA has come through recognition that the operational monitoring is necessary to generate the data to address the science questions. If no other organization is providing the data, then the research agencies may have to. The International Union of Forest Research Organizations (UUFRO), which provides a forum for the discussion of forest related research, has yet to address the research and development issues associated with the design and implementation of an operational global tropical forest monitoring system.

The operational aspect of regional and global monitoring has in the past led to some resistance by research organizations to... support tropical forest monitoring activity.

Nongovernment organizations (NGOs) and private volunteer organizations (PVOs) concerned with environmental issues have grown over the last decade. Some of these now have considerable financial support and are developing their own remote sensing and GIS capabilities to support their programs and advocacy projects. A recent study supported by the United States Agency for International Development (USAID) and managed by the World Wildlife Fund to design a global climate change program for Central Africa has demonstrated the advantage of cooperation between the science, NGO, and remote sensing research communities. For example, the NGO community provides a wealth of field experience and an understanding of the local processes of deforestation which can make important contributions to data interpretation and local level technology transfer. They are also capable of providing a long-term continuity to in-country projects and can provide a useful bridge between the academic research and the development community. However, NGOs tend to work independently of the mainstream research and development community and are often independent of the academic review and publication process within which the remote sensing research and applications community operates. As a result, they are not obliged to pay attention to data quality control or quantitative assessment of results.

Institutional obstacles for global monitoring exist with the two primary U.N. agencies concerned with tropical forest monitoring: FAO and UNEP. The precise role and relationship of the two agencies with respect to tropical forest monitoring has been unclear, at least to those outside of the process. A Memorandum of Understanding was developed between the two agencies with respect to the 1990 Tropical Forest Assessment but a coordinated and integrated program of shared activities with sufficient funding from both agencies has not appeared to be forthcoming.

The role and relationship of FAO and UNEP with respect to tropical forest monitoring has been unclear.

A critical obstacle for the 1990 Assessment has been the inability of FAO to fund research. The 1990 Assessment Project started in March 1989 with the intention of providing results by late 1990. The project will end in

October 1992. Despite good intentions and a dedicated staff, the FAO 1990 Assessment project has been hampered by limited funding and understaffing. The development of any new global methodology, which incorporates satellite analysis techniques, requires operational research, development, and testing. In the author's opinion, the project was limited by being unable to support adequately this necessary research and development. A new proposal has been submitted by the 1990 Assessment Project to FAO for a continuous global tropical forest resource assessment which will apply the current methodology completing a wall-to-wall assessment of deforestation rates in ten years. The proposal outlines a coordinated program of national monitoring by the forest agencies, with support from three regional centers. The proposed budget, which includes the necessary institutional underpinning, is approximately $17 million. The proposal has been accepted by FAO and is currently looking for donor support. There are also some preliminary indications that FAO and UNEP will establish a closer working relationship for future assessments.

The overselling of the capability of remote sensing was a characteristic of the 1970s and early 1980s and can still be encountered.

Technical obstacles

The overselling of the capability of remote sensing was a characteristic of the 1970s and early 1980s and can still be encountered. Some of the resistance to adopting remote sensing approaches by national and international agencies stem from this period, although most forest services now recognize the utility of the data. The use of GIS is being heavily promoted in the developing world by a number of vendors. Different GIS systems require different hardware and operating procedures and data exchange between systems is often difficult.

Satellite image processing and analysis and GIS systems no longer require a main-frame computer capability. The development of personal computers (PCs) and workstations has lowered the hardware costs and it is now feasible, assuming a moderate level of funding for individual forest agencies, to have their own remote sensing and GIS analysis capability. One remaining problem is the incompatibility of different image analysis and GIS systems which limits data exchange and interoperability. With the developments in data media it is now possible to store and access large amounts of data with relative ease.

Satellite image processing. no longer requires main frame computers.

One of the most efficient ways to generate deforestation statistics as developed by INPE and NASA, is based on visual interpretation of imagery, digitizing the forest boundaries, and entering the digital data into a PC-based geographic information systems. This is a relatively "low-tech" approach to monitoring.

Visual interpretation of imagery, digitizing the forest boundaries and entering the digital information in a PC-based geographic information system is an efficient 'low tech' approach.

Technology transfer of remote sensing has received considerable funding and a considerable number of individuals from tropical countries have attended remote sensing training courses. Unfortunately the institutional support for the technology is not always available when the trainees return to their host institute. There is currently a shortage of trained personnel in remote sensing and GIS techniques at most forest agencies in the tropics. However, careful consideration needs to be given to the utility of con-

ventional training courses. On-the-job training in the use of remote sensing and GIS at the trainees' institute appears to be the most effective process. Some training courses now include hardware donations and continued system support and technological backstopping which should lead to a greater success in the adoption of the techniques. Most tropical forest agencies have had some exposure to remote sensing and GIS. The establishment of the operational use of remote sensing and GIS is, however, a separate task which has seen very little support within national forest agencies. Lateral transfer of technology between neighboring countries offers considerable potential for increasing the appropriate use of new technologies.

Most tropical forest agencies have had some exposure to remote sensing and GIS but they lack trained personnel and there is little support for operational use of remote sensing information.

There is currently a risk that the existing technology gap between the developed and the developing countries will continue to widen with the introduction of the proposed new sensing and data systems. For example, ERS-1 data will require the full cycle of research, development, and testing prior to transfer of the new technology. Research results which appear to be satisfactory in one locale need to be fully tested over a range of conditions to which they will be applied on an operational basis. Although the forest services should be involved in that process, it is inappropriate for them to be given the full burden of research and development in new technology in addition to their own tasks. Technical assistance with operational research and development may best be provided by the university remote sensing and forestry research communities.

The NASA Earth Observing System (EOS) planned for the late 1990s will carry new sensing systems with significantly increased data rates and volume, increased spectral range, and improved spectral and spatial resolution. It is difficult to see how those institutes currently struggling to apply the current Landsat technology will be able to integrate the newly available data from such systems.

Compared to other regions of the world, tropical forests have received very little focused attention in terms of remote sensing research and development of applications. Little is published on the temporal or spectral properties of tropical forest and much is to be done to assess the full potential of the existing technology. The focus of satellite tropical forest monitoring to date has been on the closed humid forest. The seasonal forests and woodland savannas which are undergoing considerable land transformation have received relatively little attention from the remote sensing community to date.

Little is published on remote sensing applications for tropical forests compared to temperate regions.

The Future

The broad system specification

The challenge is to develop an effective satellite-based global monitoring system. It is the author's assumption that the information needs of the forest management community and the science community are not sufficiently different at the global and national scales to warrant the development of separate global tropical forest monitoring systems. Neither are the financial resources available for such duplication.

The exact specifications for such a system need to be developed but there are some broad requirements which need to be met. The system should provide an accurate and spatially comprehensive assessment of the global extent of tropical forests and the nature and rates of change at a spatial and temporal scale which will capture the land transformation occurring in the tropical forests and permit regional planning and biogeochemical cycle modeling. The current mapping by INPE and NASA at 1:250,000 appears to be appropriate.

In areas of rapid change it is necessary to monitor on an annual or biannual basis. In areas where changes are happening slowly, a comprehensive mapping every five years may be adequate, as long as the system is capable of identifying and predicting new fronts of deforestation in the interim. A combination of high and low spatial resolution sensing systems would facilitate identifying new fronts of deforestation. A spatially explicit GIS with information, for example on new roads, current logging concessions and population dynamics should be an integral part of the system and would be needed to run a predictive model. The system should generate spatial as well as statistical data which should be subject to independent verification and validation. The data need to be made available in a timely fashion to the broadest possible community. The system needs to be evolutionary and sufficiently flexible to incorporate new developments in remote sensing and GIS technology.

In areas of rapid change it is necessary to monitor on an annual or biannual basis.

Previous experience has shown that operational satellite monitoring systems which do not foster and support a close link to the research and development community are soon overtaken by improved technology or methods and become obsolete. Currently, research and development to support operational monitoring systems falls between the institutional responsibilities and interests and, in this respect, should be supported by the project it is serving.

A GIS system with information on roads, logging concessions and population should be integral to forest monitoring by satellite.

Approaches to implementation

Assuming that funding is available for a global tropical forest monitoring system, there are currently two schools of thought as to how it should be implemented. One approach advocates a distributed monitoring system with the national forest services generating national and regional assessments with a global synthesis at a centralized facility. The second advocates an independently funded centralized institution generating the complete global assessment. There are advantages and disadvantages to both.

The distributed system has the advantage of placing the national level monitoring in the hands of the agencies that are responsible for management. It also takes advantage of the interpretation skills that may reside with that agency. It would require a significant amount of coordination particularly to have the data generated in a timely fashion. The satellite and modeling data would have to be shipped to a number of locations and each location would have to have the means for image enhancement and GIS analysis. One would also have to assume that each of the forest services involved will be given the necessary institutional underpinning as

well as project funding to support a long-term operational satellite-based monitoring program. With national agencies providing the input data for the global assessment it will be important to resolve any potential conflict between data accessibility and sovereignty. The national forest service estimates will also require some level of independent assessment. The central synthesizing facility and the national forest agencies could be supported by regional coordination centers but these centers would have to be established and their long-term funding would have to be secured.

The centralized approach is attractive in that it would be relatively easy to manage. Analysis would be performed in-house with possible assistance from visiting scientists from the national forest agencies or consultants with the necessary in-country experience. Data shipment would be minimized and the timeliness of the results could be more easily controlled. The centralized facility could house the necessary image analysis and GIS equipment and could obtain the data needed for the predictive modeling. An independent assessment of the centralized estimates would have to be developed and could be coordinated through funded collaboration with the national forest agencies.

Even with a significant increase in funding it is unlikely that both approaches can be tested. The urgency for the information would indicate a centralized approach to be most appropriate. The institutional underpinning which is a prerequisite for the national forest services to be effective players in a distributed system has yet to be identified or guaranteed over the next five- to ten-year period. The task of integrating remote sensing and GIS techniques in forest service activities must be given a high priority but should not delay the provision of a global assessment. It might be possible in the next five years for those forest services in the tropics currently unable to participate in the program to be ready to provide a complete and regular national assessment. This will, however, require an effective and coordinated, well-funded program of institutional support on an unprecedented scale.

The task of integrating remote sensing and GIS technique in forest service activities must be given a high priority but should not delay the provision of a global assessment.

It is perhaps worth looking at the structure of other environmental monitoring systems for a guide as to how to proceed. The meteorological community for example undertakes its global assessments and modeling at a separate facility. The national agencies are not burdened with the analysis needs for the global assessment.

Future needs

Both the ISY WFW activity and the FAO 1990 Assessment terminate in 1992. The U.N. is reviewing its 1990 Assessment and planning its future program. The space agencies are preparing to find a new institutional umbrella for the present forum for the discussion of forest assessment methods and results. It is, therefore, a good opportunity to stand back and assess the future needs of a satellite-based monitoring system. The likely magnitude of the funding needed to implement a long-term monitoring program will necessitate coordination of shared financial support from a number of different sources. The magnitude of the coopera-

tion needed between the various agencies will also necessitate a new mechanism for coordination of the different agency activities.

There is an urgent need to take the necessary steps towards developing an effective and comprehensive global monitoring program. The diverse group of individual agencies currently undertaking regional, national, and sub-national tropical forest monitoring will no doubt continue their programs until a new and effective global initiative supersedes their efforts. The space agencies and remote sensing research institutes currently undertaking regional forest assessments will continue until there is an alternative reliable source for the data to fulfill the requirements of the science community.

In moving toward a new global initiative there are some immediate actions that can be taken and some longer term developments which need to be planned and initiated. Given the urgency for comprehensive monitoring it is also necessary to identify the appropriate communities responsible for these different component parts of a global program.

Immediate Needs

Space agencies and remote sensing research institutes should continue to undertake research to develop procedures for the analysis of satellite data for forest monitoring. There is a need to raise the current level of support for research on satellite-based tropical forest analyses. The space agencies should continue supporting current monitoring efforts, until a comprehensive program of global forest monitoring is established or national forest monitoring programs become operational. In most cases, data interpretation could be enhanced by a closer working relationship with national forest agencies and nongovernmental organizations. The resulting data need to be fully evaluated prior to general dissemination. When completed the data should be made available in formats appropriate to a wide user community, both in digital and photographic form.

A solution needs to be found to the prohibitive cost of high resolution satellite data, especially for forest services and researchers in poorer nations.

Efforts should be made to secure the existing historical archives of high resolution satellite data for the tropical regions. Perhaps most importantly those responsible for satellite data acquisition should develop a coordinated strategy to obtain complete global cloud-free coverage of the tropics each year. This would, for example, involve coordination between EOSAT, SPOT Image, and the various ground receiving stations through such organizations as the LGSWG. The metadata associated with the satellite data coverage of tropical regions both for the central facilities as well as the various ground stations should be made complete and more easily accessible.

A solution needs to be found to the current problem of the prohibitive cost of high resolution satellite data. Without increased access to these data national forest services and the research community will be unable to use the available technology. Clearly the costs of the satellite systems and the data need to be met, however, with the current system some of the poorest government agencies in the poorest countries of the world are expected to spend what amounts to more than their annual operating costs on purchasing satellite data. The discussion and coordination of satellite

data acquisition strategies and pricing policy, data formats, metadata availability, and data distribution could be addressed within the framework of the Committee for Earth Observation Satellites (CEOS).

The national forest agencies should continue to develop their forest monitoring capabilities and make known their data needs with respect to satellite-based monitoring. Remote sensing and field experience should be developed to permit sound interpretation of satellite data at a national scale. Improved coordination should be sought between forest agencies to develop common methodologies and exchange experience in the use of remote sensing and GIS technology. Improved cooperation between the national forest agencies and remote sensing agencies is a high priority.

The future global monitoring program will have to be an international effort. Currently there are national and international fora for discussion and planning within individual disciplines or communities. There is no suitable forum for bringing together all the necessary international players required for a global assessment program. One of the immediate international priorities is to create such a forum and call a meeting of the various communities which will be required to participate in the design and implementation of an effective global monitoring system. The objective of such a meeting would be to bring together the appropriate delegates or representatives of the various communities to discuss their requirements and participation in a global monitoring system. A list of the current players and their associated roles in a global monitoring program are provided in Table 1.

The international development community should coordinate their programs with respect to tropical forest inventory and monitoring. Round table discussions between national agencies and the current and potential future donors would help identify duplication and gaps in support. Similarly, long-term funding commitment is needed to provide institutional underpinning as well as project support for a continuous assessment. Training of personnel should continue to be an important component of forestry support programs but focus should be given to remote sensing and GIS for national forest monitoring. The role of the UNEP in future global tropical forest monitoring programs needs to be clarified.

The results of the FAO Forest Resources Assessment 1990 could benefit from an external review.

When the results of the FAO 1990 Assessment are completed the project could benefit from an external review. The review should evaluate the results and procedures, and identify the difficulties encountered during the project. This would help the global community in the development of future plans and the identification and anticipation of possible problems for subsequent global assessments. The wide range of players involved in tropical forest monitoring within the international community should be involved in the design phase for a future continuous assessment project. The future FAO program should include a research and development component which will help develop and integrate new satellite-based monitoring techniques into the operational system. Involvement of the national forest agencies within this program must be matched by the provision of the institutional underpinning to enable them to provide the necessary

data in a timely fashion and fulfill a long-term monitoring commitment, without impacting their current program of activities.

There is a need for the science community to adopt an interdisciplinary approach to the study of tropical forests if we are to better understand the process and effects of deforestation needed for predictive modeling of forest transformations. In particular, there is a need for the ecological community to address the effects of land transformations within the tropical forest on ecosystem functioning and the effects of ecosystem fragmentation on biodiversity making use of the regional scale satellite-derived data sets now becoming available.

The international science community should participate in the evaluation of the methodology and results of the various satellite-based forest monitoring efforts and the appropriateness of these derived data to address the pressing questions of global change science. The International Geosphere Biosphere Programme (IGBP) Data and Information System (DIS) would be a suitable forum for the evaluation of methodologies, data quality, and accuracy and to determine ways of presenting the data in a form suited to the needs of the science community.

The international forest research community needs to address the requirements of a global satellite monitoring program from the forest management perspective. In particular, attention needs to be given to developing methods for integrating remote sensing methods in national-scale tropical forest monitoring programs. Similarly there is a need to develop a suite of operational tools to monitor the complete range of tropical forest alteration including the more subtle forms of forest degradation. Methods and procedures need to be developed to link closely satellite-based forest monitoring with forest management and regional planning. The International Union of Forest Research Organizations (IUFRO) would be a suitable forum for this discussion.

A combination of optical and microwave sensors with a high temporal frequency would appear to be most appropriate for forest monitoring.

Long Term Needs

Long-term institutional commitments are needed for the future global monitoring system and new mechanisms need to be found for the long-term funding of this activity.

The space agencies need to review the tropical forest monitoring capabilities of the planned sensing systems and see whether improvements can be made to satisfy the global monitoring requirements. Specifications for a dedicated system might provide guidance in this task and in the longer term would provide the design for a sensing mission specifically for this purpose. A dedicated system might be the best solution to the current problem associated with the utilization of data from a variety of sensing systems and platforms. A combination of optical and microwave sensors with a high temporal frequency would appear to be the most appropriate for tropical forest monitoring. The space agencies which also serve the role of research organizations need to assess their long-term role with respect to operational forest mapping.

The international agencies need to provide the long term strategy for institution building within the tropical forestry sector. A program of assistance needs to lead to the capability of the national forest agencies to monitor their own forests on a timely and regular basis. Once operational, the national satellite-based monitoring programs can then perhaps be fully integrated with the global assessment.

The international agencies need to provide the long term strategy for institution building within the tropical forestry sector.

The results of the global change research programs which are now being initiated on climate modeling, carbon modeling, ecosystem fragmentation, biodiversity and will use the satellite derived data, will need to be translated into effective policies for improved forest management. Such an interdisciplinary problem will require a dialogue between the earth and social science and forest management communities.

Conclusion

The previous commentary addresses the major issues associated with the current institutional roles in satellite-based tropical forest monitoring. The technology to provide a comprehensive and regular global survey has been available for the last decade. The obstacles to progress are diverse but none appear to be insurmountable. Of all the global environmental issues currently facing us, improved monitoring and management of the tropical forests is one of the most pressing. We need to move quickly to implement an effective global monitoring system.

There are technical problems associated with current methodologies which need further attention, some of which will be addressed during the meeting. The institutional problems are more difficult to resolve. Without a significant increase in the current institutional commitment to operational global monitoring and a greater degree of international and interagency coordination, little progress will be made.

The space agencies have made some recent major advances in the field of tropical forest monitoring, in part through the International Space Year World Forest Watch activities. Now that the International Space Year is coming to an end, it is important that these activities continue and their coordination be transferred to a new organizational structure. If we are to succeed in establishing an effective global monitoring system, it is critical that the space agencies participate actively as one of the major players in the design and implementation of a new international initiative for satellite-based tropical forest monitoring.

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Figure 1: **The basic steps involved in satellite-based forest monitoring**

Monitoring System Design

Formulation of Data Acquisition Policy and Design
Operational Research and Development
System Testing

Operational Implementation
Data Collection
Data Preprocessing
Data Distribution

Data/Image Processing and Analysis
Interpretation (Forest Mapping / Change Detection)
Accuracy Assessment

Integration into a GIS Forest Information System
Generation of Statistics and Spatial Information

Table 1: **The various groups that are needed in the design and implementation of a global tropical forest monitoring program and their respective roles**

Space Agencies:
Sensor Design and Engineering, Satellite Operations, Data Acquisition Policy, Data Distribution Policy, Scientific Research

Data Suppliers (private and public sector):
Data Acquisition Policy, Quality Assessment, Data Distribution

Remote Sensing Research Community (universities and research institutions, regional remote sensing centers):
Monitoring System Design, Development of Data Processing and Interpretation Techniques, Technology Transfer

National Forest Agencies:
Inventory and Monitoring of National Forest Resources, Forest Management

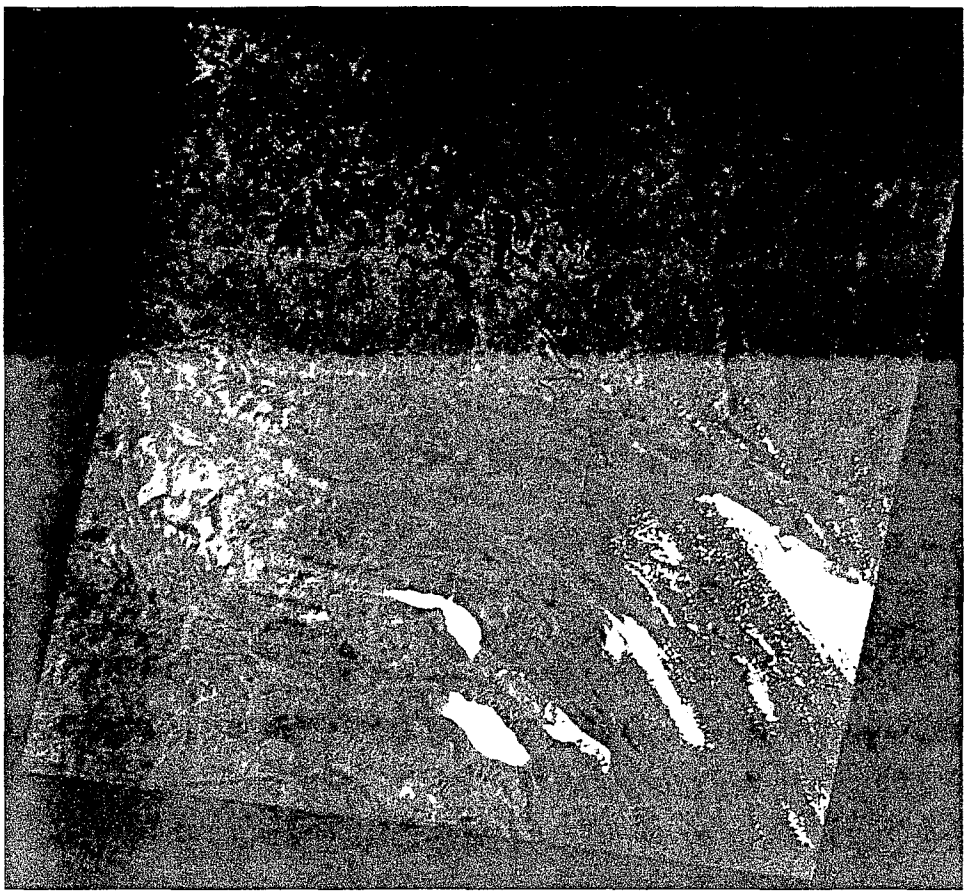
International Organizations (U.N. agencies, development agencies, ITTO):
Support for National Forest Inventory and Monitoring, Support for Regional Centers, Global Assessment

Nongovernment Organizations (national and international):
Research, Development, Advocacy

Scientific Community (universities, research institutes):
Global Change Research, Biogeochemical Cycle Modeling, Climate Modeling

International Research Organizations (IGBP, IUFRO):
Research and Development, Design and Evaluation of Methodologies, Evaluation of Results

A PATHFINDER MSS Triplicate Set of Satellite Images. The dark red hue is closed forest.



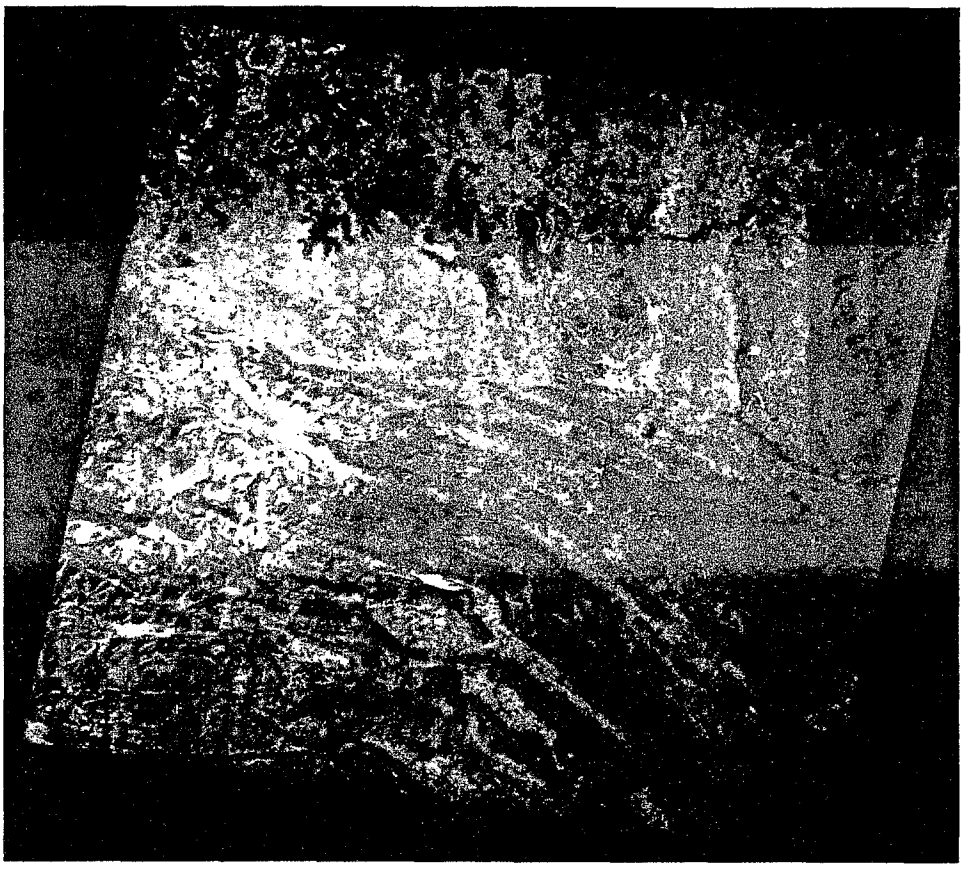
1974

19

Land use and land cover change is captured in these Landsat images taken of the Mexican and Guatemalan border region in 1974, 1984, and 1992. The dark red hue is closed forest. The international border (inset) is clearly revealed by land stripped of closed forest on the Mexican side before and during the 18 year period, while Guatemala's rainforest remains largely intact. On the lower half of the images, valley settlements and cleared land can be observed between mountainous ridges still in rainforest. The images are being analyzed for the EPA PATHFINDER project in collaboration with Mexican scientists.

By Alex Tait/Equator Graphics. Produced for USAID by the Environment and Natural Resources Information Center (ENRIC). ENRIC is a project of Datex, Inc., Arlington, Va

Set of Satellite Images.



1984

se Landsat images taken of the Mexican
1992. The dark red hue is closed forest.
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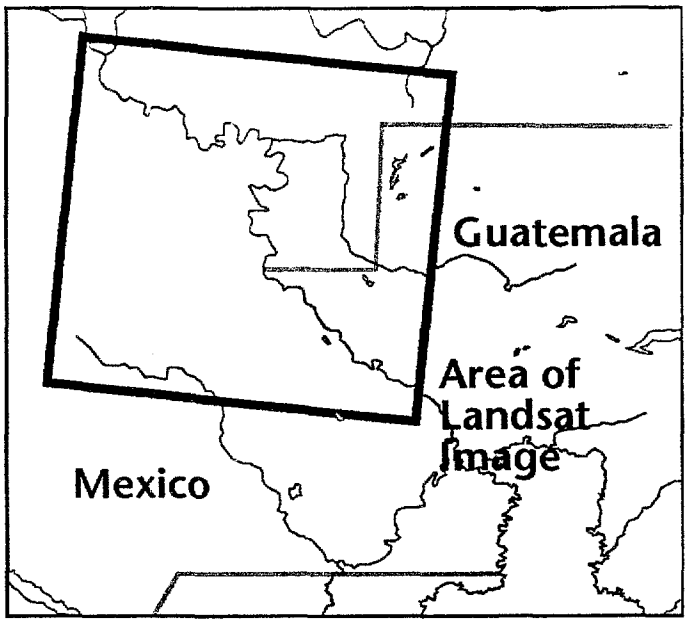
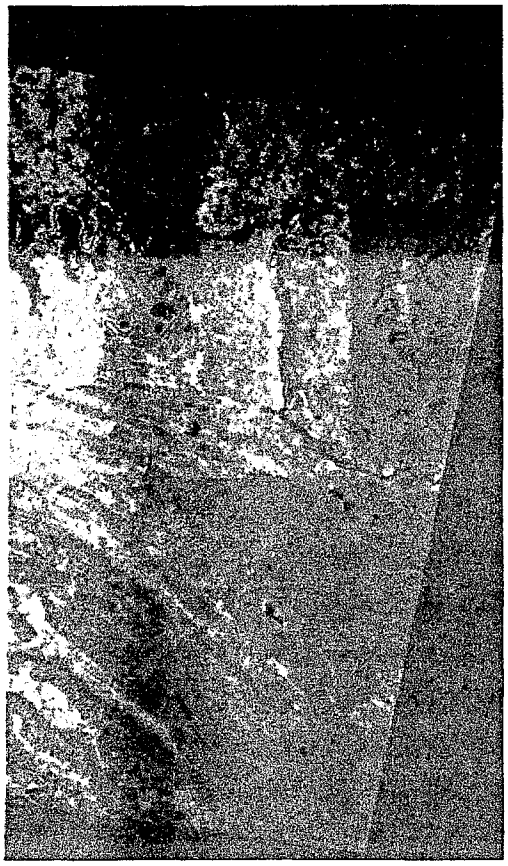
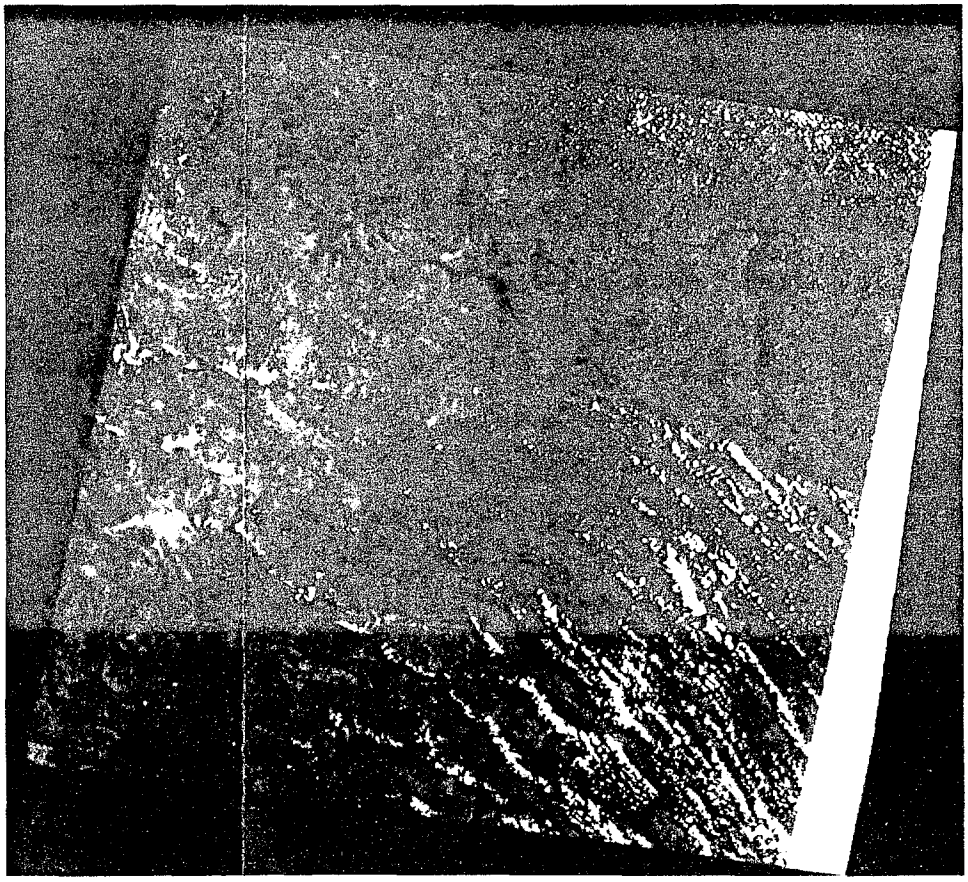




84



1992

ENRIC SECTION II

On-Going Efforts to Map Tropical Deforestation and Forest Cover Change

The Index Maps

The Pathfinder Landsat Project:
South America, Central Africa and Southeast Asia

The Pathfinder Landsat Project:
Mexico, Central America and the Caribbean

FAO Forest Resources Assessment 1990
Sample Survey

PANAMAZONIA Project

ON-GOING EFFORTS TO MAP TROPICAL DEFORESTATION AND FOREST COVER CHANGE

Three distinct efforts, profiled in this section, are under way to map and measure change in the world's tropical forests over the past 10 to 20 years using high resolution imagery from Landsat satellite sensors. They are:

- NASA's Pathfinder project. A part of the U.S. Global Change research program, this NASA/EPA/USGS project will map forest cover change in all the major tropical forests. It is being executed by the Universities of Maryland and New Hampshire, the Goddard Space Flight Center and the EPA.

- FAO's Forest Resources Assessment 1990 (FRA1990). One component of this largely statistical worldwide survey is a unique effort to map the nature of forest cover change in tropical regions as revealed in satellite images over time.

- The PANAMAZONIA project. The objective of this regional project is to map forest cover change in the world's largest closed tropical forest. A collaborative effort among the nine nations that share the Amazon River basin, the project will strengthen national remote sensing analysis and mapping basin-wide with assistance from the Brazilian space agency, the Instituto Nacional de Pesquisas Espaciais (INPE).

These mapping efforts began between 1989 and 1992. The USA-sponsored change mapping is the most ambitious and geographically extensive effort. Initial progress has been slowed by the sheer number of images to be acquired, the need to develop data management and analysis methods, and the poor condition of archived imagery from the 1970's. These difficulties have been overcome and analytical work is proceeding apace.

Work is also under way to map general categories of present forest cover with coarse resolution (1.1 km) AVHRR imagery. The CEC's TREES program aims to map forest cover worldwide, eventually to provide the basis for fast detection of forest cover change. The U.S. Forest Service began mapping forest cover of Mexico, Central America and Panama in 1993 and may extend this work to Indonesia. The work is being undertaken under the aegis of the 1993 Resources Planning Act and was planned as a means to support the forest assessment work of the FAO.

THE INDEX MAPS

The index maps on the following pages were prepared by ENRIC to display the geographic scope of various forest assessments profiled in this section. The satellite images used by each project are presented on the maps corresponding to the three world regions with tropical forests: 1) Latin America and the Caribbean; 2) Sub-Saharan Africa and Madagascar; and 3) Southern and Southeast Asia, and the South Pacific. The maps were developed from digital data sources using geographic information system (GIS) technology.

Each map displays the "footprints" of Landsat images used in a particular project. A footprint represents the geographic extent of an image on the Earth's surface. Each image is approximately 185 x 185 kilometers or 34,000 km2 and is indexed according to its orbital path and scene row. The location and dimensions of each footprint were determined using the ArcWorld GIS database developed by Environmental Research Systems Institute (ESRI). ESRI generated the footprint data using an algorithm provided by the Earth Observation Satellite Company (1992). The data applies only to images from Landsats 4 and 5. Since satellite orbits may vary from one pass to the next, the exact dimensions and location of each image may differ slightly from those displayed on the map.

The Landsat path and row reference grid for each map was generated by ENRIC using image center coordinates from the ArcWorld database.

The data on closed tropical moist forests was created by the World Conservation Monitoring Centre. The data was derived from a variety of sources including satellite imagery, paper maps, survey data, and aerial photographs.

Data on country boundaries and hydrography are also from the ArcWorld database. The original source of this data is the World Data Bank II (WDBII) developed by the U.S. Government (1988). ESRI updated the country boundaries from the WDBII to reflect political conditions as of January 1, 1992. The data has a nominal scale of 1:3,000,000.

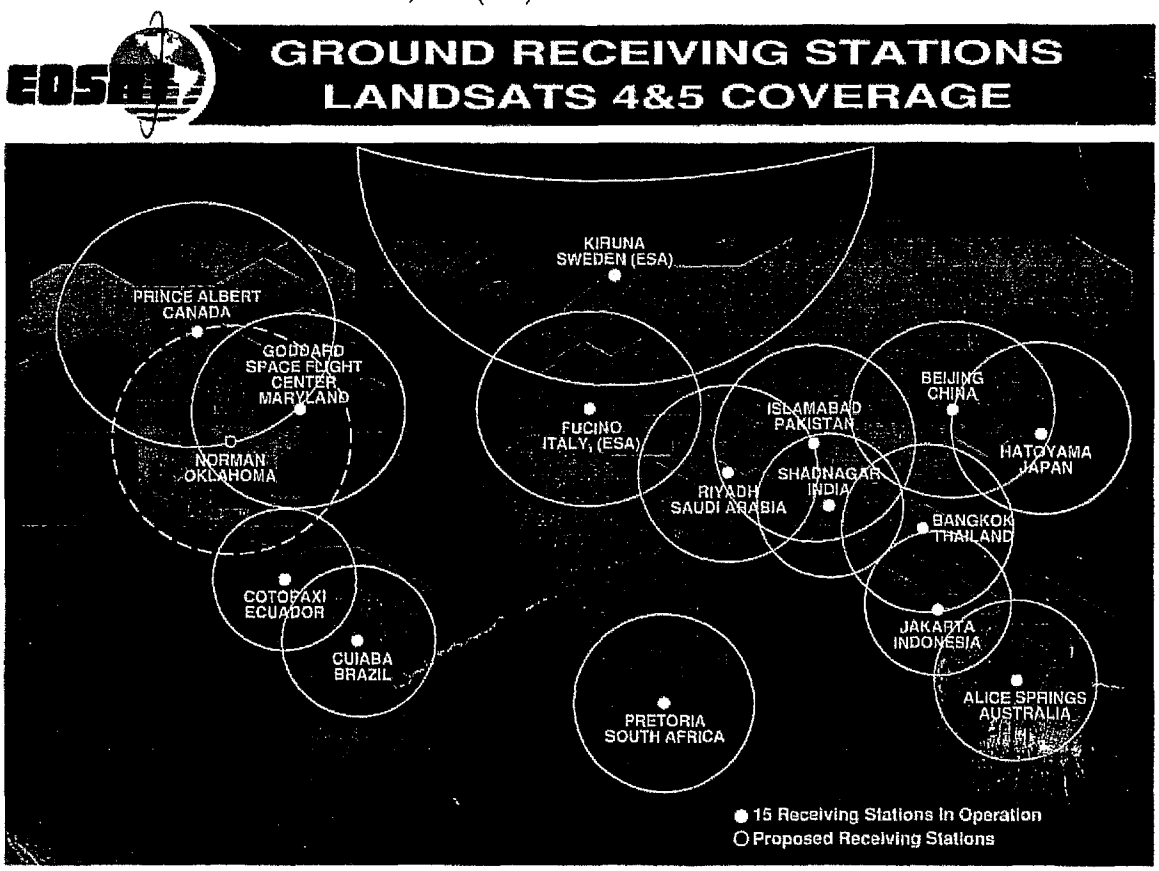
The Satellite Images

The Landsat satellites did not have an on-board recorder for later direct data ground feeds to one central collection point. Images are acquired in one of two ways. The first is through a relay satellite (TDRS), which collects imagery from the satellite and in turn passes it to a central collection point. The second means is by a direct download to local ground stations as the satellites pass over the respective "ground station

footprint" circles. There are a total of fifteen Landsat ground receiving stations worldwide (inset), one of which is in the United States(Norman, OK). A substantial amount of imagery has been acquired by overseas stations, particularly in Brazil. Many of the overseas stations have made financial arrangements with EOSAT to acquire imagery on its behalf as satellites pass over their respective "footprint" circles.

All MSS imagery acquired by Landsats 1-5, dating from 1973 to October, 1992 (when its collection was discontinued) is indexed and held by U.S. Geological Survey's EROS Data Center, Sioux Falls SD. An interactive computer program accessible by modem link, the Global Land Information System (GLIS), has been developed to allow users to determine the status and availability of particular scenes. GLIS permits a direct modem link-up with the EROS Data Center. The coverage for each scene (identified by path and row) is indexed and can be reviewed via GLIS. Cloud cover and overall image quality is specified. In 1994, EROS-GLIS will begin making available low resolution representations of the actual imagery, which will permit instant checks for cloud cover. A GLIS program diskette and instructions are available free of charge from EROS.

The MSS imagery itself can be purchased for $200 a scene from the Sioux Falls EROS facility (as 9" x 9" black and white positive or film prints, or in full color on 9 track tape). TM imagery is available from the Earth Observation Satellite Company (EOSAT), a commercial corporation in Lanham, MD (301) 552-0500.



The Pathfinder Landsat Project: South America, Central Africa and Southeast Asia

Quick facts:

Under this NASA-funded effort, tropical forest cover and change during the last 20 years will be mapped in South America, Central Africa and Southeast Asia. The work is being carried out by the University of Maryland (UMD) Geography Department (for Central Africa and the non-Brazilian portions of the Amazon basin) and by the University of New Hampshire (UNH) Complex Systems Research Center (for the Brazilian Amazon basin and Southeast Asia). Both Landsat MSS and TM imagery will be used to detect and map forest cover and deforestation.

Contacts:

Dr. William Lawrence (301) 405-6809 (UMD) and Dr. David Skole (603) 862-1792 (UNH).

Project name:

NASA Landsat Pathfinder Tropical Deforestation Project.

Implementing agencies:

Goddard Space Flight Center, the University of New Hampshire Complex Systems Research Center and the University of Maryland Geography Department.

Project objectives:

This three year (1993-96) collaborative effort seeks to develop a methodology for classifying the condition of the tropical forest cover using Landsat data, maps of tropical deforestation, a tropical forest GIS data base, and an information management and product distribution system.

Satellite imagery used:

Approximately 3,000 images, mostly acquired with the Landsat Multi-Spectral Scanner sensor, are being acquired in the form of 1:250,000 color composites and 8 mm tapes for three time periods. The Landsat images for the mid-1970s, mid-1980s, and 1989 to present are being acquired from the USGS, EROS Data Center archives in Sioux Falls, SD. Approximately 340 scenes from the Amazon basin (including the Orinoco river drainage system and parts of the Guayanas), 255 scenes for Central Africa, and 320 scenes for Southeast Asia are being acquired for each interval. Where shortfalls exist, substitute Thematic Mapper(TM) or SPOT coverage may be sought. Some TM acquisitions for 1992, the third reference period, may be made through satellite ground receiving stations in Brazil, Ecuador, Thailand and India.

Satellite imagery available to other users:

Digital satellite imagery will not be available to other users. Maps of land cover and deforestation will be available, including as datasets through Internet.

Methodology:

The images are interpreted at a 1:250.000 scale. Analysts sample and study areas of each image and assign ground cover codes. A computer program then evaluates the entire image in digital format based on the sampled land cover area. The results are then entered directly into a GIS for editing, management, hardcopy production, geo-rectification and analysis and printed out in vector format for editing and verification. Individual analysts works on a single Landsat scene until completed, checking their progress with plots and error edits. Once finished, the image is checked over by a small expert group, working together to assure that the same

decision path is used in delineation. The map is then returned for a final edit and archived prior to further analysis. Additional quality control and assurance will be provided by collaboration with in-country experts from Central Africa, the Amazon basin and Southeast Asia.

Ten to twenty sites are chosen within each of the geographic research areas for more detailed study, including ground observations. The sites will be used to test the data interpretation, and will be chosen to coincide with previous or ongoing field studies and areas where collaborative research with local experts will be the most productive. Many of these sites will be the locations of ongoing carbon cycle research.

Forest and other land cover classification used:

The six classes are forest cover, deforestation, non-forest vegetation, water, clouds and "other".

Intermediate and final products:

The large amounts of data to be acquired by this project entail close attention to data availability, order placement, quality control and the tracking of data through the many stages of processing, editing and calculation of spatial statistics. The UNH has developed a menu-driven, graphic Information Management System (IMS) for the project that interfaces with the UMD data management system. The IMS has three components: data query and browse, data management and archive management. Data query allows the user to search both U.S. and foreign archive image metadata (which describe image quality and geographic position). It permits detailed views of selected scenes. Data management tracks imagery through each step of the processing stream and provides detailed information about individual scenes. Archive management presents the user with a graphical, point-and-click interface to the archive, similar to the query and browse and data management modules. Ground observations, including photos and voice recordings collected in areas of the Amazon and southeast Asia, are also archived and accessible through the multimedia archive manager. The field data consist of 35 mm photographs, geographic locations obtained with a Geographic Positioning System (GPS) and tape-recorded voice descriptions.

Nature and availability of products, costs and expected dates:

A 1:4 million scale draft map on deforestation in the Legal Amazon (Brazil) between 1978 and 1988 has been produced. In 1994, maps to be generated will include "Deforestation in the Non-Brazilian Amazon by 1985" at a 1:500,000 scale and a map series on "Deforestation in the Amazon Basin, 1978 and 1985" at the scale of 1:100,000.

Further proposed analysis:

Knowledge of landuses after conversion from forest cover is an important factor in carbon cycle modeling. Once land uses are established, analyses can be conducted on their effect on regional and global carbon cycling. As techniques are developed and the datastream established, a second analysis phase could examine environmental impacts of forest utilization, forest recovery time and the sustainability of forest utilization in addition to biodiversity topics, already explored in the Science magazine article by Tucker and Skole reprinted in the next section.

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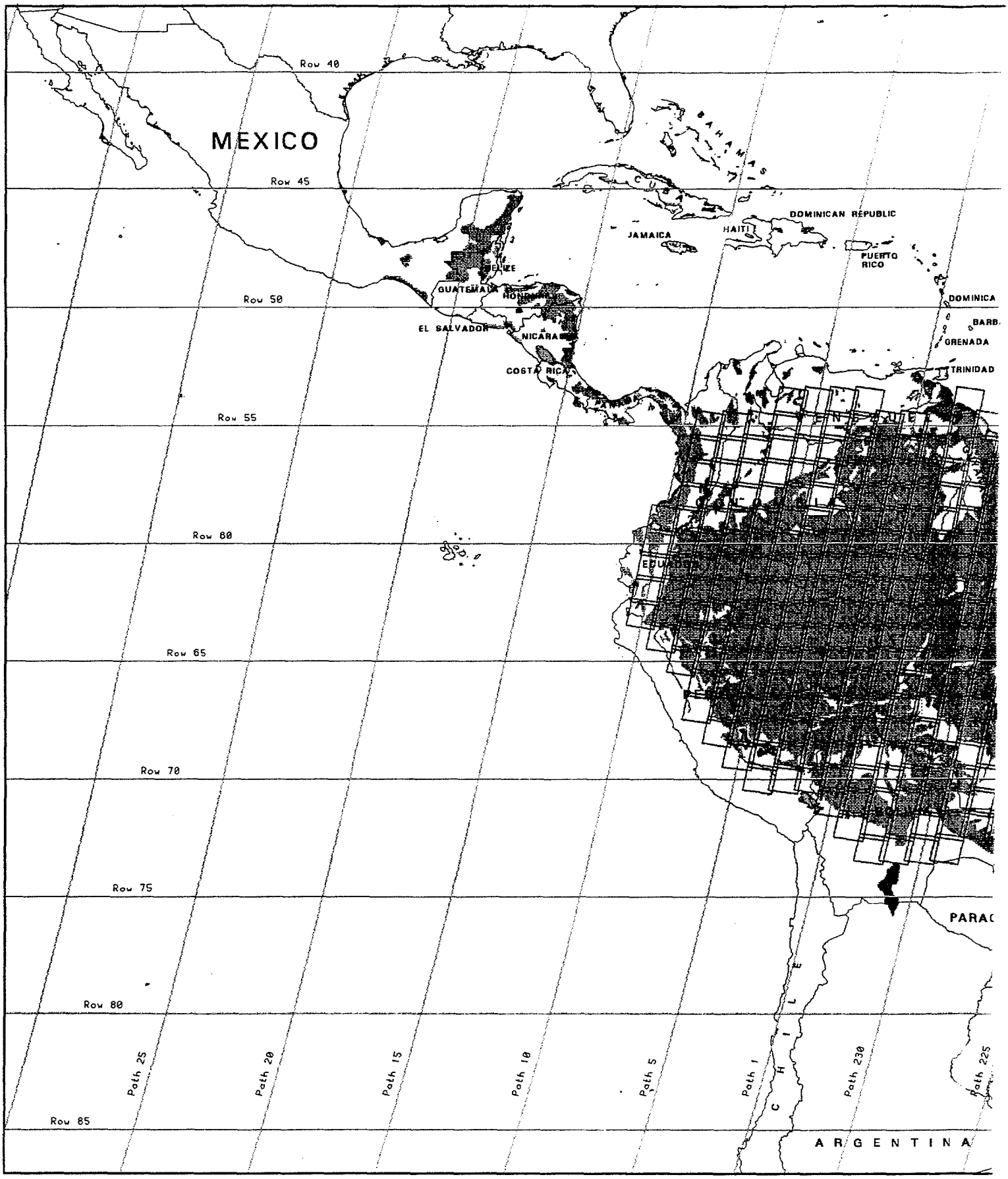
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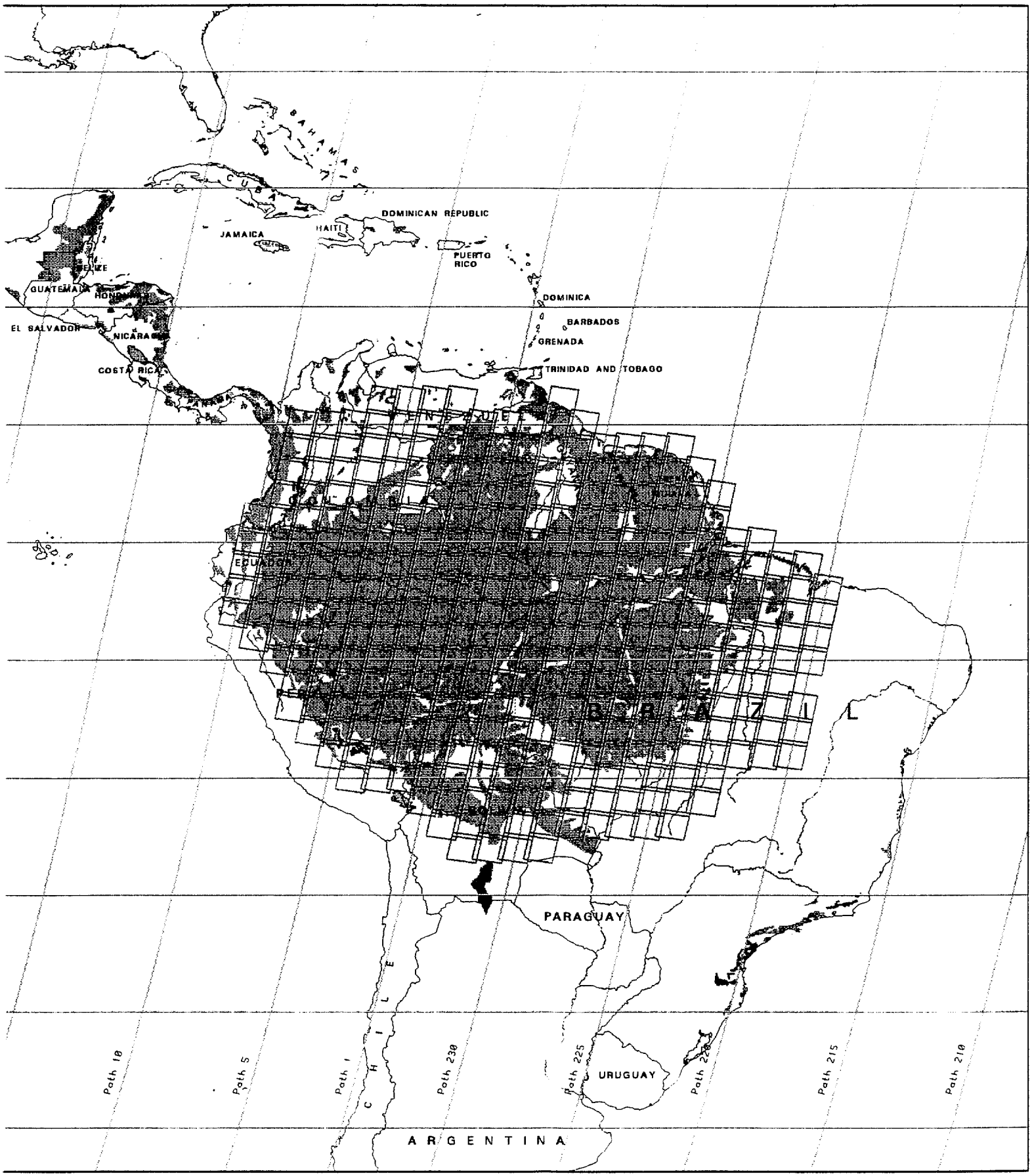
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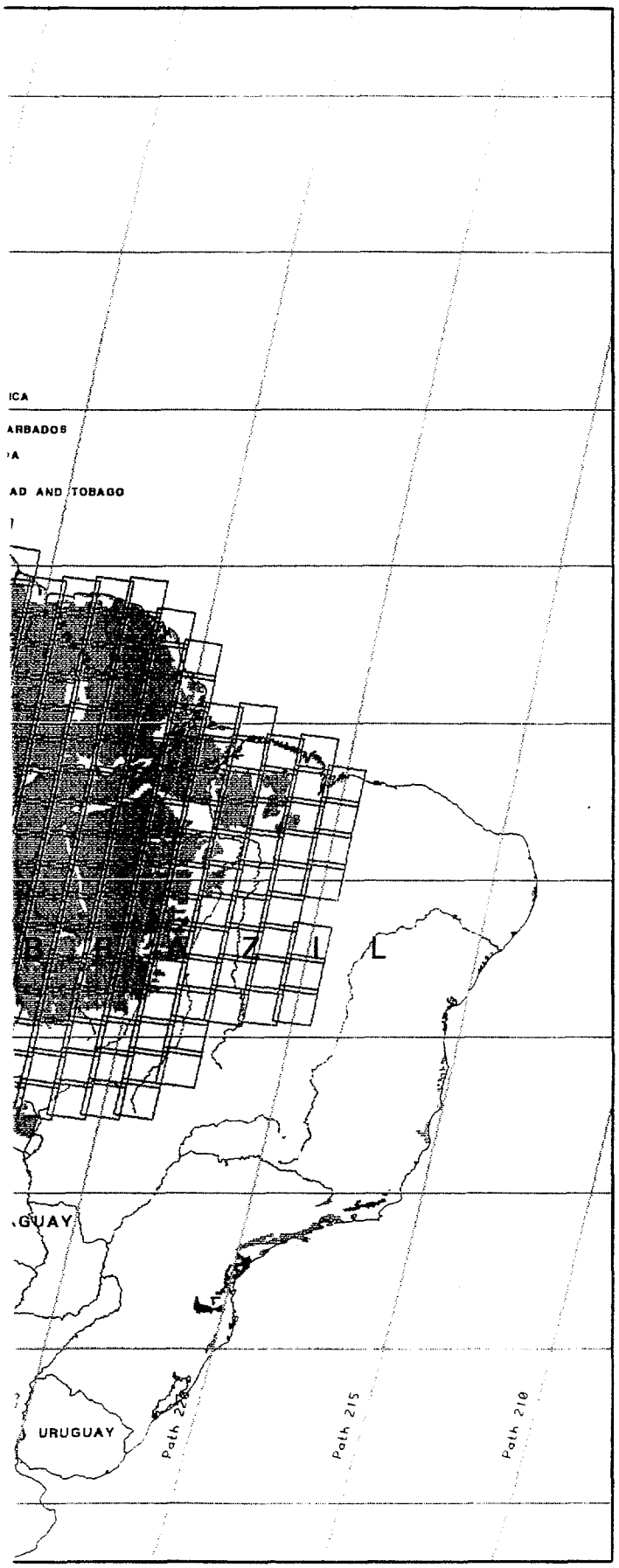

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NASA Pathfinder Program
South America

Landsat Scene Footprint

Closed Tropical Forest
- Mangrove
- Inland Swamp
- Lowland Rainforest
- Montane Rainforest
- Monsoon Forest

Rivers

Water Bodies

Landsat Path & Row Grid

Country Boundaries
- Demarcated
- Disputed or Indefinite

Scale 1:33,500,000

Produced for USAID by the Environment and Natural Resources Information Center (ENRIC). Researched by Robert W. Fox. Compiled by Steven R. Davis. Sources of data: Landsat image footprints - U.S. National Aeronautics and Space Administration (NASA); closed tropical forest cover - World Conservation Monitoring Centre (WCMC); country boundaries and hydrography - Environmental Systems Research Inc. (ESRI). ENRIC is a project of Datex, Inc., Arlington, Va.

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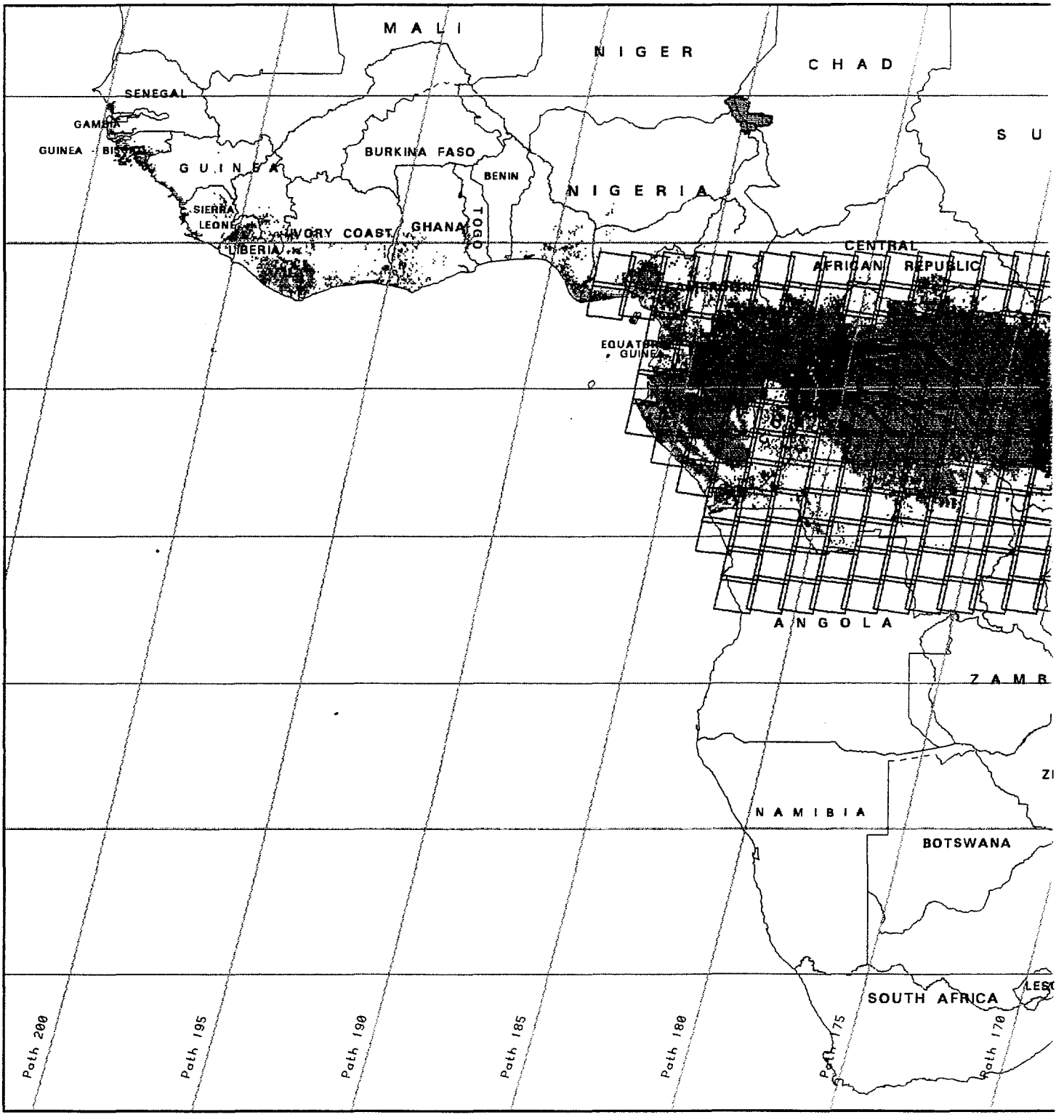
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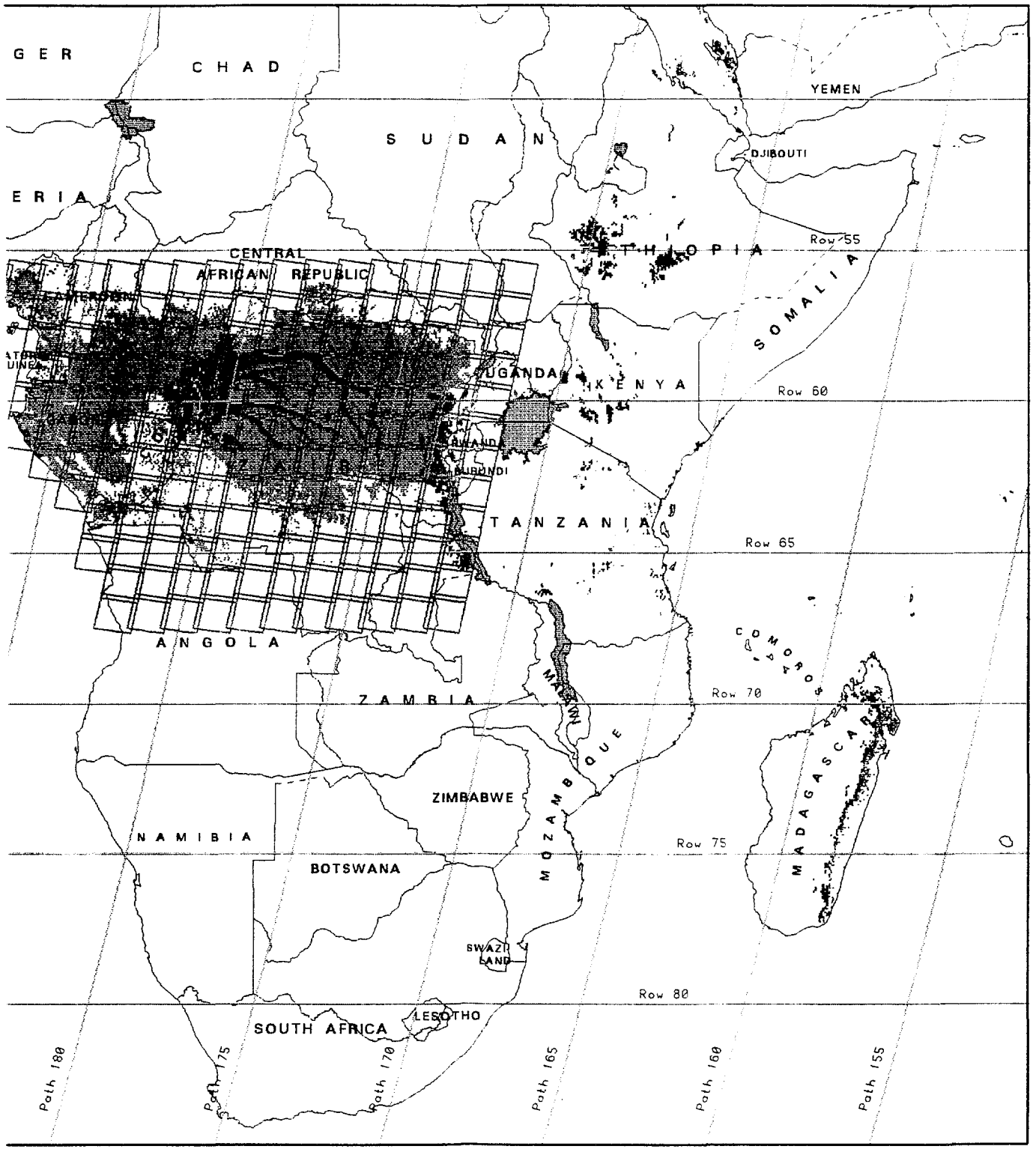

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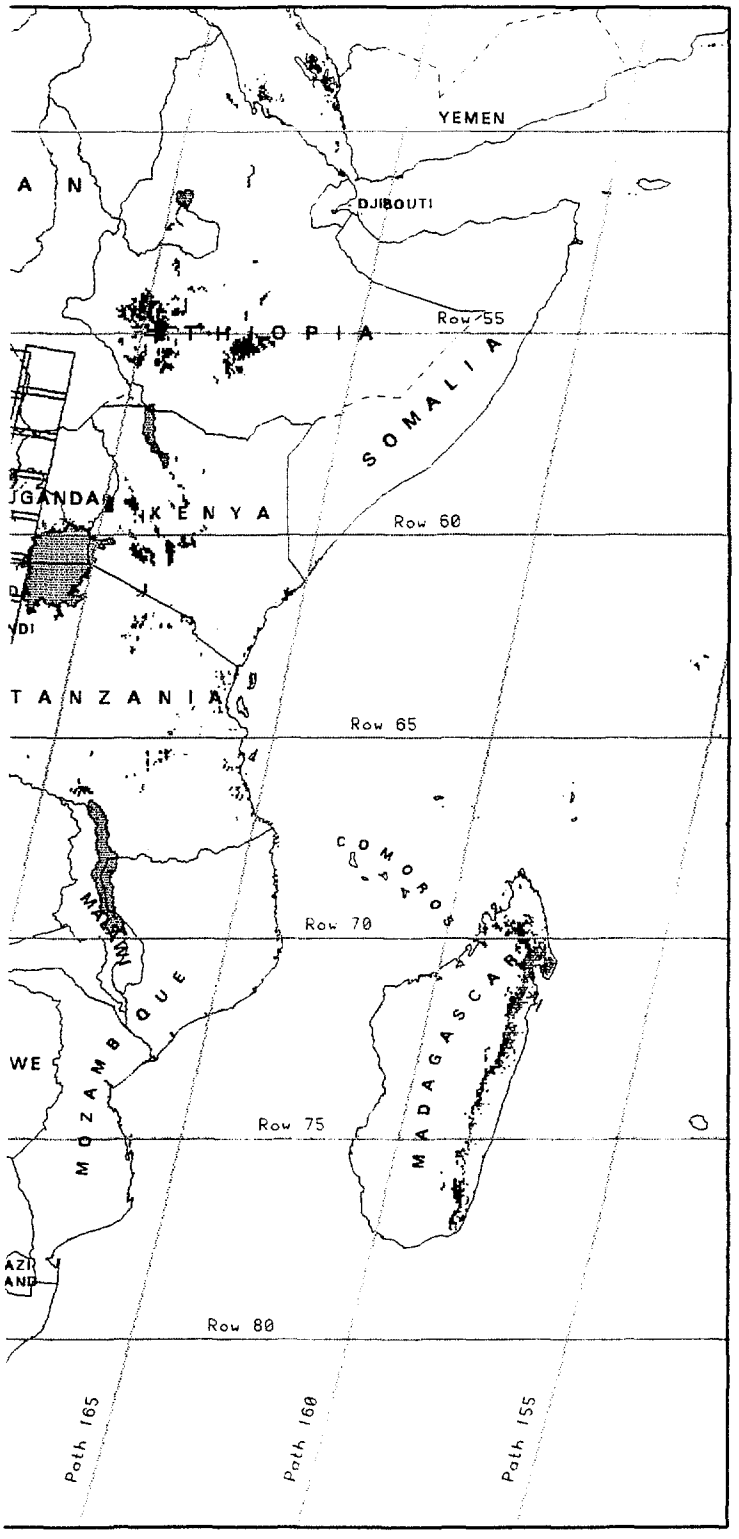
NASA Pathfinder Program
Central Africa



Landsat Scene Footprint

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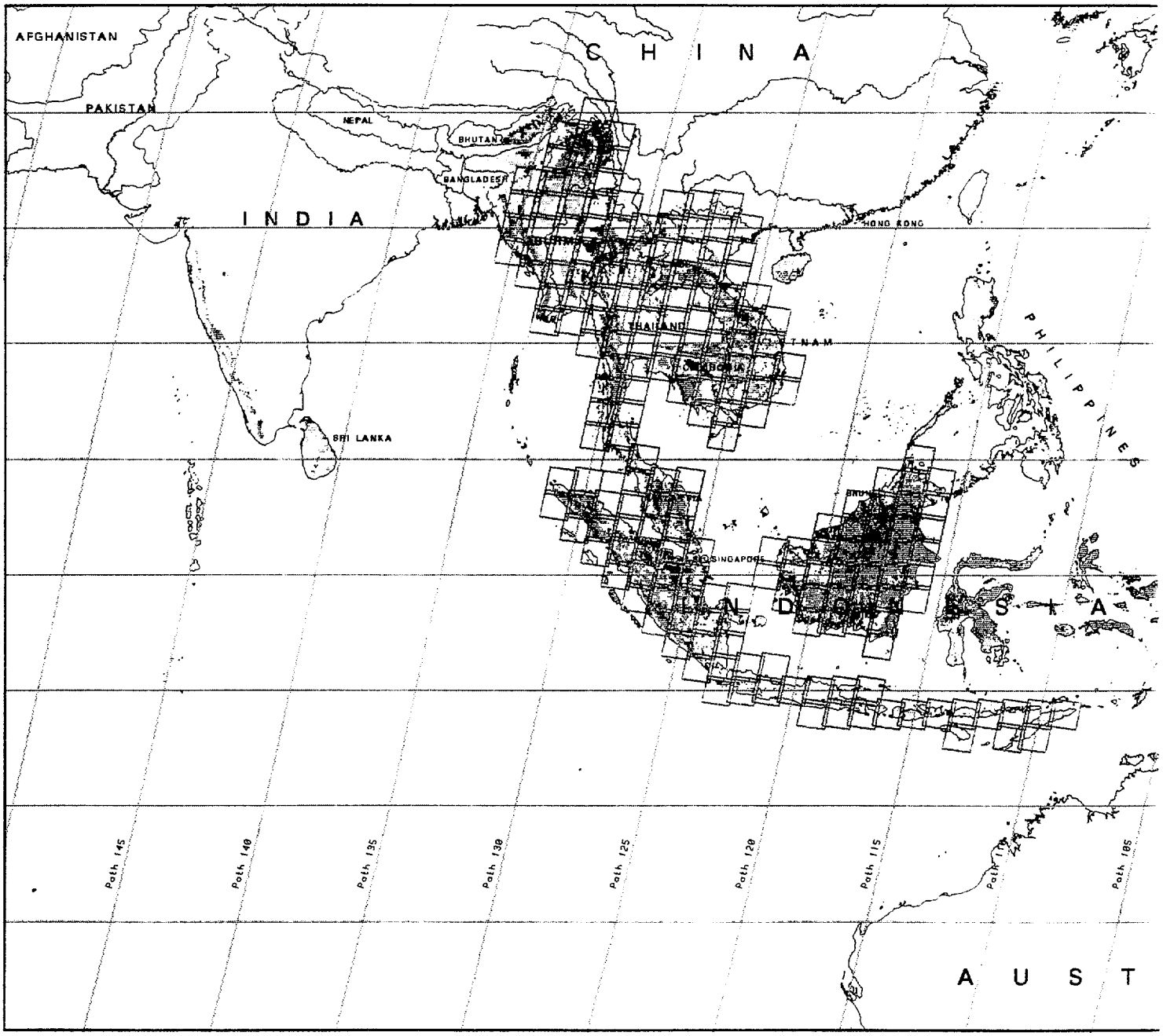
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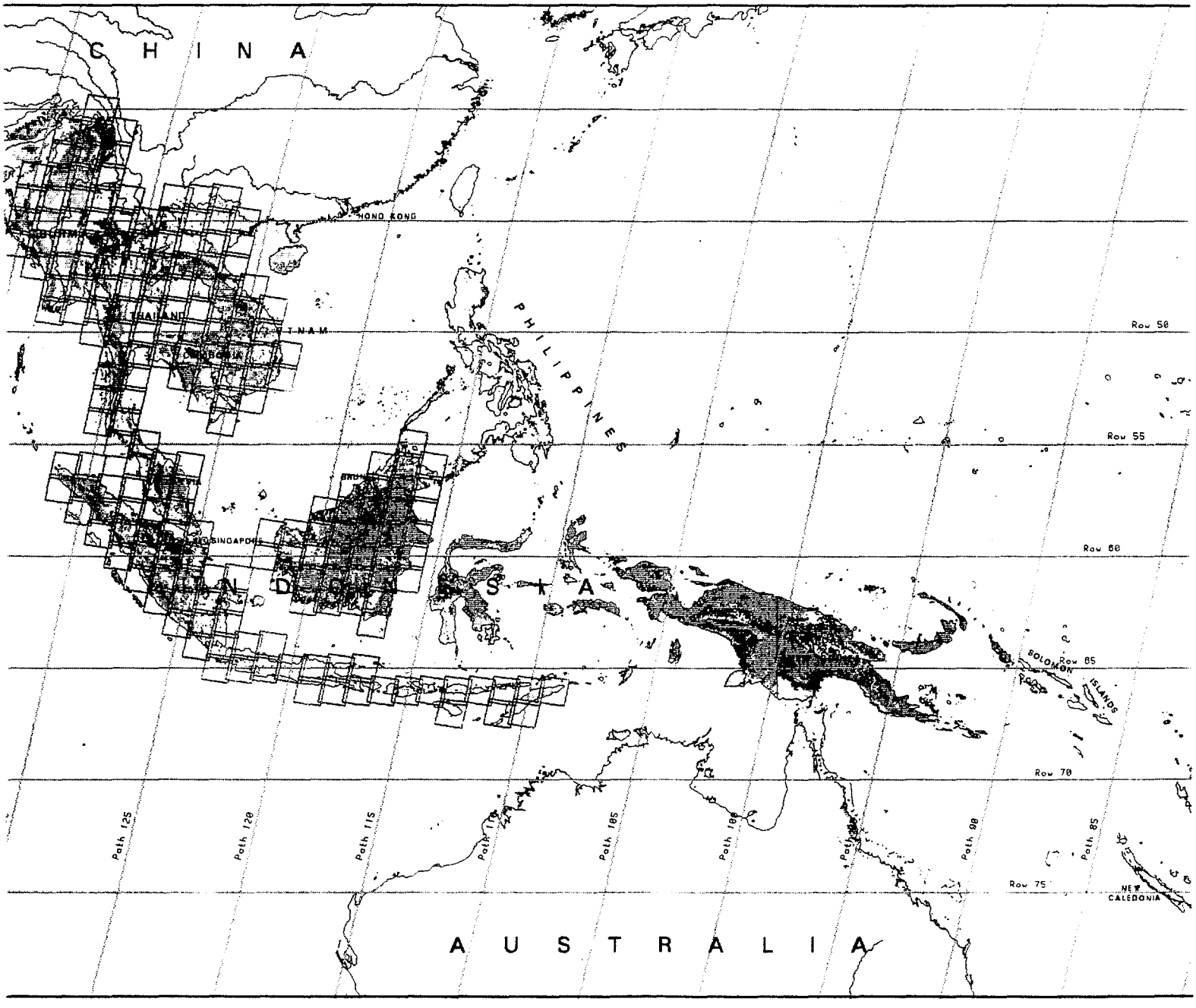
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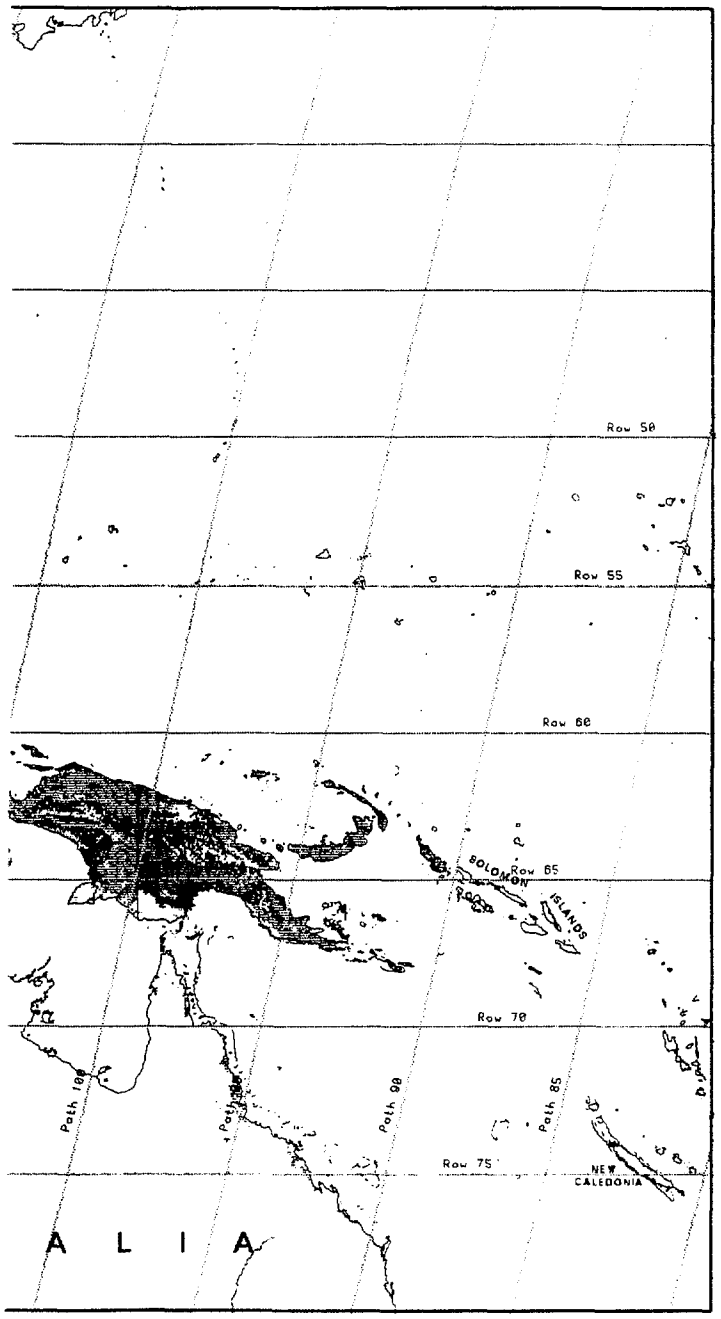
NASA Pathfinder Program
Southeast Asia



Landsat Scene Footprint

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Scale 1:40,900,000

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April 1994

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The Pathfinder Landsat Project: Mexico, Central America and the Caribbean

Quick facts:

This component of NASA's PATHFINDER program is being implemented by the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey Eros Data Center (EDC). An integral part of the comprehensive North American Landscape Characterization Program by these two agencies, it will map the changes in tropical forests in Mexico, Central America and the Caribbean using Landsat MSS imagery.

Contact person:

Dorsey Worthy (EPA) (702) 798-2175.

Project:

North American Landscape Characterization Program (NALC)-Pathfinder. This program covers most of the North American continent, Central America and the Caribbean. Satellite imagery for the Brazilian Atlantic forest region is also being produced by the EDC for possible inclusion. The study period is 1993-1995.

Implementing agency(ies):

U.S. Environmental Protection Agency (EPA). This component of the National Aeronautics and Space Administration's (NASA) Pathfinder series is funded by the EPA's Office of Research and Development (ORD) and the Global Change Research Program (GCRP) in cooperation with the EDC. Principal NALC cooperators include the EPA's Environmental Monitoring Laboratory at Las Vegas, Nevada, the EDC, and NASA's Ames Research Center at Moffett Field, California.

Project objectives:

"To determine the quantity of tropical forests and the rate of conversion to other land uses" in Central America, Mexico and the Caribbean, in order to provide preliminary data for national inventories of terrestrial carbon stocks and greenhouse gas emissions in support of the work of the Intergovernmental Panel on Climate Change (IPCC). Immediate objectives are to produce standardized remote sensing data sets, develop standardized analysis methods and derive standardized land cover change products.

Satellite imagery used:

Triplicate Landsat images sets from 1991, 1986, and 1973 (plus or minus one year). Triplicates for a total 184 individual Landsat MSS scenes are being compiled and processed from EDC archives. Mexico will be covered by 102 scenes, Central America by 34 and the Caribbean islands by 48 scenes. It is also noted in the research plan that a separate effort in Brazil will be conducted for the Atlantic Forest region under the "Deforestation Monitoring Program".

Availability of imagery to other users:

All data, methods, and land cover products will be made available to the global change research community. Data will be sold at the nominal cost of duplication and distribution. All data and products will be archived by EDC and listed in their Global Land Information Management System (GLIS) so as to facilitate indexing, archiving and data distribution and provide user access. Information about NALC products and ordering may be obtained from: Customer Services, EROS Data Center, USGS, Sioux Falls, SD, 57198, (605) 594-6151.

Methods:

Analysis and classification methods are similar to those being undertaken at UMD and UNH. Extensive field work in Mexico, Central America and the Caribbean is not proposed in the plan but pilot scenes and classification accuracy are being tested in Mexico (Chiapas) with help from local collaborators at the University of Mexico's Geography Department.

Land cover and forest cover classification:

The overall NALC Program utilizes a categorization scheme that combines features from two main systems in use by Federal agencies (Anderson, et al. and Cowardin. et al., 1976). This is a hierarchical system with three levels of progressively detailed information. For the areas south of the U.S., the EPA will use the first two levels as follows (level two within each category is shown in parenthesis): 1) barren or developed land (exposed land, developed land); 2) woody (forest, scrub/shrub); 3) herbaceous; 4) arid (arid vegetation, riparian); 5) snow/ice; 6) water and submerged land (ocean, coastal, near-shore, inland); 7) other (cloud, shadow, missing, indeterminable).

Details for change detection are still under research. The research plan notes that "The goal of NALC change detection...research is to select or develop standard change detection methods."

Intermediate and final products:

Standardized data sets will feature Landsat MSS triplicate images that have been georeferenced and presented in earth coordinates. Products will include land cover and land cover change data products at 3.2-5.8 hectare (8-14 acre) spatial resolution. The data sets will include: 1) coregistered/georeferenced Landsat MSS triplicates; 2) digital elevation/terrain model (DEM) data; 3) spectral cluster or categorized ground cover data for each scene; and 4) change detection images. All data sets will be clipped to the Landsat World Reference System 2 (WRS2) image sampling frame. In the case of the 1970's images, which conform to the World Reference System 1 sampling frame, multiple scenes are being assembled and clipped to the WRS2 sample frame boundaries.

Nature and availability of products, costs and expected dates:

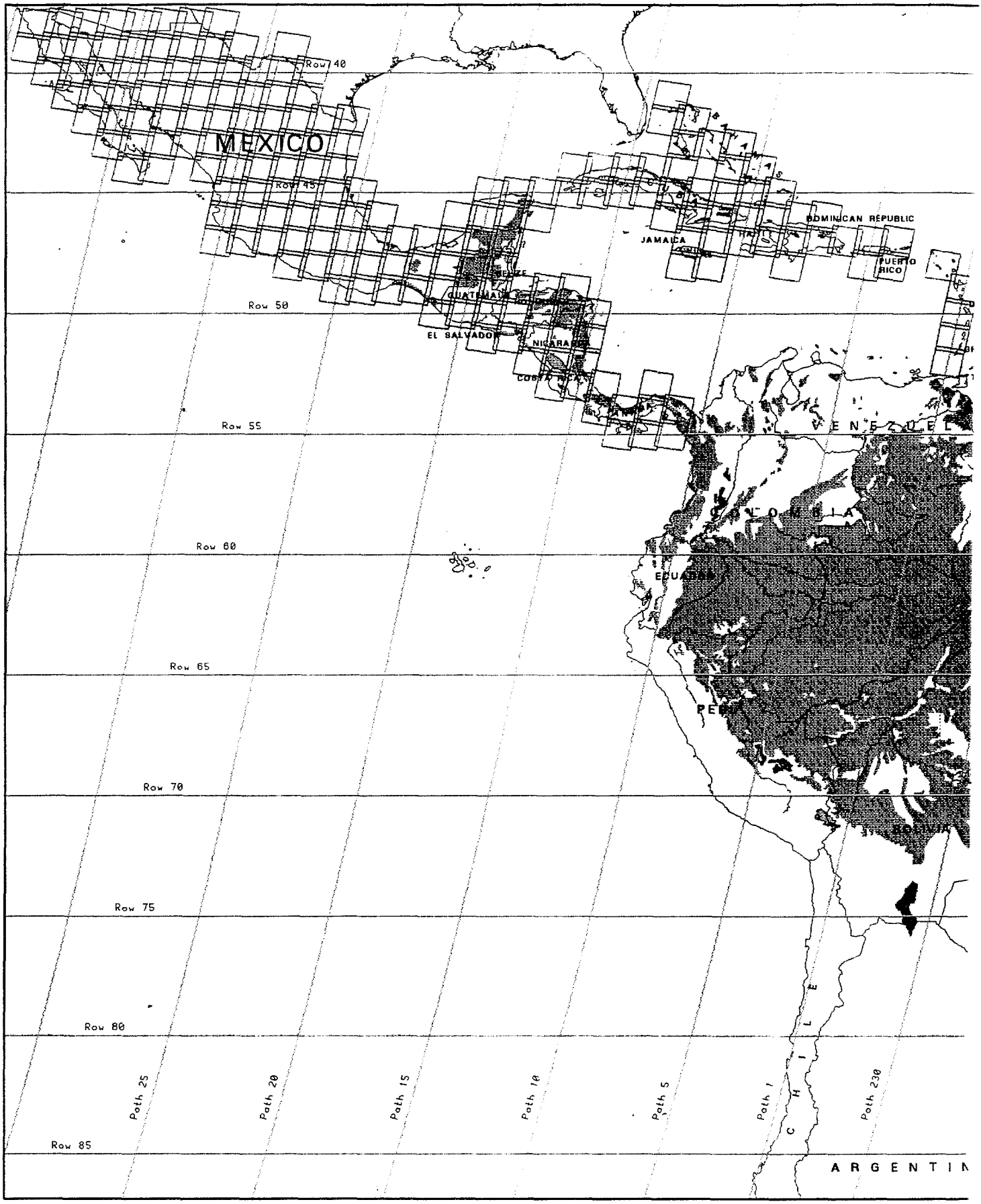
NALC scheduling calls for the production of regional triplicate LANDSAT image scenes to be under way in 1993 with applications to be under way in 1994.

References:

Anderson, J., Hardy, E., Roach, J., and Witmer, R., 1976, A Land Use Classification System for Use with Remote-Sensor Data, U.S. Department of the Interior, U.S. Geological Survey Professional Paper 964, Washington, D.C. 28 pp.

Cowardin, L., Carter, V., Golet, F., and LaRoe, E., 1979, Classification of Wetlands and Deepwater Habitats of the United States, U.S. Department of the Interior, U.S. Fish and Wildlife Service. Rep. No. FWS/OBS-79/31, Washington, D.C. 103 pp.

USEPA, Office of Research and Development. 1993. North American Landscape Characterization (NALC) Research Plan, LANDSAT PATHFINDER. (EPA/600/R-93/135) Washington, D.C. U.S. Government Printing Office. 419 pp.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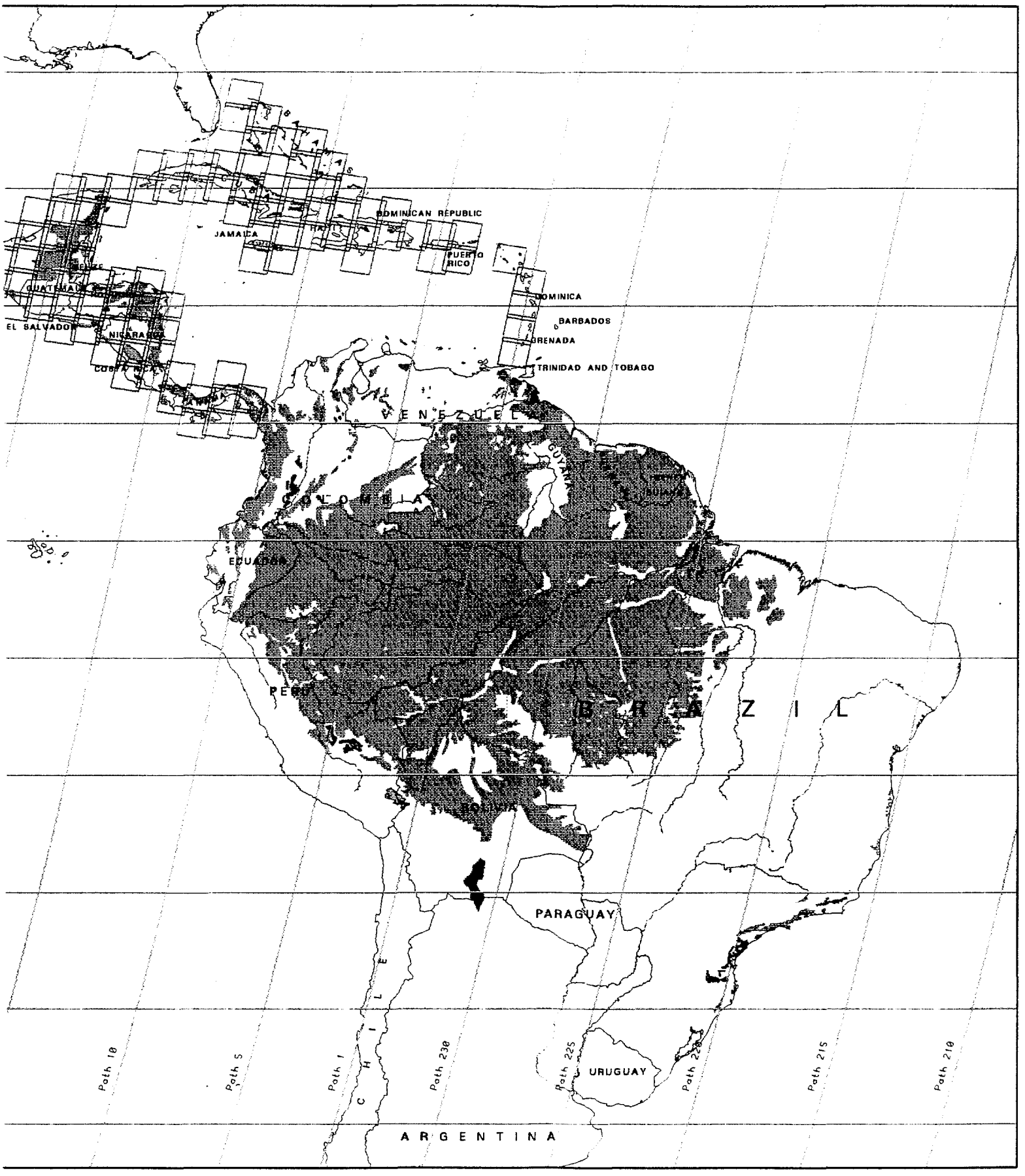
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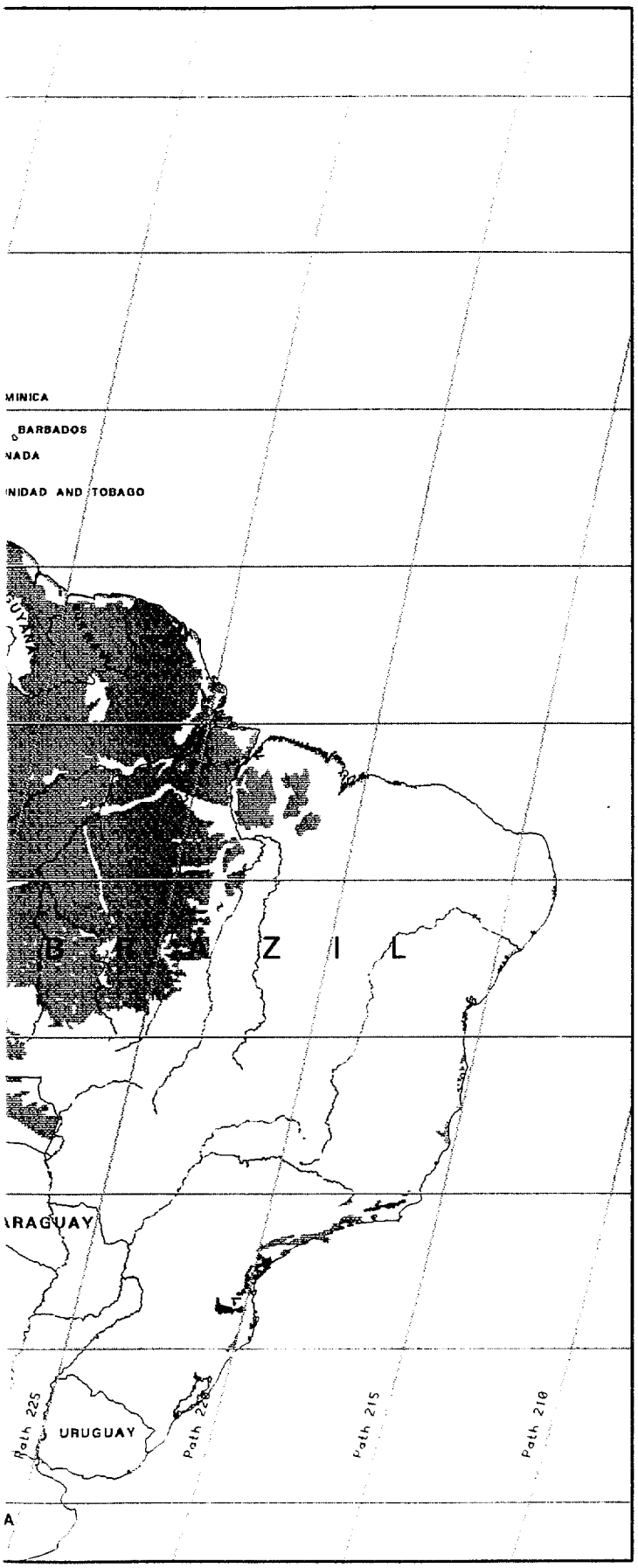

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EPA/NASA Pathfinder Program
Mexico, Central America and the Caribbean

Landsat Scene Footprint

Closed Tropical Forest
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- Inland Swamp
- Lowland Rainforest
- Montane Rainforest
- Monsoon Forest

Rivers

Water Bodies

Landsat Path & Row Grid

Country Boundaries
- Demarcated
- Disputed or Indefinite

Scale 1:33,500,000

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April 1994

FAO Forest Resources Assessment 1990 Sample Survey

Quick facts:

As part of its Forest Resource Assessment 1990 for tropical nations, FAO undertook a satellite image-based sample survey of the state and change of tropical forests, including the entire range of woody vegetation formations. The sample covered roughly 10 percent of the global tropical forest area. Two Landsat images from dates approximately 10 years apart are interdependently analyzed to classify forest cover and change for each scene. Much of the interpretation is undertaken in the countries by local forestry experts, using detailed guidelines prepared by the Project. The work continues through 1994.

Contact person:

Dr. K.D. Singh, Forest Resources Assessment Project (FAO, Rome) 011 396 5797 4115.

Project name:

Forest Resources Assessment 1990 Project.

Agency/organization(s), cooperative arrangements:

FAO in cooperation with the donor countries, the United Nations Environmental Programme (UNEP), the U.S. Forest Service, forest management agencies of the various national governments, NGO's and a large number of research institutions.

Satellite Imagery Used:

117 Landsat scenes were selected from a universe of 1,228 scenes, 47 in Africa, 30 in Asia and the Pacific and 40 in Latin America and the Caribbean. Two cloud free images are sought for each scene — a recent image from near 1990, and an image from near 1980. MSS images are preferred for comparability reasons, but TM imagery was used where suitable MSS imagery was not available. The two scenes used must be at least 5 years apart for change analysis. The three index maps identify the specific Landsat scenes selected for the sample.

Brief Description of Products:

The sample survey results will include a "change information" matrix designed to lead to an understanding of changing land use patterns and land-cover overlays and imagery archive for the 117 sample locations. FAO's Forest Resources Information System (FORIS), which stores and distributes FAO's global forest statistics, will contains the results of the sampling program. Work completed on 31 of the 47 change pairs in Africa was employed to develop a change matrix for all of Africa, whose results were analyzed and published in Forest Resources Assessment 1990: Tropical Countries (Rome: FAO. 1993). The same report presents a preliminary and simplified change matrix for Asia and Latin America by "ecological zone" (moist lowland, dry lowland, and moist montane) and compares the results with those from Africa.

Methodology:

A stratified random sampling procedure was employed to select the sample scenes. The sample frame was the Landsat World Reference System 2. Individual Landsat scenes were the sample units. The tropical region was divided into sub-regions on a geographical basis. Sub-regions were then divided into forest cover strata from which a predetermined

number of samples (a minimum of 10 per sub-region) were randomly selected. The allocation of samples to the sub-regions is made proportional to the estimated deforestation. The three index maps identify the specific Landsat scenes selected.

Visual interpretation and analysis is recorded on clear film overlays of 1:250,000 scale false color prints. Image interpretation is performed at regional and national forestry and/or remote sensing institutions. Workshops were held in Thailand, Kenya and Mexico to train 81 technicians from 27 different countries in interpretation and data compilation procedures. Land cover classes are interpreted for the two images and entered into a simple spreadsheet format for the production of a change matrix for each image pair.

FAO has encouraged, and in instances funded, the verification of the image interpretation using larger scale imagery, ground or low level aerial observations, and corrections based on existing inventory and plot survey data. Interpretation verification (for some if not all sample country scenes) were carried out in Brazil, India, Indonesia, Mexico, Mozambique, Thailand, Uganda, Viet Nam and Zaire.

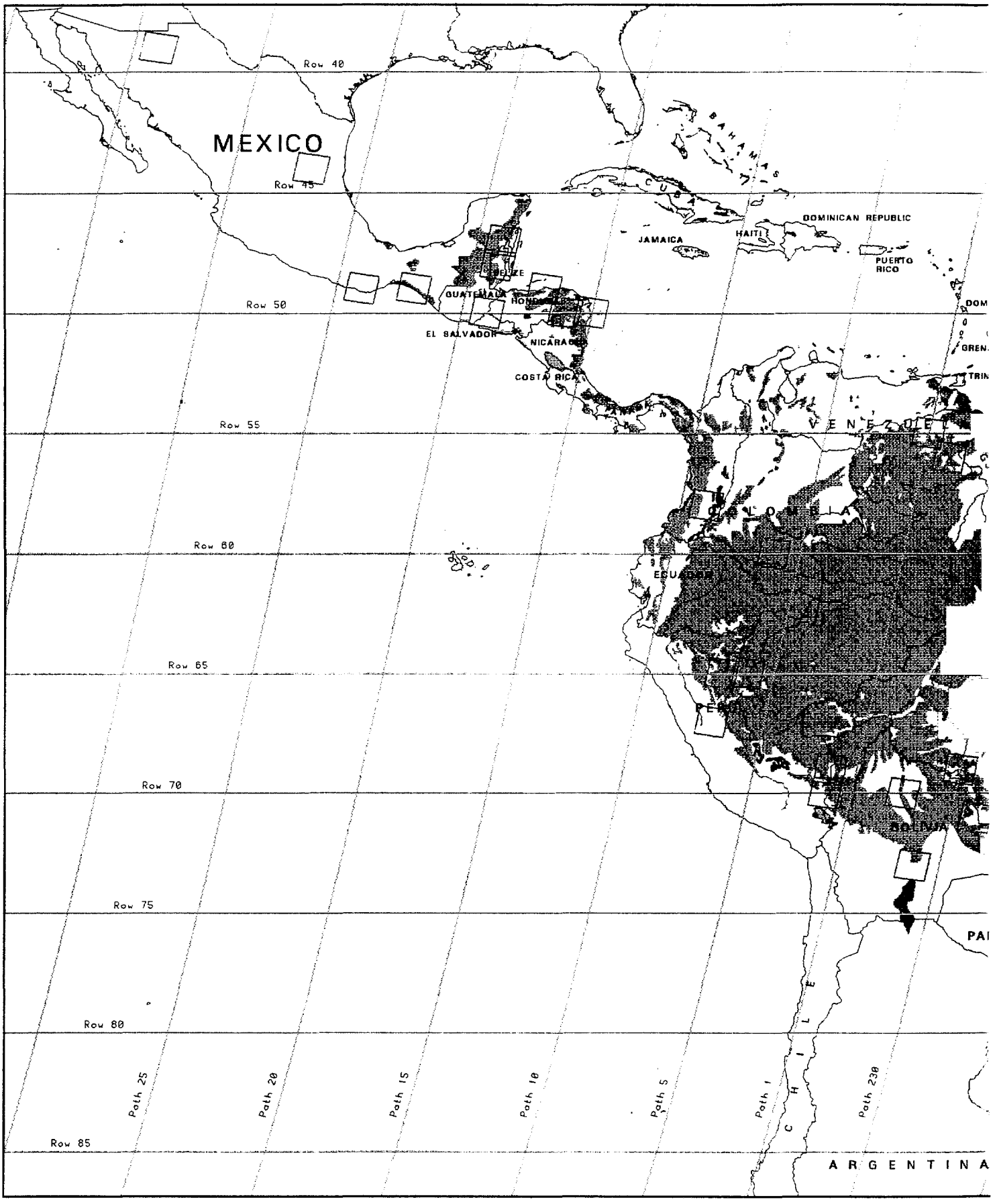
Land cover and forest cover classification schemes:

Preliminary image interpretation classes were:

- **Land**
  - Woody vegetation
    - natural
    - man-made
      - forest plantation
      - agricultural plantation
  - Other land cover
- **Water**
- **Other non-interpreted**

Additional classes of woody vegetation cover:

- **Forest**
  - Continuous
    - agricultural impact
      - short fallow
      - long fallow
    - no agricultural impact
    - closed canopy forest 40%
      - dense forest >70%
      - dense forest 40-70%
    - open canopy forest 10-40%
  - Fragmented (mosaic of forest and shrubs/other land cover)
    - forest fraction 40-70%
    - forest fraction 10-40%
- **Shrubs**
  - Dense > 40%
  - Sparse 10–40%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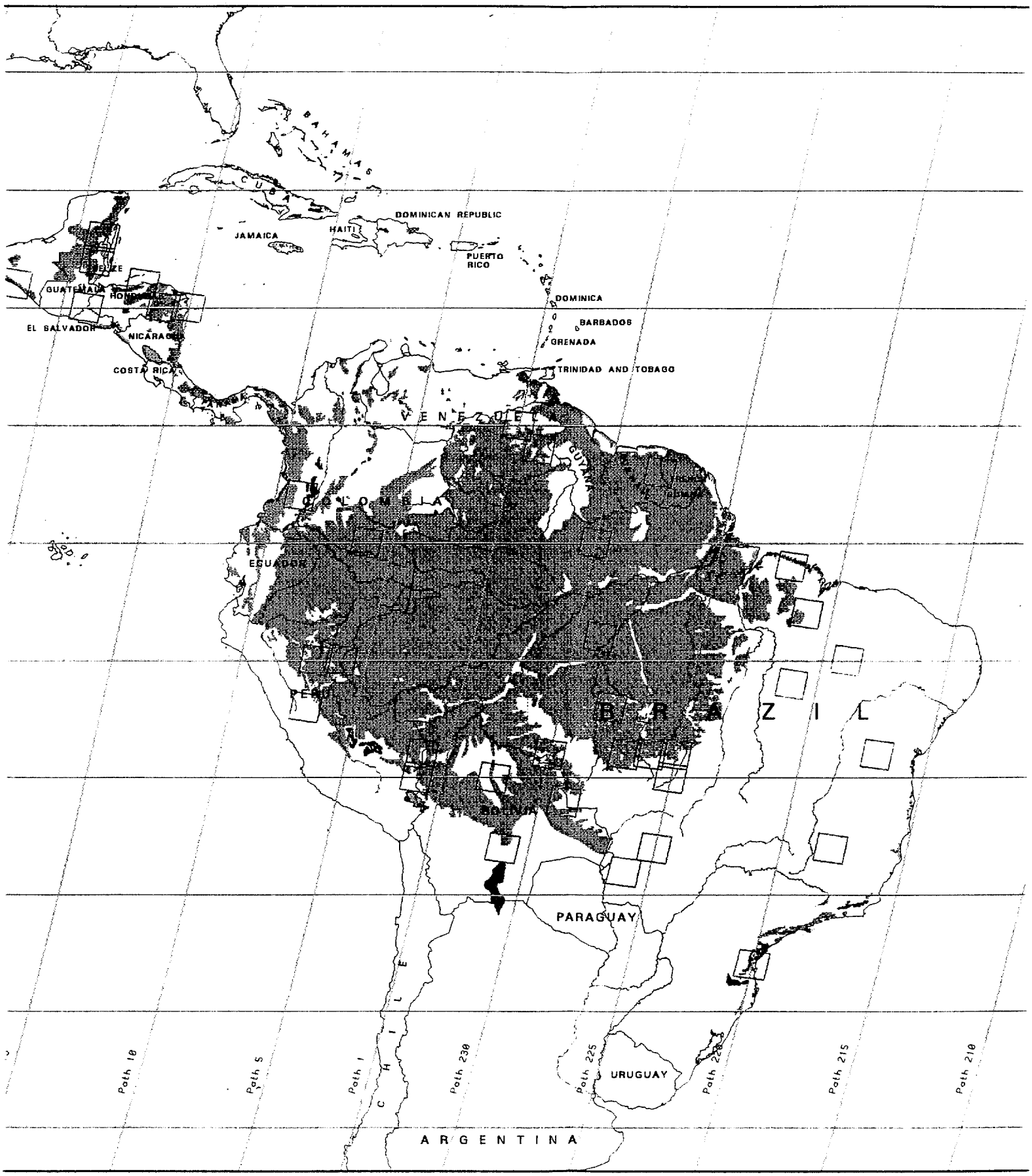
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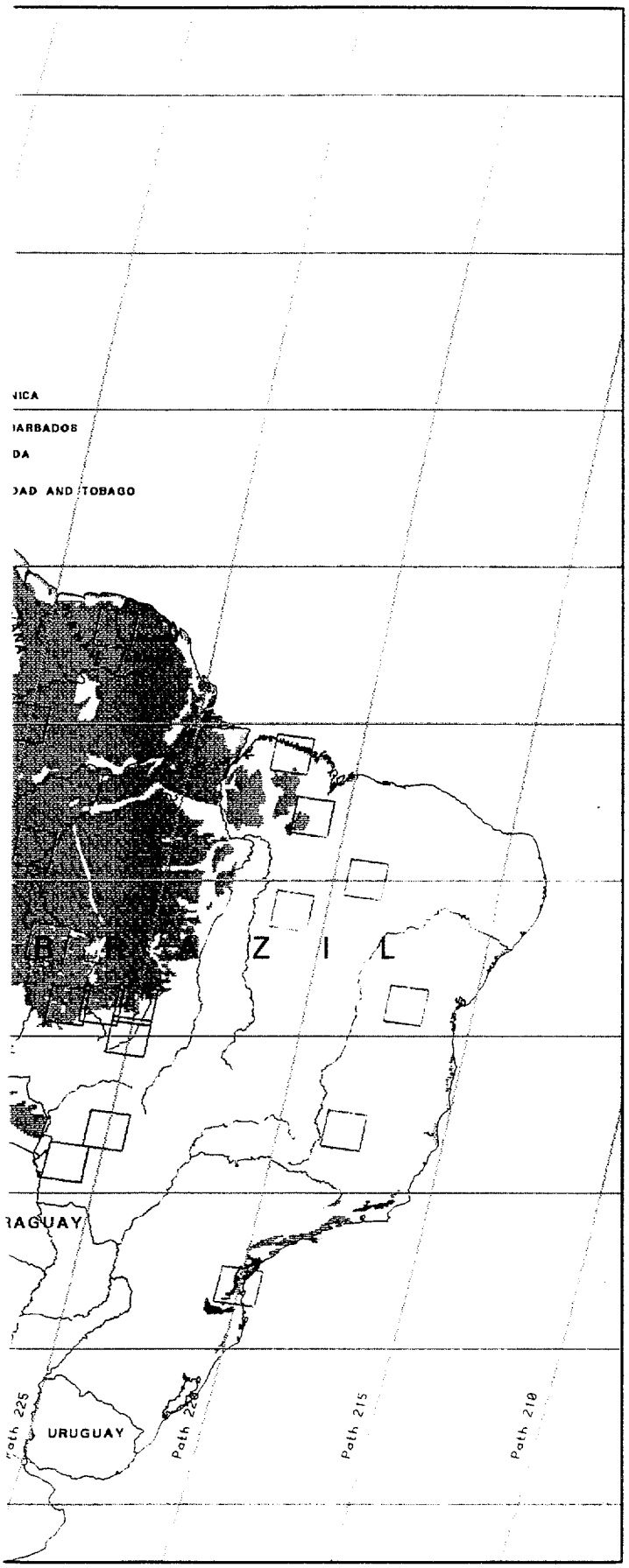

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FAO Forest Resources Assessment 1990
Latin America

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- Monsoon Forest

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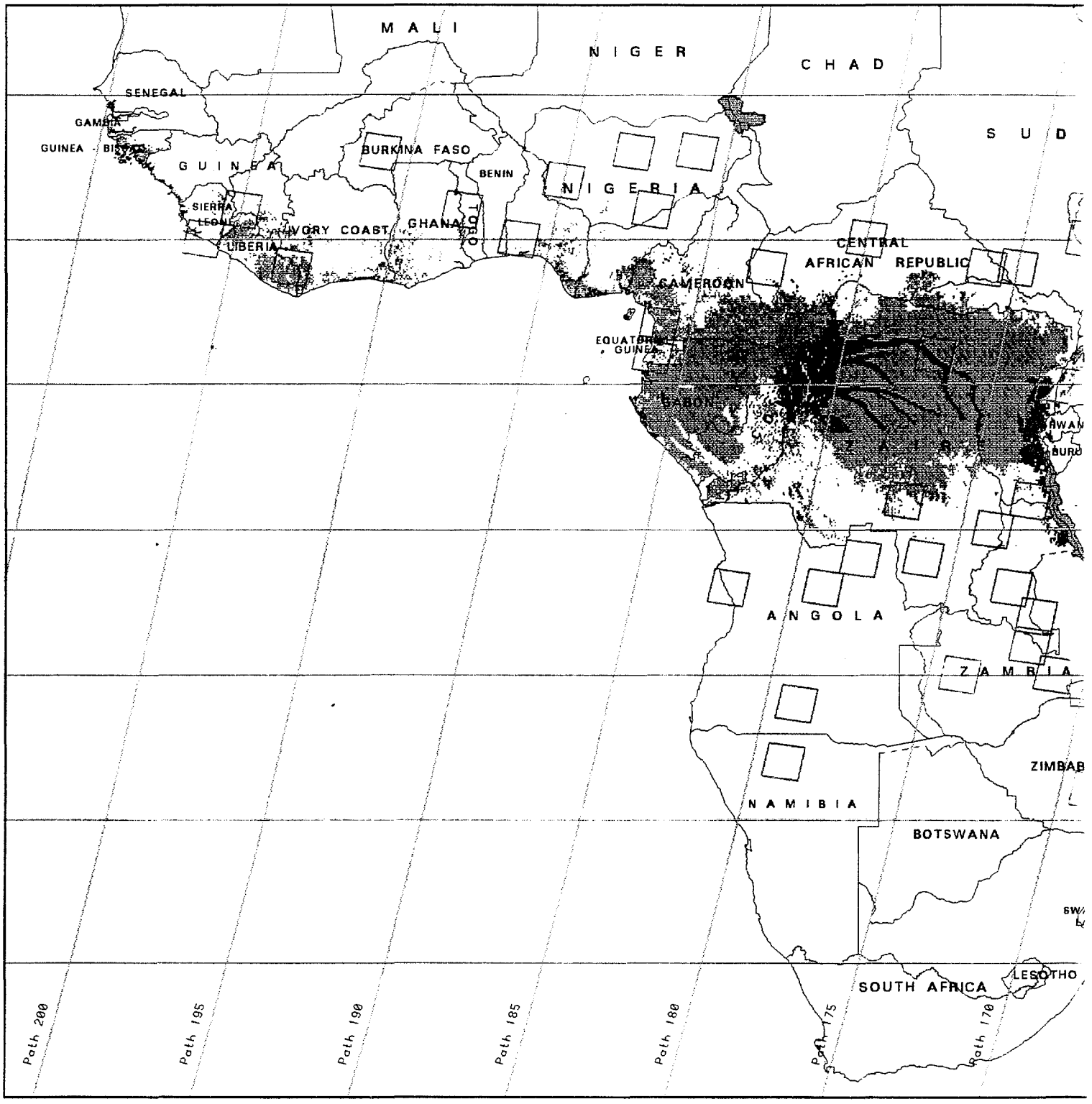
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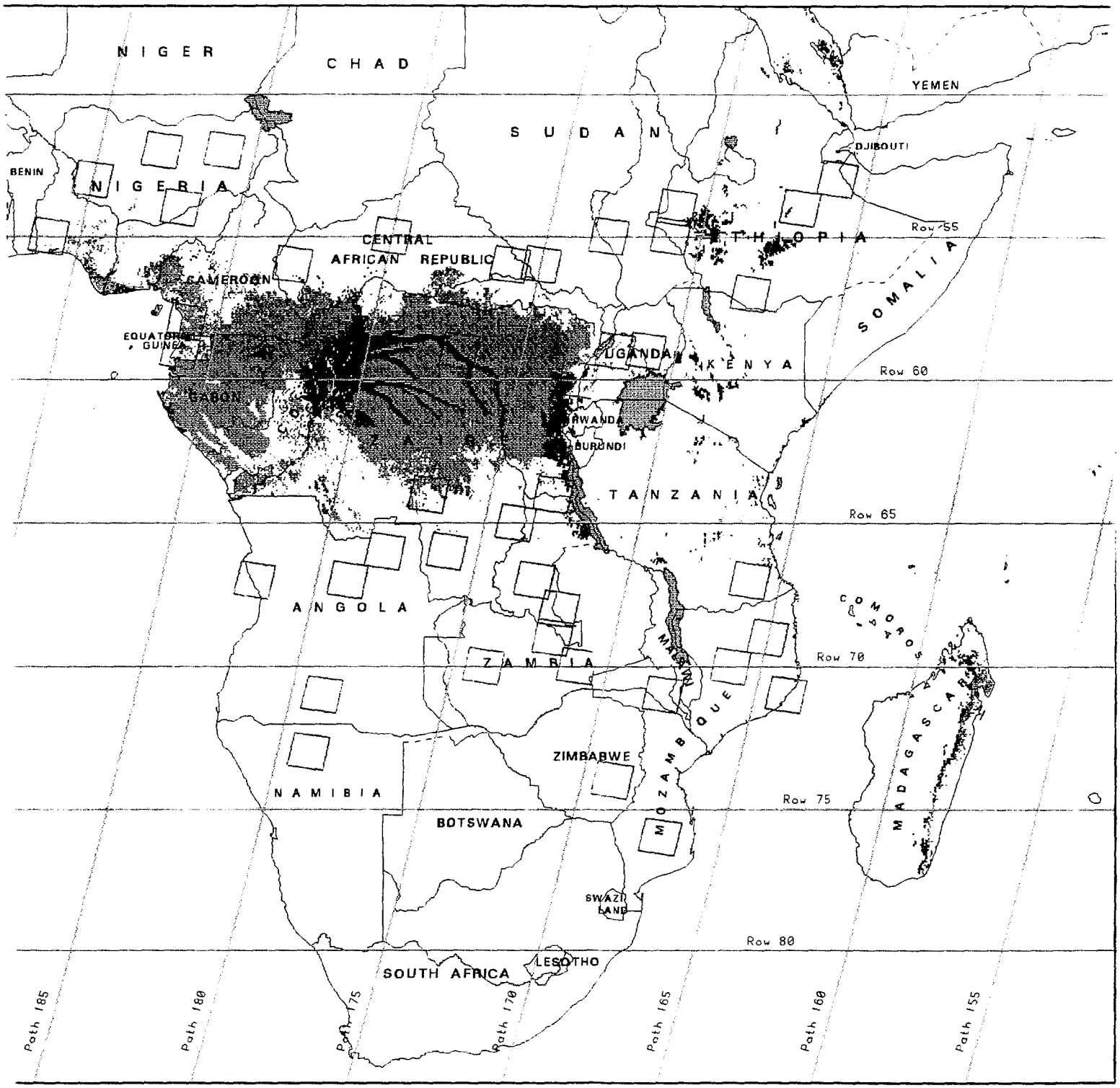
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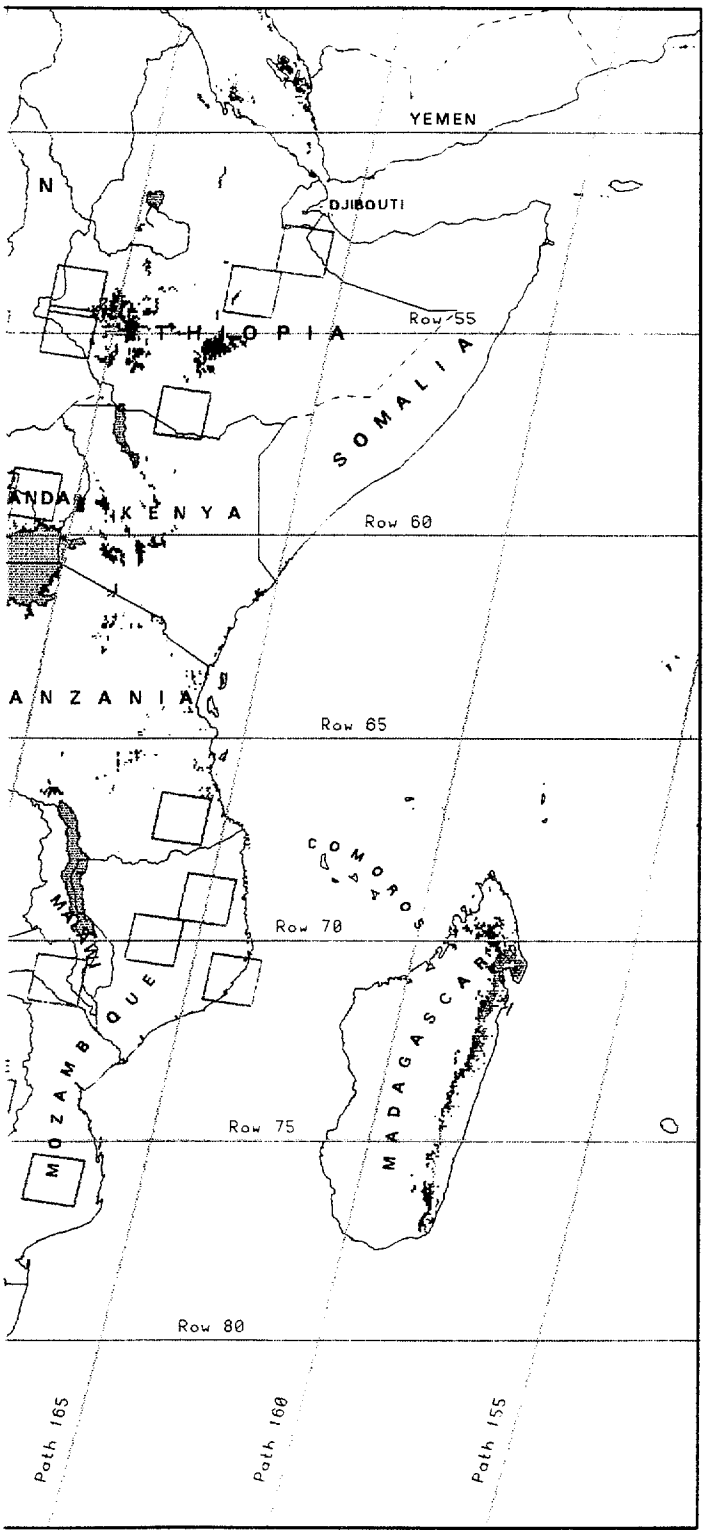
FAO Forest Resources Assessment 1990
Africa



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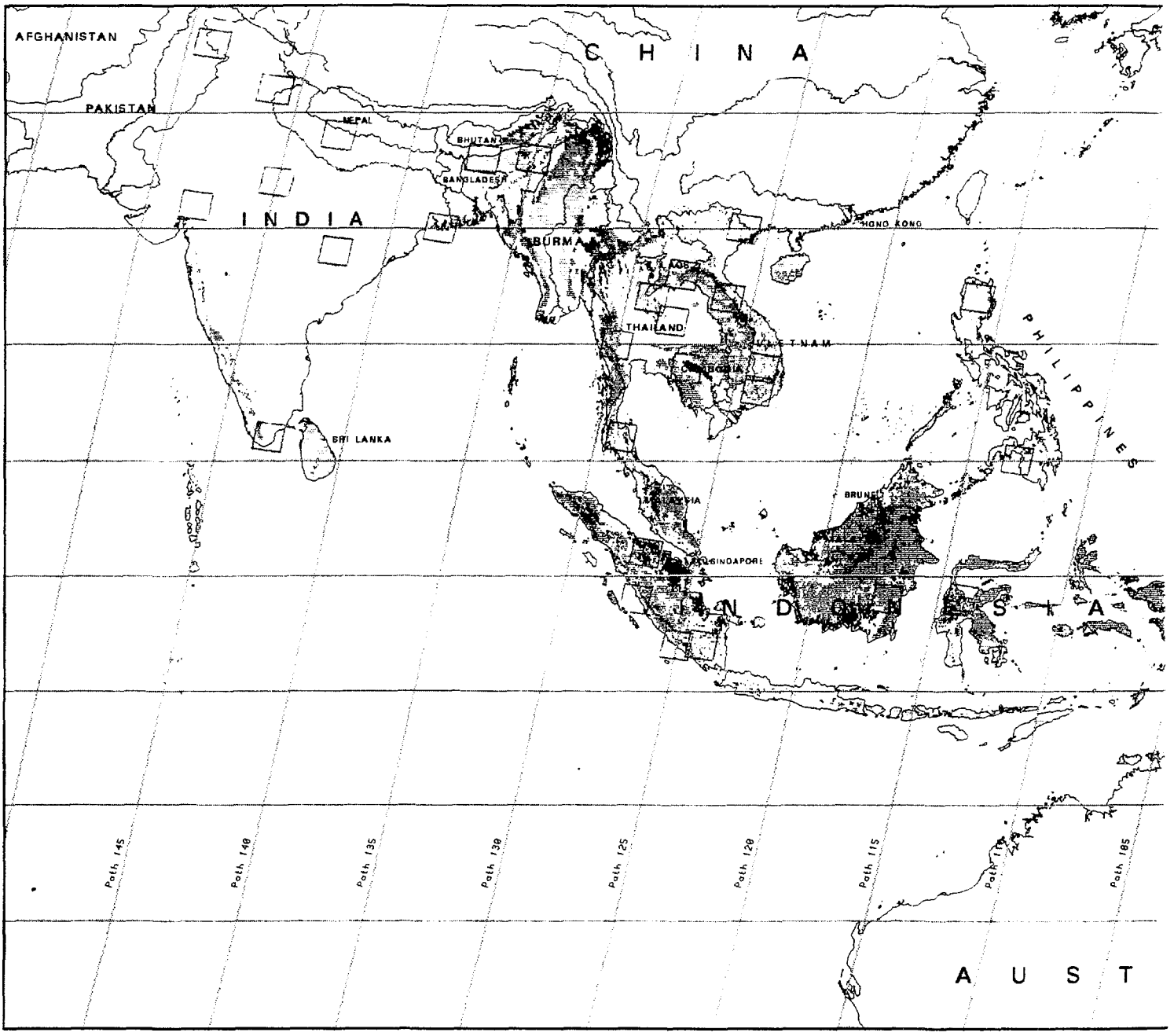
April 1994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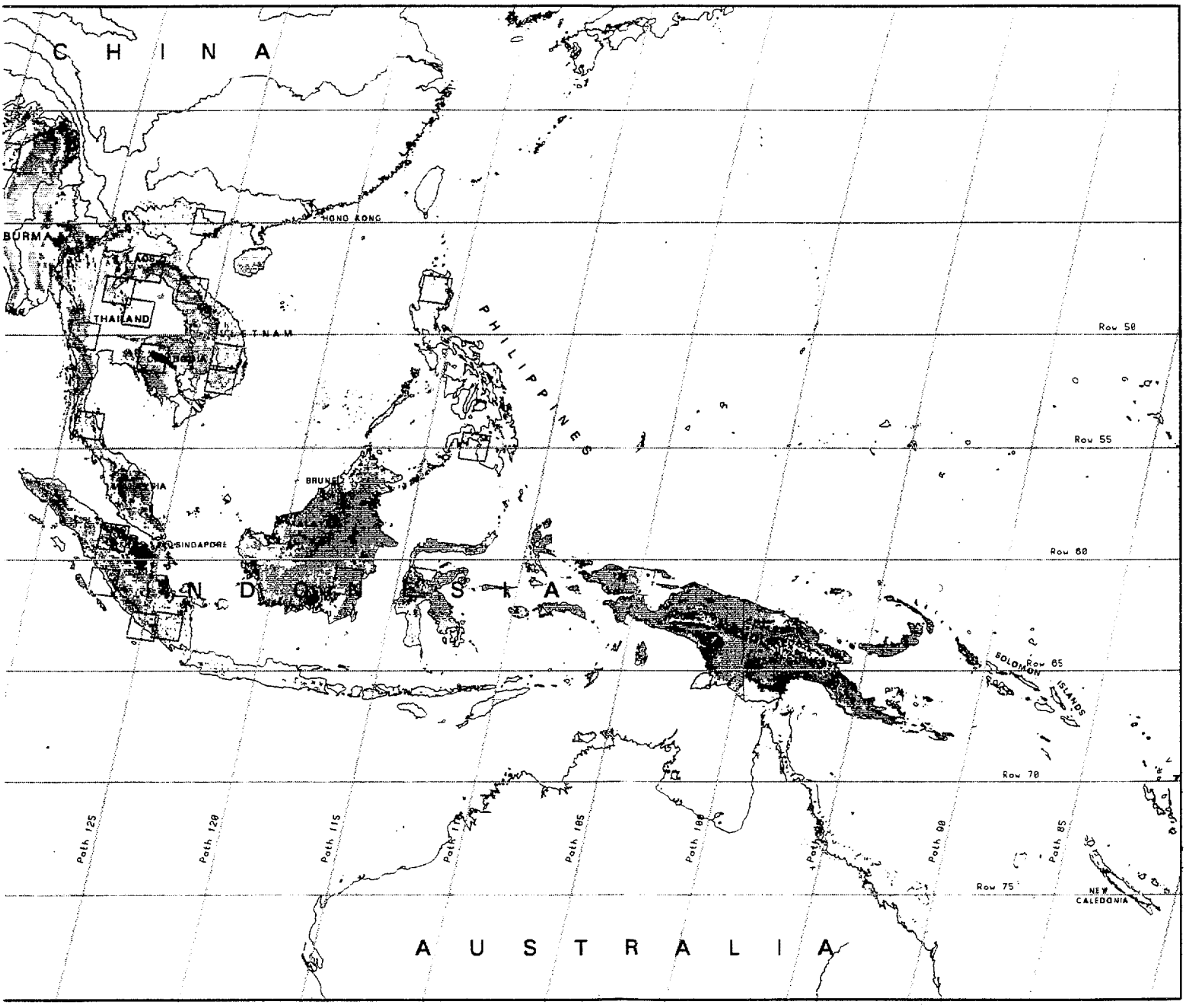
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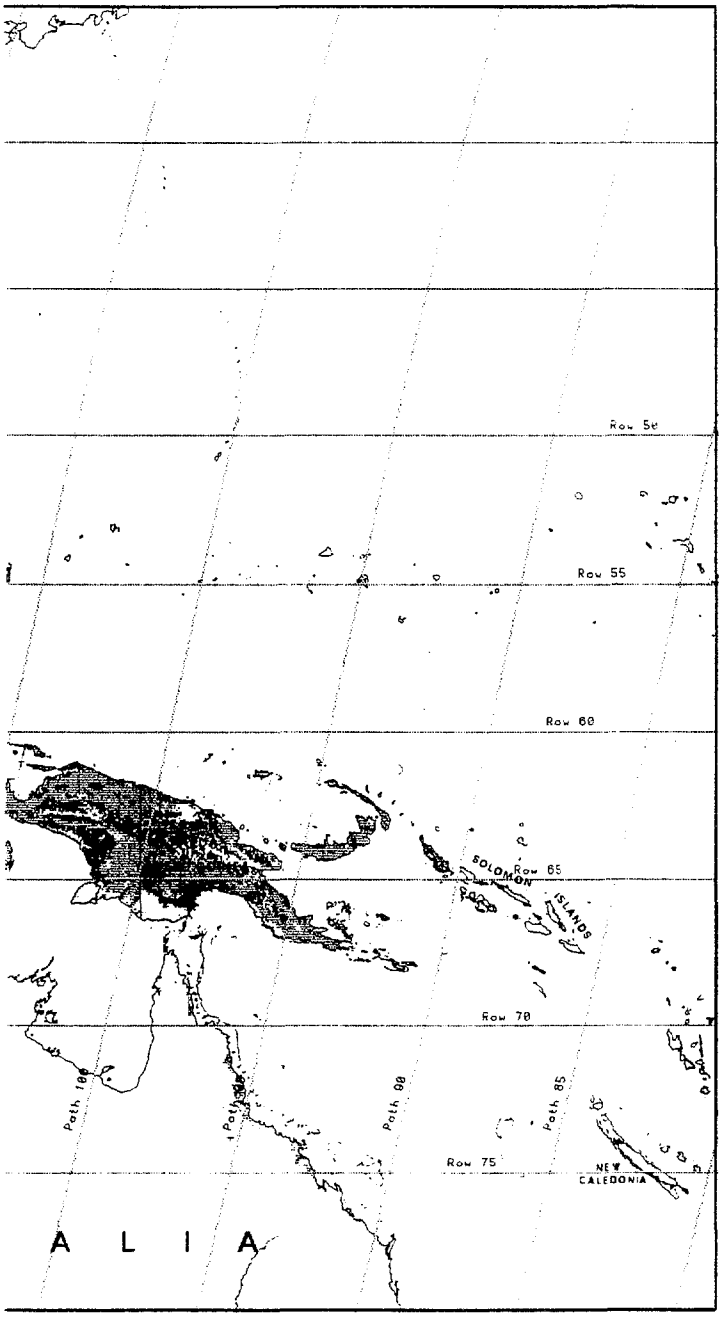
FAO Forest Resources Assessment 1990
South and Southeast Asia



Landsat Scene Footprint

Closed Tropical Forest
- Mangrove
- Inland Swamp
- Lowland Rainforest
- Montane Rainforest
- Monsoon Forest

Rivers

Water Bodies

Landsat Path & Row Grid

Country Boundaries
- Demarcated
- Disputed or Indefinite

Scale 1:40,900,000

Produced for USAID by the Environment and Natural Resources Information Center (ENRIC). Researched by Robert W. Fox. Compiled by Steven R. Davis. Sources of data: Landsat image footprints - U.N. Food and Agriculture Organization (FAO); closed tropical forest cover - World Conservation Monitoring Centre (WCMC); country boundaries and hydrography - Environmental Systems Research Inc. (ESRI). ENRIC is a project of Datex, Inc., Arlington, Va.

April 1994

PANAMAZONIA Project

Quick facts:

The PANAMAZONIA Project is a cooperative effort among the nine Amazon River basin countries to map and monitor the status of the Amazon forest with remote sensing tools. Leadership and technology transfer is provided by Brazil's remote sensing research institute, the Instituto Nacional de Pesquisas Espaciais (INPE). Landsat images will be produced covering the entire Amazon basin region, while image analysis, GIS, and related technologies will be transferred from Brazil to the other nations.

Contact:

Contact: Paulo Roberto Martini, INPE/DSM, São José dos Campos, SP, Brazil. Tel. (23) 41 8977.

Project name:

PANAMAZONIA Project.

Agency/organization(s), cooperative arrangements:

This is a cooperative venture among the nine Amazon basin countries (Brazil, French Guiana, Suriname, Guyana, Colombia, Ecuador, Peru and Venezuela, and Bolivia). The Latin American Society of Remote Sensing Specialists (SELPER) is providing technical and scientific support. The majority of the in-country participants are SELPER members. Brazil's INPE is supplying technical know-how and leadership. INPE is experienced at evaluating the Brazilian deforestation situation. Some additional assistance is being provided by the Goddard Space Center in Greenbelt, MD. The other implementors are Bolivia's CUMAT Institute, Colombia (IGAC), Ecuador (CLIRSEN), Guyana (METEOSERVICE), Peru (ONERN), Suriname (Forest Service), Venezuela (SAGECAN), and French Guyana (EGREF-Centre Kourou).

Project objectives and plan:

The objective is to provide training and computer hardware/software from Brazil to neighboring countries in order to facilitate assessments of the rate of tropical deforestation in the Amazon basin and continuously monitor the situation.

No specific mention is made in the project report of proposed coverage for Brazil. Brazil, however, has conduct its own Landsat-based forest assessments as far back as 1973. INPE has a Landsat satellite ground receiving station at Cuiaba, Mato Grosso and image storage and production facilities in São Jose dos Campos. It appears that Brazil will bring into the PANAMAZONIA project the results of its most recent assessment in order to complete a composite picture of the entire region's tropical forest status.

Satellite imagery used:

Satellite imagery used: The total nine country basin area consists of 333 satellite image "footprints" as shown on the index map. However, due to numerous overlapping scene duplications along border areas, this requires 229 thematic mapping (TM) image scenes for the Brazilian portion and 156 scenes covering portions of the Amazon basin in the bordering countries. Two hundred and seventy Landsat thematic mapping (TM) images were produced and distributed by INPE as of March, 1992 to the countries outside Brazil. Another 80 TM images were to have been purchased through EOSAT.

Further proposed analysis or potential through GIS applications:

Project applications beyond deforestation may include land use mapping; forest inventories; cadastral mapping; spatial distribution determinations of ecosystems; and the establishment of "early warning" protection boundaries of bioecological sites.

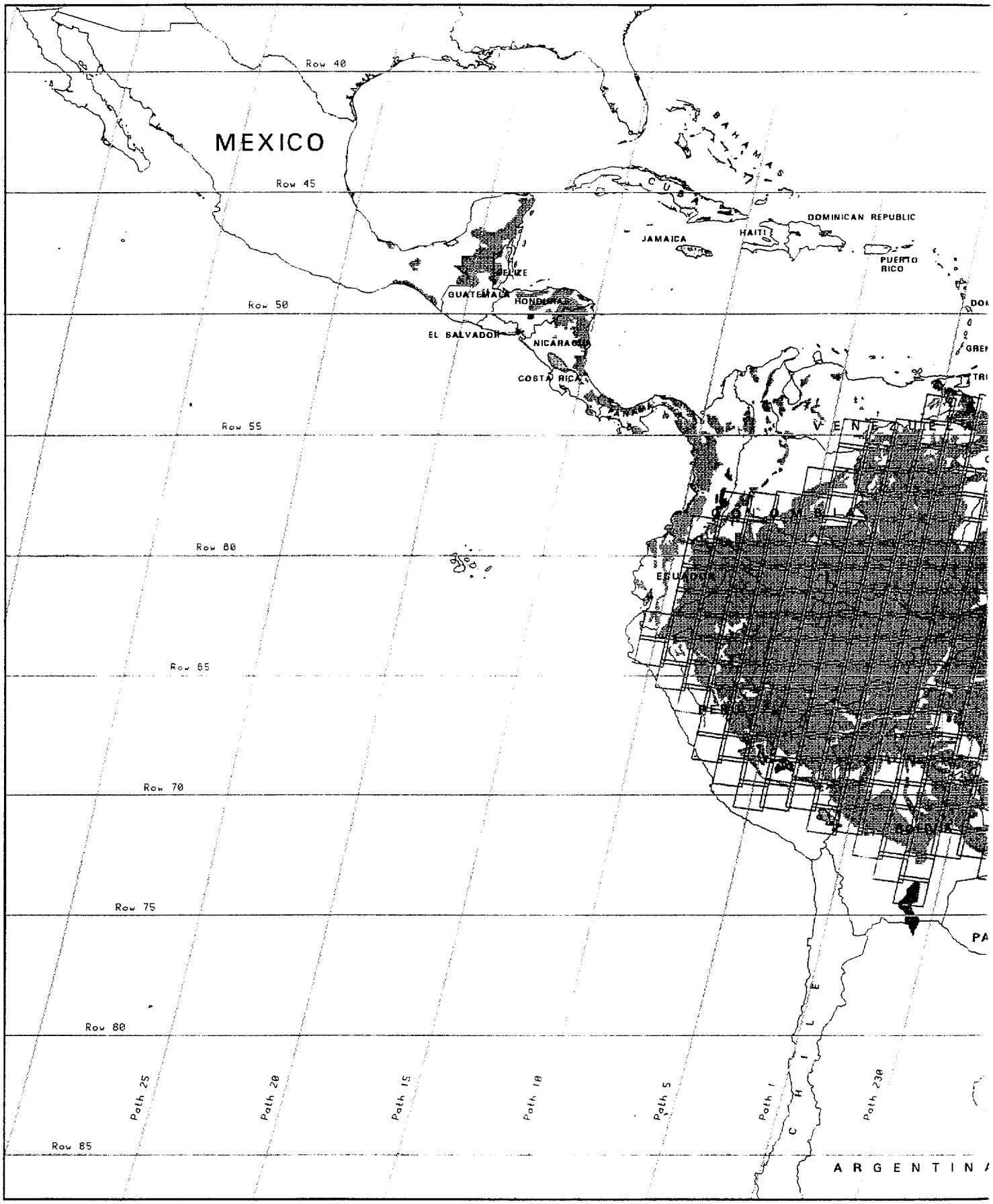
Methodology:

This project involves a): selecting and generating Landsat image scenes at a 1:250.000 scale for two periods (1984-87 and 1988-91); b) transferring geographic information system (GIS) technology from Brazil and implementing computer data techniques in countries where these procedures are not available, and; c) training technical staff in the different countries.

The analysis and mapping will include 1) deforestation in the first period (1985-87); 2) deforestation in the second period (1988-91); 3) a deforestation index; 4) a reference to the date of the image by path and row. A GIS data grid will be organized into 1:250.000 scale quadrangles divided by 15 x 15 minute cells and information may be retrieved from these small cells in digital format.

Forest and other land cover classifications used:

Two classes of vegetation will be mapped: (1) forest areas, both rainforest and high "selvas,"and (2) naturally "non forested" areas (e.g. savannas, grasslands). In addition country, state or department boundaries; lakes, dams, reservoir boundaries; main rivers and roads; and main cities will be mapped.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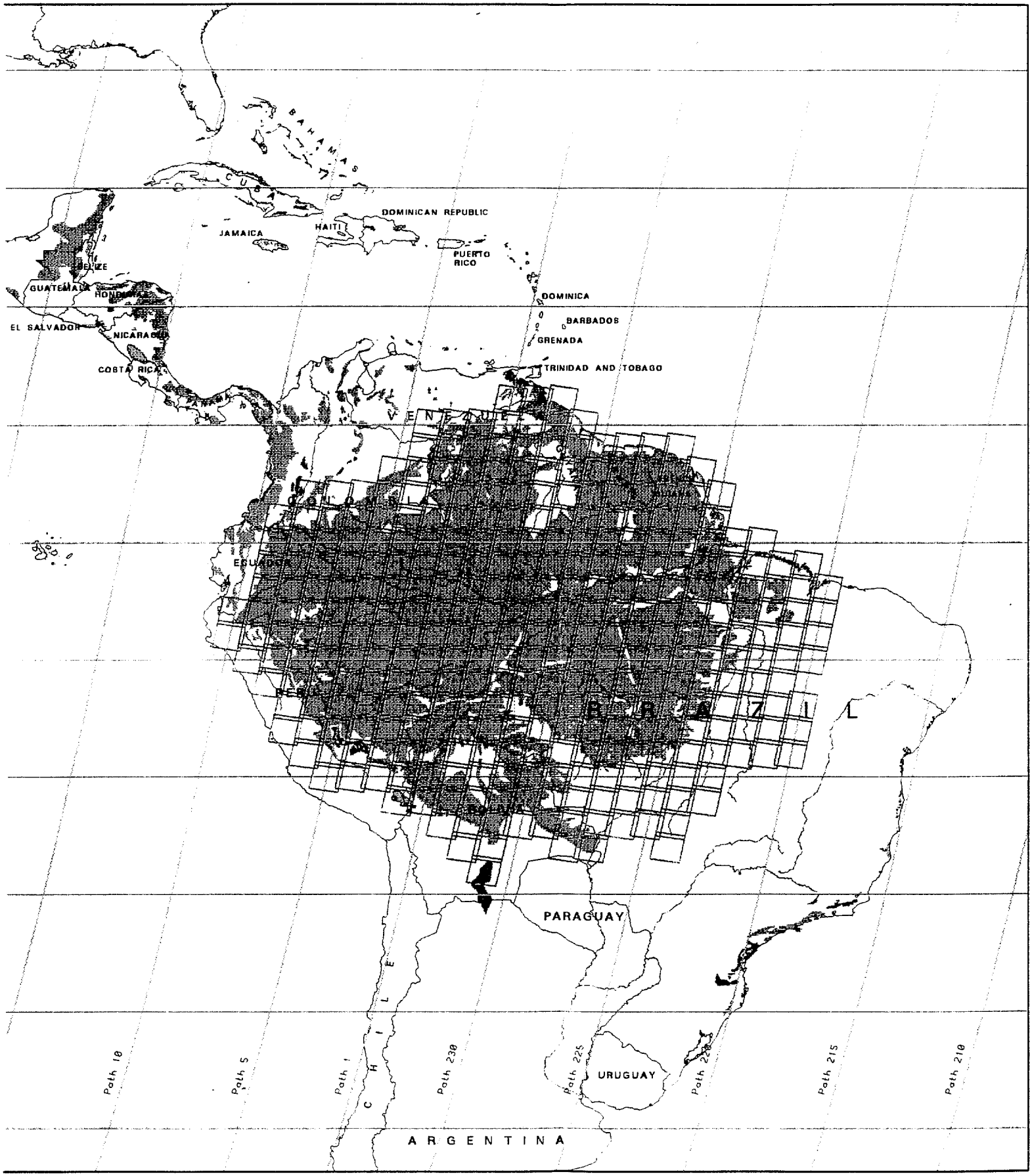
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BARBADOS
GRENADA
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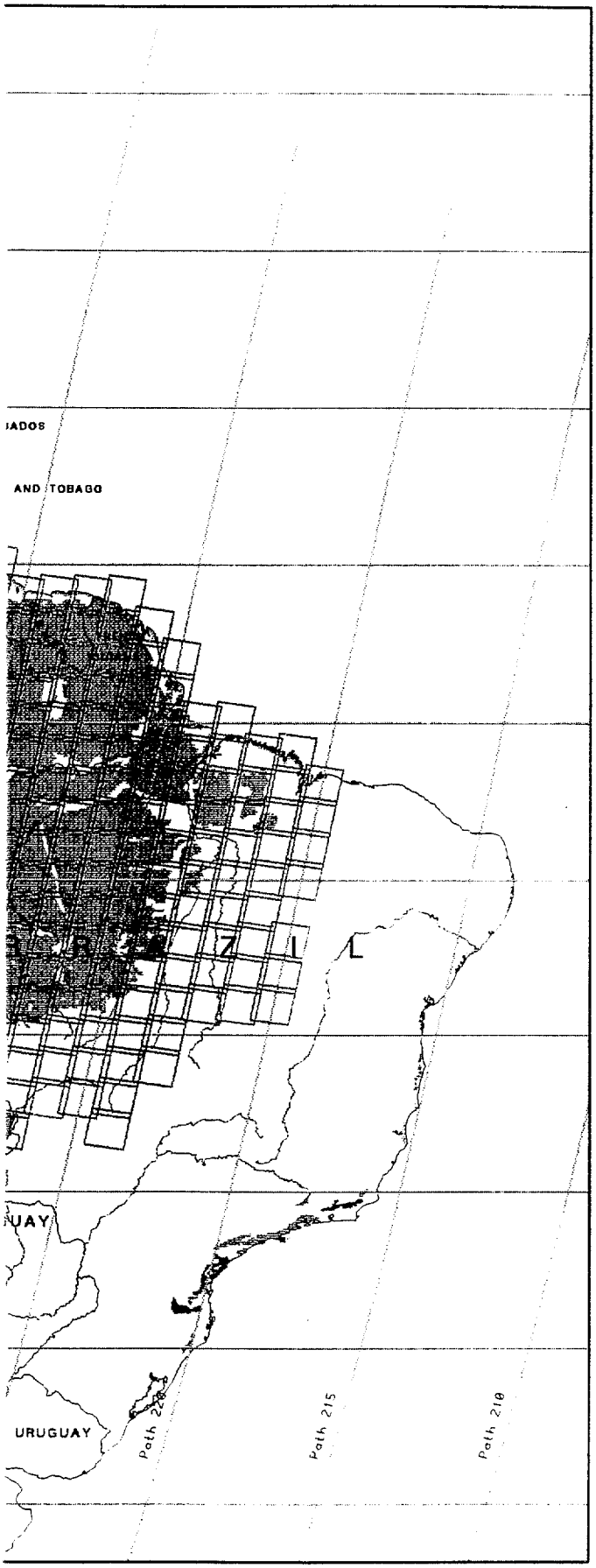

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PANAMAZONIA Project
Amazon River Basin

Landsat Scene Footprint

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- Monsoon Forest

Rivers

Water Bodies

Landsat Path & Row Grid

Country Boundaries
- Demarcated
- Disputed or Indefinite

Scale 1:33,500,000

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ENRIC Section III

The Results

"The Deforestation Debate," *Richard Monastersky*

Deforestation and Forest Cover Statistics from FAO's Forest Resources Assessment 1990: Tropical Countries

"Tropical Deforestation and Habitat Fragmentation in the Amazon: Satellite Data from 1978 to 1988," *David Skole and Compton Tucker*

THE RESULTS

The Data Debate

The questionable reliability and accuracy of tropical zone deforestation estimates has been an issue. Richard Monastersky's *Science News* article, "The Deforestation Debate", reviews the range of estimates that have been published. Large differences among them have confounded a consensus on the rate of deforestation and the relative urgency of action. The arbitrator in this debate was to be the 1990 FAO Forest Resource Assessment for the tropical countries, which at the time (July, 1993) had not been released.

FAO's Results

The publication of *Forest Resources Assessment 1990: Tropical Countries* by FAO in late 1993 produced the newest generation of global forest statistics as well as preliminary results of FAO's satellite imagery analysis.

Statistical results. A series of graphics in this section capture highlights of the FAO statistical database. This baseline will now serve as the authoritative source for deforestation and other forest resources data until satellite based analyses yield comparable information.

Satellite image sample survey results. Pages illustrating the outcome of this innovative work are reproduced in this section. The satellite based sample survey, still in process, has lagged behind FAO's statistical compilation. However, in Africa analyses of 31 sample frames (of the 47-frame total), representing a total of 71.6 million hectares of land area, had been completed by late 1993. The image analyses were tabulated by type of change, e.g. from forest to non-wooded or to other wooded land, and by ecofloristic zone, one of the GIS layers with which FAO worked. The analysis revealed that the process of deforestation varies by ecological zone, being more permanent in the African highlands than in the moist lowlands, where short or long woody fallows follow a number of years of cropping.

Deforestation patterns also vary by region. FAO compared forest cover change in West Africa and in the Amazon, using AVHRR imagery. In West Africa the closed forest exists as several islands in a fragmented mosaic of croplands and forest fallow. In the Amazon deforestation was detected as advancing from a perimeter or from roads into the core, unaltered forest.

Pathfinder

Initial results from the Pathfinder project were published in a June 25, 1993 Science article by C. Tucker and D. Skole, reprinted in this section. In addition to measuring deforestation between 1978 and 1988 in the Brazilian Amazon, forest fragmentation and the increase in forested areas within one kilometer of the edge of the forest perimeter were mapped and measured. The increase was ten times the extent of actual deforestation. The biological diversity of this accessible strip of forest is endangered by hunters, selective loggers, and shifting cultivators — the so-called "edge effect". The analysis foreshadows the value of the Pathfinder work beyond climate change research.

The Deforestation D · E · B · A · T · E

Estimates vary widely over the extent of forest loss

By RICHARD MONASTERSKY

As tales of burning forests captured headlines in the late 1980s, a string of rock stars, movie actors, and even ice cream makers joined the fight to save tropical woodlands, helping to transform the awkward term "deforestation" into a household word. But recent studies have produced markedly different estimates of the pace of clearing, raising questions about the accuracy of deforestation figures that have floated around policy circles in recent years.

While tropical forests are certainly vanishing at a disturbing rate, the widespread disagreement over deforestation estimates makes it difficult for government officials and scientists to assess the problem. That, in turn, hampers efforts to gauge the threat of related issues, such as habitat destruction and global warming.

Concerns about previous deforestation estimates emerged in the last few years as researchers from a number of countries looked into the problem, often using more reliable methods than before. Most recently, a study published in the June 25 SCIENCE confirmed suspicions that several earlier assessments had drastically overestimated the rate of forest destruction in the Brazilian Amazon basin, thereby inflating some global estimates.

The Brazilian case provides a dramatic example of how different researchers can arrive at markedly divergent conclusions concerning the extent of deforestation. In 1988, Alberto Setzer of Brazil's National Space Research Institute (INPE) used data collected by infrared sensors on a U.S. weather satellite to gauge the number and extent of fires within the legally defined Brazilian Amazon – an area that includes only part of Brazil's tropical forests. Assuming that 40 percent of the fires occurred on recently cleared forest, Setzer's team calculated that 8 million hectares of forest were cleared during 1987 within the legal Amazon – an almost unfathomable amount equal to 2.2 percent of the forest.

Although contested by other researchers, that alarming number found its way into several global deforestation estimates at the time. In particular, the Washington, D.C.-based World Resources Institute (WRI) included Setzer's Amazon figure in a 1990 worldwide assessment. The high number for Brazil drove up WRI's global estimate for tropical forest loss, which was calculated at 16.4 to 20.4 million hectares per year.

Despite the controversy over the Brazilian estimate, WRI's global total seemed to agree with a provisional number issued by the United Nations Food and Agriculture Organization (FAO), which put tropical deforestation at 17 million hectares per year for the period 1981 to 1990 (SN: 7/21/90, p.40).

Brazil emerged from the WRI study and others looking like the ultimate forest destroyer, responsible for roughly one-third to one-half of the global deforestation total. That triggered a round of international finger-pointing, focusing criticism on Brazil for allowing such rapid clearing of the Amazon. Brazil, however, complained that the estimates were inaccurate and that deforestation rates had never reached such heights, says Jayant A. Sathaye, an energy and forestry analyst at the Lawrence Berkeley (Calif.) Laboratory.

More recent studies have backed up Brazil's claims. In the last few years, researchers at INPE and the National Institute for Research on Amazonia, based in Manaus, Brazil, challenged Setzer's fire-counting technique and began gauging deforestation by mapping cleared areas on images taken by Landsat satellites. Studies that relied partly on this technique indicated that deforestation within the Brazilian Amazon averaged 2.1 million hectares per year between 1978 and 1989 and 1.4 million hectares from 1989 to 1990.

The newest estimate for Brazil goes even lower. David Skole of the University of New Hampshire in Durham and Compton Tucker of NASA's Goddard Space Flight Center in Greenbelt, Md., studied some 200 Landsat images covering the entire Brazilian Amazon for 1978 and 1988, allowing them to map the extent of forest and cleared land for those two years. The images showed that deforested areas covered 7.8 million hectares in 1978 and 23 million hectares in 1988, implying an average annual loss rate of 1.5 million hectares, Skole and Tucker report in their recent SCIENCE paper.

Conventional wisdom holds that Brazil's deforestation slackened dramatically after peaking in 1987, in part because the country's economy slowed, reducing the land speculation that had motivated people to clear forest for new farms or rangeland. If true, that standard theory could explain why Setzer and others found so much more deforestation going on at the peak period than others have seen in the last four years.

But Skole dismisses that explanation. "A lot of people are using it as a convenient excuse for being wrong," he contends. Although he, too, finds that deforestation rates have dropped in Brazil, he says the average for the late 1980s did not range much above 2 million hectares per year – not high enough to explain the earlier estimates.

If Brazil's actual rate of forest loss is so much lower than studies had previously suggested, how accurate are the various global estimates? Skole, for one, has little faith in the sea of numbers. "All of the published global studies do not use a systematic approach," he says. "They use secondary and tertiary sources, anecdotal reports, different time periods, different methodologies, different terminology. It's the state of affairs right now in deforestation monitoring. It's kind of a sad state of affairs, but people are using whatever resources they have, which are not adequate."

Before deforestation gained widespread attention in the late 1980s, most researchers relied on an estimate by FAO, which concluded in 1981 that tropical deforestation worldwide averaged 11.3 million hectares per year during the late 1970s. That number stood uncontested because it was the only figure available.

Since 1989, FAO has been working to update that global estimate. In 1990, it released a provisional figure of 17 million hectares of deforestation per year; but this March it lowered the global total to 15.5 million hectares per year for the period 1981 through 1990. K.D. Singh, leader of FAO's forestry assessment team in Rome, explains the change by saying that his organization's 1981 study overestimated the amount of forest remaining in the tropics at that time, a mistake that had inflated its 1990 estimate.

By all accounts, the latest FAO assessment represents the most comprehensive global study to date, having collected scattered data from individual countries or provinces and woven them together using a mathematical model based on information about forest conditions, population density, and ecological zones. Singh says his team has striven to find the best data available, although the quality and type of data vary from one region to

another. Some local and national governments have conducted forest surveys using satellite images, while others have used ground-based approaches for estimating deforestation.

The success of the FAO effort remains uncertain, however. Forestry researchers cannot yet check the new global assessment against other studies because FAO released only regional deforestation estimates and has not yet issued tallies for individual countries.

For instance, the FAO numbers reported in March include 6.2 million hectares of forest lost annually in tropical South America from 1981 through 1990. That region includes Brazil and six other nations. To some researchers, the South American total appears unrealistically high. If FAO chose the best data available at the time (the Brazilian estimates of 2 million hectares lost annually in the legal Amazon during the 1980s), that would leave more than 4 million hectares cleared each year outside the Brazilian Amazon.

Where, then, is all that missing South American deforestation? That is precisely the issue raised by an international committee of researchers called the Intergovernmental Panel on Climate Change. In a 1992 report, the panel questioned FAO's South American estimate (which has since decreased slightly), saying, "This seems to ascribe a very high proportion (about 70 percent) of the total deforestation in South America in the late 1980s to the region outside the Brazilian Amazonia, even though this region accounts for very little of the total amount of forest on the continent."

But FAO's Singh says researchers have not appreciated the extent of South American deforestation in the open forest outside of the rainforest of the Brazilian Amazon. "This has been one of our main findings – that the deforestation outside the legal Amazon basin is quite high," he told SCIENCE NEWS. The open forest faces a greater threat because it is more accessible and because more people live there than in the rainforest, Singh says.

Beyond those hints, Singh says he cannot respond fully to criticisms of the new deforestation assessment until FAO publishes its more complete report, which will include a breakdown of figures for individual countries. The report should come out in late summer, he says. Singh also hopes to submit the study to a panel of scientists for peer review.

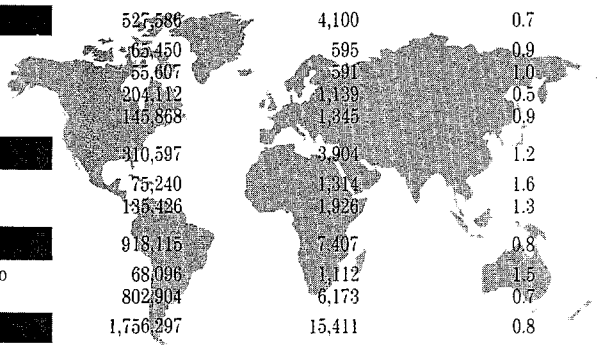
Some researchers, however, wonder whether the FAO will delay releasing the long-awaited numbers, perhaps indefinitely, in hopes of avoiding the intense scrutiny that will descend on this study.

Ken Andrasko, chief of a forestry section in the Environmental Protection Agency's climate change division, suggests that deforestation studies have acquired political significance in the wake of last year's Earth Summit in Rio de Janeiro, where countries signed treaties on biodiversity and climate change. The climate change convention requires all countries to provide an inventory of their greenhouse gas emissions, including those caused by deforestation. Since future treaties may call for all countries to limit their emissions, the deforestation estimates will partly determine how much a country needs to cut back.

"It's going to be increasingly difficult to publish those individual country [deforestation] estimates. If the number is higher or lower, it has very real political consequences now," Andrasko says.

DEFORESTATION HOT SPOTS

Region	Forest remaining as of 1990 (thousands of hectares)	Annual deforestation 1981-1990 (thousands of hectares)	Annual rate of deforestation (percentage)
Africa	527,586	4,100	0.7
East Sahel Africa	65,450	595	0.9
West Africa	55,607	591	1.0
Central Africa	204,112	1,139	0.5
Tropical Southern Africa	145,868	1,845	0.9
Asia	310,597	3,904	1.2
Continental S.E. Asia	75,240	1,314	1.6
Insular S.E. Asia	135,426	1,926	1.3
Latin America	918,115	7,407	0.8
Central America and Mexico	68,096	1,112	1.5
Tropical South America	802,904	6,173	0.7
World Total in Tropics	1,756,297	15,411	0.8



Source: Food & Agriculture Organization

That lesson was not lost on Brazil, which released its own deforestation data on the eve of the Rio summit. Such studies, as well as the one by Skole and Tucker, show that while Brazil may still be number one, it no longer sits in a category of its own, far and above every other nation on the list of forest destroyers.

Although the FAO did not provide estimates for individual countries, the data released earlier this year clearly indicate that tropical forests are shrinking worldwide. Indeed, parts of other continents are losing a greater percentage of their forests than is South America, which has much more intact forest than other parts of the globe. According to FAO, the highest percentages of deforestation during the 1980s occurred in southeast Asia, Central America and Mexico, and West Africa.

Looking beyond the problem of absolute deforestation, experts say fragmentation and degradation of remaining forests also present substantial threats, especially to the diversity of plant and animal life in some of the most biologically rich habitats on Earth. Indeed, Skole and Tucker found that the area of disturbed habitat surrounding cleared areas grew by more than 4 million hectares per year in Brazil's Amazon, much faster than the pace of deforestation there. "Even though the rate of deforestation was much lower than previous estimates, the effect on biological diversity was much greater," says Tucker.

To address such concerns, the second phase of the FAO study will examine the extent to which people have broken up forest or removed trees without stripping an area bare. As part of this work, Singh's team has purchased high-resolution satellite images for 117 randomly selected regions corresponding to about 10 percent of the forest-covered land in the tropics. For quality control, his group also used these satellite images in the first phase of the study to improve its deforestation estimates.

Ideally, FAO would purchase satellite images for the entire tropical belt. But Singh says the organization cannot afford the thousands of images needed to cover the tropics.

An ongoing NASA project may help complete the picture. In a program called Landsat Pathfinder, NASA is funding the purchase of satellite photos covering some three-quarters of the world's tropical rainforest. According to Skole, a participant in the project, it will provide the most accurate assessment of deforestation to date. As with the Brazilian case, the research done with satellite data could show that past estimates have been inflated. But Skole says the new study may also uncover much more deforestation than had been suspected.

The NASA effort does have some critical limitations. Because it focuses mostly on tropical rainforest, it will not include all open forests and dry forests, which cover just as much territory as do rainforests. Moreover, the project is a one-shot deal, not to be repeated. Experts say periodic updates are needed, not only to assess the changing deforestation threat but also to gauge the resulting increase in concentrations of carbon dioxide.

Despite its drawbacks, however, the NASA project should finally provide a means of checking the global estimates. "I feel confident," says Skole, "that in the next two to three years, as our work comes forward, we will have a much better idea because we are applying a consistent method." □

Deforestation and Forest Cover Statistics from FAO's Forest Resources Assessment 1990: Tropical Countries

The charts that follow graph key statistics on tropical forest covered and deforestation trends. The were prepared from the FAO's FORIS database files.

Definition of tropical forest. In the FAO assessment, the term "forest" encompasses lowland evergreen rainforests and deciduous moist forests as well as forests in dry, very dry, desert (hot/cold) and hill/montane ecological settings. FAO defined the lower threshold of forest cover at 10 percent of the land area. "Open" forest corresponds to 10 to 40 percent forest cover. More than 40 percent classifies as "closed" forest. Average biomass of forests in different climates show a correspondingly wide range — from 60 metric tons per hectare(mt/ha) in sparse, slow growing forests in dry climates to almost 250 mt/ha in South American rainforests.

Total forest cover. Table 1 ranks all categories of open and closed forests in the 90 tropical countries. The cumulative percentage listing shows that 75 percent of the world's tropical forests are found in just 16 countries. Brazil, with 561 million hectares in forests had 5 times more forested land than Indonesia in 1990, the second country in the rankings. Brazil houses 32 percent of the world's tropical forests. Deforestation amounts by decade (1960-1990) show that Brazil is also leading the tropical world in area deforested.

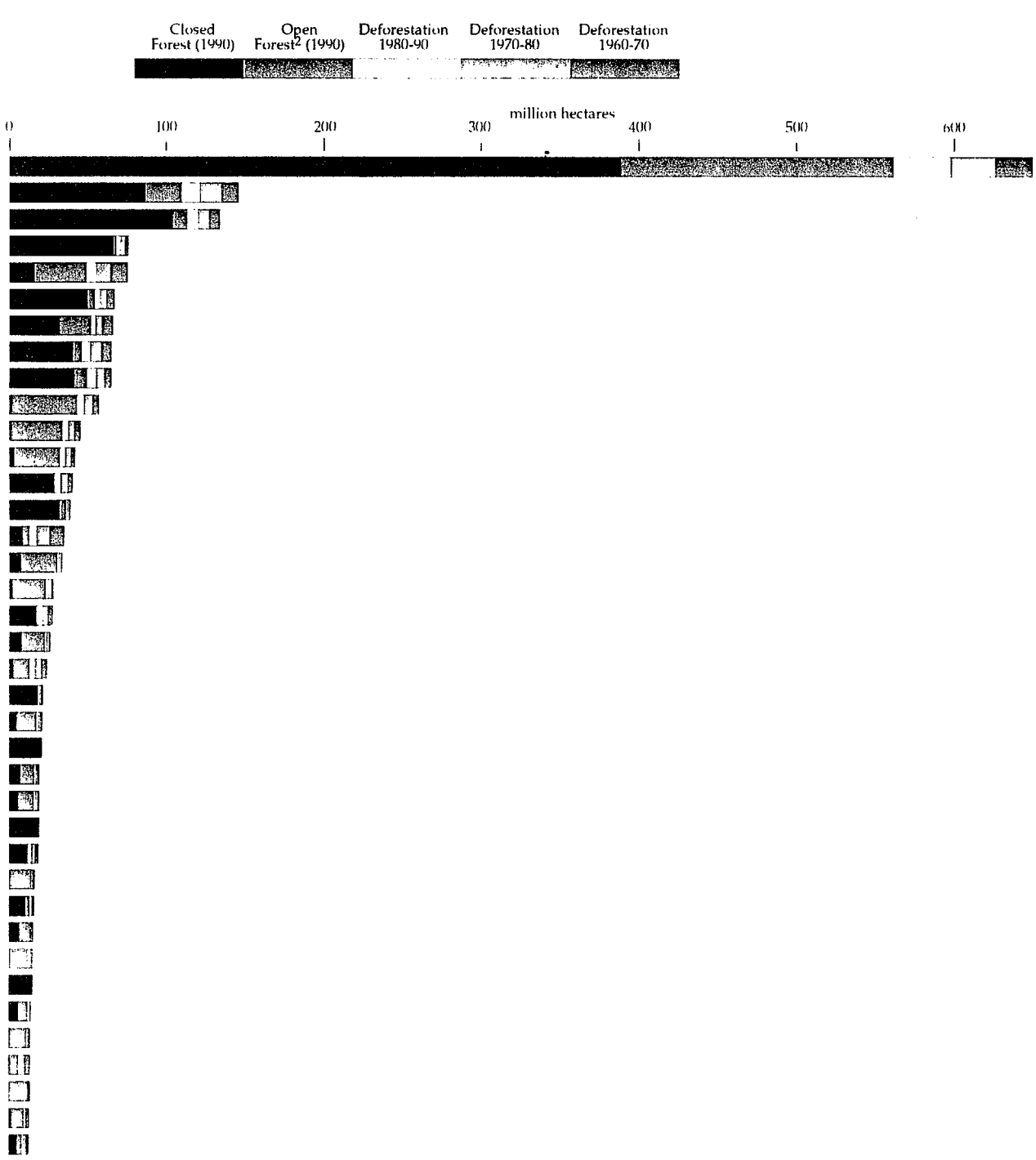
Deforestation 1960-1990. Table 2 shows deforestation as a percentage of the total forest cover existing in 1960, with absolute amounts in forest noted for 1960 and 1990. It can be observed that Jamaica has lost 75 percent of its forest cover in the period. For many countries, the amount of land deforested in each of the three decades is about the same. Only in four nations — French Guyana, Niger, Puerto Rico and Mauritania— has the amount of forest remained unchanged.

Rainforests and moist deciduous forests. Concern for tropical deforestation has focused on the tropical evergreen rainforests. In fact, closed forests in the tropical lowlands contain enormous tracts of moist deciduous stands in addition to the evergreen rainforest. Table 3 shows the percentage and absolute changes for this combination during the last decade. In this brief interval several countries with considerable areas of forest — Paraguay, the Philippines, and Thailand among them — experienced deforestation of more than a quarter of the forest extant in 1981. Jamaica, lost more than 50 percent, dropping from 499,000 to 235,000 hectares.

It should not be a surprise that densely populated nations figure prominently among the countries that suffered the greatest loss of forest cover.

TABLE 1. Tropical countries: land area in forests 1960–1990; 1990 shares of the world's tropical forest.[1] Countries ranked by forest size.

		Tropical forest area in 1990 (000 ha.)	Tropical forest area in 1960 (000 ha.)	Tropical forest area as % of land area in 1960	1990 % share of world tropical forest	Cumulative share of world tropical forest (1990)
1	Brazil	561,107	649,758	76	32.02	32.0
2	Indonesia	109,549	145,952	77	6.25	38.3
3	Zaire	113,275	134,086	57	6.46	44.7
4	Peru	67,906	75,711	59	3.88	48.6
5	Mexico	48,586	75,490	39	2.77	51.4
6	Colombia	54,064	67,034	59	3.09	54.5
7	India	51,729	65,848	20	2.95	57.4
8	Venezuela	45,691	65,144	72	2.61	60.0
9	Bolivia	49,424	64,937	59	2.82	62.9
10	Sudan	42,976	57,052	23	2.45	65.3
11	Tanzania	33,554	45,506	54	1.91	67.2
12	Zambia	32,301	41,707	56	1.84	69.1
13	Myanmar	28,856	40,688	61	1.65	70.7
14	Papua New Guinea	36,000	38,920	83	2.05	72.8
15	Thailand	12,735	34,936	68	0.73	73.5
16	Central African Rep.	30,562	33,809	54	1.74	75.2
17	Angola	23,074	27,971	22	1.32	76.6
18	Malaysia	17,583	27,817	85	1.00	77.6
19	Cameroon	22,740	26,443	57	1.30	78.9
20	Paraguay	12,859	24,228	60	0.73	79.6
21	Gabon	18,235	21,711	84	1.04	80.6
22	Mozambique	17,329	21,172	27	0.99	81.6
23	Congo	19,865	20,718	60	1.13	82.8
24	Madagascar	15,782	19,333	32	0.90	83.7
25	Nigeria	15,634	19,223	21	0.89	84.5
26	Guyana	18,416	18,935	96	1.05	85.6
27	Ecuador	11,962	18,725	71	0.68	86.3
28	Botswana	14,233	16,427	28	0.81	87.1
29	Laos	13,173	16,283	69	0.75	87.8
30	Ethiopia	14,165	15,575	12	0.81	88.7
31	Mali	12,144	15,254	12	0.69	89.3
32	Suriname	14,768	15,088	93	0.84	90.2
33	Cambodia	12,163	14,250	83	0.69	90.9
34	Chad	11,434	13,827	11	0.65	91.5
35	Cote d'Ivoire	6,127	13,746	43	0.35	91.9
36	Namibia	12,569	13,624	17	0.72	92.6
37	Ghana	9,555	13,131	55	0.55	93.1
38	Vietnam	8,312	12,975	39	0.47	93.6



14	Papua New Guinea	36,000	38,920	83	2.05	72.8
15	Thailand	12,735	34,936	68	0.73	73.5
16	Central African Rep.	30,562	33,809	54	1.74	75.2
17	Angola	23,074	27,971	22	1.32	76.6
18	Malaysia	17,583	27,817	85	1.00	77.6
19	Cameroon	22,740	26,443	57	1.30	78.9
20	Paraguay	12,859	24,228	60	0.73	79.6
21	Gabon	18,235	21,711	84	1.04	80.6
22	Mozambique	17,329	21,172	27	0.99	81.6
23	Congo	19,865	20,718	60	1.13	82.8
24	Madagascar	15,782	19,333	32	0.90	83.7
25	Nigeria	15,634	19,223	21	0.89	84.5
26	Guyana	18,416	18,935	96	1.05	85.6
27	Ecuador	11,962	18,725	71	0.68	86.3
28	Botswana	14,233	16,427	28	0.81	87.1
29	Laos	13,173	16,283	69	0.75	87.8
30	Ethiopia	14,165	15,575	12	0.81	88.7
31	Mali	12,144	15,254	12	0.69	89.3
32	Suriname	14,768	15,088	93	0.84	90.2
33	Cambodia	12,163	14,250	83	0.69	90.9
34	Chad	11,434	13,827	11	0.65	91.5
35	Cote d'Ivoire	6,127	13,746	43	0.35	91.9
36	Namibia	12,569	13,624	17	0.72	92.6
37	Ghana	9,555	13,131	55	0.55	93.1
38	Vietnam	8,312	12,975	39	0.47	93.6
39	Philippines	6,104	12,558	42	0.35	94.0
40	Zimbawe	8,897	10,706	28	0.51	94.5
41	Senegal	7,544	9,404	48	0.43	94.9
42	Nicaragua	6,013	9,207	78	0.34	95.2
43	Guinea	6,692	9,204	37	0.38	95.6
44	Uganda	6,346	8,110	34	0.36	96.0
45	French Guyana	7,997	8,003	90	0.46	96.4
46	Honduras	4,605	7,595	68	0.26	96.7
47	Benin	4,947	6,856	59	0.28	97.0
48	Guatemala	4,225	6,596	61	0.24	97.2
49	Nepal	5,023	6,417	44	0.29	97.5
50	Liberia	4,633	5,349	54	0.26	97.8
51	Burkina Faso	4,416	5,264	19	0.25	98.0
52	Malawi	3,486	5,060	54	0.20	98.2
53	Panama	3,116	4,768	64	0.18	98.4
54	Pakistan	1,855	4,238	5	0.11	98.5
55	Bhutan	2,809	3,287	70	0.16	98.7
56	Costa Rica	1,428	3,056	60	0.08	98.8
57	Guinea-Bissau	2,021	2,969	87	0.12	98.9
58	Cuba	1,715	2,749	26	0.10	99.0
59	Sri Lanka	1,746	2,719	41	0.10	99.1
60	Niger	2,550	2,550	2	0.15	99.2
61	Dominican Republic	1,077	2,343	48	0.06	99.3
62	Sierre Leone	1,889	2,210	31	0.11	99.4

41	Senegal	7,544	9,404	48	0.43	94.9
42	Nicaragua	6,013	9,207	78	0.34	95.2
43	Guinea	6,692	9,204	37	0.38	95.6
44	Uganda	6,346	8,110	34	0.36	96.0
45	French Guyana	7,997	8,003	90	0.46	96.4
46	Honduras	4,605	7,595	68	0.26	96.7
47	Benin	4,947	6,856	59	0.28	97.0
48	Guatemala	4,225	6,596	61	0.24	97.2
49	Nepal	5,023	6,417	44	0.29	97.5
50	Liberia	4,633	5,349	54	0.26	97.8
51	Burkina Faso	4,416	5,264	19	0.25	98.0
52	Malawi	3,486	5,060	54	0.20	98.2
53	Panama	3,116	4,768	64	0.18	98.4
54	Pakistan	1,855	4,238	5	0.11	98.5
55	Bhutan	2,809	3,287	70	0.16	98.7
56	Costa Rica	1,428	3,056	60	0.08	98.8
57	Guinea-Bissau	2,021	2,969	87	0.12	98.9
58	Cuba	1,715	2,749	26	0.10	99.0
59	Sri Lanka	1,746	2,719	41	0.10	99.1
60	Niger	2,550	2,550	2	0.15	99.2
61	Dominican Republic	1,077	2,343	48	0.06	99.3
62	Sierre Leone	1,889	2,210	31	0.11	99.4
63	Belize	1,996	2,130	93	0.11	99.5
64	Equatorial Guinea	1,826	2,026	72	0.10	99.6
65	Togo	1,353	2,002	35	0.08	99.7
66	Bangladesh	769	1,931	14	0.04	99.7
67	Kenya	1,187	1,398	2	0.07	99.8
68	Jamaica	239	968	89	0.01	99.8
69	Somalia	754	859	1	0.04	99.9
70	Mauritania	554	554	0	0.03	99.9
71	Brunei	458	511	88	0.03	99.9
72	Puerto Rico	300	300	34	0.02	99.9
73	El Salvador	123	299	15	0.01	99.9
74	Burundi	233	264	10	0.01	99.9
75	Trinidad and Tobago	155	253	49	0.01	100.0
76	Rwanda	164	177	7	0.01	100.0
77	Gambia	97	123	12	0.01	100.0
78	Haiti	23	80	3	0.00	100.0
79	Djibouti	22	22	1	0.00	100.0
80	Cape Verde	6	7	1	0.00	100.0
81	Singapore	4	6	10	0.00	100.0
82	Other Caribbean Is.[3]	408	750	38	0.02	100.0

[1] Includes all forest cover in the six ecological zones: tropical rainforest, moist deciduous, dry deciduous, very dry, desert (hot/cold), hill/montane zones.

[2] Open forests have 10-40% of ground cover in forest, closed forests have 40% or more.

[3] Antigua and Barbuda, Bahamas, Dominica, Grenada, Guadeloupe, Martinique, St. Kitts and Nevis, St. Lucia, St. Vincent.

Sources: FAO, FORIS database.

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TABLE 2. Tropical countries: forest cover change by decade, 1960-1990.[1] Country ranked by loss as a percent of 1960 total.

		Forest cover[2] in 1990 (000 ha.)	Forest cover in 1960 (000 ha.)
1	Jamaica	239	968
2	Haiti	23	80
3	Thailand	12,735	34,936
4	Bangladesh	769	1,931
5	El Salvador	123	299
6	Pakistan	1,855	4,238
7	Cote d'Ivoire[3]	6,127	13,746
8	Dominican Republic	1,077	2,343
9	Costa Rica	1,428	3,056
10	Philippines[3]	6,104	12,558
11	Paraguay	12,859	24,228
12	Other Caribbean Is.[4]	408	750
13	Honduras	4,605	7,595
14	Trinidad and Tobago	155	253
15	Cuba	1,715	2,749
16	Malaysia	17,583	27,817
17	Ecuador	11,962	18,725
18	Guatemala	4,225	6,596
19	Vietnam	8,312	12,975
20	Sri Lanka	1,746	2,719
21	Mexico	48,586	75,490
22	Nicaragua	6,013	9,207
23	Panama	3,116	4,768
24	Togo	1,353	2,002
25	Guinea-Bissau	2,021	2,969
26	Malawi	3,486	5,060
27	Venezuela	45,691	65,144
28	Myanmar	28,856	40,688
29	Benin	4,947	6,856
30	Guinea	6,692	9,204
31	Ghana	9,555	13,131
32	Tanzania	33,554	45,506
33	Indonesia	109,549	145,952
34	Sudan	42,976	57,052
35	Bolivia[3]	49,424	64,937
36	Zambia	32,301	41,707
37	Uganda	6,346	8,110
38	Nepal	5,023	6,417
39	India	51,729	65,848
40	Gambia	97	123
41	Mali	12,144	15,254
42	Senegal	7,544	9,404
43	Colombia	54,064	67,034
44	Laos	13,173	16,283
45	Nigeria	15,634	19,223
46	Madagascar	15,782	19,333
47	Mozambique	17,329	21,172
48	Angola	23,074	27,971
49	Chad	11,434	13,827
50	Zimbawe	8,897	10,706
51	Burkina Faso	4,416	5,264
52	Gabon	18,235	21,711
53	Zaire	113,275	134,086
54	Kenya	1,187	1,398
55	Cambodia	12,163	14,250
56	Sierra Leone	1,889	2,210
57	Bhutan	2,809	3,287
58	Cameroon[3]	22,740	26,443
59	Brazil	561,107	649,758
60	Liberia	4,633	5,349
61	Botswana[3]	14,233	16,427
62	Somalia	754	859
63	Burundi	233	264
64	Peru	67,906	75,711
65	Brunei	458	511
66	Equatorial Guinea	1,826	2,026
67	Central African Rep.	30,562	33,809
68	Ethiopia	14,165	15,575
69	Namibia	12,569	13,624
70	Papau New Guinea	36,000	38,920
71	Rwanda	164	177
72	Belize	1,996	2,130
73	Congo	19,865	20,718
74	Guyana	18,416	18,935
75	Suriname	14,768	15,088
76	French Guyana	7,997	8,003
77	Niger	2,550	2,550
78	Djibouti	22	22
79	Puerto Rico[3]	300	300
80	Mauritania	554	554

[1] Excludes Cape Verde and Singapore, each with fewer than 7,000 hectares in forest.

[2] Includes all forest cover in the six ecological zones [tropical rainforest, moist deciduous, dry deciduous, very dry, desert (hot/cold), hill/montane zones] computed from the INVDATA6 file in the FORIS database.

[3] The GLOBTAB file in the FORIS database shows different totals (in thousand hectares) than the INVDATA6 file for the following countries: Cote d'Ivoire (10,904), Cameroon (20,350), Philippines (7,831), Bolivia (49,317), Botswana (14,261) and Puerto Rico (321).

[4] Antigua and Barbuda, Bahamas, Dominica, Grenada, Guadeloupe, Martinique, St. Kitts and Nevis, St. Lucia, St. Vincent.

Sources: FAO, FORIS database, files INVDATA6 and GLOBTAB.

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TABLE 3. Tropical countries: rainforest and moist deciduous forest cover change, 1981-1990.[1]

Remaining forest in 1990 | Deforestation during 1981–1990

		Forest cover[2] in 1990 (000 ha.)	Percent change (0 – 100)	Forest cover in 1981 (000 ha.)
1	Jamaica	235		499
2	Haiti	14		23
3	Bangladesh	769		1,144
4	Pakistan	11		16
5	Philippines	5,141		7,344
6	Thailand	8,314		11,780
7	Paraguay	6,037		8,524
8	Costa Rica	625		842
9	Dominican Republic	614		814
10	El Salvador	45		56
11	Honduras	1,723		2,141
12	Trinidad and Tobago	155		192
13	Malaysia	16,339		20,028
14	Nicaragua	4,060		4,898
15	Ecuador	8,819		10,574
16	Guatemala	4,157		4,957
17	Panama	1,869		2,205
18	Sudan	12,472		14,605
19	Mexico	13,551		15,809
20	Vietnam	6,276		7,310
21	Togo	1,318		1,534
22	Tanzania	14,128		16,406
23	Malawi	2,948		3,398
24	Myanmar	22,521		25,834
25	Ghana	9,151		10,491
26	Venezuela	35,067		39,911
27	Sri Lanka	852		969
28	Benin	4,183		4,750
29	Guinea	6,565		7,413
30	Uganda	1,091		1,229
31	Bolivia	35,582		39,993
32	Chad	3,932		4,414
33	Other Caribbean Is.[3]	348		389
34	Zambia	21,676		24,221
35	Cote d'Ivoire	10,831		12,020
36	Indonesia	97,316		107,947
37	Cambodia	5,299		5,872
38	Mali	3,706		4,083
39	Cuba	1,361		1,498
40	Laos	8,502		9,325
41	Mozambique	6,526		7,146
42	Burundi	47		51
43	Madagascar	8,284		8,972
44	Nigeria	13,208		14,290
45	Guinea-Bissau	2,021		2,180
46	Gambia	79		85
47	Angola	11,942		12,841
48	Burkina Faso	2,112		2,265
49	Senegal	2,586		2,767
50	Sierra Leone	1,864		1,985
51	Nepal	1,909		2,031
52	Gabon	18,235		19,399
53	Zaire	105,646		112,264
54	Colombia	51,556		54,735
55	Cameroon	17,913		18,947
56	India	15,288		16,161
57	Bhutan	176		186
58	Brazil	488,679		515,864
59	Liberia	4,634		4,887
60	Central African Rep.	28,974		30,206
61	Equatorial Guinea	1,752		1,821
62	Brunei	458		476
63	Papau New Guinea	30,028		30,962
64	Peru	52,657		54,181
65	Belize	1,996		2,046
66	Congo	19,865		20,188
67	Suriname	14,768		14,896
68	Guyana	16,504		16,535
69	French Guyana	7,996		7,999
70	Kenya	13		13
71	Puerto Rico	200		173

[1] Tropical countries without rainforest or moist deciduous forest cover include Mauritania, Niger, Djibouti, Ethiopia, Somalia, Botswana, Namibia, Rwanda, Zimbabwe and Cape Verde. Singapore, with less than [illegible] percent of its original forest, is not shown.

[2] Excludes forests in the following ecological zones: dry deciduous forests, semi-arid forests, desert (hot/cold) and hill/montane zones.

[3] Antigua and Barbuda, Bahamas, Dominica, Grenada, Guadeloupe, Martinique, St. Kitts and Nevis, St. Lucia, St. Vincent.

Source: FAO, "Forest Resources Assessment 19[illegible] Tropical countries," FAO Forestry Paper 112, tables 7 and 8 (annex), Rome, 1993.

Guide to country rankings in the statistical tables.

	Table 1. Absolute forest loss 1960-1990	Table 2. Forest % loss 1960-1990	Table 3. Rainforest/ moist deciduous forest change 1981-1990
Angola	17	48	47
Bangladesh	66	4	3
Belize	63	72	65
Benin	47	29	28
Bhutan	55	57	57
Bolivia	9	35	31
Botswana	28	61	--
Brazil	1	59	58
Brunei	71	65	62
Burkina Faso	51	51	48
Burundi	74	63	42
Cambodia	33	55	37
Cameroon	19	58	55
Cape Verde	80	--	--
Caribbean Islands	82	12	33
Central African Rep.	16	67	60
Chad	34	49	32
Colombia	6	43	54
Congo	23	73	66
Costa Rica	56	9	8
Cote d'Ivoire	35	7	35
Cuba	58	15	39
Djibouti	79	78	--
Dominican Republic	61	8	9
Ecuador	27	17	15
El Salvador	73	5	10
Equatorial Guinea	64	66	61
Ethiopia	30	68	--
French Guyana	45	76	69
Gabon	21	52	52
Gambia	77	40	46
Ghana	37	31	25
Guatemala	48	18	16
Guinea	43	30	29
Guinea-Bissau	57	25	45
Guyana	26	74	68
Haiti	78	2	2
Honduras	46	13	11
India	7	39	56
Indonesia	2	33	36
Jamaica	68	1	1
Kenya	67	54	70
Laos	29	44	40
Liberia	50	60	59
Madagascar	24	46	43
Malawi	52	26	23
Malaysia	18	16	13
Mali	31	41	38
Mauritania	70	80	--
Mexico	5	21	19
Mozambique	22	47	41
Myanmar	13	28	24
Namibia	36	69	--
Nepal	49	38	51
Nicaragua	42	22	14
Niger	60	77	--
Nigeria	25	45	44
Pakistan	54	6	4
Panama	53	23	17
Papua New Guinea	14	70	63
Paraguay	20	11	7
Peru	4	64	64
Philippines	39	10	5
Puerto Rico	72	79	71
Rwanda	76	71	--
Senegal	41	42	49
Sierre Leone	62	56	50
Singapore	81	--	--
Somalia	69	62	--
Sri Lanka	59	20	27
Sudan	10	34	18
Suriname	32	75	67
Tanzania	11	32	22
Thailand	15	3	6
Togo	65	24	21
Trinidad and Tobago	75	14	12
Uganda	44	37	30
Venezuela	8	27	26
Vietnam	38	19	20
Zaire	3	53	53
Zambia	12	36	34
Zimbawe	40	50	--

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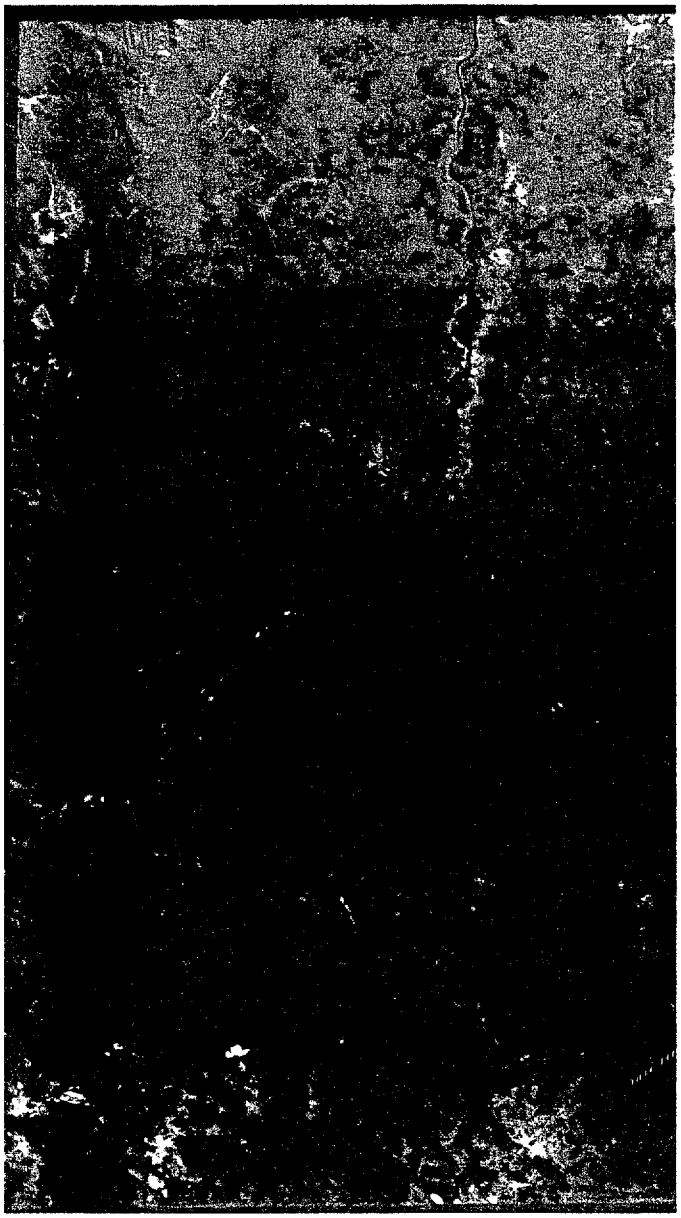
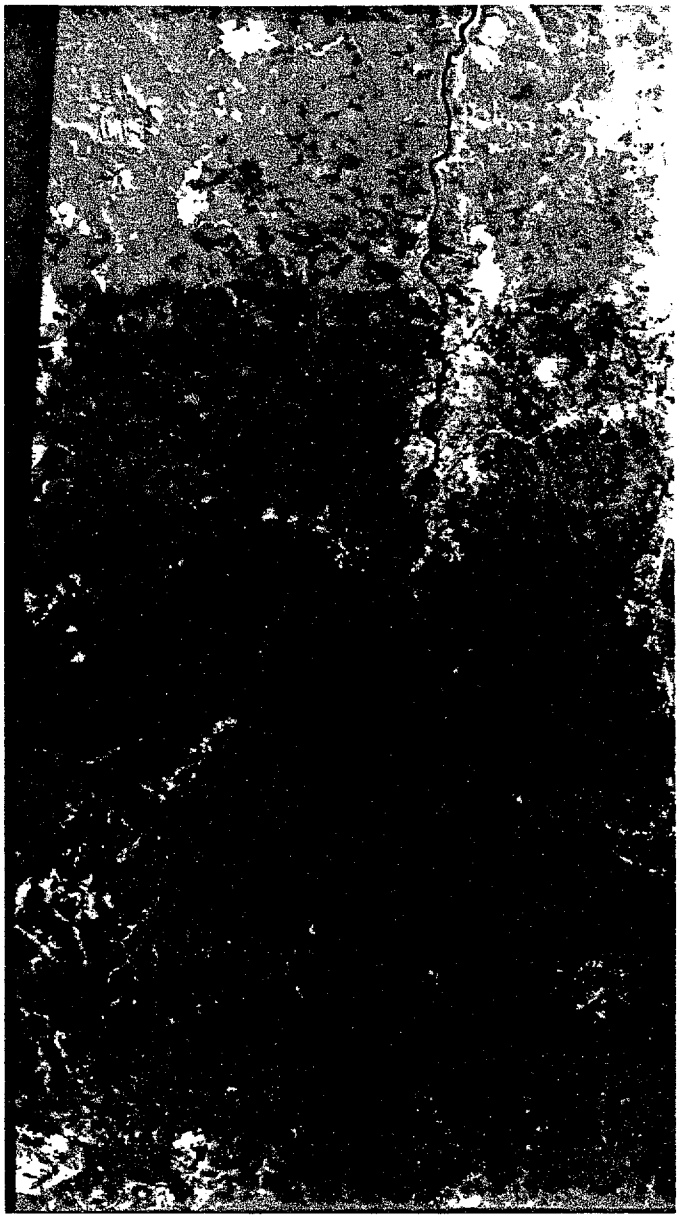
1980-1990 Forest and Land Cover Change: The FAO Sample Survey



1981



1989

FAO's method to measure deforestation and forest degradation is illustrated in this example. The partial Landsat MSS scenes are shown above. This is one of the 117 scenes selected in the 10 percent sample of the world's tropical forests. The location is along the Zaire and Zambia border.

FAO's change detection mapping procedure is displayed at right. Images from circa 1980 and 1990 (a) were analyzed separately. In this case two images from circa 1980 were needed to produce a complete one that was cloud free. The results were compared (b) and a map of forest cover change was produced. Adjustments to standard dates (1980 and 1990) were made in the accompanying statistical report (c). Among the findings, the closed forest was determined to have dropped from 2.11 to 1.63 million hectares in the period, or a reduction from 71.2 to 56.6 percent of the nearly 3 million hectare land area.

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Facing page: FAO. 1993. Forest Resources Assessment 1990: Tropical Countries. FAO, Rome. p. 19.

Change: The FAO Sample Survey

1989

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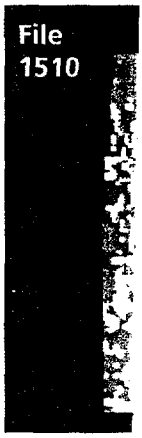
Figure 5
Example of spatial and statistical outputs - sample

a: Maps derived from interpretation of sa

RECENT IMAGE



04/07/1989

b: Change maps produced by comparison of common areas of recent and historical images. The 100 possible class combinations (10x10) have been reduced to 14 change classes for display purposes.

change

c: Sample no. 1510
– Standardized transition matrix comput

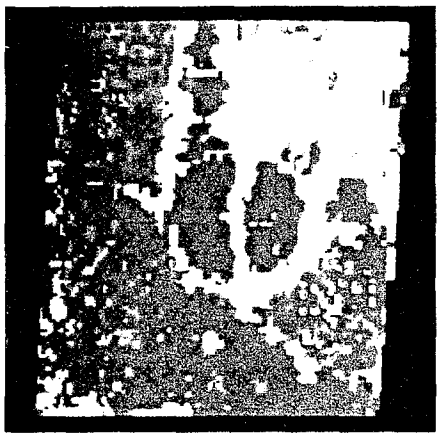
The two matrices reporting the cover class changes fo
mathematically adjusted to the standard period 1980-
and subsequently combined to form the comprehensi

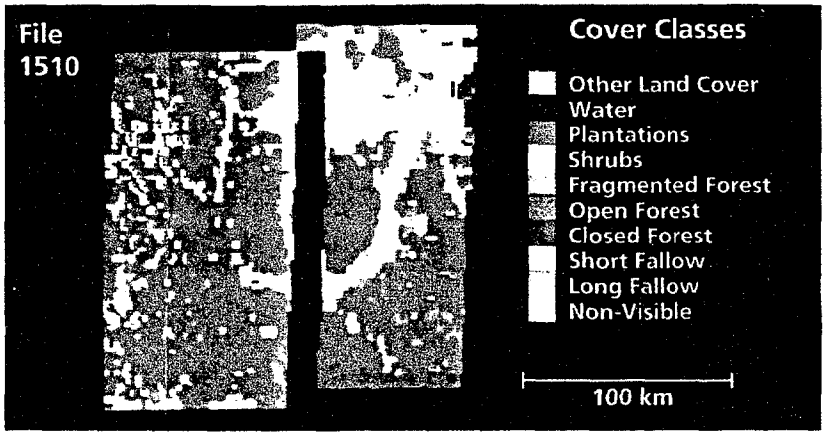
				Cover Classes	
Cover Classes at year 1980		Closed Forest	Open Forest	Long Fallow	Fragm. Forest
Closed forest		1672.3	143.3		
Open forest		0.9	84.9		
Long fallow					
Fragm. forest					
Short fallow					
Shrubs					
Other land cover					
Water					
Manmade W.veg					
Total at	'000 Ha	1673.2	228.2		
year 1990	%	56.6	7.7		

Figure 5
Example of spatial and statistical outputs - sample no. 1510, located along Zaire/Zambia border line

a: Maps derived from interpretation of satellite images of sample no. 1510 -

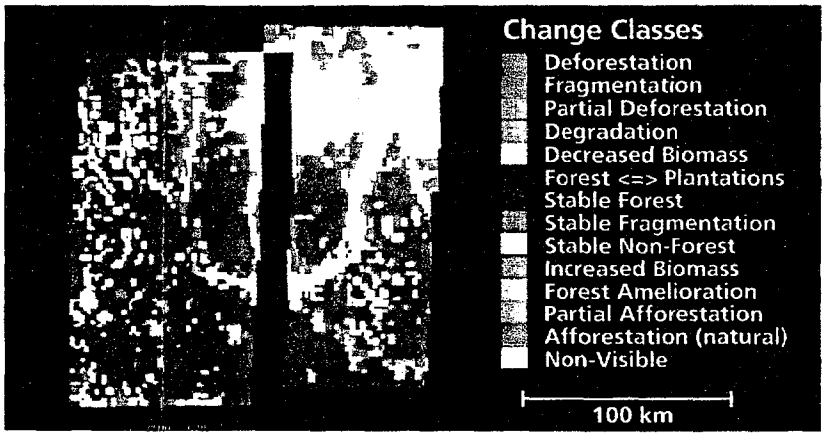
RECENT IMAGE **HISTORICAL IMAGES (common areas)**





04/07/1989 **13/06/81** **20/07/79**

b: Change maps produced by comparison of common areas of recent and historical images. The 100 possible class combinations (10x10) have been reduced to 14 change classes for display purposes.



changes (1981-89) **changes (1979-89)**

c: Sample no. 1510
– Standardized transition matrix computed for the reference period 1980– 1990

The two matrices reporting the cover class changes for periods 1981–1989 and 1980–1989 have been mathematically adjusted to the standard period 1980–1990 on the basis of transition probabilities and subsequently combined to form the comprehensive change matrix presented here.

	Cover Classes at year 1990										
Cover Classes at year 1980	Closed Forest	Open Forest	Long Fallow	Fragm. Forest	Short Fallow	Shrub	Other Land Cover	Water	Manmade Woody Veg.	Total at year 1980 '000 ha	Total at year 1980 %
Closed forest	1672.3	143.3			273.4		17.5			2106.5	71.2
Open forest	0.9	84.9			4.2		0.0			90.0	3.0
Long fallow											
Fragm. forest											
Short fallow					574.9		1 3			576.1	19 5
Shrubs											
Other land cover							160.6			160.6	5.4
Water								21.2		21.2	0.7
Manmade W.veg									2.4	2.4	0.1
Total at year 1990 '000 Ha	1673.2	228.2			852.4		179.4	21.2	2.4	2956.8	
%	56.6	7.7			28.8		6.1	0.7	0.1		100.0

Tropical Deforestation and Habitat Fragmentation in the Amazon: Satellite Data from 1978 to 1988

David Skole and Compton Tucker

Landsat satellite imagery covering the entire forested portion of the Brazilian Amazon Basin was used to measure, for 1978 and 1988, deforestation, fragmented forest, defined as areas less than 100 square kilometers surrounded by deforestation, and edge effects of 1 kilometer into forest from adjacent areas of deforestation. Tropical deforestation increased from 78,000 square kilometers in 1978 to 230,000 square kilometers in 1988 while tropical forest habitat, severely affected with respect to biological diversity, increased from 208,000 to 588,000 square kilometers. Although this rate of deforestation is lower than previous estimates, the effect on biological diversity is greater.

Deforestation has been occurring in temperate and tropical regions throughout history (*1*). In recent years, much attention has focused on tropical forests, where as much as 50% of the original extent may have been lost to deforestation in the last two decades, primarily as a result of agricultural expansion (*2*). Global estimates of tropical deforestation range from 69,000 km^2 $year^{-1}$ in 1980 (*3*) to 100,000 to 165,000 km^2 $year^{-1}$ in the late 1980s; 50 to 70% of the more recent estimates have been attributed to deforestation in the Brazilian Amazon, the largest continuous region of tropical forest in the world (*2, 4, 5*).

The area and rate of deforestation in Amazonia are not well known, nor are there quantitative measurements of the effect of deforestation on habitat degradation. We used 1:500,000 scale photographic imagery from Landsat Thematic Mapper data and a geographic information system (GIS) to create a computerized map of deforestation and evaluate its influence on forest fragmentation and habitat degradation. Areas of deforestation were digitized into the GIS and the forest fragments and edge effects that result from the spatial pattern of forest conversion were determined.

Background

Tropical deforestation is a major component of the carbon cycle and has profound implications for biological diversity. Deforestation increases atmospheric CO_2 and other trace gases, possibly affecting climate (*6, 7*). Conversion of forests to cropland and pasture results in a net flux of carbon to the atmosphere because the concentration of carbon in forests is higher than that in the agricultural areas that replace them. The paucity of data on tropical deforestation limits our understanding of the carbon cycle and possible climate change (*8*). Furthermore, while occupying less than 7% of the terrestrial surface, tropical forests are the home to half or more of all plant and animal species (*9*). The primary adverse effect of tropical deforestation is massive extinction of species including, for the first time, large numbers of vascular plant species (*10*).

Deforestation affects biological diversity in three ways: destruction of habitat, isolation of fragments of formerly contiguous habitat, and edge effects within a boundary zone between forest and deforested areas. This boundary zone extends some distance into the remaining forest. In this zone there are greater exposure to winds; dramatic micrometeorological differences over short distances; easier access for livestock, other nonforest animals, and hunters; and a range of other biological and physical effects. The result is a net loss of plant and animal species in the edge areas (*11*).

There is a wide range in current estimates of the area and rate of deforestation in Amazonia. Scientists at the Instituto Nacional de Pesquisas Espaciais (*12–15*) estimated a total deforested area of 280,000 km^2 as of 1988 and an average annual rate of 21,000 km^2 $year^{-1}$ from 1978 to 1988. Other studies (*2, 4, 5*) have reported rates that range from 50,000 to 80,000 km^2 $year^{-1}$ (Table 1). Additional deforestation estimates have been made for geographically limited study areas in the southern Amazon Basin of Brazil with Landsat and meteorological satellite data (*16–20*).

The Amazon Basin of Brazil has been defined by law to include the states of Acre, Amapá, Amazonas, Pará, Rondônia, and Roraima plus part of Mato Grosso, Maranhão, and Tocantins and is referred to as the Legal Amazon (*21*). It covers an area of

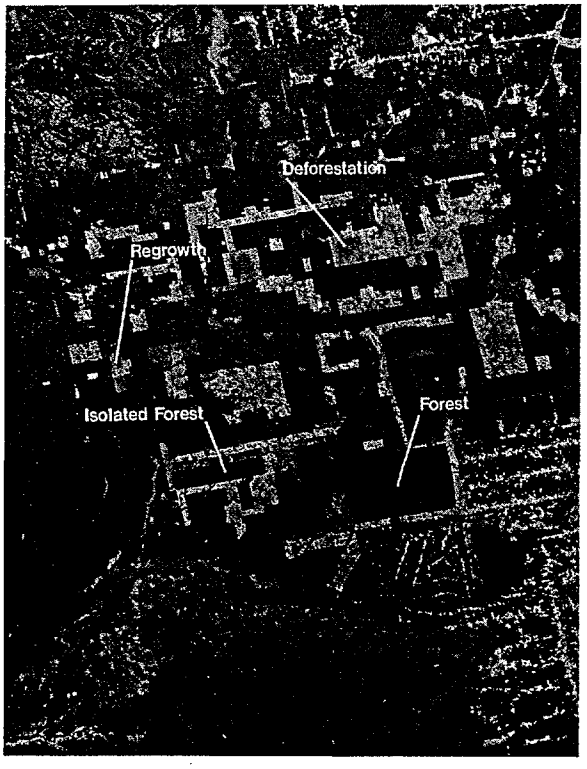


Fig. 1. Landsat Thematic Mapper color composite image of southern Rondônia state, Brazil, for path 230 and row 69 acquired on 5 June 1988. Areas of tropical forest, deforestation, regrowth, and isolated forest are labeled. The area identified as isolated forest is about 3 km by 15 km in size.

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Table 1. Tropical forest area (*3*) and reported tropical deforestation rates by country. The deforestation rates from the 1970s are from the Food and Agriculture Organization (FAO) (*3*). The 1980s data are from Meyers (*2*) and the World Resources Institute (WRI) (*5*).

Country	Total forest area (km²)	Percent of world total	Deforestation rate, 1970s (km²)	Percent of world total	Deforestation rates, late 1980s			
					Myers (km²)	Percent of world total	WRI (km²)	Percent of world total
Brazil	3,562,800	30.7	13,600	19.7	50,000	36.1	80,000	48.4
Indonesia	1,135,750	9.8	5,500	8.0	12,000	8.7	9,000	5.4
Zaire	1,056,500	9.1	1,700	2.5	4,000	2.9	1,820	1.1
Peru	693,100	6.0	2,450	3.6	3,500	2.5	2,700	1.6
Columbia	464,000	4.0	8,000	11.6	6,500	4.7	8,200	5.0
India	460,440	4.0	1,320	1.9	4,000	2.9	15,000	9.1
Bolivia	440,100	3.8	650	1.0	1,500	1.1	870	0.5
Papua, New Guinea	337,100	2.9	210	0.3	3,500	2.5	220	0.1
Venezuela	318,700	2.7	1,250	1.8	1,500	1.1	1,250	0.8
Burma	311,930	2.7	920	1.3	8,000	5.8	6,770	4.1
Others*	2,829,930	24.4	33,300	48.3	44,100	31.8	39,610	23.9
Total	11,610,350	100.0	68,900	100.0	138,600	100.0	165,440	100.0

*Sixty-three other countries.

~5,000,000 km², of which ~4,090,000 km² is forested, ~850,000 km² is cerrado or tropical savanna, and ~90,000 km² is water (Table 2). Confusion has arisen among researchers regarding the stratification of the Brazilian Amazon into forest, cerrado, and water strata. A Food and Agriculture Organization (FAO)–United Nations Environmental Program (UNEP) study (*3*) found 3,562,800 km² of forest, whereas Fearnside and co-workers claim there is 4,195,660 km² of forest, 793,279 km² of cerrado (*17*), and 4,906,784 km² total (*13*). Meanwhile, an IBGE study (*22*) found 20,972 km² of water, 3,793,664 km² of forest, and 1,149,943 km² of cerrado for a total of 4,964,920 km². These differences prevent comparison of different deforestation studies.

The use of satellite data and the GIS make it possible to explicitly stratify Amazonia on the basis of cover types (*22*), thereby providing a means of comparison with other studies. This approach is also necessary for spatial analysis of habitat fragmentation and edge effects of deforestation. Finally, GIS provides a data management tool with which we could manage large amounts of spatial data and precisely merge and geocode information from the more than 200 satellite images used in this study.

Remote Sensing

The large area of the Brazilian Amazon necessitates a straightforward and accurate method of measurement. Landsat Thematic Mapper photo products are inexpensive and of sufficient spatial and spectral resolution for the determination of deforestation. Analysis with visual interpretation techniques produces quantitative results similar to digital processing of full-resolution, multispectral data from the Thematic Mapper and SPOT (*23*).

We acquired 210 black and white photo-

Table 2. Predeforestation water, forest, and cerrado land cover for the Brazilian Amazon by state as used in this study. The values determined in this study were based on the IBGE vegetation map and by interpretation of satellite data (*22*). Areas obscured by clouds were excluded from deforestation and affected forest habitat analyses (97% of the cloud-affected data were over tropical forest).

State	Water area (km²)	Forest area (km²)	Cloud total (km²)	Cerrado area (km²)	Total area (km²)
Acre	393	152,394	0	0	152,787
Amapá	1,188	137,444	53,566	978	139,610
Amazonas	29,842	1,531,122	94,058	14,379	1,575,343
Maranhão	1,344	145,766	13,444	114,675	261,785
Mato Grosso	4,212	527,570	8,630	368,658	900,440
Pará	49,522	1,183,571	56,807	28,637	1,261,730
Rondônia	1,462	212,214	474	24,604	238,280
Roraima	1,817	172,425	15,232	51,464	225,706
Tocantins	2,914	30,325	0	244,005	277,244
Total	92,694	4,092,831	(242,211)	847,400	5,032,925

Table 3. Tropical deforestation, forest isolated or cut off by deforestation, and the area of forest adversely affected by a 1-km edge effect from adjacent areas of deforestation in the Brazilian Amazon. Areas that were obscured by clouds were omitted from this analysis. Parentheses following the edge effect entries contain the ratio between a 500-m buffer and a 1,000-m buffer.

State	Deforested (km²)	Isolated (km²)	Edge effect (km²)	Total (km²)
		1978		
Acre	2,612	18	4,511	7,141
Amapá	182	0	368	550
Amazonas	2,300	36	6,498	8,834
Maranhão	9,426	705	13,120	23,251
Mato Grosso	21,134	776	25,418	47,328
Pará	30,449	2,248	49,791	82,488
Rondônia	6,281	991	17,744	25,016
Roraima	196	4	812	1,012
Tocantins	5,688	337	6,584	12,609
Total	78,268	5,115	124,846	208,229
		1988		
Acre	6,369	405	23,686 (0.517)	30,460
Amapá	210	1	689 (0.537)	900
Amazonas	11,813	474	36,392 (0.582)	48,679
Maranhão	31,952	2,123	28,147 (0.626)	62,222
Mato Grosso	47,568	2,542	71,128 (0.580)	121,238
Pará	95,075	6,837	116,669 (0.633)	218,581
Rondônia	23,998	2,408	52,345 (0.657)	78,751
Roraima	1,908	1	5,236 (0.521)	7,145
Tocantins	11,431	1,437	6,760 (0.659)	19,628
Total	230,324	16,228	341,052 (0.610)	587,604

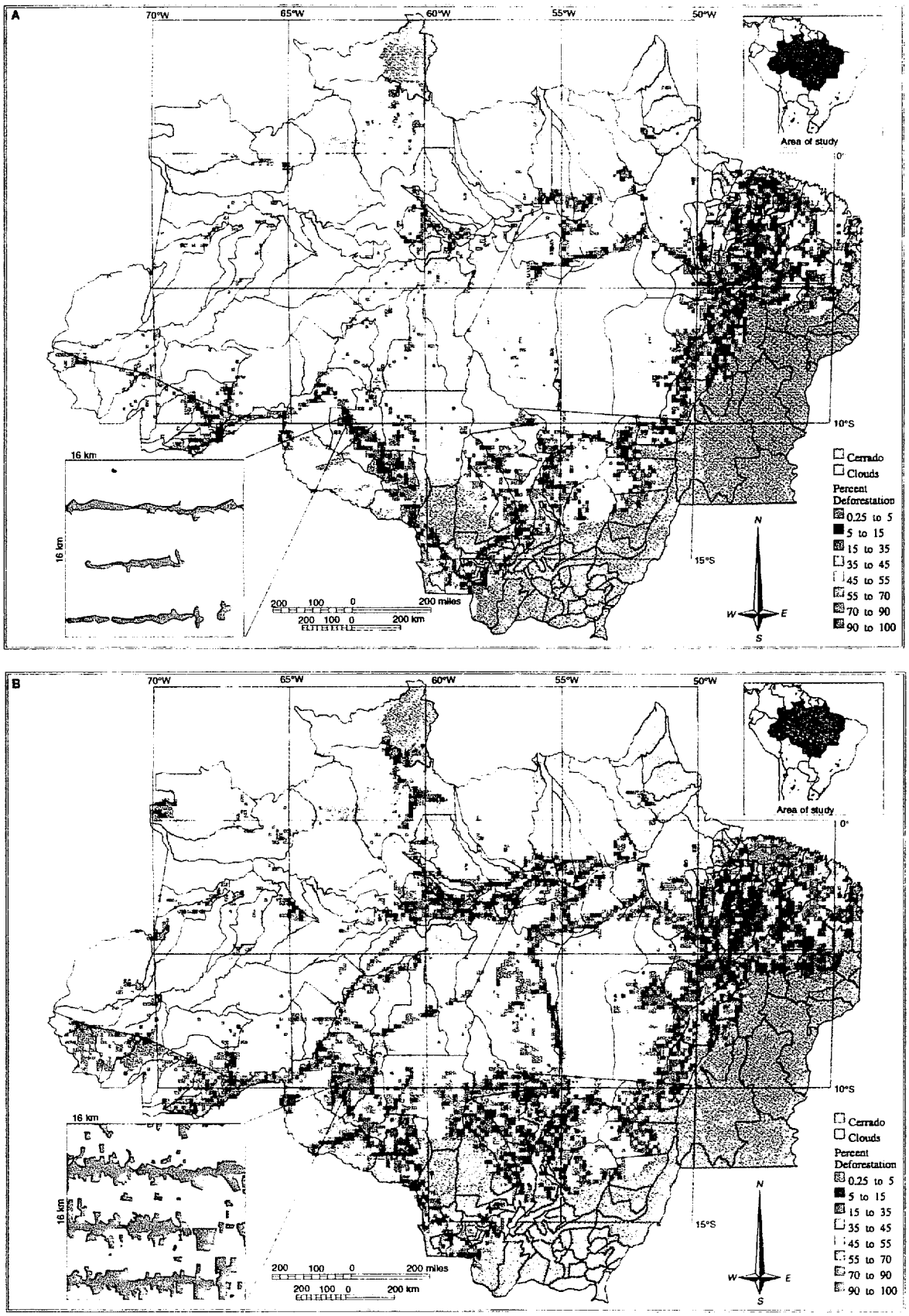

Fig. 2. Representation of deforestation in the Amazon of Brazil from (**A**) 1978 and (**B**) 1988. The deforestation represented in these figures is confined exclusively to the forest strata. The data were averaged into 16 km by 16 km grid cells.

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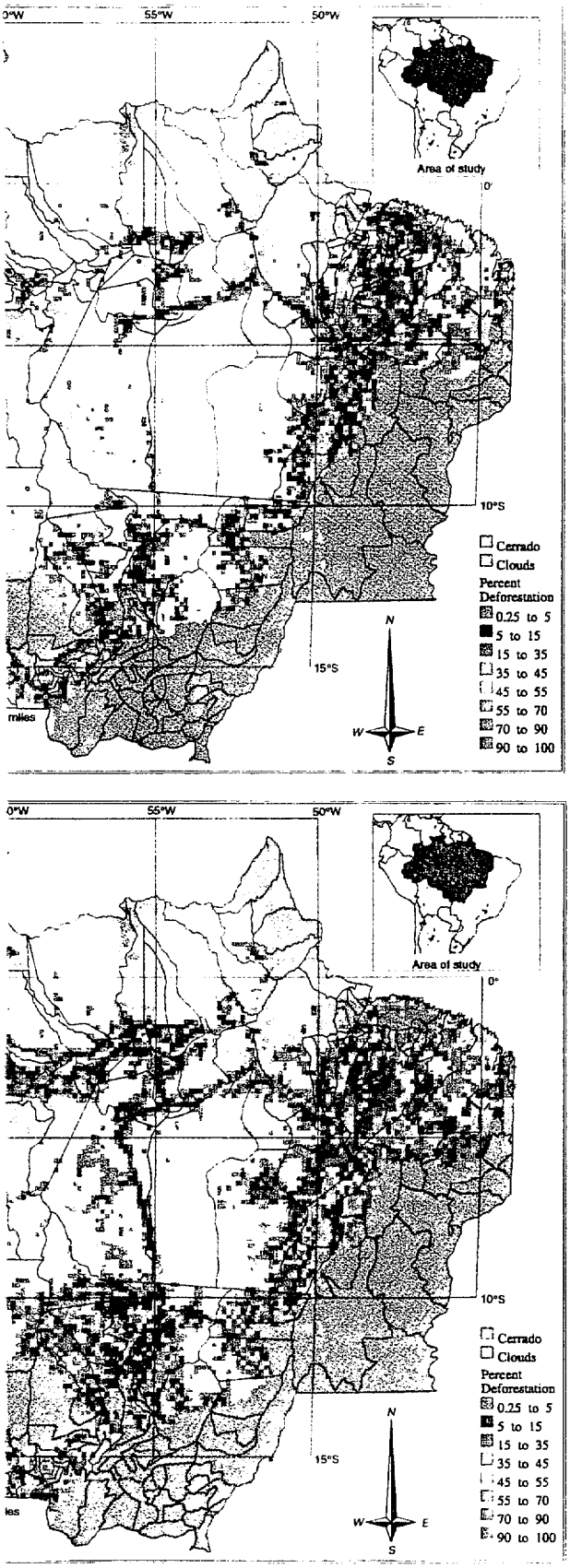

1978 and (**B**) 1988. The deforestation represented in these figures is confined 6 km grid cells.

graphic images of the entire Brazilian Amazon. They were obtained with channel five of the Landsat Thematic Mapper (1.55 to 1.75 μm) at 1:500,000 scale and were primarily from 1988 (24). We digitized the deforested areas with visual deforestation interpretation and standard vector GIS techniques (Fig. 1). The digitized scenes were projected into equal-area geographic coordinates (latitude, longitude), edge matched, and merged in the computer to form a single, seamless data-

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Table 4. Spatial characteristics of isolated and remaining tropical fo determined by analysis of 1988 Landsat Thematic Mapper imagery of forest <100 km² surrounded by deforestation. Remaining forest not been deforested and includes both isolated and larger areas remaining areas of tropical forest are contiguous among states omitted from this analysis.

State	Isolated forest		Undisturbed remaining forest	
	Area (km²)	Polygons (no.)	Area (km²)	Polyg (no
Acre	405	603	146,025	6
Amapá	1	2	83,676	
Amazonas	474	464	1,425,253	
Maranhão	2,123	1,035	100,554	1,0
Mato Grosso	2,542	2,016	478,619	2,0
Pará	6,837	4,030	1,032,194	4,0
Rondônia	2,408	1,587	187,743	1,5
Roraima	1	2	155,326	
Tocantins	1,437	493	18,894	5
Total	16,228	10,232	3,628,284	10,2

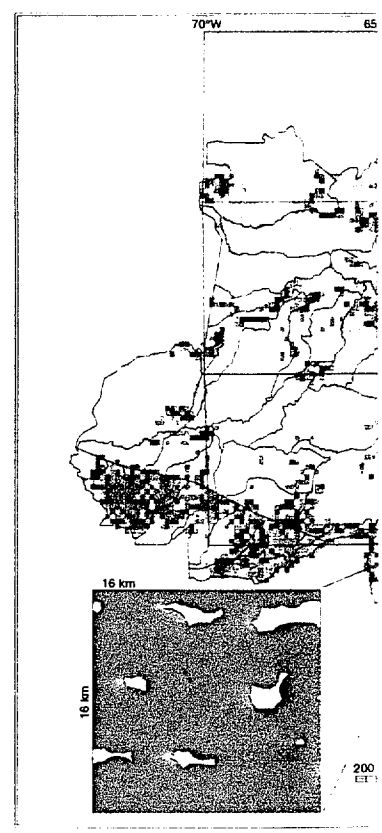

Fig. 3. Map of the Brazilian Amazon Basin showing where biological diversity was adversely affected in 1988 by deforestation, isolation of forest, and the 1-km edge effect of deforestation. The largest contributor to the area of negative effects on biological diversity was the 1-km edge effect from adjacent areas of deforestation. Isolation of forest patches was not a large contributor to this problem. The affected-habitat data were averaged into 16 km by 16 km grid cells.

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graphic images of the entire Brazilian Amazon. They were obtained with channel five of the Landsat Thematic Mapper (1.55 to 1.75 μm) at 1:500,000 scale and were primarily from 1988 (24). We digitized the deforested areas with visual deforestation interpretation and standard vector GIS techniques (Fig. 1). The digitized scenes were projected into equal-area geographic coordinates (latitude, longitude), edge matched, and merged in the computer to form a single, seamless dataset for the entire Brazilian Amazon.

Spatial analysis of the geometry of deforestation is critical to the estimation of forest fragmentation and the edge effect. If 100 km^2 of tropical deforestation occurs as a 10 km by 10 km square and we assume that the edge effect is 1 km, the total area affected is ~143 km^2. In contrast, if the 100 km^2 of deforestation is distributed as ten strips, each 10 km by 1 km, the affected area is ~350 km^2.

We extracted forest fragments <100 km^2 that were isolated by deforestation and computed edge effects for a zone of 1 km along the boundaries. All areas of closed-canopy tropical forest deforested by 1988 were delineated, including areas of secondary growth on abandoned fields and pastures where visible (Fig. 1). Areas of long-term forest degradation along river margins in central Amazonia were also included, as were scattered small clearings associated with rubber tappers, mining operations, airfields, and other small disturbances. All visible roads, power line right of ways, pipelines, and similar human-made features were also digitized into the GIS and treated as deforestation. We used 50 digital Landsat Multispectral Scanner (MSS) scenes from 1986 and 15 digital Thematic Mapper images from 1988 for detailed examination of Acre, Amazonas, Mato Grosso, Pará, and Rondônia.

To determine the extent of deforestation in 1978, we used the GIS to digitize maps of scale 1:500,000 from single-channel Landsat MSS data, produced jointly by the Instituto Brasiliero de Desenvolvimento Florestal (IBDF) and the Instituto de Pesquisas Espaciais (INPE) in the early 1980s (*12, 23*). These maps did not differentiate between forest and cerrado clearing. We compiled forest, cerrado, and water data by combining a vegetation map with analysis of Landsat images and meteorological satellite data (*25*). Our deforestation and affect-

Table 4. Spatial characteristics of isolated and remaining tropical forest within the Legal Amazon as determined by analysis of 1988 Landsat Thematic Mapper imagery. Isolated forest refers to areas of forest <100 km^2 surrounded by deforestation. Remaining forest refers to tropical forest that has not been deforested and includes both isolated and larger areas of forest. Many of the largest remaining areas of tropical forest are contiguous among states. Areas affected by clouds were omitted from this analysis.

State	Isolated forest		Undisturbed remaining forest		Range of areas (km^2)	
	Area (km^2)	Polygons (no.)	Area (km^2)	Polygons (no.)	Minimum	Maximum
Acre	405	603	146,025	605	<1	139,215
Amapá	1	2	83,676	3	<1	83,675
Amazonas	474	464	1,425,253	465	<1	1 424,779
Maranhão	2,123	1,035	100,554	1,042	<1	70,057
Mato Grosso	2,542	2,016	478,619	2,027	<1	471,792
Pará	6,837	4,030	1,032,194	4,032	<1	1,021,263
Rondônia	2,408	1,587	187,743	1,588	<1	185,335
Roraima	1	2	155,326	6	<1	152,414
Tocantins	1,437	493	18,894	508	<1	6,982
Total	16,228	10,232	3,628,284	10,276		

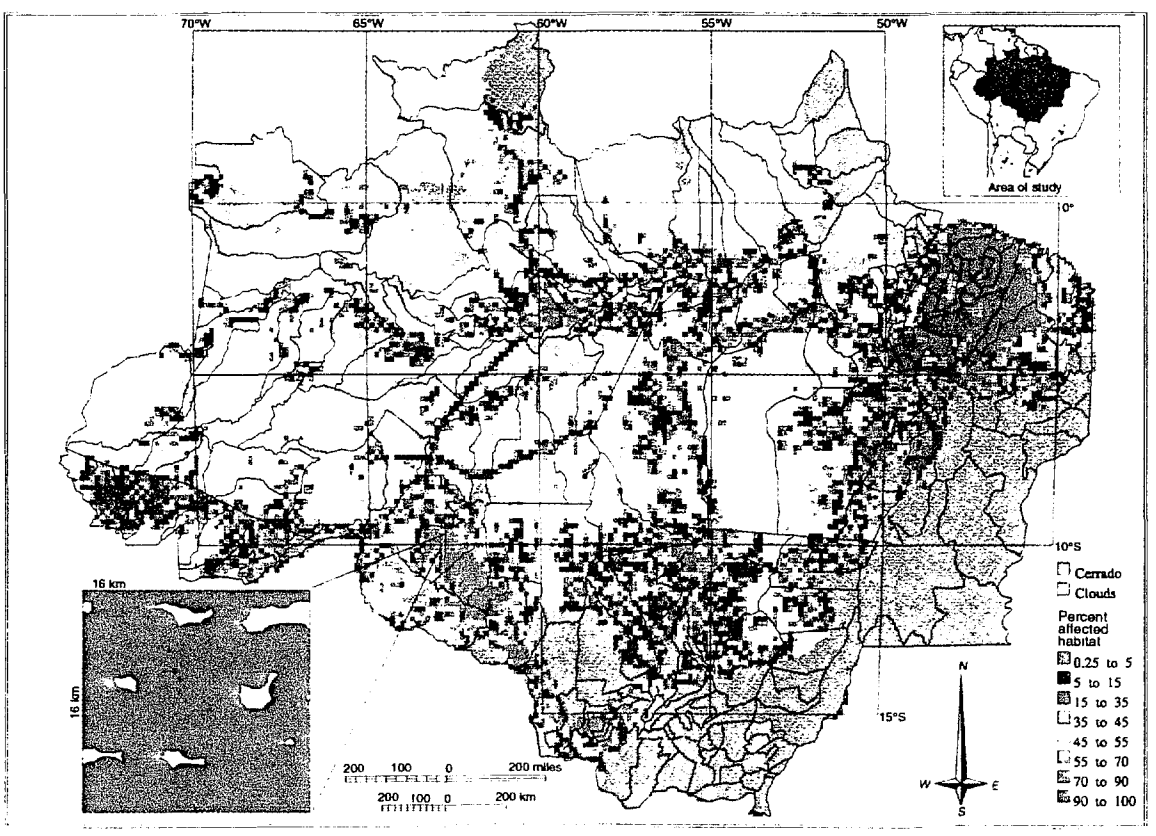

Fig. 3. Map of the Brazilian Amazon Basin showing where biological diversity was adversely affected in 1988 by deforestation, isolation of forest, and the 1-km edge effect of deforestation. The largest contributor to the area of negative effects on biological diversity was the 1-km edge effect from adjacent areas of deforestation. Isolation of forest patches was not a large contributor to this problem. The affected-habitat data were averaged into 16 km by 16 km grid cells.

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ed habitat analyses for 1978 and 1988 were restricted to closed-canopy forest of the Brazilian Amazon.

Deforestation and Forest Fragmentation

Distribution of deforestation and affected habitat in the Brazilian Amazon for 1978 and 1988 (Figs. 2 and 3) was concentrated in a crescent along the southern and eastern fringe of the Amazon [a spatial pattern similar to the distribution of fires observed from thermal anomalies in data from Landsat's Advanced Very-High Resolution Radiometer (AVHRR) (*20*)] and along major transportation corridors in the interior of the Amazon. Deforestation increased between 1978 and 1988 (78,000 to 230,000 km^2), while the total affected habitat increased (208,000 to 588,000 km^2) (Table 3). The total area deforested increased by a factor of two to three or more in every state except Amapa; but it is likely that the deforested area in Amapa is higher than our assessment because excessive cloud cover in this region prevented complete analysis (Table 2). We found that 6% of closed-canopy forest had been cleared as of 1988 and ~15% of the forested Amazon was affected by deforestation-caused habitat destruction, habitat isolation, and edge effects (Fig. 2 and Table 3).

Our analysis of the spatial pattern of deforestation found a strong tendency toward spatial concentration; areas of undisturbed tropical forest tended to be sizable (Table 4). This is more pronounced than Table 4 indicates because many of the large areas of undisturbed tropical forest are contiguous among states.

For the entire Brazilian Amazon, our deforestation estimate is close to, but lower than, the estimates of Fearnside *et al.* (*13*) and the INPE (*15*) of ~280,000 km^2 as of 1988. The difference is a result of three factors: (i) different stratification of forest, cerrado, and water; (ii) slightly different estimates of secondary growth, which is spectrally similar to intact forest in channel five; and (iii) positional accuracy, interpretation, and boundary generalization. We estimate that ~30,000 km^2 of the difference is from a different evaluation of the forest-cerrado boundaries in Mato Grosso and Tocantins. By comparison, our analysis suggests that deforestation estimates based on coarse-resolution meteorological satellite data in the southern Amazon of Brazil have overestimated deforestation by ~50% (*18, 23*).

The average deforestation rate in the closed-canopy forests from 1978 to 1988 (~15,000 km^2 $year^{-1}$) (Table 3) is higher than the rate from 1975 to 1978 (*3*) but considerably lower than recent estimates (*2, 4, 5, 20*). Our estimates can be used in assessments of net flux of carbon from land clearing and biomass burning in the Brazilian Amazon. Current estimates of these fluxes have largely been based on model calculations with deforestation values much higher than we report. In addition, many deforested areas are in stages of regrowth following abandonment (*26*). If regrowth is widespread, estimates of the net flux of carbon should be further reduced because carbon accumulates in regrowing biomass.

The preponderance of affected habitat results from proximity to areas of deforestation (~341,000 km^2 for a 1-km edge effect) and not from isolation of forest (~16,000 km^2) or deforestation per se (~230,000 km^2). While the rate of deforestation averaged ~15,000 km^2 $year^{-1}$ in the Brazilian Amazonia from 1978 to 1988, the rate of habitat fragmentation and degradation was ~38,000 km^2 $year^{-1}$. Implications for biological diversity are not encouraging and provide added impetus for the minimization of tropical deforestation.

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ENRIC SECTION IV

Emerging Directions

"Strategies for Environmental Monitoring and Assessment of Tropical Forest Ecosystems," *Sandra Brown, Ariel E. Lugo, Andrew J.R. Gillespie*

"A Satellite-Based Tropical Forest Information System," *David L. Skole, C.O. Justice, J.P. Malingreau*

"New Sensors Eye the Rainforest," *Thomas O'Neill*

EMERGING DIRECTIONS

New remote sensing technologies, advances in the use of existing technologies, and the integration of on-the-ground monitoring with remotely sensed monitoring are some of the more important emerging directions in tropical forest mapping and monitoring.

In the first paper of this section, "Strategies for Environmental Monitoring and Assessment of Tropical Forest Ecosystems", two United Nations organizations, UNEP and FAO, draw on expert advice to outline steps to...

> "address broader environmental issues of forests and the global carbon and hydrologic cycles, change in biodiversity and sustainable forest development."

The push in this direction recognizes that "in recent years there has been a perceptible change with respect to the role and functions of forests. There is a growing consensus that all aspects of goods and services offered by the forests...should be considered in a holistic manner. To formulate policies and strategies, methodologies need to be developed to assess and monitor the relevant environmental parameters".

The next paper returns to the global monitoring possibilities offered by NOAA, Landsat, and SPOT satellite sensors, both low and high resolution, and the experience to date of the TREES and Landsat Pathfinder projects. Skole, Justice and Malingreau propose a U.S.A. and European partnership to periodically map tropical forest cover at the 1:250,000 scale with these sensors and to continuously monitor change.

"New Sensors Eye the Rain Forest" published in September, 1993 in the *National Geographic Magazine* reports on a new multi-spectral remote sensor which is being tested in Belize and which may become part of NASA's Earth Observation System. The greatly expanded spectral discrimination of the sensor could make possible analysis as detailed as the chemistry of leaves. This experimental sensor supports Malingreau's suggestion that "there may be novel information on the nature and dynamics of the forest cover imbedded in the data set, information linked to the spectral and spatially integrated nature of the measurement".

Strategies for Environmental Monitoring and Assessment of Tropical Forest Ecosystems.

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Executive Summary

The purpose of this background paper is to present a strategy and design for future global assessments of tropical forests that build on present knowledge and methods and that can address broader environmental issues of forests and the global carbon and hydrologic cycles, change in biodiversity, and sustainable forest development.

The present FAO global assessment of tropical forests (FRA90 project) is focusing on estimating the state and change in forest cover for the period 1980-90 for all developing nations. It has taken a two-pronged approach. First, it updated and developed a data base based on existing, reliable forest inventory data with emphasis on subnational units. This data base was used to derive models of forest cover versus population density, stratified by ecological and geographic regions. The models were used to adjust all data to common reference years and to estimate forest cover for 1980 and 1990 and the change in the intervening period. GIS technology was also used for analysis and integration of spatial, statistical, and remote sensing data, as well as for reporting results. Second, a new design and analysis of paired remote sensing scenes was used to estimate change in forest cover. In addition, a first attempt was made to estimate biomass of tropical forests. Little to no analyses of biodiversity and hydrology were made.

Recommendations for information needs and methodology for future assessments so that global environmental issues can be addressed include:

- Building of ancillary GIS data bases at the country level, to include climatic and edaphic parameters, elevation, potential vegetation, land use, forest use, demography, and fragmentation indices (e.g., perimeter-area ratios). This would be immensely useful for analysis of all global issues.

- The present statistical modeling approach (forest cover versus population density) be continued in the short term until it is possible for more tropical countries to do national-level continuous forest assessment either wall-to-wall or some statistical design using remote sensing imagery). However, attempts should be made to add new data and perform further validation. The results should also be put into a GIS format.

- Production of wall-to-wall forest maps based on satellite imagery should not be the focus of FAO's effort in future assessments; rather they should focus on working with and coordinating other ongoing efforts by national and international organizations. This would reduce duplication of effort and allow for FAO to focus on the other issues, such as classification systems suitable for use with satellite imagery to detect deforestation and forest degradation, linking national to global efforts, and data management.

- The improved estimates of state and change in forest cover will partly increase the accuracy of carbon flux estimates from the tropics; further improvements will come about with more accurate and precise estimates of aboveground biomass. Reliable and tested methods of estimating biomass from forest inventories are available; improvements to the current biomass regression equations could be brought about by increasing the data for large diameter trees. Improvements in forest inventories for biomass estimation include: greater coverage in all forest types, report stand tables in at least 10 cm classes to a minimum diameter of 10 cm, no-grouping of large diameter trees in one open-ended class, include all species, archive results and make available to interested parties, and locate sampling locations using GPS.

- Add soil sampling and measurements of coarse woody litter to inventory designs to improve estimates of forest carbon budgets.

- To begin to incorporate biodiversity information into global assessments by synthesizing existing data using ancillary GIS data layers; cooperating with other programs that are establishing large biodiversity plots around the tropics; adding biodiversity parameters into forest inventories; and including botanists/zoologist with the inventory teams.

To accomplish many of the above recommendations involves establishing a single sampling framework within which all forest monitoring activities would take place, including satellite imagery interpretation and field data collection. Individual countries would receive support and be responsible for data collection, using global standards, and reporting in their country. Data should be aggregated, reported, and disseminated at global levels (e.g. FAO). To make this system work will require cooperation from all member countries; they will benefit as the plan is also one that promotes sustainable forest development.

We recommend a three-phase plan of action to get this job done. For the first, conceptual phase (about 1 yr), two experts meetings need to be held (UNEP/FAO taking the lead) where a workable strategy, including work plans, standards, guidelines, etc., is developed. The key aspect of the second, preparatory phase (3-4 yr) is the development and establishment of pilot studies in key countries, particularly those who currently monitor their forest resources by remote sensing. The final operational phase would be to revise methods, standards, guidelines, etc. if needed; provide training to other countries; develop data sharing, reporting and aggregation protocols; and scale up to the whole tropics.

Introduction

The United Nations Conference on Environment and Development (UNCED) held in Brazil in 1992 focussed world attention on forests. Extensive discussion within the UNCED process led to agreement to a global forest action program. Three of the problems singled out for global action, i.e., (1) protection of the atmosphere, (2) protection and management of land resources, and (3) conservation of biodiversity, are directly related to the world's forests. Now that the world's leaders have shown commitment to these global issues, it is time to evaluate what we know and what we need to know about global forest resources.

There have been numerous world forest assessments and for the tropics alone (Table 1); the 1990 tropical forest assessment project (FRA90) represents the state of the art. However, because global interests on forests continues to evolve rapidly and because conducting a global assessment requires about a decade of effort, we are now evaluating the best strategies for conducting future global forest assessments even before the 1990 assessment is completely finished. Future global assessments of forests must answer the same questions that previous assessments were designed to answer: i.e., area of forests, rates of deforestation and degradation, productive potential of forests, human impacts on forest lands, etc. as well as being useful for addressing resource management and assessment questions that have been posed very recently, some even after the 1990 assessment was already in progress.

The purpose of this background paper is to suggest strategies for the design and execution of future global assessments of tropical forests.

The purpose of this background paper is to suggest strategies for the design and execution of future global assessments of tropical forests. To accomplish this we will (1) discuss the present state of knowledge about tropical forests based for the main part on the FRA90, (2) discuss what we need to know in future assessments, and (3) how to obtain reliable information to meet these needs. Of importance here is whether the assessment can provide sufficient information about the broader environmental issues of the role of forests in the global carbon cycle and global greenhouse effect, change in biodiversity, the hydrological cycle, and sustainable forest use.

Current State of Knowledge

During the last decade or so, the FAO/UNEP has done a more in-depth assessments of tropical forests using a uniform approach (Table 1). The resulting FAO/UNEP 1980 and 1990 (the present tropical FRA90) assessments, the most comprehensive to date, are probably the most used and most discussed of any global assessments of forests). Now is the time to evaluate these assessments to determine if they address the current as well as the constantly changing needs of society at the national and global scales.

The focus of the 1990 assessment is to present both an estimate of the forest cover as of 1990 and an estimate of the changes in forest cover during 1980-90 for all developing countries (104 countries, with 87 tropical ones). The 1990 assessment built and expanded on the 1980 one. It first

updated and developed a data base based on existing forest inventory/survey data, with emphasis on the subnational level, compiled in a standard format. Emphasis was placed on historical data to develop multi-date data for estimating trends in changes of forest cover. Geographic information system (GIS) technology was also introduced for analysis and integration of a variety of spatial, statistical, and remote sensing data sources. New analysis of remote sensing data were used to make independent estimates of changes in forest cover in a statistically sound manner. In addition, special projects were included to deal with other related issues such as forest degradation, biomass content, and biodiversity. Because the FRA90 project differed considerably from its predecessor most of the further discussion will be restricted to this assessment.

Classification schemes for tropical forests

The FRA90 defined forests as ecosystems with a minimum of 10% crown cover of trees and/or bamboos, generally associated with wild flora, fauna, and natural soil conditions and not subject to agricultural practices.

The data base on existing inventories classifies forest lands by local vegetation types, forest formation (closed, open, broadleaf, coniferous, etc.), forest ecosystem function, ownership, legal status, use (protection, production, logged, etc.), and plantations. This method of data gathering allows for summary statistics by country, region, or globe to be presented by any one of these classification systems.

A major addition to the FRA90 assessment was the introduction of a GIS component.

A major addition to the FRA90 assessment was the introduction of a GIS component. The impetus for inclusion of this component was that it would allow for analysis and integration of data from a variety of sources and in a variety of formats including statistical and spatial data. The additional benefit of this component is that it allows for different ways of integrating and presenting the data to meet the various needs of the users. GIS data bases were obtained from a variety of sources or generated by the project and included: ecofloristic zone maps, vegetation maps, demographic data at subnational levels, topography, FAO soils map, and protected areas map. The emphasis in these GIS data bases is global. All of them are useful for developing several of the classification systems commonly used.

The FRA90 project also developed a land-use classification scheme to be used with remote sensing scenes to assess changes in forest lands other than just deforestation. The land-use classes included closed forests, open and degraded forests, fragmented forests, other wooded lands, and non-wooded lands. Completing these land-use change matrices from the sampled remote sensing scenes at this level of classification, coupled with the GIS data bases described above, will greatly enhance our knowledge of the dynamics and processes of tropical land-use change.

Estimates of current status of forest cover

Statistical data from existing surveys

Almost all countries in the tropical zone have conducted one or more surveys of their forest resources. The information in these surveys varies tremendously, from broad data on extent of forests to detailed data on commercial timber, legal status of forests, etc. The scale also varies from national inventories at multi-dates to an inventory of a small region at one time. Summaries of the information have often been published in reports, but a lot more detailed data generally remain hidden in files in the countries or with the cooperating institutions. In addition, much of the information is scattered all over the world and is reported to different standards, definitions, and classifications.

One of the main activities of the FRA90 was the extensive collection, compilation, and review of the existing reliable data from national inventories into a standard, computerized format, referred to as the Forest Resources Information System (FORIS 1990). All data included in this data base were reviewed and incorporated into a common framework of definition and classification. The FORIS 1990 served as the basis for one set of estimates of forest area in 1980 and 1990 and the rate of change (deforestation) during this period. Because the data on forest area contained in the FORIS 1990 data base have different reference years, a modeling approach was taken to adjust all data to common reference years of 1980 and 1990. The models developed were logistic functions of percent forest cover versus population density at the subnational scale. These were applied to the data in the FORIS 1990 data bases to estimate forest area for 1980 and 1990, using subnational level data on population density and its growth rate, and ecological zone distribution of the geographic area under study.

One of the main activities of the FRA90 was the extensive collection, compilation, and review of the existing reliable data from national inventories into a standard, computerized format, referred to as the Forest Resources Information System (FORIS 1990).

Because the data were gathered and estimated at the subnational scale, a spatial representation of sorts is possible, although spatial delineation of forest boundaries is not possible (i.e., a forest map). The resolution will vary from country to country based on the size of the subnational units. With a spatial representation of forest cover, manipulations with other GIS data layers are possible. Results can be reported by any of the GIS data layers given above.

Satellite imagery

Assessment of forest cover will be estimated from the statistical sampling procedure of remote sensing scenes. It will also be possible to report results using a classification system for forest vegetation types (closed, open, degraded, recovering, etc.) . This phase of the FRA90 will not be completed by the end of the project in October 1992.

Estimate of change in forest cover

Statistical data

Deforestation is defined by FRA90 as change of land use with the depletion of tree crown cover to less than 10%. Forest degradation, not included in the assessment of change here, is defined as changes within the forest class (from closed to open), which negatively affect the stand or site and, in particular, lower the production capacity.

Deforestation is defined by FRA90 as change of land use with the depletion of tree crown cover to less than 10%.

Deforestation rates reported by the FRA90 are the average annual rates for the period 1980 to 1990. The methods described in the section above were used to estimate forest cover for 1980 and deforestation during 1981 to 1990, with estimates expressed as an average annual rate for the period. Average national rates were derived from subnational results, the regional rates from the national, and the global rates from the regional. As with the forest cover estimates, results could be represented spatially to the subnational level of resolution. Also, results can be reported by the six ecological zones and by demographic factors.

Satellite imagery

Remote sensing played a key role in addressing change in forests in the FRA90. All options available were considered, in consultation with experts in the field, for using remote sensing to assess forest change. A new technique of change assessment was developed based on high resolution Landsat TM imagery. A sampling intensity of approximately 10% was chosen resulting in the selection of 117 pairs of scenes. The future plan is to continue the process each year so that the whole tropics would be covered on a 10 year cycle if sampling is without replacement. As the cycle restarts, the first set of images could be updated using new imagery.

A classification system of forest vegetation types was developed so that a land-use change matrix could be produced to allow for estimation of deforestation, forest degradation, and forest recovery, either through amelioration of current stands or afforestation. Analysis of the images produces estimates of the state of forest cover for '1990', and change in the interval. About 30% of the 117 selected images have been interpreted to date, thus results at regional and global scales are not yet available. This methodology will provide the capability to determine what kinds of forests (closed or already degraded) are being cleared or degraded. Areas of each of the land-use categories can also be derived giving another estimate of the area of tropical forests, but at a finer level of detail.

Carbon cycle of tropical forests

Land use changes in the tropics produce sources and sinks of atmospheric carbon dioxide. Carbon sources are produced when forests are cleared or degraded; carbon sinks occur during forest recovery and reforestation/afforestation. To determine the contribution of tropical forests to the global carbon cycle requires information on rates and types of forest land-use change and their initial and final carbon contents.

The present state of knowledge on forest area and rates of change described above will partly improve estimates of carbon fluxes from tropical forests. To further improve the carbon flux estimates from the tropics requires improved estimates of the carbon content or biomass of forests undergoing change.

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Biomass

The total biomass of a forest includes: all trees above a minimum diameter, including main stem, branches, twigs, leaves, and bark, roots, understory, vines, palms, fine and coarse forest litter, and soil organic matter. This quantity is usually referred to as the biomass density with units expressed in t/ha or Mg/ha. However, the present estimates of biomass include only the aboveground mass of trees above 10 cm diameter because these can be made from forest inventories. The biomass density of other aboveground plants tends to be a small percentage of the total (<5% in closed forests; Brown and Lugo 1992), although in open forests it may be a larger proportion. Biomass of roots varies widely from about 20 to >50% of the aboveground biomass density but the small, available data base prevents reliable extrapolation to large spatial scales. Estimates of fine litter (leaves, twigs, fruits, flowers) by main ecological zones is reasonably well known for tropical forests (Brown and Lugo 1982), but estimates of coarse litter (woody debris) are very poorly known, and could be as much as 30% or more of the aboveground biomass density in mature forest stands.

Biomass estimates reported in FRA1990 are based on much data consisting of educated guesses.

It is feasible to make estimates of aboveground biomass density because methods are available for converting traditional information such as volume per unit area (gross volume over bark in m3/ha for trees to a minimum diameter of 10 cm [VOB]) to biomass density (Brown et al. 1989, 1991, Gillespie et al. 1992). These methods were used to estimate aboveground biomass density and total biomass (biomass density x forest area) as part of the FRA90. The basis for the estimates was the VOB data reported in the FORIS 1990 data base. This approach is of unknown reliability because much of the VOB data in the FORIS data base was produced by educated guesses. There are few forest inventories that produce VOB estimates that include all species and all trees to a minimum diameter of 10 cm. Future inventories must overcome this limitation. Unreliability also exists in the expansion factors and specific gravities used to convert volumes to biomass units.

Biodiversity

No assessment of biodiversity has been made for the whole tropics. A data base on the biodiversity of protected tropical areas was prepared by the World Conservation Monitoring Centre as a special project for the FRA90. All surveys of flora and fauna that had been done in the protected areas were summarized in this document. As the locations and extent of the protected areas are in a GIS data base, it will be possible to overlay this data base with other relevant layers (e.g., ecological zones, subnational demographic data) as a first step in investigating relations between biodiversity and environmental and/or human factors. Other topics that could

No assessment of biodiversity has been made for the whole tropics.

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be addressed by this GIS analysis are the adequacy of the network of protected areas and whether all the important ecological zones are represented.

Hydrologic cycle

No assessment of this issue has been made in the FRA90.

Forest health

No assessment of this issue has been made in the FRA90.

Information Needs and Methodology for Future Global Assessments

Forest classification

The FRA90 assessment has made great strides in presenting results suitable for a variety of users by incorporating GIS, from forest planners to policy makers (national and global) to scientists dealing with global environmental issues. By stratifying the tropics according to several classification systems, the FRA90 has been able to make more reliable estimates of state and change of forest cover even down to national and subnational levels. Future assessments should build on the current methods, particularly with respect to GIS application. All countries or regional centers should be encouraged to generate the ancillary GIS data bases summarized in Table 2. Any national system that is in map form can be combined with the global system through GIS methods. The key is that national systems must be mapped and must be able to be aggregated into the global scale. All GIS data bases at the national level must be based on standard, reliable, and objective guidelines.

We know that the structure and function of forest ecosystems are regulated by environmental and human factors and their interaction. The distribution of forest lands can be correlated to these factors. We need to know how these factors interact to produce changes in the landscape that affect the global environment. An understanding of the causal relationships between environmental and human factors and their influence of forest ecosystems enables the building of models for projecting future trends in resource management and environmental issues.

An ideal system for classifying forest lands should be hierarchical, starting with the fundamental environmental factors that are believed to regulate their structure and function at supranational spatial scales, and ending with subnational scales. Additional data can be added to this overall system to take into account the human influence on the landscape, as well as the multiple uses of forest lands. All assessments of resources should take advantage of GIS technology to generate pertinent data layers. This approach results in maximum flexibility and usefulness of future resource assessments and is possible because the GIS technology is now at a stage of development that allows for general use and application at relatively low costs.

An ideal system for classifying forest lands should be hierarchical, starting with the fundamental environmental factors that are believed to regulate their structure and function at supranational spatial scales, and ending with subnational scales.

For analysis of tropical forests, the factors to be considered include the following (Table 2): rainfall (average annual amount), seasonality of rainfall, growing season length, elevation, slope classes, soil textural classes, and soil quality classes (e. g., flooded, stoney/rocky, shallow, etc.). GIS data layers of these factors should be produced using a uniform approach across all countries and regions. Many of these GIS data bases can be or have been produced by the FRA90. The digital soils map is an exception, and efforts must be made by the appropriate organizations to revise this. New interpolation algorithms must be developed to produce realistic "surfaces" of these data rather than geographical representations of point data. Then more complex combinations of these factors can produce other layers of interest such as potential productivity of the land.

The present FRA90 EFZ data base should be retained and refined as it provides a measure of the potential vegetation as well as climatic or ecological zones. Data layers can be aggregated to produce maps of broad climatic or potential vegetation zones similar to those used in the present FR A90. This needs to be done with input from national, regional, and global experts. For example, is the present grouping of EFZs into the six ecological zones appropriate? We recommend that the present grouping for global reporting be re-evaluated to include the following considerations: (1) the hill/montane zone needs to disaggregated to include climatic factors and (2) the lowland rainforest zone needs to divided into at least two classes to identify the very wet zones (> 3,500-4,000 mm/yr of rainfall) because of the implications to biodiversity (Gentry 1982), biomass density (Brown and Lugo 1982) and water resources. Use of GIS to generate systems for classifying lands based on climatic and physical factors and potential vegetation would meet national needs (based on fine resolution data) and must be amenable for regional and global assessment through aggregation.

FAO's forest classes of open and closed do not account for activities that reduce their biomass and biodiversity but not enough to change their appearance on remote sensing imagery (e.g., illicit logging).

Actual vegetation cover or land use would be the next level of the hierarchical classification system as this reflects human activity. Here various types of forest cover need to be distinguished. The present system used by FRA90 for interpreting remote sensing scenes needs to be amended for use at all scales. The present use of the closed and open forest classes is too broad as they do not account for activities that reduce their biomass and biodiversity but not enough to change their appearance on remote sensing imagery (e.g., illicit logging). Nor can such broad categories always distinguish between mature forests and some secondary forests (those recovering from past disturbance such as logging, recently logged, long-cycle forest fallow) that once again may look similar on remote sensing scenes. Various degrees of degraded forests (intense logging, short cycle fallow, over-burning, over-grazing, intense fuelwood collection, etc.) and younger secondary forests also need to be distinguished. Not only do all these different land uses influence the carbon, nutrient, and water cycles, and biodiversity, but they directly impinge on the value of the forests for timber and non-timber products. Clearly, to classify forests into all these categories is an immense task and will require field data collected at the national to subnational level. However, it is obvious that this information is needed to address national and global needs.

A classification based on local forest types is desirable and usually of more of interest at the national scale, although it does have implication for biodiversity. Better inferences on biodiversity can be made when forests are classified in greater detail, i.e., more categories.

A system for classifying degree of forest fragmentation should also be included as this has an impact on biodiversity and biomass density. Studies suggest that isolated forest fragments lose species. A measure of fragmentation is also useful for identifying forest at risk for deforestation or degradation. Other studies have shown that the more fragmented the forest, the greater potential there is for deforestation or degradation as the forest are more accessible to human use (Brown et al. 1993, Liu et al. 1992). These studies used perimeter to area ratios of GIS vector-based forest maps. Developing a system of classifying forest lands by perimeter to area ratios is clearly a task for the national to subnational scale as it requires maps of forest lands in a GIS vector format.

A system for classifying degree of forest fragmentation should also be included as this has an impact on biodiversity and biomass density.

Finally, a classification system based on social and economic factors should be developed as the last level of the hierarchical approach that we recommend. Factors to be included are population density, land ownership, and forest use (preservation/protected areas, timber production, non-production, minor forest products, etc.). Once again, GIS data bases for these factors would be the system of choice and they should build on those already produced by the FRA90.

As remote sensing data will be used more and more in future assessments of forest lands, classification systems based on vegetation cover or land use must be compatible with what can be interpreted remotely. This will generally entail greater use of high resolution data and field studies. A wall-to-wall map for the whole tropics based on a simple forest/nonforest classification has limited relevance to the carbon cycle and biodiversity.

A wall-to-wall map for the whole tropics based on a simple forest/nonforest classification has limited relevance to the carbon cycle and biodiversity.

Future assessments must continue to refine the definitions of forest land-use classes in a more objective way. Because forest degradation is becoming just as important as deforestation, objective criteria must be developed to distinguish the various classes of degraded forests as each class has different impacts on global phenomena as well as its own management challenges. Furthermore, other wooded areas such as living fences, community and family gardens, line plantings, etc must be assessed as they can contribute significantly to global biomass pools, etc.

State and change of forest cover

Statistical data

We recommend that the present approach (based on the model of percent forest cover versus population density) be continued for the near future until it becomes feasible for more tropical countries to do a national-level continuous forest assessment. However, the models should be further validated with additional data collection. Future efforts should also attempt to increase the sample size for each ecological zone (strata) to

increase precision. This should be feasible as results from new and ongoing forest inventories are completed. Furthermore, this analysis will be compatible with the high resolution satellite imagery work as it will provide insights to the human dimension and enable new models to be developed.

Present and future assessments using modeling of statistical data should be put into a GIS format (percent forest cover and change by subnational units for the whole tropics) for use by interested parties. For example, such a product would be useful to scientists modeling the past and present role of tropical forests in the global carbon cycle (part of the US DOE effort to Global Change Program) as it would complement and extend similar data bases produced and in process of being produced as far back as 1850 to 1980 (Flint and Richards 1991,1993). A GIS data base of percent forest cover and change in cover would also be useful for investigating other relationships between these data and other environmental and/or human factors that are or will be in a GIS data base form. This could be useful at regional to global scales, but of limited use at national scales because of the low resolution.

Satellite imagery

The current method for assessing state and change of forest cover based on a sampling of remote sensing imagery is adequate, and has greatly improved the 1990 assessment. Considering the level of support provided to this assessment by FAO, the FRA90 has done an admirable job. However, there is room for improvements. The interpretation of satellite data could be improved if additional data were gathered to increase the number of categories of forest cover identified. It is of particular importance that "no change" in the closed or open forest category really means that no change has occurred when in fact biomass could have been reduced by illicit logging or fuelwood collection, for example.

We recognize that field validation of these images is very difficult, but as the images are often interpreted by experts in the area it may be possible to quantify potential risks of activities that reduce biomass. Indices of fragmentation or socioeconomic factors in GIS data bases may be ways of approaching the problem. Case studies in selected areas are needed to address this question.

The present FRA90 does not include the production of wall-to-wall forest maps for the tropics using satellite imagery. Part of this was caused by the cost, and corresponding lack of resources, of such an operation and part by technology problems. There has been much discussion on this topic from technical and needs perspective. There are many problems with producing such maps because of resolution, classification, multi-date, and cost/time considerations.

The advantage of wall-to-wall forest maps is that it would allow for the full power of current computer technology, e.g., GIS, to be used to develop relationships between forest cover and change and other environmental or human factors and improve models of the global carbon cycle of forests. This advantage must be sought after.

We recommend that the production of wall-to-wall forest maps based on satellite imagery be the focus of FAO/UNEP's effort in future global assessments. Because there are currently a number of organizations (e.g., TREES, NASA, Dutch initiative), countries (e.g., Brazil, Thailand, Zaire), projects (e.g., SEAMEO) involved with mapping forests using satellite imagery, future assessments by FAO /UNEP should not use their resources to duplicate this effort. Rather they should concentrate on the other issues raised in this paper (biomass, biodiversity, GIS data bases, etc.) and focus on working with the remote sensing effort to resolve various issues like (1) best classification systems of forests to account for environmental and human factors, (2) linking national to global efforts, (3) accuracy and precision requirements, and (4) data management (collection, archiving.

The carbon cycle

A conceptual model of the carbon budget of a forest is shown in Figure 1. To increase the accuracy of carbon flux estimates from tropical forest lands requires that the net carbon balance equation (Figure 1) be evaluated for each change in land use over time. This implies a modeling approach with geographic specificity, i.e., using modeling with GIS data bases on types and rates of land-use change coupled with similar types of data for each component of the carbon budget (this approach is being attempted by scientists supported by the US DOE to a multi-institutional team with Brown, Fung, Hall, Houghton, Lugo, Richards, and Skole as leaders of their respective teams).

The largest contribution to the net carbon balance occurs when the aboveground biomass density of a forest (trees of all size classes) is altered by clearing for agriculture, logging, degradation, or rehabilitation/succession. Aboveground biomass density is also the component of the carbon balance that is relatively easy to estimate right now as the data required can be readily obtained from standard forest inventory techniques, but with some modifications. The other components of the carbon balance are important but less readily measured without massive efforts. Fortunately some of these other components tend to change slowly, if at all, as long as some form of forest cover remains (e.g., soil carbon, belowground biomass, and fine litter). Mass and dynamics of coarse litter are very poorly known and additional effort will be needed to improve this state of affairs.

The present database is too unreliable to make global estimates of biomass with any degree of certainty.

Biomass

Significant improvements in accuracy of carbon fluxes could be brought about with more accurate and precise estimates of aboveground biomass density. The present data base on VOB is too unreliable to make global estimates with any acceptable degree of certainty. A GIS modeling approach offers an alternative, but to date only South and Southeast Asia are completed (Brown et al. 1993, Iverson et al 1993); the other two tropical regions will not be completed until about two years from now. Improvements in this modeling approach would benefit from a wall-to-wall map of forest cover. A remote sensing approach to estimating biomass density has been tried with limited success in temperate forests, but no success

has been possible yet with the complex tropical forest landscape (Sader 1988). We believe that more traditional approaches will have to be used until remote sensing techniques become a reality. Even then, measurements on the ground will be needed to validate the remotely sensed data.

Improvements in the near term could be brought about with improvements in forest inventories. However, first there are several problems that need correcting with the current inventories in relation to their use for biomass estimation. One area of improvement is expanding the real coverage of inventories and including more forest classes. Very few tropical countries have national inventories; many cover small subnational units and tend to be done in "commercial" forests only. In addition, many inventories often do not include all tree species and use a relatively large minimum diameter (more than 30 cm or so). Studies have shown that more than 20% of the aboveground biomass can be in the missing smaller size classes (Gillespie et al. 1992). Introducing factors to "expand" volume estimates to include these smaller trees introduces more error. Moreover, the volumes measured are not always standard across all inventories.

We recommend that future inventories should consider these factors and that standards should be set and adhered to so that future inventories can be used to make more reliable estimates of forest biomass density. Identifying the locations of inventoried plots using a global positioning system (GPS) would be useful for biomass modeling studies. Furthermore, globally located simple soil sampling for texture classes, depth, and presence of particular edaphic conditions as part of the inventory would contribute to improving the present FAO soils map. Concurrent studies can also be done to improve the accuracy and precision of the conversion factors. Generally volume estimates from inventories are within <10% of the mean 95% of the time; errors in the conversion factors are not known at this time, but are likely to exceed 10%.

We believe that more reliable estimates can be made with inventory data using a different approach. A standard method of estimating forest biomass is the application of biomass regression equations to allometric measurements of all trees (to some minimum diameter, usually 10 cm) in plots of known area. The regression equations generally relate the biomass of a tree to its diameter or (diameter)2 * total height. Different functions are used including polynomials or geometric (c.f. discussion in Brown et al. 1989).

Brown et al. (1989) collated and analyzed biomass data that had been produced by the harvest of individual tropical trees. The data were stratified by three major ecological zones (dry, moist, and wet) and sets of separate biomass regression equations (based on different independent variables of diameter alone or diameter and height) were developed for each strata. Various analyses demonstrated that grouping all trees from the same ecological zone, regardless of region of origin, was valid. Recent work in Brazil compared a locally derived biomass regression equation with the corresponding one reported in Brown et al. and found excellent correspondence (I. F. Brown et al. 1992). These pantropical equations have been used to estimate aboveground biomass density (point and 99%

confidence interval) using forest inventory stand tables for many tropical countries (e.g., Brown et al. 1991). Production of forest biomass maps are also possible using this approach when stand tables are keyed to mapped forest types (Brown et al. 1993). Error due to the regression equation was on average <10%.

We believe that this approach for estimating biomass density is the best one available, and it is amenable for use in any continuous forest monitoring program (section 4.0). However, at least two improvements are needed before wider use. First, the data base for the biomass regression equations needs to be increased, particularly in the number of large diameter trees (>70 cm). A systematic collection of such data from a variety of forest types and geographic and ecologic zones would accomplish this. Cutting and measuring trees for producing local volume tables is often standard practice in forest inventories; biomass of these trees is obtained relatively easily with a few additional measurements. We believe that the emphasis should be on pantropical equations because the large sample size needed to reduce regression errors at local scales may be impractical.

Secondly, stand tables need to be developed using uniform standards. For example, diameter classes should be uniform in width and preferably no more than 10 cm, and large diameter trees should not be lumped into one open-ended class. The distribution of the large diameter tees (>70 cm) is important because trees above this size class can contribute up to 45% of the aboveground biomass density.

To improve biomass density estimates to the same level of precision as the improved land-use change estimates, within the next decade or so, will require ground sampling. One approach is to establish a permanent plot network. Stand tables could be produced from this network for the various forest classes, and biomass density estimated. These would serve as the baseline for subsequent measurements. If a completely new sampling design is developed along the lines discussed in section 4.0, establishment of permanent plots for biomass assessment must be part of this plan.

To improve biomass density estimates to the same level of precision as the improved land-use change estimates, within the next decade or so, will require ground sampling.

Other forest components

The establishment of a permanent plot network will enable estimates of several of the other carbon budget components to be made. Soil sampling and analysis for carbon content is well established and relatively straightforward. This component could be readily added to inventory work. Estimating the amount of coarse litter, or woody debris (diameter >10 cm) is also straightforward and could be included in inventory designs. The method of choice, based on its simplicity of measurement, is the line intersect method used to estimate forest fuel loads (Brown 1974). The biggest hurdles in these additional measurements most likely will lie with institutional and technical interest and support for the job.

Biodiversity

The term "biodiversity" is a vague concept, with different meanings to different people. From the perspective of environmental monitoring and assessment, it is necessary to define biodiversity in terms of exactly what is to be measured and monitored. For our purposes, it is appropriate to speak of diversity of species (or genus), recognizing that different sampling methods will be required for different types of organisms (trees, vines, herbs, animals, insects, etc.). Furthermore, "diversity" itself is generally considered to encompass two concepts, evenness and richness. We limit our discussion to assessing tree species richness in tropical forests at this point as accomplishment of this task alone would greatly enhance our understanding of global biodiversity.

"Diversity" itself is generally considered to encompass two concepts, evenness and richness.

The incorporation of biodiversity information into global assessments of forests presents a significant challenge because identification to species of many organisms is poorly known. Among plants, trees are better known than any other group, with useful herbs, vines, etc. (chiefly medicinal) following. Birds and hunted animals are probably among the best known groups of animals. In addition, the number of trained biologists that can identify organisms is at best limited. Initially, assessments will have to be limited to the most fundamental aspects of the biodiversity issue, namely the species richness component. Other aspects of biodiversity such as genetic diversity or intra-population variation are impractical to approach at global scales at this time. However, from species richness information, quantitative estimates of tree density, and a variety of GIS data bases, it will be possible to estimate indices of species evenness, and spatial aspects of species diversity such as the geographical distribution.

We propose a four-phase approach to the problem of species richness assessment. The first phase is already in progress and it deals with a quantitative synthesis of the patterns of species richness in tropical forests (one of the FRA90 special topics). Such a synthesis would take advantage of current ecological understanding of how species numbers change in time and space in different ecological zones. This analysis should build on the few generalizations accepted by ecologists who deal with the problem of explaining the patterns of species richness (Table 3). Of particular value in this initial phase would be the degree to which the variation in species numbers can be explained by climatic factors, ecological zones, area considerations, ecosystem maturity, and forest condition (disturbed, degraded, fragmented, etc.). Correlations such as these would allow extrapolation of data to larger spatial scales as they are compatible with GIS data bases proposed to be used with the overall forest assessment.

We propose a four-phase approach to the problem of species richness assessment.

A second phase, also in progress in the scientific community, would be the testing of suggested correlations of species richness and specific field situations. This requires a network of plots where species counts of any plant or animal group can take place. The best model for this is the fixed, large plot approach formalized recently by the Smithsonian Biodiversity Program (Dallmeier 1992). In these biodiversity plots, plant and animal species can be inventoried quantitatively over extensive time

periods, similar to the CFI plots traditionally used by foresters. The innovation of the Smithsonian is their almost exclusive focus on biodiversity assessment. To be useful for national inventories of biodiversity, these plots need to be established under a variety of land uses and forest types so that a better idea of the effect of state and change of forest cover on regional biodiversity can be attained. More coordination between FAO/UNEP and this effort is needed.

A third phase of our proposal involves the incorporation of biodiversity parameters into routine field inventories. Forest inventory data can be used to make some inferences regarding species richness of trees in tropical forested landscapes. Many inventories (both past and present) made a substantial effort to identify trees to the level possible (e.g., to the family or genus level if not to the species level), and to include all trees above some lower diameter limit. These inventories have tended to be ignored by the scientific community based on the belief that they have not been conducted by professional botanists, which is not always true. While such data are typically summarized in final reports, it is possible that interim reports and/or raw data are available which can be used to draw some inferences about the richness and evenness in the distribution of tree species. Research in this area is ongoing, but greater effort is needed for future assessments.

At the ground level, slight modification in traditional inventory methods would yield large returns in our ability to assess tree species richness. Experienced local botanists should be included in the inventory team, to train field crews in proper species identification, as well as to identify rare or unknown trees from samples returned by field crews. All trees should be included in the inventory. Other vascular and non-vascular plants need to be inventoried using smaller subplots. Raw data should be made accessible to appropriate researchers and other users. We strongly recommend that complete tree counts and identification be part of the normal tropical forest timber inventories. We believe this can be started relatively quickly. FAO and other donor agencies should consider recommending such policies in all inventories with which they become involved in the future.

Ultimately, it would be desirable to develop models of expected plant species richness given environmental and human factors (Table 2) as well as geography. This would allow use of GIS data bases to refine sampling for monitoring tree species richness by increasing sampling in areas of high diversity and high expected change.

The fourth phase of our proposal is the development and application of modeling techniques for the estimation of biodiversity. The data bases that will result from the previous three phases should be diverse enough in terms of types of forests and land uses that are sampled and groups of organisms covered, such that fairly accurate predictors of species richness can be attained. When properly calibrated, such models should become the predominant tool for extrapolating results from small scale work to larger scales and to predict potential changes associated with human use of the landscape.

The hydrologic cycle

Like the carbon budget, the issues of interest here are the effects of land-use change on the water budget, including, primarily, effects on the quantity and seasonality of surface flow, or stream discharge, and evapotranspiration. Common knowledge tells us that forest clearing and degradation significantly impact these pathways of the hydrologic cycle. Also of concern is the potential impact forest clearing has on local to regional rainfall patterns. To date no assessment has been done to address any of these issues at national to global scales in the tropics.

Ideally, hydrological models (empirical and process oriented) need to be developed that are suited for simulations at global to regional scales as with the carbon budget models. We suspect that this goal is still a ways off, partly caused by the lack of a coordinated effort to generate global data bases. Nevertheless, modeling the hydrologic cycle is much simpler than modeling the carbon cycle. Therefore, we believe that it is technically feasible to simulate water models using a GIS approach and land-use change data bases.

We recommend that a committed effort be made to gather all the stream discharge data scattered around the tropics in such a way that it can be developed into a GIS data layer.

A first step in assessing the impact of changing tropical forest land use on the hydrological cycle has been taken, namely generation of GIS data bases of long-term, average annual rainfall amounts and patterns (input to the hydrologic cycle). To complement this data base, one for stream discharge also needs to be developed. It is likely that the vast changes in tropical land cover over the last several decades have altered the quantities and seasonality of discharge. With the availability of long-term records, this could be analyzed by experts in this field. Evapotranspiration data are more difficult to obtain and will, most likely, need to be assessed via modeling approaches.

We recommend that a committed effort be made to gather all the stream discharge data scattered around the tropics in such a way that it can be developed into a GIS data layer. Units will need to be standardized and the preferred choice is on a unit area of catchment basis (e.g., cm or mm per yr). Full documentation of each station will also have to be made, including: the exact location of the station (latitude, longitude, elevation), the length of record, how frequently the data are collected (continuous, daily, weekly, etc.), stage-discharge relationships and how frequently they are re-calibrated, etc. The capability must also exist for scaling up to regions and the globe. The FRA90 project demonstrated that such a data gathering operation is feasible as witnessed by the compilation of the FORIS 1990 data base; this approach could be used as a model for gathering hydrologic data.

Forest health

Forest health, like human health, is a concept. It cannot be directly measured; rather, one measures a variety of indicators and, based on the joint values of those indicators, makes an assessment as to the present state of health. Forest health is a topic of great interest in the temperate zones,

where environmental degradation associated with industrial development is perceived to adversely impact the forested environment through mechanisms such as acidic deposition and increased ozone levels. Forest health outside the context of deforestation is not presently a topic of great concern in the tropics; however, it is likely that interest will increase along with increases in industrialization and public awareness of industrial-environmental interactions. This is an area where FAO should anticipate great interest in the next forest assessment, and where we might begin planning for addressing that interest now.

Various types of forest health monitoring systems are in place in temperate countries. Most of these systems combine remote sensing of large areas with on-the-ground monitoring of various indicators of forest health, e.g. mensurational, biogeochemical, visual, and other obvious symptoms. Such a system would be technically straightforward to develop or expand for tropical regions; the logistics of implementation within and across countries might be more difficult. There would be great value in establishing a baseline now, against which future changes in forest health might be measured. Such a system would be readily incorporated into a systematic sampling frame appropriate to many other global forest resource assessment activities.

Forest health monitoring systems combine remote sensing of large areas with on-the-ground monitoring of various indicators of forest health, e.g. mensurational, biogeochemical, visual, and other obvious symptoms.

Strategy for Future Needs

Tropical forest assessment includes an interest in knowing both the state and change of tropical forests area and condition, and their effects on biomass density, other carbon pools, biodiversity, water resources, etc . (Table 4). From a monitoring perspective, this implies the existence of some kind of periodic assessment, with the assessment at any given time being our best estimate of the present state of the resource, and the difference between assessments used to estimate the rates and magnitudes of change in the resource.

For state and change in forest area and condition, production of wall-to-wall maps from high resolution satellite imagery is the best approach as this reduces sampling errors to a minimum. An alternative is to use the combination of coarse imagery for stratifying a sampling design using high resolution imagery. Production of global forest maps from satellite imagery should be the goal of the many projects already involved with this task. Production of such maps should not be the focus of FAO/UNEP's future goals; their role in this effort should be as described in the "satellite imagery" section.

For state and change in forest area and condition, production of wall-to-wall maps from high resolution satellite imagery is the best approach as this reduces sampling errors to a minimum.

There are many sampling considerations in devising a monitoring system to address both state and change in the other aspects (biomass, biodiversity, etc.) of forest resource assessment. There are trade-offs involved in using independent assessments at each point in time (as was done from 1980 to 1990, when the methodology changed dramatically) vs. using a single set of permanent plots over time. There are numerous possible compromises, e.g., sampling with partial replacement (Ware and Cunia 1962).

Estimation of change is obscured if the sampling methodology changes over time. Changes in the sampling method, sampling frame, or assessment criteria will introduce additional variation or "noise" into the estimation of change, reducing our ability to measure and detect "true" change. For this reason, the more stable the monitoring system over time, the more powerful is the assessment.

Many things can be done to reduce the "noise" in the system. One approach would be to develop a uniform sampling frame covering the whole tropical forest area. This sampling frame could be used for forest cover and change assessment (basis for sampling high resolution satellite imagery) as well as ground studies for biomass, biodiversity, forest health, etc. If wisely designed, such a frame could not only be used to design a monitoring system suitable for the global scale, but could also be readily intensified locally (e.g., for a single country or part of a country). This would allow for smaller scale inventories which could be readily linked to the global scale, and would address national needs as well as regional or global interests. FAO has already made a step in this direction by adopting the sample-based forest assessment of 1990. This concept could be expanded upon to include sampling at more stages (e.g., on the ground). It is apparent that GIS technology will play an important role in this sampling framework, thus GIS analysts will need to be included in the design team so that any new and innovative hardware and software needs are developed at the same pace.

The goal would be a single sampling framework, stable over space and time, within which all forest monitoring activities could take place.

This approach would require multilateral cooperation to develop minimum set of mutually agreeable standards, while allowing for more specific standards to be used within any country. Cooperation and support by many institutions from developing and developed countries would be necessary to implement such a system; the larger global community should also be involved, sharing experiences gained in present monitoring activities and sharing the burden of the cost.

The goal would be a single sampling framework, stable over space and time, within which all forest monitoring activities could take place. Individual countries would receive support and be responsible for data collection within their country. Data collection would agree with the broad global standards, but could include extra in formation of local interest (e.g., nationally-used timber types or land use classification schemes). The data should be aggregated, reported, and disseminated at regional scales by regional centers and at the global level by FAO. The system would be flexible to address both current policy questions, as well as future, unanticipated policy questions.

This proposed system would be substantially more complicated and expensive than the present system to devise and implement. Nonetheless, if the global community is committed to monitoring the state and change of the tropical forest resource base, some kind of uniform system is the most economical approach. Having just finished one assessment, and with global interest in the environment increasing yearly, the time is ripe to begin planning this next logical step in our monitoring capabilities.

Challenges to development of a global strategy

To implement our proposal requires an unprecedented level of coordination at national, regional, and global levels. The immense progress that has been made between the forest assessments of 1980 and 1990 in response to many of the changing needs of society demonstrates that this is feasible. However, we anticipate several challenges in implementing our proposal but we feel confident that the global community can rise to these challenges as all elements to resolve them are available. These challenges are :

1. Development of institutions and human resources such as knowledge and skills, at the national and regional levels.
2. Development of technical capabilities, such as access to remote sensing and GIS technology, at national and regional levels.
3. Development of the interest to contribute to global assessments at the country level.
4. Development of the overall coordination of the global network. This needs a tremendous amount of coordination and organization to keep information flowing between all levels and to develop ways to reconcile global assessments with country needs. We believe that this should be a future role of the forestry division in FAO. Obviously, this will require additional staffing and resources.

Recommended Action Plan

To make the future strategy for a global assessment of tropical forests work requires an immense input from and support for many kinds of organizations and institutions, from national to global levels. The key will be to obtain cooperation from all member countries who will benefit from this approach as the kinds of information needed for the global assessment are the same as those that promote sustainable forestry development programs. Thus the above strategy is not just one to improve global assessments but also one that promotes sustainable development of forest resources at the country level.

Here we suggest a plan of action for the short-term (next 5 yr) and longer term (10 yr) that is, we believe, necessary to get the job done. It has three phases: (1) conceptual, (2) preparatory, and (3) operational.

Conceptual

a. The experts meeting organized by UNEP in Nairobi, December 1992 is the first step. This meeting must strive to produce an agreement and recommendations for a workable strategy for future assessments that deals with the present global environmental issues as well as being flexible enough to address future, unanticipated ones (section 4.0). Key "players" must also be identified for the remote sensing effort (international organizations, regional centers, countries?).

b. An experts meeting composed of representatives from developing and developed countries, regional centers, and other international organizations (e.g., IUFRO, IGBP, IPCC, EROS Data Center, TREES, NASA) in early 1993 (UNEP/FAO taking lead), to decide operationally how to

accomplish the various aspects of the overall strategic plan. Preparation of coordination tasks, working plan, field guidelines, standards, quality assurance programs, etc. would be products from this meeting.

Prepatory

a. Meeting of representatives from a few interested countries, particularly those already in possession of remote sensing-based forest maps (e.g., Brazil, India, Thailand, etc.), with UNEP/FAO as lead coordinators in mid-year 1993 to develop proposals for pilot studies (at subnational levels or that build on present national forest inventories) that incorporate the recommendations from the above two meetings. These proposals must show linkages to the global assessment strategy; must plan to use the uniform methods, guidelines, and quality assurance programs; must show that cooperation is planned between national forestry departments, research institutions, and regional centers; and must have a training component. These proposals would be used to secure funding (e.g., from the GEF) for the pilot studies. These pilot studies would propose to essentially plan to measure the parameters identified in Table 4 according to the methods, etc. developed by the two meeting in the conceptual phase.

b. Put pilot studies into operation (about 2-3 yr). Periodic meetings of representatives from each pilot study, hosted on a rotating basis by participants, to share results, experiences, problems, solutions, etc.

c. Reevaluation of standards, guidelines, QA program etc. at end of pilot studies. Revise as needed.

Operational

a. Identification and development of regional centers. Meeting of representatives from regional centers and pilot studies and FAO and remote sensing projects to develop guidelines for role of centers with respect to developing wall-to-wall maps for regions; data sharing, management, and documentation; data aggregation; sample analysis; etc.

b. Training and expansion into whole tropics in second five year period (1995-2000).

c. Meeting of representatives from regional centers and overall coordinating institution to discuss methods of data sharing, reporting, aggregation, etc.

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Table 1: Characteristics of FAO forest resource assessments

Characteristics	1950–60	1980	1990	
	Questionnaire Approach	Centralized Evaluation	Centralized Evaluation and Modeling	Sampling Technique
1. Input data				
1.1 Acquisition and source of data	Compilation of country statistics	Compilation of existing survey data (and some remote sensing data)	Compilation of geo-referenced existing survey data and maps	New survey data from remote sensing including, use of existing survey data and maps; approach following Continuous Forest Survey Inventory Design
1.2 Reporting unit	Country	Country	Province	Sampling unit
1.3 Errors due to variations in classification and measurement standard among countries	Very high (10–50%)	High (10–30%)	High (10–30%)	Little (< 5%)
1.4 Variations in reference data among countries	2–20 years	2–20 years	2–20 years	2–3 years
1.5 Variations in data quality among countries	Very wide (10–40%)	Wide (10–20%)	Wide (10–20%)	Narrow (5–10%)
1.6 Spatial compatibility	Low	Low	Low	High
1.7 Temporal compatibility	Low	Low	Low	High
2. Processing techniques	Simple data aggregation and adjustment to reference date	Empirical adjustment to achieve common classification and reference date	Standardization to common classification; modeling to estimate state and change	Common classification; statistical evaluation to estimate state and change
3. Output data				
3.1 Assessment unit	Country	Country	Country	Initially global/regional; later by country
3.2 Variations in specification	High	No	No	No
3.3 Variations in reference date	High	No	No	No
3.4 Reliability of state assessment	Low	Medium–high	Medium–high	High
3.5 Reliability of change assessment	Very low	Low	Low–medium	High
4. Costs	Very low	Medium	Medium	High

Table 2: **Data bases required, in GIS format, to meet forest classification needs at national to global scales**

Data needs	Scale		
	Global	Regional	National
Environmental factors:			
Annual rainfall/seasonality	◆	◆	◆
Growing season length	◆	◆	◆
Elevation	◆	◆	◆
Slope classes	◆	◆	◆
Soils (texture and quality)	◆	◆	◆
Potential vegetation			
Ecofloristic zones	◆	◆	◆
Human factors			
Actual vegetation cover		◆	◆
General forest types	◆		
Forest use (protection, timber, minor forest products, etc.)			◆
Fragmentation	◆	◆	◆
Demography	◆	◆	◆
Resolution	Low		High
Aggregation capability	High		Low

Table 3: **Some generally accepted statements about patterns of species diversity based on scientific observations.**

- The diversity of most groups of plants and animals increases toward the tropical latitudes and within tropical latitudes species diversity increases towards the equator.
- The number of species (plants and animals) together per unit area of land is usually greater in the tropical rain forests and lower in high latitudinal ecosystems.
- Tropical forests have a higher diversity than high-latitudinal forests in all scales of measure: within habitat, between habitats, and landscapes.
- Within a given altitudinal belt in the tropics, the number of tree species increases with increasing rainfall.
- Across altitudinal belts, the number of tree species and bird species decreases with increasing altitude.
- In islands, the number of animal species increases with the size of the island and with proximity to a continent. If the topography of the island is rugged, the number of species also increases.
- Tropical mountainous areas (particularly high mountains) support a larger number of species (plant and animal) than equivalent temperate mountains because environments range from lowland tropical at the base to alpine conditions at the summit.
- Ecosystems with severe limiting factors such as high salinity, flooding, or freezing temperatures have reduced species richness.
- As rain forests recover from disturbance by acute events such as hurricanes or fire, species diversity increases in the disturbed area until a peak is reached after several decades.
- High-yield systems under intensive human management are species-poor, and increase in species richness to values observed in less disturbed and more mature systems when management pressure for high yield is reduced.
- The landscape is not uniform in terms of its species diversity. Often pockets with a large number of species can be interspersed within areas of low species diversity.

Table 4: Summary of strategy for future forest assessments

Items	Parameters	Strategy	Main Players
Classification forest lands	GIS data bases of parameters in table 2.	Collect necessary data and build GIS data layers; revise present systems.	All levels
	Forest land-use and condition (mature, degraded, etc. classes).	Refine definitions to be compatible with national needs and satellite imagery.	All levels
State of forest cover	Area of land-use and condition classes.	Wall-to-wall map using low/high resolution data and sampling framework.	National and international projects and FAO
Change of forest cover	Change of forest cover by land-use and condition (deforestation/degradation).	Multi-date maps with low/high resolution data and sampling framework.	National and international projects and FAO
Carbon cycle	Aboveground biomass of all forest classes assessed in state and change of forest cover.	Develop standard sampling framework for continuous monitoring coupled with RS.	Global
		Use network for sampling.	National
		Improve present and future inventories.	National FAO
	Soil organic carbon and dead wood.	Same as for biomass.	National and FAO
Forest products	Timber, fuel, fodder.	Derive from biomass.	National and FAO
Biodiversity	Species richness of trees and understory plants.	Same as for biomass.	FAO and national
		Development of models of relations between species richness and environmental/human factors.	International
Hydrological cycle	Forest cover by catchments.	Part of forest cover and change assessment with additional data on catchments.	Regional to global
	Forest phenology.	Part of forest cover change assessment.	National to regional
	Global GIS data base on all steam discharge data.	Collate data and produce GIS data base (using FORIS 1990 data base as model).	All levels
Forest Health	Various parameters that measure health (section on forest health).	Same as Biomass.	All levels

A Satellite-Based Tropical Forest Information System

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A Satellite-Based Tropical Forest Information System

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The System Design

The importance of having a comprehensive operational tropical forest monitoring system has been expressed in nearly all areas of scientific and policy endeavor. The United Nations Conference on Environment and Development (UNCED) highlighted the need and urgency of such a system.

There already exists considerable technical and scientific expertise, as well as an installed infrastructure, to bring such a program immediately on-line. This document provides a blueprint for the development of a Tropical Forest Information System (TFIS), which could be developed with U.S. leadership in cooperation with European partners. It is possible that such a program could be operational within one year by expanding existing U.S.and European tropical forest monitoring activities.

Required characteristics of a tropical forest monitoring and information system

A comprehensive Tropical Forest Information System will need to meet an array of basic requirements, fulfilling the needs of both the global science and international policy communities, and at the same time remain useful at the national level for forest management concerns. Moreover, while the overall objective would be to create a system in support of an operational monitoring program, it must be recognized that an effective operational program must also contain, or couple to, a basic research and development component. Research and development is crucial to the system, since it provides the means to keep the effort current with state-of-the-art technology and methods, as well as focused on emerging scientific and forest management issues. Thus, the system should meet a set of mandatory requirements, which include:

- the data and information generated by the system need to be made available in a timely fashion to the broadest possible user community,
- the system must incorporate global and national objectives. The analyses and results must therefore be amenable to nesting at different scales,
- the key forest parameters to be analyzed must be clearly identified; scientific and management issues can be addressed using the data and information,
- the system must support forest planning and management as well as global change scientific objectives including, biogeochemical modeling, hydrological modeling and biodiversity studies,
- it must also have permanent observing capabilities,

Editor's Note: The text has been excerpted from a longer paper by the same title prepared in June, 1993. The proposed information system addresses the global monitoring needs related to international efforts discussed at UNCED to slow greenhouse gas emissions and the loss of forest cover in the tropics. The system described adopts a remote sensing approach employing experience to date in detecting and mapping forests and forest cover change from space. A coordinated program that links European and U.S. efforts is proposed.

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- it should be sufficiently flexible to incorporate new developments in satellite sensing technology and geographic data analysis. The system should be supported to ensure that the necessary research and development is undertaken in tandem with operational activities,
- any such continuous monitoring system must have an "alert component" to identify areas of potential and new alteration,
- the system must provide regular comprehensive coverage of all forested areas by high resolution instruments for measuring changes with a desired accuracy of 10% every three to five years. Areas of rapid alteration may need to be monitored at a higher temporal frequency,
- data-bases produced from the system must be spatially explicit and include information on rates of forest change, forest type, biomass densities and information related to the process of deforestation such as population density and distribution, infrastructure, access and land use,
- all analyses must be supported by an independent validation mechanism,
- results of remote sensing data analyses must feed into more comprehensive analyses, which incorporate a series of essential geographical and historical information to permit predictive modeling of trends in forest use,
- and the system must incorporate the accumulated experience of numerous international and national agencies in forest survey.

Components of the Tropical Forest Information System

The component parts of the proposed Tropical Forest Information System (TFIS) are outlined in Figure 1. Essentially there are two components: a remote sensing component which provides the basis for monitoring, and a non-remote sensing component includes the provision of a ground based biomass, soil carbon and other data. Similarly the information system should be able to support the development of predictive models of forest change and the data sets needed to run such models. The latter models would be used to focus the monitoring system to areas of potential alteration, and for strategic policy assessments.

Remote Sensing

The remote sensing component of the TFIS has two parts:

1. A periodic deforestation assessment at high spatial resolution.
2. A continuous forest cover assessment at low spatial resolution.

Both components are operated at global scales, with complementary objectives. The high resolution component provides the capability for detailed mapping of location of deforestation, rates of deforestation, and an assessment of regrowth and reforestation rates. The low resolution component provides a baseline assessment of forest/non-forest areas, coarse mapping of forest types and capability for continuous monitoring of forest conversion events such as fire detection. Together, these components also provide a continuous and instantaneous "Alert System" and a means for predictive modeling of deforestation trends.

The result is a comprehensive system, combining the high frequency coverage of coarse resolution satellite systems with the spatially detailed, periodic mapping from high resolution satellite systems.

Therefore, operational and programmatic linkages between low and high resolution remote sensing information gathering should be developed and maintained. Since the major low (TREES) and high (Pathfinder) resolution activities being implemented today are now separate programs, it would be mutually beneficial to establish a coordinated program.

High resolution remote sensing

High resolution data from the Landsat series of earth observation satellites can be employed to make regular measurements of deforestation. Large amounts of these data exist in national and foreign archives, dating back approximately 20 years. This satellite data system has been perfected over years of development (5 satellites have been launched) and it is expected to be an operational system into the next century (Landsat 6 is ready for launch, 7 and 8 are being designed)[1]. Thus, a continuous and consistent source of data is available upon which a high resolution, fine-scale (1:250,000 scale mapping) information system could be developed.

The Landsat Pathfinder Project mentioned above has developed and implemented a full scale test of the application of high resolution data to mapping deforestation. This program is now under way, being implemented to support the global change research community and NASA's EOS Data and Information System activities. This program provides the proof-of-concept that a fully operational effort could be developed quite readily.

Forest monitoring using high resolution data such as that provided by Landsat or Spot would provide wall-to-wall mapping for the entire tropical zone. The approach would be as follows:

- An initial mapping effort would define where and how much deforestation exists in the tropical forests (a baseline assessment). The stratification of forest types and critical regions could be enhanced by the use of coarse resolution information from AVHRR (see below).
- Acquisition of Landsat imagery can be coordinated regularly every 3-5 years to obtain cloud-free coverage systematically throughout the tropics. The best way to achieve this is to rely heavily on the foreign ground stations. For example, routine and complete coverage for the Amazon Basin and Southeast Asia is possible from several foreign ground receiving stations in these regions. As a rule these stations regularly collect data from every orbital pass within the line-of-sight radius of their antenna. For regions, such as central Africa where no ground station exits, programmed acquisitions from the satellite are possible.
- The imagery are analyzed for deforestation using a methodology analogous to that developed by the Landsat Pathfinder project, where a simple delineation of the boundary between intact forest and cleared areas is recorded into a geographic information system. Areas of secondary growth would also be delineated. Subsequent years are compared to the baseline and the increment of new deforestation and secondary growth is recorded. The resulting dataset provides a 1:250,000 to 1:500,000 scale

1. Editor's Note: Landsat 6 failed. Landsat 7 will be launched in 1998.

map of deforestation at a regular repeat interval, and from this a rate of deforestation is derived.

- These geographically-referenced measurements can directly support the IPCC process, which is being established to make inventories at approximately 5 year intervals. An important contribution to the IPCC methodology concerned with biotic carbon dioxide emissions would be this accurate and precise deforestation dataset.
- An accuracy assessment effort will need to be put into place to define and track the measurement variance and error. This component will need to determine accuracy with respect to: (a) variance due to positional accuracy, ie. the mapping precision, and (b) the variance associated with image interpretation.
- An effort focused on establishing in-country cooperation will be necessary. Such cooperation fulfills several ancillary but vital objectives: (a) it builds a process of national acceptance of the methods and results through active involvement, (b) it provides a mechanism for technology transfer and training for eventual implementation of remotely sensed-based national inventories, (c) it facilitates logistical coordination of the field component, (d) it provides direct cooperation at various foreign ground stations, and (e) it enables cooperation with national and regional experts in the interpretation of imagery.

It must finally be noted that these measurements of deforestation from high resolution satellite remote sensing can also support the UN/FAO Forest Assessment by providing quantitative and spatially comprehensive measures of changes in forest cover for the tropics.

Low resolution remote sensing

Tropical deforestation has affected areas which have heretofore been relatively unaffected by human impact (i.e parts of the Amazon Basin, edge of the Central Congo Basin, Borneo). Rates of deforestation in new areas tend to be exponential and explosive in nature. To bring an effective and timely management response, an observation system must be able to detect new fronts of deforestation early. Such an approach must leave no area of the tropics uncovered, and must have re-visit capabilities which can detect, signal, and otherwise measure fast changing situations.

The NOAA AVHRR instrument is a low resolution sensor. Data is acquired at 1 km resolution on a daily basis. This 1 km data can be received at local ground stations while the satellite is within receiving range, or by onboard tape recorders. In addition a resampled 4 km global data set is acquired daily. Despite its obvious limitations in terms of spatial resolution the NOAA AVHRR instrument offers unique capabilities in this respect. The system can insure global coverage at relatively frequent intervals of time. This continuous monitoring ability of the coarse resolution instruments such as AVHRR increases the chance of obtaining cloud free data, thereby providing truly global observations.

The AVHRR sensor is not as attractive as Landsat for precise mapping of areas or for estimating deforestation rates, but its continuous cover-

age makes it extremely useful as a "constant surveillance" tool. Forest impact activities which require constant monitoring, such as fires or droughts, could be observed, measured, and assessed on a daily to weekly basis. The low resolution component also provides a means to stratify forest cover, by delineating the extent of different forest areas through the analysis of vegetation phenology using the existing multi-year data record.

The European TREES program, the U.S. AVHRR Pathfinder Project, and the IGBP 1km Dataset have developed several prototypes of such an approach. The results of these efforts have shown that a worldwide tropical forest monitoring effort structured as just described is readily feasible. In the United States several on-going programs using AVHRR data, including the AVHRR Pathfinder Project and the IGBP 1km Dataset Project being coordinated at the Eros Data Center, could readily link to the TREES Program in Europe. Most of the necessary components of this part of the program are already in place.

The following describes the essential elements of the coarse resolution component:

- Regular, daily acquisition schedule of 1 km AVHRR data would be provided through a coordinated network of ground stations positioned in forested areas around the world. An effort is already under way to put together such a coordinated network, and an initial dataset from it is already under way in the International Geosphere-Biosphere Data and Information System (IGBP-DIS) Global 1 km coverage project and the European TREES Project.
- This low spatial resolution, high temporal resolution component (1 km resolution) would allow for the early production of a truly global forest/non forest map. This effort could provide a baseline map as soon as 1993. The baseline map would be used in conjunction with the high resolution component to define the extent of the tropical forest zone for which high resolution mapping would be performed.
- Validation of the low resolution forest/non-forest delineation would link to the high resolution satellite data in test and validation sites using Landsat Thematic Mapper and SPOT satellite. A sample of images across continents can be acquired to 1) confirm or inform the AVHRR classification over the sample area and 2) to derive correction coefficients taking into account the fragmentation of the forest cover not visible on the low resolution data set. The sampling scheme to be established should be coordinated with the high resolution analysis component of the observation system (see above).
- Forest types throughout the tropics could be mapped using the multitemporal 4 km data product. Currently an AVHRR Pathfinder project is under way in the U.S. to generate global datasets from the existing 10-year archive. This data will add essential information on seasonality characteristics to be used in the forest classification as well as, at some stage in the future, in series of models dealing with biomass and productivity.
- The AVHRR-derived maps would be prepared using a set of uniform classification criteria. This classification would rely upon a set of methodologies adapted to the particular forest types and conditions and would draw upon a growing body of current research material.

- Once the basic data have been acquired and organized in the information system, the analyst should be in position to point to fast changing or anomalous situations and release a preliminary "alert notice". An effort can then be made to focus on the identified area using higher resolution data, possibly at higher temporal frequency than the periodic 3-year assessment. This higher resolution data, as well as a wide range of ancillary information, can be used to confirm preliminary findings and to measure ongoing processes with more accuracy.
- Given some uncertainty in the delivery of complete high resolution coverage due to persistent cloud cover, the low resolution data could also be used to fill the gaps where data are missing.

Research and development of new technologies

New remote sensing and data management technologies and methods are continually being developed. To maintain a state-of-the-art system, a program of research and development must be incorporated directly with the remote sensing activities mentioned here. In particular, development of microwave technologies could be emphasized since it has great potential as a data source which will eliminate the cloud cover problem. Emphasis should be given to collect and analyze radar data for those areas of persistent cloud cover.

Non-remote sensing information

Remotely sensed data provides information on deforestation rates. Non-remote sensing data includes information to improve the satellite data interpretation (eg. topography), or to enhance the information derived from remote sensing analysis for the purpose of forest assessment (eg. soil type, population density, land use, logging concessions, land tenure, access). These other data sources are a fundamental component to the data analysis. Additional information is required to estimate carbon dioxide emissions, for example information on aboveground biomass, soil organic matter, and how these parameters are changed after forest clearing. These data need to be included within the Forest Information System in a spatial format completely compatible with the forest and deforestation maps.

These ancillary data would be organized and obtained by:

- An effort to catalog existing information from national forest maps and inventories, the FAO timber volumes, census records, scientific literature, and other existing sources,
- A program of field measurements established systematically throughout the tropical forests, and supported by a collaboration between national forestry agencies and FAO. Currently, field data collection during the Landsat Pathfinder project is being aided by close involvement of the NGO community, local organizations within regions being studied, and national agencies.

Indicators of change

Some examples of indicators of change are: the appearance of fires, the opening of roads, gross changes in canopy cover, or the appearance of

drought and pollution stress. The analysis consists of detecting changes in surface conditions indicative of forest change itself. The analysis must be performed by analysts who are familiar with forest conditions and the mechanisms by which forests are disturbed, used, or converted. Initial efforts can be developed in a set of predetermined "hot spots" (i.e., Borneo, parts of the Amazon, Pacific Northwest etc.). It should also be supported by a systematic documentation effort drawing upon reports, local news, correspondents, etc.

Indicators of change can also be derived from non-remote sensing information. Demographic statistics provide information on changes in population and population pressure. Studies also show very good correlation between agriculture statistics and their change over time and deforestation activities in tropical countries.

The remote sensing and non remote sensing derived indicators of change include:

- the appearance and dynamics of fire;
- the appearance or extension of new roads and logging trails;
- changes in the spatial pattern of forest-non forest interface;
- changes in population pressures;
- changes in the seasonal vegetation index (NDVI) development, under the assumption that degradation enhances the seasonal amplitude of the signal;
- changes in economic policies and conditions, land ownership, or land management.

Modeling

A systematic means for synthesizing this data within the Forest Information System is required. Methods must also be developed to provide predictive and diagnostic information. Some uses of this kind of synthetic, predictive or diagnostic modeling are as follows:

- To make credible short-term predictive analyses (10 year forecasts) of the spatial and temporal trends in deforestation. This kind of information is valuable to both management and research communities. Mapped estimates of trends could be based on the deforestation dataset itself in conjunction with a model which utilizes information on projected population growth, infrastructure such as roads, macro economic factors, and other information.
- To provide a systematic way to make estimates of greenhouse gas emissions, and thus create a world-wide emission inventory on a regular basis. Such models exist and can be implemented as soon as the dataset is made available. The IPCC methodology for determination of national greenhouse gas emissions from forest clearing is under development and when accepted could also be utilized. The approaches are similar and will also need deforestation assessments and the ancillary field data. In conjunction with a short-term forecast of deforestation trends, this kind of modeling could also provide emission forecasts. As programs of improved forest management are implemented, projections can also be compared to actual trends to measure policy effectiveness.

Relationship of the Proposed System to Existing Activities

The program outlined here builds on a "proof of concept" for the high resolution satellite forest monitoring methodology which was demonstrated by the Brazilian space agency (INPE), the U.S. National Aeronautics and Space Administration (NASA), the University of New Hampshire, and the University of Maryland. The proof of concept for the coarse resolution assessment and alarm system has been demonstrated by the CEC TREES project, NASA/GSFC, and the United Nations Environment Programme Global Resource Information Database (UNEP/GRID).

The International Space Year ended in December 1992, however there was a strong recommendation from the WFW Meeting that its program of activities continue under a new organizational structure. The remote sensing methods have been developed and it was recommended that the program focus now on serving the needs of the international science community and the objectives of national forest management. Two organizations have been proposed to continue selected International Space Year activities (including the World Forest Watch project): the International Geosphere-Biosphere Program Data and Information System (IGBP-DIS), and the Committee on Earth Observing Satellites (CEOS).

The International Geosphere Biosphere Program Data and Information System (IGBP-DIS) is the natural conduit of data and information to the international science community. One of roles is to stimulate and coordinate the generation of global data bases critical for the science of global change. The transition of the World Forest Watch effort to IGBP-DIS is currently being evaluated by IGBP-DIS.

The Committee on Earth Observing Satellites (CEOS) could provide the framework for the international coordination of satellite data acquisition and data formats.

The Committee on Earth Observing Satellites (CEOS) could provide the framework for the international coordination of satellite data acquisition and data formats. For instance the satellite-based monitoring program described above relies heavily on the use of foreign ground stations as the major point of data acquisition. Yet the formats and processing standards are not uniform throughout the world. CEOS can provide the mechanism by which an agreement on a common data format can be developed. Similarly, CEOS could also provide the forum for making known to the operators of current satellite systems and the designers of future systems the data needs and requirements of the science and forest management communities.

Traditionally the Food and Agriculture Organization of the United Nations (FAO) has taken the lead in assessing the state of the tropical forests on a decadal basis. The methodology designed for the 1990 Tropical Forest Assessment (TFA) integrates the use of remotely sensed data on a sample basis to generate global statistics of rates of deforestation. The output product does not provide the wall-to-wall high resolution assessment needed to fulfill the scientific and national management requirements. The FAO Tropical Forest Assessment project places a high priority on building national capability in tropical forest monitoring as part of their monitoring program and relies on a distributed network of nation-

al forest agencies to generate the data which is currently synthesized at FAO Headquarters. A proposal by the TFA project to transform their ten year assessment into a continuous assessment is currently being submitted to potential donor agencies for support. The proposed approach will rely on a centralized compilation of the results of national scale forest monitoring by the forest agencies supported by three new regional centers.

The United Nations Environment Programme (UNEP), through a series of Memoranda of Understanding, has played a supporting role in the FAO Tropical Forest Assessment Program and through its UNEP/GRID program offers the opportunity for access to and dissemination of the output products of the FAO Assessment.

The national forest agencies of the tropical countries are at various stages of development in providing up-to-date inventories of their national forest resources. Remote sensing which has been developed primarily in the developing world is in various stages of technology transfer to these agencies. There is a wealth of knowledge at the national forest agencies concerning the state of forest resources and clearly there is a priority to develop national capabilities to apply the most appropriate tools for national forest monitoring. At some point in the future it will be possible to obtain accurate and up-to-date inventories of national forest resources for the entire tropical region from the component national forest agencies. However this will necessitate considerable institutional underpinning and coordinated capacity building by the development community. Clearly FAO has a central role to play in this long term development activity.

There is a wealth of knowledge at the national forest agencies concerning the state of forest resources and clearly there is a priority to develop national capabilities to apply the most appropriate tools for national forest monitoring.

A U.S. Role and European Role

It would be feasible to begin a global monitoring program now by tapping the existing tropical forest monitoring activities and programs developed in the United States and Europe. In particular it would be quite feasible to build upon these existing satellite monitoring activities through a U.S. initiative with possible European collaboration.

Although an initiative could be developed solely in the U.S., and while this might be the best way to proceed at first, a program developed in cooperation with the CEC would provide strong expertise and technical infrastructure by combining the low resolution activities of the CEC TREES project with on-going high resolution activity under the NASA Landsat Pathfinder Project. It would also benefit from the different regional expertise which such a cooperation would bring to the program. Additional U.S. contributions from NOAA, USGS/Eros Data Center, EPA, and the Forest Service would provide important technical and resource backstopping.

This coordinated bilateral initiative could be readily developed, and could provide an optimal mix of expertise in Europe and the United States with minimal duplication of effort.

Additional participation and contribution to the program by additional partners with existing expertise could be accommodated.

Guidelines for Implementation

General Principles

The most important principle is that of timeliness. The present uncertainty concerning the implications of tropical land transformation to biogeochemical cycling, climate change and biodiversity necessitate urgent action. A geographically comprehensive assessment of the past and current rates of deforestation and modeled predictions could be produced and evaluated in the next three to five years and would be made available to the widest possible community.

This urgency would indicate that in the near-term, and based on previous experience, the implementation cannot rely solely on the national forest agencies to provide the necessary satellite derived information or for new regional centers to be established and become fully functional. A centralized or semi-centralized approach to implementation of the monitoring is recommended in the short-term (3-5 years). This should be matched by an unprecedented effort by the international development community to establish operational satellite based forest monitoring capability within the national forest agencies.

It is recognized that where possible the national forest agencies should be involved in the proposed monitoring program. In particular their field knowledge and expertise should be integrated in the data interpretation process and in the evaluation and validation of the resulting assessment.

As a general principle it is important to establish an independent assessment of the results. It might be that the national forest agencies could provide such an assessment on a sample basis through close support from the centralized facility.

Access to the results of the assessment should be unlimited. The output should be in a variety of media suited to the needs of the science and national monitoring communities. It is envisioned that statistical, map data and model outputs would be delivered by the system. Access to the original data and the interpretations are both necessary. The results should be delivered in a timely fashion.

The implementation of the program should be overseen by a steering/advisory committee consisting of representatives of both the science and management communities. It is important that these individuals truly represent the interests of their respective communities and may be best selected from representative international bodies.

The Necessary Partners

Effective implementation of the program in the short-term will involve coordination of several communities:

- The international science community will need to be involved in an evaluation of the proposed system design ensuring that the output products

of the system will serve their data needs. This may be best coordinate through the International Geosphere Biosphere Program (IGBP).

- The forest management community will need to be involved in an evaluation of the proposed system design ensuring that the output products of the system will serve their national scale data needs. At a minimum, key national forest agencies from the tropics will need to be involved and supported to advise on the data interpretation and participate in the validation of the results. This could be coordinated through the FAO, which has established a network of active forest agencies.
- The environmental research community will need to be involved in an evaluation of the proposed system design ensuring that the output products of the system will serve their data needs. Representation of this community could be coordinated by the United Nations Environment Program (UNEP).
- The international forest research community should be involved in assisting with the evaluation of the proposed methodologies in particular to assist in the design of methods for the collection of the necessary ground based data for biomass estimation. The International Union of Forest Research Organizations (IUFRO) could represent this community.
- The satellite data providers will need to be involved in the development of a coordinated data acquisition policy. Similarly they will need to be involved in establishing the protocol for satellite data dissemination, and standardization of data formats and data products. This may be best coordinated through the Committee for Earth Observation Systems (CEOS).
- The remote sensing and GIS research communities need to be involved and supported to assist in the evolution of the monitoring system to take advantage of new developments in the relevant technologies and research disciplines. The professional societies of these organizations may provide the best representation of these communities.

Concluding Remarks

The program outlined above has as its objective the provision within 3-5 years of an accurate global assessment of tropical deforestation. This timely delivery of critical environmental information is possible by building onto existing operational monitoring programs.

While we recognize the sensitive nature of forest surveillance, national sovereignty, and the need to develop national forest resource monitoring capabilities, the urgency to provide accurate information both for improved resource management and global change studies necessitates a centralized approach to this analysis.

To receive the maximum benefit from this plan of action, it is our intention to assure the widest possible access to the information in a variety of formats suited to the diverse international community of potential users. For example data could be made available in computer compatible tapes, personal commuter diskettes, photographic products, or paper maps.

A partnership between existing tropical forest monitoring projects in the U.S. and Europe would give an international solution to meeting these

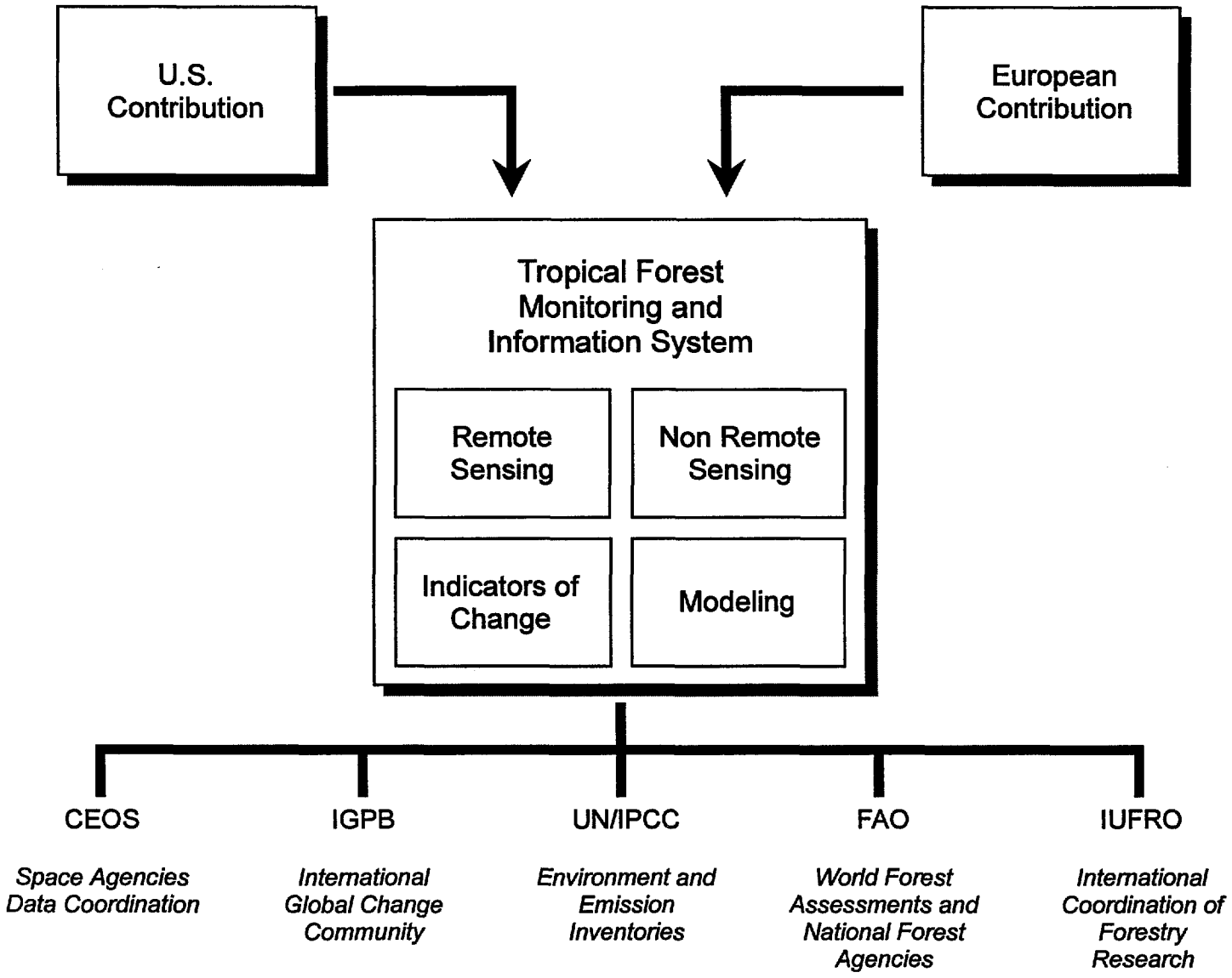
current data needs and would lead to a pooling of international expertise and a sharing of the financial resources needed to implement an effective monitoring program to the benefit of the global environmental community.

The Next Step

To move this activity forward, an implementation plan will be required. To get such a plan off the ground we suggest the following next steps:

- Convene a meeting of U.S. agencies and individuals who would potentially be involved in such a program to examine their interest in participation, identify common interests, and hear other ideas concerning the structure of such a program.
- If the proposal is accepted, then convene a meeting with potential European counterparts to identify areas of mutual interest and financing. This meeting could also be used to establish an initial Program Steering Committee, which would be charged with overseeing the development of a Program Action Plan.
- Have a core group comprised of individuals with the needed technical expertise, devise a Technical Implementation Plan.
- The Technical Implementation Plan would then be reviewed by the Program Steering Committee. The Plan would be augmented as necessary and then implemented.

Figure 1: The component parts of the proposed Tropical Forest Information System (TFIS)



DATA GATHERING ON THE BELIZE FRONTIER

MIGUEL FAIRBANKS (ABOVE)

By THOMAS O'NEILL SENIOR EDITORIAL STAFF

Images by NASA/Jet Propulsion Laboratory

Another stand of tropical rain forest turns to fiery embers (above) to make way for a cornfield. Just how much damage can this ecosystem sustain and still recover, as it did after the Maya farmed here centuries ago?

Questions like this are being raised all over the earth. To help answer them, an ambitious experiment was recently undertaken in Belize. Three advanced remote-sensing devices were flown over the forest on NASA research aircraft to develop new ways of examining landscapes.

The devices, designed by Caltech's Jet Propulsion Laboratory (JPL), were used in the Tropical Rain Forest Ecology Experiment (TREE), a project supported by NASA, the Seaver Institute—a frequent contributor to National Geographic projects—and the Society. Similar sensors are candidates to go into space after 1998, when NASA plans to launch a new series of earth-monitoring satellites.

Covering an area 40 miles long by 30 miles wide, a false-color radar mosaic (right) depicts a variety of vegetation, from savanna and cleared land (deep blue) to upland broad-leaved forest (bluish hues) and lowland swamp (yellow).

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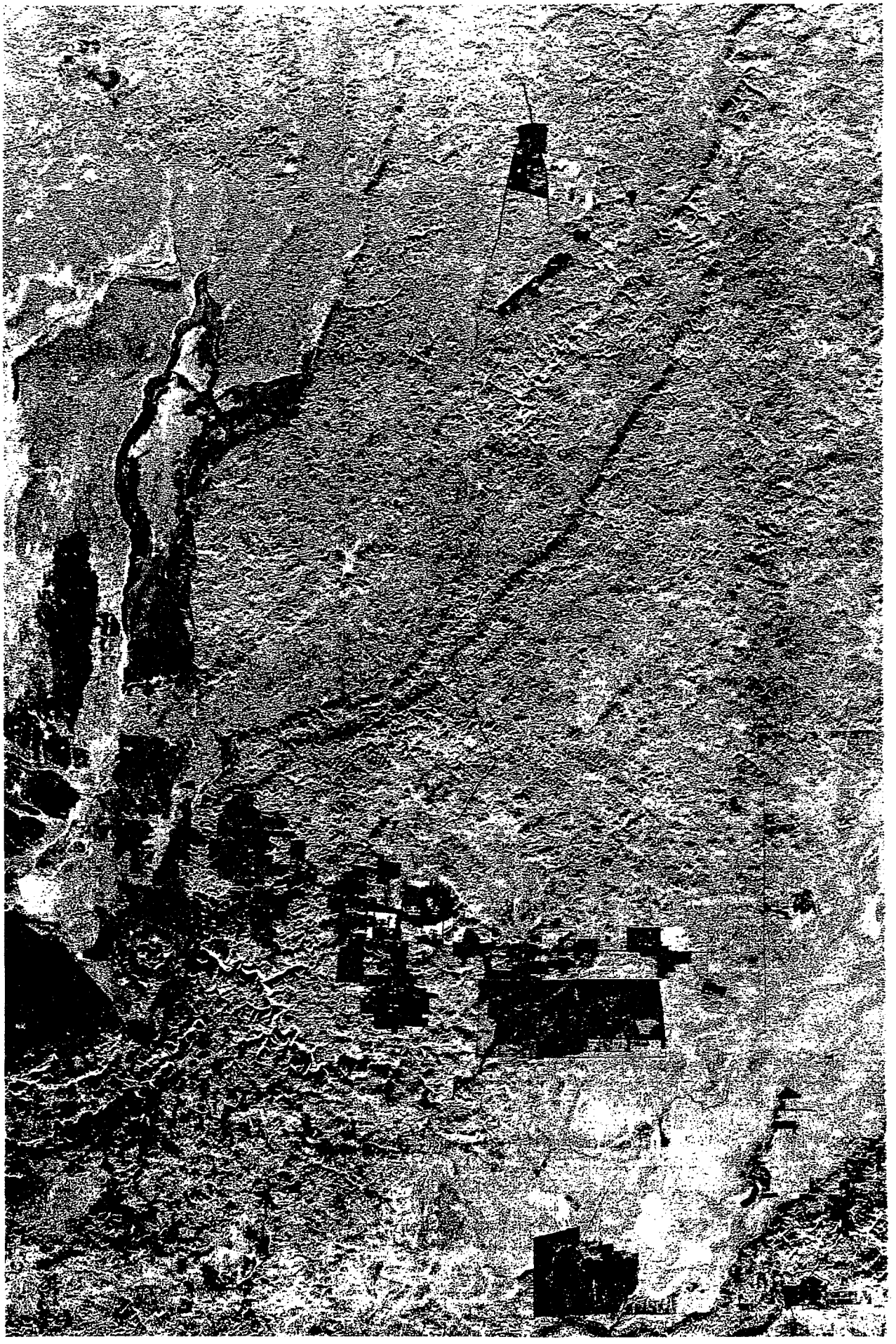

JON SCHNEEBERGER, NGS STAFF (LOWER RIGHT); KENNETH GARRETT

Testing airborne sensors against rain forest reality

While airborne sensors registered data remotely, down on the hot forest floor two dozen researchers gathered ground data. Measuring and monitoring plant specimens and locations, they supplied facts against which the instruments were calibrated and the images interpreted.

JPL ecologist Reiner Zimmermann (upper right) stands at the head of the "octopus"—his name for a data recorder wired to an array of solar-charged devices scattered about a plot. The team took readings of temperature, precipitation, and water use by trees, and collected leaf and soil samples.

Weather gauges were placed a hundred feet high in the canopy by local residents skilled in scaling the tall trees to harvest chicle, an ingredient of chewing gum. "Other than ants crawling into the computer and termites eating the table legs, everything worked," said Zimmermann.

Matching ground features with radar image, Wendy Weiher, a graduate student at Duke University, notes a mound that hides a Maya structure, possibly a burial site (above). Normally, encountering unexcavated ruins would have thrilled field researchers. These were simply in the way.

"We needed plots of pure vegetation, but everywhere we looked, we found something Maya," said Duke ecologist Ram Oren, chief scientist for TREE and designer of the ecology experiments. "Finally we had a plot that seemed right, and we began to dig for soil samples. Then we heard *clank clank*. Can you believe it? We apparently hit stones of a Maya courtyard."

Some 30,000 feet overhead flew a DC-8 research aircraft, its cabin stocked with gear (right) to operate the synthetic-aperture radar, a system powerful enough to detect standing water under the forest canopy. By correlating ground data with digital data from such sensors, scientists work toward the creation of computer programs to interpret future images.

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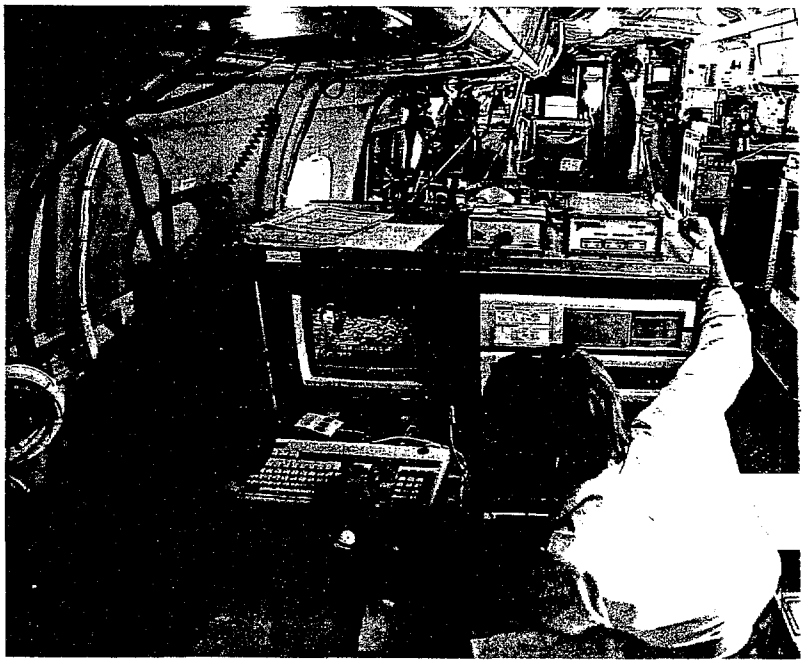
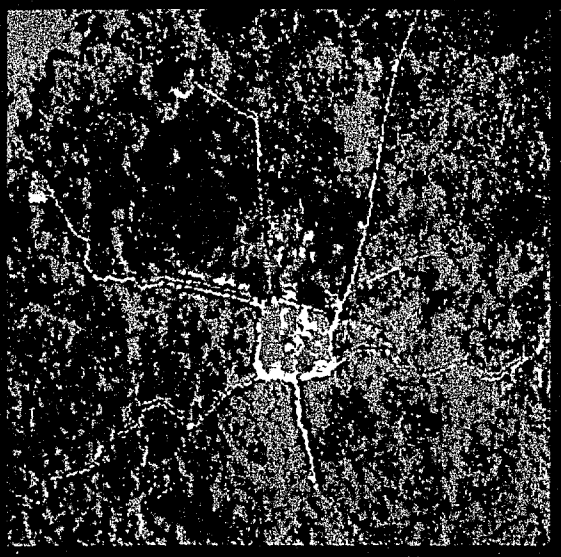
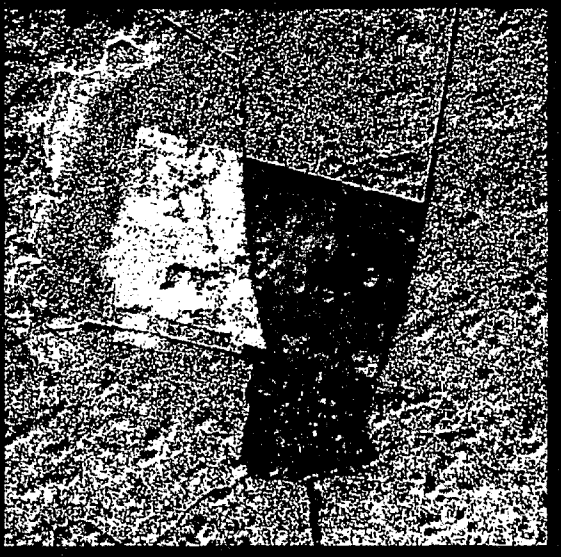


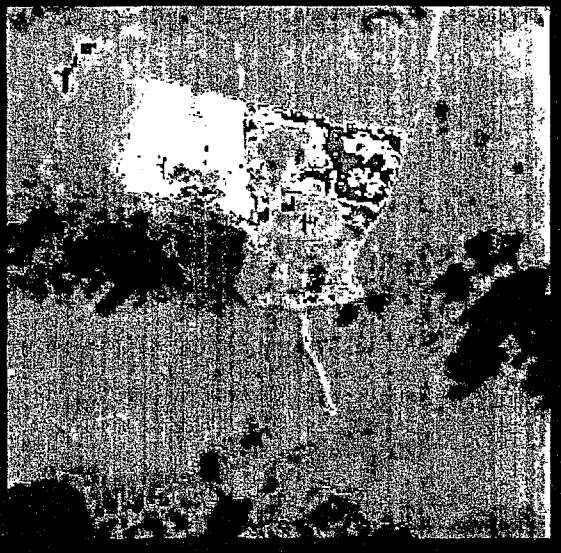
Four electronic eyes focus on a farm in the rain forest

LANDSAT
Landsat began monitoring earth's surface in 1972. Landsat 5 takes readings of reflected sunlight and surface temperature, which, when processed, distinguish forest from fields. This false-color image of 2,200-acre Gallon Jug farm in northern Belize is shown for comparison with images from TREE's newer remote sensors.

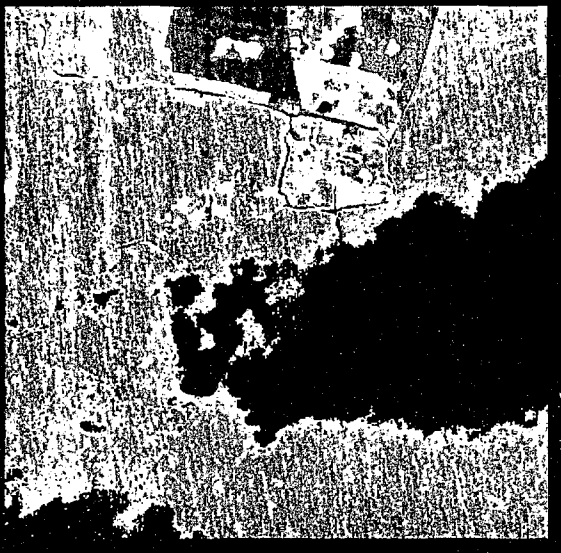


RADAR
Seeing through clouds from 30,000 feet, the Airborne Synthetic Aperture Imaging Radar (AIRSAR) gathers information from three wavelengths, providing both a relief map and a vegetation map. AIRSAR is able to detect crops under native trees, as well as fallen logs (yellow) on a recently cleared field.





THERMAL SCANNER
The cool of the canopy and the heat of cleared fields come into view from surface-temperature readings provided by the Thermal Infrared Multispectral Scanner (TIMS). TIMS picks out differences between crops (light green), areas of recently felled trees (yellow), and bare fields (red). Various shades of green in the forest reflect how much water vapor the trees pass into the atmosphere.



IMAGING SPECTROMETER
The Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) registers data from 224 bands of the electromagnetic spectrum, compared with seven for Landsat. AVIRIS depicts, among other things, vegetation densities, from thick forest (reddish yellow) to cleared land (blue). Yellow indicates less vegetation, including a coffee plantation beneath the canopy.

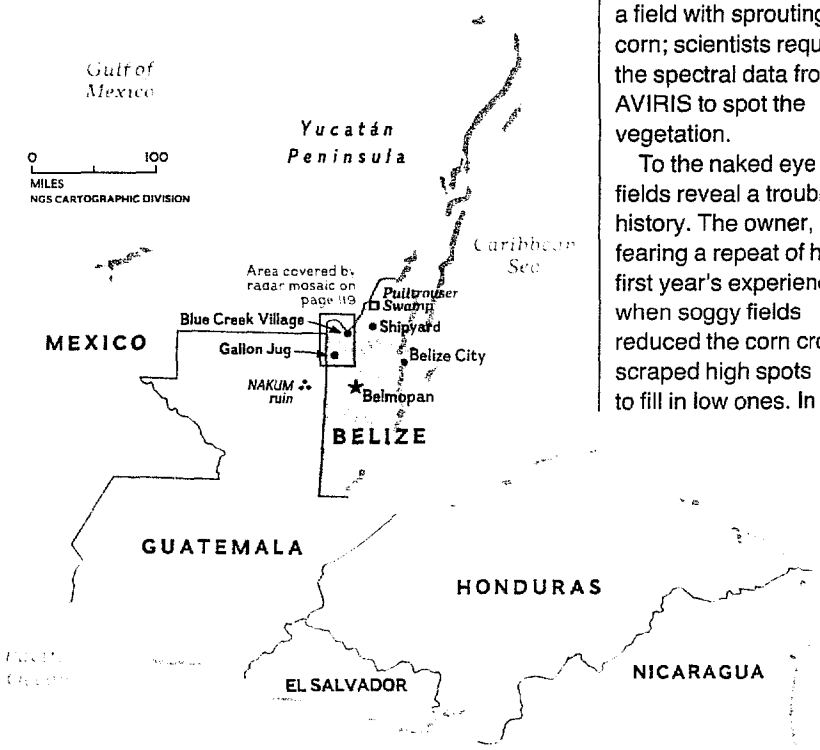
KENNETH GARRETT (ABOVE); JOHN C. STENNIS SPACE CENTER, NASA (FACING PAGE, TOP LEFT)

Scientists harvest data from a cleared piece of land

Seen in its true colors, the farmland of Gallon Jug, an unmistakable shape on the remote-sensing images, appears raw and naked in the midst of thick forest. The scientists chose Gallon Jug—here seen looking south—so they could compare instrument readings of the natural landscape with those of altered areas such as cattle pasture. They soon concluded that no sensor by itself provides a complete picture. The radar, for instance, could not distinguish between a freshly plowed field and a field with sprouting corn; scientists required the spectral data from AVIRIS to spot the vegetation.

To the naked eye the fields reveal a troubled history. The owner, fearing a repeat of his first year's experience when soggy fields reduced the corn crop, scraped high spots to fill in low ones. In doing so he bared large patches of infertile limestone. Ideally, farmers could take advantage of remote-sensing images to identify areas for farming that would be more easily worked and have less impact on the environment.

The TREE study area—a region of forest, swamp, and savanna in northwestern Belize—is part of the most extensive rain forest left in Central America. It is not virgin forest. To feed a large population, the Maya cleared most of this area, which is filled with signs of their presence. Sponsors of the TREE project were curious as to whether the airborne sensing devices could detect undiscovered ruins beneath the canopy. So far, any ruins have stayed hidden.



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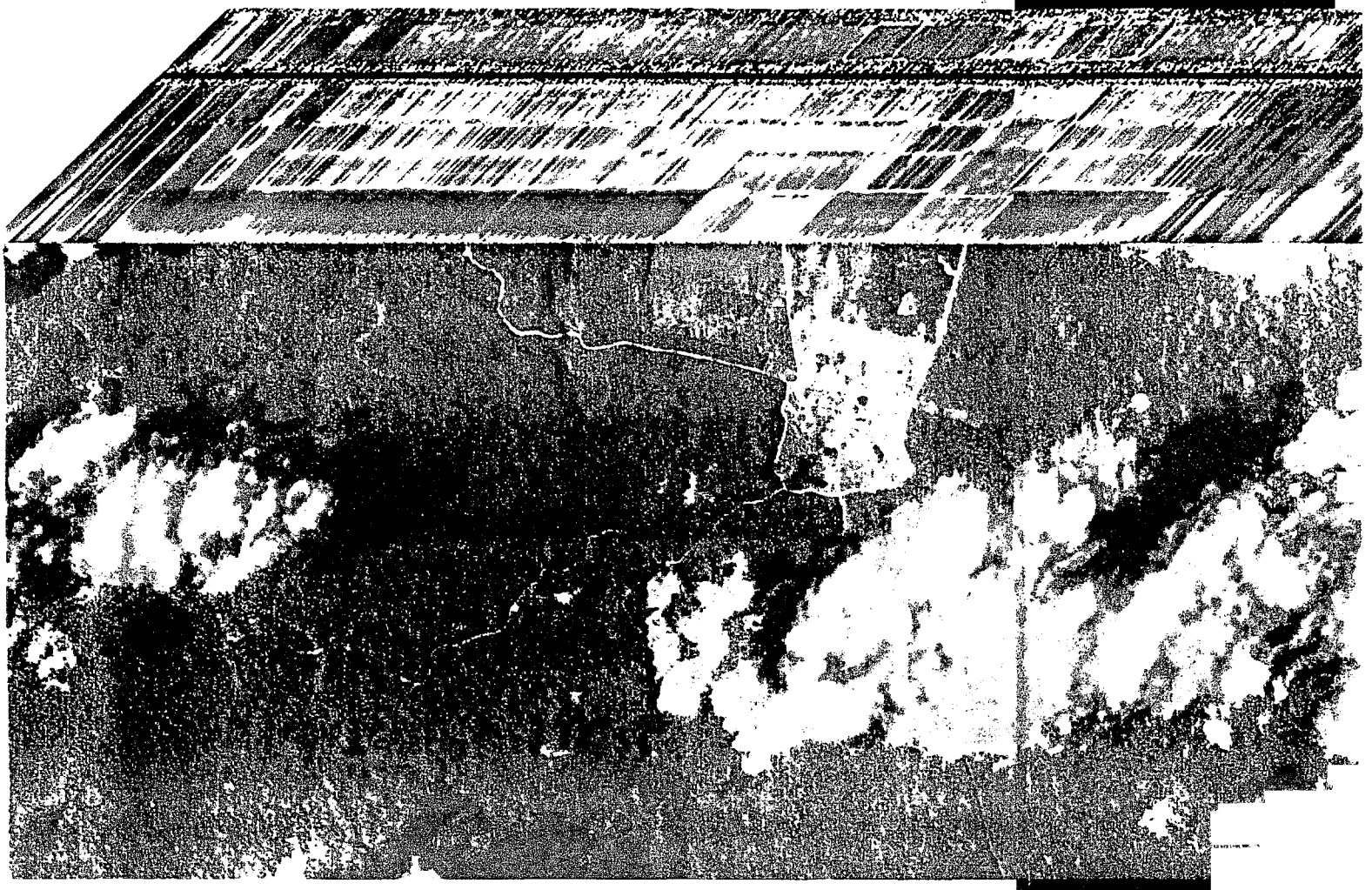


lultilayered, multicolored tack of spectral data

treasure chest of information awaits ientists analyzing ages produced by /IRIS, the new multi- ectral sensor. The strument scanned a e-by-ten-mile swatch land across Gallon g farm. AVIRIS sepa- es sunlight reflected m the surface into 4 wavelengths across the electromagnetic spectrum. Processing the data, TREE project head Gregg Vane and his team at JPL produced a stack of 224 images, rather like a deck of cards where each card represents a single spectral band.

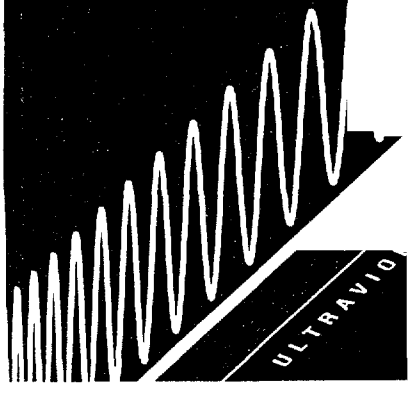
Since materials have spectral signatures, based on their chemical composition, scientists can match the signatures to specific plant properties, such as the chlorophyll, lignin, and water content of leaves, and infer how the vegetation will respond to changes in its environment. Thus data about plant chemistry can be gathered from regions too large or remote to allow ground surveys.

The JPL team and cooperating universities are working to devise computer programs that will rapidly access the information embedded in the AVIRIS data. While some programs are already available, others will take months or years to complete.

"Yes, it is a treasure box," says Ram Oren about the unabridged data, "and it has been unlocked, but we have more to do before we get the lid all the way open."

Remote sensors over Belize registe as specific wavele of the electromagn spectrum. Compar with existing satelli images from Lands AVIRIS provides m continuous covera over a portion of the spectrum.

DIAGRAM BY DAVID MERRILL



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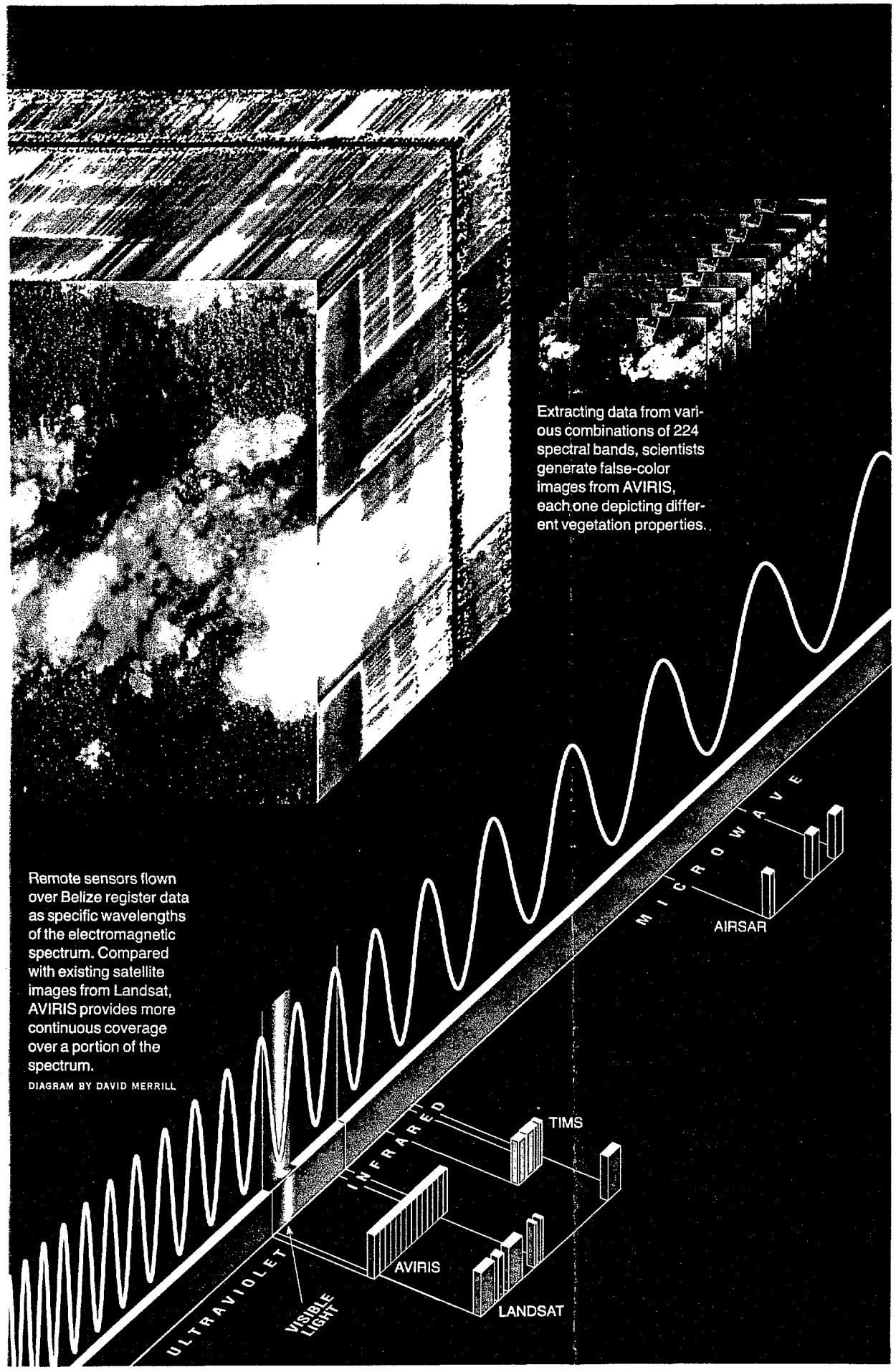

Extracting data from various combinations of 224 spectral bands, scientists generate false-color images from AVIRIS, each one depicting different vegetation properties.

Remote sensors flown over Belize register data as specific wavelengths of the electromagnetic spectrum. Compared with existing satellite images from Landsat, AVIRIS provides more continuous coverage over a portion of the spectrum.

DIAGRAM BY DAVID MERRILL

CONCLUSION

The documents and images in this source book capture a brief period in which unprecedented efforts have been undertaken to measure and monitor tropical forests, propelled by an historic conjunction of events. The threat of global warming spawned the U.S. Global Change Research Program which funds the NASA Landsat Pathfinder efforts described in this source book. Fast paced advances in PC-based remote sensing image analysis and GIS software have made image analysis technology widely accessible. Costs of the necessary equipment have dropped from $200,000 in the 1970's to between $8,000 and $13,000 for a PC-based system in the 1990's. Recent methodological advances involving high and low resolution imagery and the use of GIS layers are enhancing image interpretation, vegetation classification, and statistical analysis of forest cover and change. Twenty years after the launch of the first Landsat satellite, the promise of global land cover mapping is now being fulfilled.

The technology-driven information revolution coupled with the broader values now ascribed to tropical forests is generating major changes in the way forest management and monitoring is carried out. Advances in monitoring and information management will challenge forest management institutions operating with much slower, less frequently updated and more closely held information systems. At the same time it is clear that to exploit the full potential of satellite based forest monitoring an extensive ground truthing effort will required involving field plots as well as low level aerial observations. This will entail the active participation of diverse national and local partners, some of whom are being challenged by the new concerns embodied in global forest monitoring.

The implications for USAID are several. First, USAID can use the results of global forest monitoring for its own program planning and impact monitoring. Second, and more importantly, USAID can provide strategically important technical and financial assistance to a range of partners, especially local resource managers. Neither global tropical forest monitoring nor forest ecosystem management can be done without the participation of scientists, managers, and technicians who live in the tropical countries. Field partners in the research, mapping and monitoring of biological diversity as well as forestry must be engaged. Both groups will need more assistance than has been forthcoming to date to be able to both assist in collection of data and apply monitoring results.

The building of in-country capacity to participate in tropical forest and related biodiversity monitoring can constitute an important new program focus in USAID. No other U.S. Government agency has the demonstrated track record or mandate to initiate training and technology transfer programs or to fund and to channel efforts from the U.S. Government, NGO, and private sector partners – all of whom must be enlisted in such a program. For USAID the challenge will be to orchestrate the necessary assistance and work effectively with the multiple actors engaged in the myriad tasks that must be accomplished.

GLOSSARY

AVHRR Advanced Very High Resolution Radiometery. Imagery of 1 km resolution obtained every day for the entire globe.

CEC Commission of European Communities.

CEOS Committee on Earth Observing Satellites.

EDC Eros Data Center. USGS's facility in Sioux Falls, South Dakota for archiving and distributing satellite imagery and other datasets.

EOS The Earth Observing System. One component of NASA's contribution to the U.S. Global Change Research Program. It is comprised of a number of satellites, an information system, and a research program.

EOSAT Earth Observation Satellite Company. Commercial outlet for Landsat imagery, based in Lanham, MD.

EPA U.S. Environmental Protection Agency.

ERS-1 European Resource Satellite. It will have on board a microwave (radar) sensor.

DEM Digital Elevation Model.

FORIS FAO's Forest Information System, a database containing the results of FAO's Forest Resources Assessment, 1990.

FRA1990 FAO's Forest Resources Assessment 1990. A statistical compilation of the forests of the world, started in 1989 and published for the tropical countries in August, 1993.

GAC Global Area Coverage. 4 km resolution AVHRR imagery resampled from 1 km imagery.

GLIS Global Land Information System. A USGS Eros Data Center program for on-screen searching and viewing of available satellite imagery and other global databases.

GPS Global Positioning System. Mobile ground-to-satellite communication systems used to establish location on the ground with accuracy of up to 10 meters.

ICSU International Council of Scientific Unions.

IGBP International Geosphere Biosphere Program. Established by the International Council of Scientific Unions in 1986, IGBP is a series of linked projects to investigate interactions within and between the land, atmosphere and ocean components of the Earth system.

IUFRO International Union of Forestry Research Organizations.

NALC North American Land Cover survey. Undertaken by US EPA, the survey presently extends south to Panama and forms part of the Landsat Pathfinder effort.

NASA National Aeronautics and Space Administration.

MSS Multi-Spectral Scanner. Landsat remote sensor of 80 m resolution.

Pixel Smallest picture element in a satellite image.

SPOT System Pour l'Observation de la Terre. French satellite with sensor of 10-meter resolution.

TM Thematic Mapper. Landsat satellite sensor of 30-meter resolution.

TREES Tropical Ecosystem Environment Observations by Satellite. A CEC-financed forest monitoring project using AVHRR imagery.