Remote Sensing of Tropical Forests: An Overview of Research and Applications Using Non-Photographic Sensors

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ABSTRACT: Remote sensing techniques coupled with geographic information systems and modeling approaches offer an outstanding opportunity to monitor regional ecosystem processes in tropical environments that are undergoing rapid change. This paper provides a comprehensive overview of how remote sensing technology has been applied to tropical forest monitoring over the past 20 years and suggests research needs for monitoring the condition and extent of tropical forest. The discussion focuses on non-photographic sensors, especially those on orbiting satellites. For example, information derived from coarse spatial resolution sensors that have high temporal data acquisition rates (e.g., NOAA AVHRR) are required to accommodate the vast land area included in tropical surveys. Higher resolution sensors (MSS, TM, SPOT, aircraft scanners and mapping cameras) are necessary tools to record the spectral and spatial detail needed to link intensive ecological field studies to the forest community and biome levels. In regions with frequent cloud cover where sensors that operate in the visible and near-infrared have limited utility, active microwave sensors can provide information about the land surface and forest canopy that would otherwise be unobtainable. Additional research and technique development is needed to advance the utility of remotely sensed data for tropical forest monitoring. However, there is sufficient information available to form a basis for implementing a tropical forest monitoring system utilizing sensors currently available on-board orbiting satellites complemented with airborne sensors. Implementation of geographic information systems and multistage inventory techniques for tropical forest assessments are suggested as important components of a global tropical forest information system.

INTRODUCTION

TROPICAL FORESTS ARE BEING CLEARED at perhaps the highest rates in history. Recent estimates are that some 140,000 km^2 to 200,000 km^2 per year (Houghton, 1990; Blasco and Achard, 1990; Myers, 1989) are being cleared for agriculture, timber products, pasture, and land speculation. The detrimental impacts of extensive forests conversion on rural communities, plant diversity, soils, wildlife, watersheds, and ultimately global climatic patterns can not be ignored. The current rates of change may mean nearly complete loss of the extant tropical forests for much of the world over the next few decades. Some countries, formerly rich in forests, now have little or no primary forest left. It seems apparent, given such rapid changes over such large areas, that intensive and detailed investigations of those forests must occur before they are lost. It also seems apparent that clearing and development of the majority of the tropical moist forests will occur unless current trends are dramatically altered. If development is to occur, it should proceed in the most sustainable manner possible with a better understanding of the forest's structure, function, composition, biotic diversity, and current extent. One fundamental set of tools crucial for monitoring tropical forest conditions will be the data provided by remote sensing, the data management capacity of geographical information systems (GIS), and the synergistic capability of this technology for the derivation of new interpretive information through modeling.

Several reports have been compiled to describe the environmental impacts of forest clearing in tropical regions (U.S. Department of State, 1978, 1980; U.S. Congress, 1984; Zerbe *et al.*, 1980; Barney, 1980, 1980; Lanly, 1982; FAO, 1985; World Resources Institute, 1985). However, there are fundamental questions and many uncertainties concerning actual rates and trends of tropical "deforestation," defined by Grainger (1980) as the temporary or permanent removal of forest cover for agricultural or other purposes. Estimates of tropical deforestation rates for the year 1980 differ by more than 100 percent (Brown and Lugo, 1980). Only three studies have estimated areas and rates of tropical deforestation globally (Myers, 1980, FAO, 1981a, 1981b, 1981c; Myers, 1989) and two of those estimates are more than ten years old. The 1981 U.N. Food and Agriculture Organization (FAO) Survey did incorporate some remote sensing interpretations derived from Landsat, radar systems, and aerial photography in an inventory conducted for 52 percent of the tropical forest biome (Lanly, 1982). An updated tropical forest survey by FAO is anticipated in the early 1990s (see Singh, 1990).

There is no standardized system for monitoring global deforestation. Despite the abundance of both low and high resolution remotely sensed data for the tropics, the data have never been assembled and analyzed by any organization despite repeated statements as to the necessity of defining the rates and area of change of the tropical forests globally (Woodwell, 1984; Woodwell *et al.*, 1983, 1987). Remote sensing techniques exist for observing the dynamics of tropical forest cover at almost any level of detail (Baltaxe, 1987).

Currently, international attention is focused on the global environment, and major funding is being secured for research in global climate change and biodiversity. It is likely that remote sensing will play an important role in the new programs. NASA's Earth Observation System (EOS) will offer a new generation of spaceborne sensors for the late 1990s. Commercial sources of satellite remotely sensed data would be guaranteed by continuation of the Landsat program and SPOT-3 and 4 launches by the French, by the Canadian's RADARSAT, and expanded programs by the European Space Agency, the Japanese, and the

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Soviet Union. As these programs develop, remote sensing of tropical forests should receive more attention in future investigations.

OBJECTIVES

The objective of this paper is to provide an overview of how remote sensing technology has been applied to tropical forest monitoring over the past 20 years and to suggest research needs for monitoring the condition and extent of tropical forest. The discussion will focus primarily on nonphotographic sensors, especially those on orbiting satellites. Some airborne systems will also be discussed, because airborne sensors provide a means for testing and validating experimental systems as prototypes for Earth observation sensors on future satellite platforms (Sader, 1987a). Aerial photograph applications, *per se*, will not be included in this review, but the exclusion of air photo applications should not be construed as a statement that photointerpretation techniques are not important for tropical forest monitoring. On the contrary, aerial photos are still the most reliable and operational source of remote sensing data available in most tropical countries. Reviews of air photo applications are provided elsewhere, albeit slightly outdated (Wacharakitti and Miller, 1975; Pettinger, 1978; Lanly, 1982).

REMOTE SENSING APPROACHES TO TROPICAL FOREST MONITORING

Remote sensing techniques coupled with geographic information systems and modeling approaches offer the best opportunity to monitor regional ecosystem processes in tropical environments that are undergoing rapid change. It is unlikely that any one type of sensor could provide all of the data needed to address important ecological processes in tropical regions. To accommodate the vast land area included in tropical surveys requires coarse resolution sensors (to reduce data volume) that have high temporal data acquisition rates (e.g., NOAA AVHRR) in order to increase the probability of acquiring cloud-free data. Higher resolution sensors (MSS, TM, SPOT, aircraft scanners, and mapping cameras) are required to record the spectral and spatial detail needed to link intensive ecological field studies to the forest community and biome levels. In regions with frequent cloud cover where sensors that operate in the visible and near-infrared have limited utility, active microwave sensors can provide information about the land surface and forest canopy structure that would be otherwise unobtainable.

NOAA AVHRR

Six NOAA satellites carrying the Advanced Very High Resolution Radiometer (AVHRR) have been launched into polar orbit. The first, NOAA-6, was launched in June 1979, and the most recent, NOAA-11, was launched in September 1988. The AVHRR acquires digital data in the visible, near-infrared, and thermal regions of the electromagnetic spectrum. The ground resolution of the AVHRR is 1.1 km at nadir. The standard AVHRR product, Global Area Coverage (GAC) data, has a 5- by 3-km resolution and is acquired daily. Data can also be provided in the 1.1- by 1.1-km Local Area Coverage (LAC) format through special arrangement with NOAA. These data are received at various stations around the world, but data collection and archiving practices vary from station to station.

There was little use of AVHRR data for vegetation mapping during the first several years following the launch of NOAA-6 because the resolution of the AVHRR was thought to be too coarse for most applications. However, after some pioneering work by scientists concerned with crop monitoring and global vegetation mapping, the advantages of the AVHRR data for deriving information about vegetation changes became apparent. Foremost among these advantages is the relatively low cost of data acquisition and analysis for the large area coverage as compared with finer resolution sensors. Also, daily coverage increases the probability of acquiring cloud-free data either through a single data set or through compositing data sets over time. Frequent cloud-free coverage offers an opportunity for both early warning monitoring and the analysis of the phenology and seasonal dynamics of vegetation over large areas (Justice *et al.*, 1985; Tucker *et al.*, 1985).

Some user's requirements about the details of vegetation may exceed what is possible with the AVHRR data (even in the LAC format). Therefore, the data are most appropriate for analyzing large areas. For example, Paivinen and Witt (1988) reported that there was approximately 87 percent agreement between AVHRR-LAC and TM data for mapping forest versus non-forest in Southern Ghana. Gervin *et al.* (1985) found that forest classification with AVHRR data was as good as with Landsat MSS data in homogeneous areas, but detection of smaller parcels was unsuccessful because of the coarse resolution of local area coverage (LAC-1 km) AVHRR data. Several AVHRR investigations of tropical deforestation have been conducted in the Brazilian portion of the Amazon Basin (Tucker *et al.*, 1984; Nelson and Holben, 1986; Woodwell et al., 1987; Townshend *et al.*, 1987; Nelson *et al.*, 1987; Malingreau and Tucker, 1988). Some researchers have found AVHHR Band 3 (3.5 to 3.9μm) to be the most useful for detecting forest clearing (Tucker *et al.*, 1984; Malingreau and Tucker, 1988; Malingreau *et al.*, 1989) and fires which are often indicators of recently deforested land (Malingreau *et al.*, 1985; Matson and Holben, 1987). Nelson *et al.* (1987) used AVHRR data to stratify the entire state of Mato Grosso and to serve as the basis for the selection of higher resolution data. Cross (1990) created a large area digital map of deforestation for the majority of the Amazon Basin by classifying and compositing several dates of LAC data.

AVHRR data have been used to examine continental and global scale biophysical parameters. The Normalized Difference Vegetation Index (NDVI) calculated from AVHRR data (ch2 − ch1/ ch2 + ch1) has been shown to be correlated with several ecological parameters including absorbed photosynthetically active radiation (APAR), Leaf Area Index (LAI), Actual Evapotranspiration (AET), and Net Primary Productivity (NPP), allowing these quantities to be monitored at global levels (Goward *et al.*, 1985; 1987; Justice *et al.*, 1985; Tucker and Sellers, 1986; Box *et al.*, 1989). However, according to Box *et al.*, (1989) the worst statistical relationships between NDVI and NPP of various vegetation biomes were reported for tropical forests. Also, annual integration of the AVHRR NDVI did not show a reliable relationship to standing biomass of forests (Box *et al.*, 1989).

In comparison with temperate and boreal forests, the ecological and physical complexity of tropical forest environments places limits on how remotely sensed data may be used to estimate forest parameters. However, due to the distinct advantages of low volume, high temporal frequency data acquisition from the AVHRR and future sensors (e.g., the MODIS sensor of EOS), the data will be indispensable for global vegetation and tropical deforestation monitoring. AVHRR data may also become a vital tool to stratify global and tropical forest lands as the first stage in a nested multistage sample design as suggested by Sader and Joyce (1985) and Woodwell *et al.* (1987). More detailed measurements of forest parameters could be made at second and tertiary stages with higher resolution sensors.

LANDSAT MSS

The Multispectral Scanner (MSS) has been operating on the Landsat satellite platform since 1972. The MSS, carried on all five LANDSAT satellites, was designed to measure reflected energy in four broad bands in the 0.5 to 1.1 μm region of the electromagnetic spectrum with an instantaneous-field-of-view (IFOV) of about 80 metres.

The first satellite data available on a repetitive basis for tropical forests were from the Landsat MSS. Some tropical countries, where national or international remote sensing projects were conducted during the 1970s and early 1980s, received priority status for Landsat data collection (outside the U.S.) and ample coverage may still exist in the archives. Other regions where data acquisition requests were low, or areas where excessive cloud cover was a constant problem, may have little or no archived coverage available from the early years of Landsat (Sader *et al.*, 1985).

During the first several years of Landsat operations, the analysis of MSS data was often conducted through visual interpretations of images (Morain and Klankamsorn, 1978). This technique was used for monitoring the entire Brazilian Amazon Basin by Tardin *et al.* (1980). In recent years, there has been widespread analysis of digital data through a variety of computer-implemented techniques. Evaluations of the accuracy of MSS data classifications were performed, but due to differences in the analysis techniques, forest complexity, and other factors, there was wide variation in the results reported for tropical forests (Baltaxe, 1980).

Investigations of tropical forest species identification and forest inventory using orbital remote sensors have met with limited success. A majority of the tropical forest studies to date have utilized Landsat MSS data. Band 5 (0.6 to 0.7 μm, visible red) and Band 7 (0.8 to 1.1 μm, near-infrared) were considered to be the most useful for tropical forest applications (Boonyoblas *et al.*, 1977; Klankamsorn, 1978). Vegetation differences were enhanced when MSS data (Bands 5 and 7) of both wet and dry seasons were processed (Hernandez *et al.*, 1984). The incorporation of site characteristics and terrain data improved the accuracy of tropical vegetation delineation using Landsat MSS data (Barringer *et al.*, 1980). Prinicpal components and Kauth-Thomas transformations improved the classification of tropical vegetation in Veracruz, Mexico (Giddings *et al.*, 1980). Green *et al.* (1987) discussed the application of MSS data for estimating habitat available for migratory birds in the Yucatan of southern Mexico.

Often, the forest categories that could be identified using Landsat MSS were too general to be of practical value to traditional forest inventory and management programs. However, some successes were reported in detecting deforestation (Williams and Miller, 1979; Pelletier and Sader, 1985) and for identifying important cash crops such as aquaje palm (ONERN, 1977) and coffee (Sader, 1980). Landsat MSS data were considered to be adequate for detecting single-species plantations, particularly when they were four hectares or larger in size (Hernandez and Liang Lee, 1986; Klankamsorn *et al.*, 1985; Chaudhury, 1985a). Stone *et al.* (1989) found that young secondary forests in eastern Amazonia could be delimited with MSS data but doubted that older secondary forests could be defined. Forest strips and riparian zones less than 100 metres wide could not be resolved using Landsat MSS (Sader, 1980). However, Birdsey *et al.* (1984) reported that Landsat MSS and panchromatic air photos gave roughly comparable estimates of forest area for the island of Puerto Rico.

Umali and Argete (1985) found little confusion between forest and open, cultivated areas, but found considerable confusion between forest and brushland in using MSS band 5 and 7 data for a Philippine study site. In Thailand, Vibulsresth *et al.* (1985) were able to separate dry dipterocarp forest into "disturbed" and "undisturbed" categories. They determine that a vegetation index from MSS data was useful for differentiation of vegetation cover density. Chaudhury (1985b) reported that there was spectral confusion between deciduous forest and barren areas during times when leaves were shed.

Landsat MSS data allowed examination of forest change dating back to 1972 for the tropical regions where archival data are available. These older data sets can be co-registered and resampled with recent acquisitions from MSS, TM, or SPOT imagery. Because the cost of MSS data is considerably less than TM or SPOT data, and the spatial resolution is much better than AVHRR, the MSS data can be attractive for change detection studies.

Deforestation estimates of Brazilian Amazonia have been made for 1975, 1976 to 1978, and 1981 (Parada *et al.*, 1981; Woodwell *et al.*, 1987; Tardin *et al.*, 1980; Tardin and daCunha, 1990; Fearnside, 1986; Santos et al., 1979). Landsat MSS data were analyzed to make forest area estimates for the Philippines for 1972, 1974, 1976, and 1980 (Sapitula and Killip, 1985). In Thailand, forest versus nonforest delineations were made for four projects using data from 1972-73, 1975-76, 1978, and 1982 (Chaudhury, 1985b). Singh (1986) compared seven different techniques for automated change detection with band 5 and 7 data acquired over northeastern India. His study showed that the highest accuracy (74.4 percent) was achieved using an image regression method with data from band 5. Image ratioing and image differencing techniques using band 5 data yielded weaker results, but the same techniques with band 7 data showed poor results, apparently due to the high near-infrared return from the herbaceous understory in cleared areas (Singh, 1986). Sader (1988) described a technique for performing tropical forest change detection in a time series using three dates of Landsat imagery (two MSS and one TM) by calculating the NDVI for each date and using a modified parallelepiped classifier and index table to create a multitemporal greenness image. The technique was supplemented with historical aerial photos to estimate forest clearing, regrowth, burning events, and agricultural conversion patterns.

The results reported in these and other studies indicate that Landsat MSS data can be used to detect forest clearing, which removed all or nearly all of the forest canopy vegetation, with sufficient accuracy and at a level of detail that is relevant an useful for national planning (e.g., scales of 1:200,000 or smaller). However, due to shortcomings in spectral and spatial resolution, MSS data have only marginal utility for monitoring forest changes related to partial removal of the canopy, successional changes, or minor canopy alterations caused by insects, disease, and other forms of stress.

LANDSAT THEMATIC MAPPER AND SPOT-1

Investigators have expressed high expectations that Landsat TM data would provide information for monitoring afforestation, canopy alterations, and other forest changes that could not be detected with MSS data (Singh, 1986; Chaudhury, 1985b). These expectations are based on improvements of spatial resolution to 30 m, additional spectral bands, and the improvement of the radiometric quantization level from 63 to 256.

Landsat TM data have been used to inventory plantations and study regeneration in burn areas in Brazil (Vettorazzi and Z. de Couto, 1986; Sampaio et al., 1986; dos Santos and de Medeires, 1986; Bueno *et al.*, 1986; Ponzoni *et al.*, 1986). The Brazilain Space Agency, INPE, now routinely uses TM photoprints to monitor deforestation (Tardin and daCunha, 1990) and have also created a photomosaic of the Brazilian portion of the Amazon Basin.

In the context of a migratory bird habitat study in Costa Rica, Powell *et al.* (1990) and Sader *et al.* (1990) determined that Landsat TM data could identify primary forest (relatively undisturbed forest) with high accuracy. Old secondary forest and disturbed primary forest could not be distinguished from each other, and early successional stages were often confused with second growth forest and regions of mixed crops. Sader *et al.* (1989) reported a poor relationship between tropical forest biomass and the NDVI computed from TM, aircraft Thematic Mapper Simulator (TMS), and Calibrated Airborne Multispectral Scanner (CAMS) data collected in Puerto Rico and Costa Rica. The NDVI did not appear to be a good predictor of stand structure and biomass in broadleaf forests composed of all age classes.

Compared to the amount of investigations that have been conducted in the tropics using AVHRR and MSS data, the published results of investigations that have utilized Landsat TM and SPOT data are relatively few. There has been practically nothing published which discusses the results of tropical forest investigations using SPOT data. Perhaps the lack of published literature relating to TM and SPOT indicates the shorter time that these sensors have been available to investigators. However, there appears to be abundant literature about TM or SPOT investigations in temperate and boreal forests (Heinicke and Justice, 1989, unpublished report). In general, suitable TM and SPOT data coverage for forest change monitoring is still lacking in many tropical regions.

SYNTHETIC APERTURE RADAR

The use of Synthetic Aperture Radar (SAR) for monitoring and analyzing tropical forests is of interest for two primary reasons. First, the microwave region of the spectrum is unaffected by the persistent cloud cover so typical of the humid tropics, and second, there is the possibility of deriving information about forest structure (height, stem diameter and frequency, basal area, canopy roughness, and above-ground biomass) from SAR backscatter measurements.

The first non-military application of radar imagery for tropical forest vegetation was performed with Ka-band data (approx. 9-mm wavelength) collected over the Darien region of Panama in the late 1960s (Visksne *et al.*, 1970; MacDonald, 1969). These data were found to be useful for separating forest from nonforest types and detecting clearings in the forest. Specific forest types could not be distinguished except through inferences based on knowledge of relationships between vegetation and topography or landform, combined with the use of large-scale air photos and local spot photography. However, it is notable that radar data were acquired for 17,000 km^2 during four hours of flight time over a tropical area that had been so continuously covered by clouds that complete air photo coverage was not possible during the previous 20 years.

Subsequent to the Darien, Panama project, the most ambitious collection of imaging radar data over a tropical forest area was the RADAM project in Brazil (DNPM, several dates and volumes). The project acquired data over a large portion of the Amazon Basin with the Goodyear/Aeroservice X-band SLAR system flown at 60,000 feet. In one study site, five of the seven forest types present could be separated from nonforest and placed into one of two groups, but these same grouping were non consistent with groupings for a second study site. Except for areas with rugged terrain, it was possible to identify "shifting cultivation" due to straight-line configurations and abrupt changes in height with respect to surrounding vegetation rather than through tonal difference from other vegetation (Sicco Smit, 1978). Difficulties in distinguishing between secondary forest and shrubs with grass and/or shrubland with trees were also encountered during interpretation of data acquired over Nigeria with the X-band Motorola system (Trevett, 1978).

The effects of standing water under the forest canopy were noted in the analysis of SIR-A data acquired over the Amazon region of Brazil (da Cunha, 1986). Tropical deforestation monitoring using SIR-A and/or SIR-B data has been reported by Stone and Woodwell (1988), Ford and Casey (1988), and Werle (1989). These studies reported some success in identifying land-use patterns and in locating forest clearings. However, great variability was recorded for radar backscatter associated with various condition classes of cleared forest land and subsequent successional stages. Stone and Woodwell (1988) indicated that SIR-A brightness increased nonlinearly with Landsat NDVI. They hypothesized the brightest radar returns were associated with cleared land containing residual trees, felled logs, and stumps that functioned as corner reflectors. Stone *et al.* (1989) used SIR-A and MSS data of eastern Amazonia and found that the area of primary forest could be defined with either the combined SIR-A/Landsat data or with the Landsat or SIR-A data alone. The SIR-A data helped distinguish a greater number of classes within the primary forest. SIR-A imagery has also been used to estimate deforestation in two regions in eastern Amazonia. The results were within 10 percent of the deforested area shown on maps analyzed with a video camera and microcomputer (Stone and Woodwell, 1985).

There have been few investigations of multiband data (various frequencies, polarizations, incidence angles, look directions) over tropical forest areas. One study, outside the tropics, examined four incidence angles (33.0°, 44.7°, 53.7°, and 58.4°) of SIR-B data from four passes over Argentina (Cimino *et al.*, 1985). They found that some vegetation types could be best separated at incidence angles less than 55°, whereas other could be best separated with data acquired at incidence angles greater than 58°. Investigations by Sader (1987b) and Wu (1990) indicate that L-band multipolarization SAR data are poorly correlated with forest biomass and stand structure variables in uneven age broadleaf forests typical of tropical regions. Temperate forest studies suggest that L-band SAR data (especially HV polarization) may be used to predict biomass and structure in pine plantations and other monotypic forest conditions (Riom and LeToan, 1981; Wu, 1986; Sader, 1987b; Hoffer et al., 1986; Lee and Hoffer, 1990).

OTHER AIRBORNE SENSOR RESEARCH

Previous discussion of the AVHRR sensor indicated that some investigators have utilized the thermal waveband to detect burning fires and temperature differences associated with recent forest clearings. Tropical investigations with mulitband thermal sensors such as the Thermal Infrared Multispectral Scanner (TIMS) have been initiated at the NASA-Stennis Space Flight Center. Differences in canopy temperatures, and modeling of thermal energy budgets and evapotranspiration rates, are research topics being investigated with the TIMS (Sader, 1987a; Luvall, 1990; Luvall *et al.*, 1990). Some experiments have been initiated using laser profilers in tropical forests (Arp *et al.*, 1982; Sader, 1987a) but results are too preliminary to comment on the utility of laser data for tree heights or stand structure estimates in these forests.

NASA-Stennis Space Center is engaged in a multi-year archaeology project (co-sponsored by the National Geographic Society) in the Petèn region of Guatemala. Good quality data from the TIMS and CAMS sensors were obtained in April 1990 (A.T. Joyce and T. Sever, NASA-Stennis Space Center, Pers. Comm. 6 Jun 90).

SUGGESTED RESEARCH NEEDS

Considerable attention has been given to defining problems associated with the operational use of remotely sensed data for survey and monitoring tropical forests at national and global levels (Grainger, 1984; Baltaxe, 1980; Woodwell, 1984; Szekielda; 1986). These documents identify crucial factors including the continuity of data, and the cost of data, equipment, and training. If these problems can be overcome, operational programs at the national and global level can proceed with data from sensors presently in orbit. An ambitious coordinated research program is needed.

Remote sensing can make a contribution to improve the information needed to model the exchanges of terrestrial carbon with the atmosphere. Currently, the two largest areas of uncertainty are the biomass of tropical forests and the rate at which they are being cleared. Existing global carbon models that treat biomass accumulation linearly in the early successional stages may not be an accurate depiction in secondary tropical forests where growth can be faster than in temperate zones. More studies are needed to determine the information about tropical forests that is inherent in fine resolution data from Landsat TM and SPOT. The development of analytical techniques for deriving spatial as well as spectral information from fine resolution data through computer-implemented analysis is needed. Some of the subtle spectral changes associated with vegetation stress may not be detectable with broad-band scanners (Rock *et al.*, 1986). Consequently, research with narrow-band imaging spectrometers such as those in the NASA research program leading to HIRIS (High Resolution Imaging Spectrometer), proposed for EOS, is crucial. Research is also needed to determine the utility of thermal data for monitoring biological and physiological processes (Putnam, 1986).

Research into the use of SAR data is justified by cloud cover problems and the potential use of radar data for acquiring information about structure and biomass of tropical forests. However, a better understanding of the radar interaction with forest vegetation (i.e., the penetration, attenuation, and backscattering of radar waves through a forest canopy) is required to determine the utility of radar data for providing information on forest structure. Also, the development of methods for performing topographic correlations to SAR data is necessary to conduct forest vegetation studies in mountainous terrain (Wu and Joyce, 1988).

Additional research to design efficient multisensor and multistage sampling schemes should be given a high priority. This is particularly important now that data from Landsat TM and SPOT sensors are becoming available for tropical areas. Also, on the basis of temperate and boreal forest investigations, there appears to be some potential for using laser profiler data (Nelson *et al.*, 1988; Aldred and Bonner, 1985; MacLean *et al.*, 1986) and video camera data (Mower, 1985) from low-flying aircraft for stand level information in multistage sampling schemes. It is likely that Global Positioning Systems (GPS) will play an important role in tropical forest inventories, especially for establishing ground control in locating field plots and for rectifying remotely sensed imagery in less accessible regions where adequate base maps are lacking (Wilkie, 1989; Welch *et al.*, 1990).

GEOGRAPHIC INFORMATION SYSTEMS

The use of remotely sensed data for forest change monitoring is logically linked to the Geographic Information Systems (GIS) technology. This compatibility goes far beyond the need to maintain information in a geographically referenced format so that data acquired at different dates can be compared. Information on tropical forest soils, topography, climate, and other land features residing in geographically referenced databases can be used to understand the measurements made with remote sensors and provide much more information than can be derived from remotely sensed data alone (Vibulsreth, 1985; Robinson, 1983; Williams and Miller, 1979; Pelletier and Sader, 1985; Green, 1990).

Gwynne *et al.* (1983) stated that the majority of deforestation estimates suffer from lack of quantitative studies into land systems and processes. Such studies are facilitated with a GIS. Sader and Joyce (1988) used a GIS approach to study the relationships between deforestation and various landscape factors in Costa Rica. They showed that deforestation rates and trends were associated with climate and landscape characteristics and discrimnant analysis techniques indicated that access to forest and spatial changes in the transportation system were among the most important variables associated with clearing of tropical forest. This study suggested that historical data analyses could be employed with predictive modeling to estimate the future impacts of development activities (e.g., road construction) on land-use conversion patterns in tropical environments. Mozeto *et al.* (in press) used a GIS to examine the relationship between the potential flooded area from a new hydroelectric dam in Rondonia, Brazil and topography in an adjacent environmental protection area.

Robinson (1983) developed a methodology to evaluate the utility of a Trend Surface Analysis (TSA) model for the reduction of misclassification of shadowed tropical rain forest. He also used the TSA model to show that the spatial modeling of radiance values can provide a useful approach to one of the problems in monitoring tropical rain forest succession. The development of GIS technology has been related to advances in computer technology. Advances in automated digitizing systems have also been necessary for the efficient input of information from existing maps. Although most of the early GIS systems were implemented on mainframe and minicomputers, the use of microcomputers has become increasingly popular within the last several years for use in analyzing tropical areas (Ahearn *et al.*, 1985; Green, 1981). It is anticipated that forest monitoring with remotely sensed data through a GIS approach will eventually become commonplace.

MULTISTAGE AND MULTISENSOR APPROACHES

Although this paper has examined the capabilities of several different sensor systems that have been used for forest monitoring, it is anticipated that an operational tropical forest monitoring system is likely to employ data acquired by two or more sensors in two or more stages. "Multistage" approaches have been used in several different contexts including various sampling designs, nested data analysis, and the use of data from one sensor to provide an adjustment to estimates made with data from a sensor with a larger IFOV. One sampling design uses remotely sensed data acquired in two or more stages in conjunction with variable probability sampling or multistage variable probability sampling (MVPS). The major requirement for increasing precision in MVPS is that a strong linear correlation must be achieved between estimates at each stage. The degree of correlation will be influenced by the design with respect to method of stratification, number of stages, sources of data for each stage, and the number and size of sample units in each stage (Grosenbaugh, 1958). More experience with MVPS is needed for the purpose of formulating an MVPS design that is appropriate for forest change monitoring in the tropics.

Studies using Landsat MSS data in conjunction with aerial photography have been conducted for some tropical forests (Chaudhury, 1985b; Wacharakitti, 1985; Birdsey *et al.*., 1984), but the authors were only able to find one reference to a study in a tropical area in which MVPS methodology was employed. This study was conducted in Brazil to estimate volume in pine and Eucalyptus plantations through a three-stage design using Landsat MSS data, near-infrared aerial photography, and field measurements (Hernandez and Liang Lee, 1986). There has been no use of microwave sensors as a data source for MVPS inventories. However, due to the persistent cloud cover in the tropics, the use of cloud penetrating radar sensors may be a necessary component of tropical forest inventory systems (Larin-Alabi, 1978; Chaudhury, 1985b; Grainger, 1984).

Some research has been conducted to develop other means of using fine and coarse resolution sensors in conjunction for deforestation monitoring. Nelson and Holben (1986) developed a method for using Landsat MSS data to define the AVHRR threshold which most accurately discriminated cleared primary forest areas in Rondonia, Brazil. Another study in the same area used Landsat MSS to provide an adjustment to NOAA-7 AVHRR data covering a larger area (Woodwell *et al.*, 1987).

CONCLUDING COMMENTS

Additional research and technique development is urgently needed to advance the utility of remotely sensed data for tropical forest monitoring. This includes research with data from Landsat, SPOT, AVHRR, TIMS, SAR, and photographic sensors as well as GIS and multistage, multisensor concepts. However, there is sufficient information available now to prototype a global tropical forest monitoring system that would utilize current satellite sensors complemented with airborne sensors for detailed measurements on sample locations. A focused program would provide more standardized data collection and analysis procedures than are currently available from individual investigators working independently. If a tropical forest inventory were to be implemented, it would require international cooperation, as well as technology transfer to developing countries. In order to make the operation possible, it may be necessary to reduce the prices of data and/or necessitate a change in policy with respect to government-furnished data gathering activities.

In the foreseeable future, the tropics will continue to be a biome experiencing rapid development pressure, population growth, and concommitant environmental change. The remote sensing community has the tools, data, and expertise available to assist in monitoring ecological processes and change in one of the Earth's least understood and most diverse biomes.

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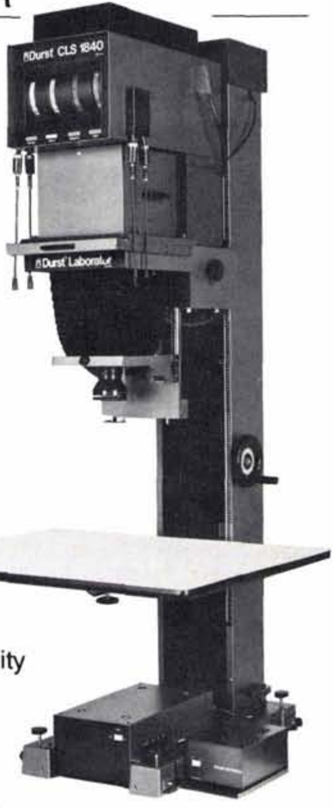

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