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Report of a Workshop on Using Remote Sensing to Estimate Land Use Change

V. H. Dale

ENVIRONMENTAL SCIENCES DIVISION
PUBLICATION NO. 3397

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REPORT OF A WORKSHOP ON USING REMOTE SENSING TO ESTIMATE LAND USE CHANGE

V. H. Dale, Editor

Environmental Sciences Division
Publication No. 3397

Summary of Panel Discussions at a Conference
held at the National Zoo
Washington, D.C.

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ACKNOWLEDGMENTS

I thank all of the participants attending the workshop for their hard work and generous contributions to the accomplishments of the workshop. The willingness of the participants to share ideas and develop a consensus was commendable. The material in this report is a compilation of drafts of material written at the workshop or shortly thereafter.

Several additional people made substantial contributions to the workshop. Diane Wickland first suggested this workshop occur and provided guidance in its organization. Kathy Warren made the workshop arrangements, provided logistical support, and processed mountains of paperwork that allowed the participants to come together. Braulio Jimenez assisted with a variety of activities ranging from reviewing the draft report to making numerous phone calls to participants.

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EXECUTIVE SUMMARY

A workshop, held in Washington, D.C., February 22-24, 1989, assembled leading international researchers to discuss recent research results and to identify short- and long-term research objectives that use remote sensing to improve estimates of the carbon flux to the atmosphere caused by changes in land use.

The first day's technical presentations outlined the latest research findings and approaches. Research summaries included remote sensing studies to estimate changes in land area, amount of biomass burning and its effect on atmospheric CO_2, and areas of human disturbances. Other presentations described the National Center for Geographic Information Analysis (NCGIA) and the Global Resources Information Database (GRID) of the United Nations Environmental Programme. A discussion of those presentations does not appear in the workshop report although some of the ideas for a research strategy are included. Information on the presentations should be obtained directly from the speakers (see list of presentations in the Appendix).

On the second day of the workshop, research strategies to estimate changes in land use that affect the CO_2 flux were discussed. Working groups were formed to concentrate on the specifics of the research strategy, the relation of remote sensing to other research activities, and the collaborative aspects of the remote sensing research. This report presents the findings of the working groups.

The suggested research strategy consists of short- and long-term components. The goal of the short-term research is to assess changes in tropical forest land use. This is an important focus because most of the changes in atmospheric CO_2 from the terrestrial system are being caused by clearing of tropical forests. It was suggested that the Carbon Cycle Program of the U.S. Department of Energy (DOE) focus its resources on tropical Asia because (1) DOE's existing data and modeling efforts focus on this region and (2) there are currently no U.S. efforts to use remote sensing to estimate regional patterns of land use change in Asia. (Efforts for tropical Africa and tropical America are being funded by other agencies.)

Components of the short-term research agenda are discussed in some detail. Two research priorities are identified: (1) to estimate regional tropical deforestation rates and (2) to obtain global vegetation cover distribution. Together, this information will allow calculation of the amount of carbon that is being lost from deforestation of terrestrial systems. Choice of the appropriate classification of forest or nonforest depends on the resolution of the analysis. The need to evaluate spectral and spatial characteristics of tropical forests and land use patterns is emphasized. A multistaged systematic stratified sampling system is called for in underrepresented categories to focus on areas where rates of change in deforestation are high or variable. The need to accommodate data at different spatial resolutions requires that data base management issues be thoroughly considered from the outset of the research. Special considerations for using remote sensing to estimate land use changes in tropical Asia are presented.

The long-term research agenda focuses on global estimates of CO_2 flux. Remote sensing can be used to reduce current uncertainties in the flux by its ability to provide up-to-date spatially comprehensive data sets. In addition, remotely sensed data can be used to increase the number of intensive study areas, refine the sampling methodology, refine the forest classification, integrate with geographic information system (GIS) capabilities, improve the historical data base, and contribute to carbon models.

Remote sensing data are viewed as one tool in a larger arena of research. Therefore, the remote sensing research should be related to historical analysis of land use change, contemporary surveys of deforestation, geographical patterning of land use change, and modeling.

Finally, the collaborative aspects of performing global remote sensing studies are emphasized. The scope of the problem of estimating global CO_2 flux dictates that the research involve collaborations between countries, agencies, and a geographically distributed scientific community.

1. INTRODUCTION

The greenhouse effect is one of the most pressing environmental problems of our day. Research results predict that the greenhouse effect will cause climatic warming and will have severe ecological and economic impacts, including a rise in sea level, altered patterns of agricultural and forest productivity, and a change in the diversity and distribution of unmanaged ecosystems.

The concept of the greenhouse effect arises from a view of the earth as surrounded by a glass house made of CO_2 and other gases. These gases allow visible solar radiation to pass through the atmosphere and warm the Earth but do not permit thermal infrared radiation emitted by the Earth to leave the atmosphere. The concentration of the gases that form the greenhouse determines the amount of heat that leaves Earth and, thus, the amount of warming that occurs in the atmosphere.

1.1 IMPORTANCE OF TERRESTRIAL SYSTEMS

Changes in the amount of carbon stored in terrestrial ecosystems are, in part, responsible for the increase in atmospheric CO_2 concentrations that have occurred since about 1750 (Bacastow and Keeling 1981, Gammon et al. 1985). In 1980, the net annual flux of carbon from terrestrial ecosystems to the atmosphere from land use change is estimated to fall within the range of 0.4 to 2.6 Pg C (1 Pg = 10^{15} g), and almost all this carbon flux originates in the tropics (Houghton et al. 1987, Detwiler and Hall 1988, Melillo et al. 1988). The annual flux due to fossil fuel emissions has been estimated to be between 5.0 and 5.5 Pg C since 1980 (Rotty 1987). As such, the contribution of carbon to the atmosphere from terrestrial ecosystems is between 10% and 50% of the flux due to fossil fuel emissions. If 10% is correct, then the estimate is probably within the aggregate bounds of the error associated with models of the global carbon cycle. However, since we cannot rule out the upper range with current information, it is important to continue research to estimate the carbon flux from terrestrial ecosystems.

The most important changes in the amount of carbon held on land are caused by shifts in forest mass that result from land clearing or other changes in land use (Houghton et al. 1983). This is because forests contain about 90% of the carbon in terrestrial vegetation, and they are being cleared at very high rates. The biogeochemistry of CO_2 in terrestrial ecosystems depends largely on the distribution of forest biomass and on factors affecting its increase or decrease.

Currently, the net flux of carbon from terrestrial ecosystems to the atmosphere is primarily from the large-scale clearing of tropical forests (Houghton et al. 1987). The tropics comprise >30% of the land surface of the earth, and about 42% of this area is forested. There has been a sharp increase in the amount of carbon released from tropical areas in recent decades (Figure 1), primarily because of deforestation. Between 0.4 and 2.5 Pg C/year are estimated to have been lost from the terrestrial surface as a result of recent changes in land use in the tropics (Houghton et al. 1987, Detwiler and Hall 1988).

1.2 HIGH CERTAINTIES IN ESTIMATES

The considerable uncertainty involved in estimating the current biotic flux must be reduced to determine whether or not land use change is a major contributor to changes in atmospheric CO_2. The variance in the estimated net annual flux of carbon to the atmosphere from land clearing has decreased over the past decade with more intensive research (Figure 2). Early estimates ranged from 2 to 22 Pg C (Woodwell and Houghton 1977); the current estimate of the net annual flux is 0.4 to 2.5 Pg C/year (Houghton et al. 1987, Detwiler and Hall 1988). The decrease in the estimated releases is attributed largely to improvements in the information from which the estimates are calculated. The wide range in current estimates of the CO_2 flux from terrestrial systems results from uncertainties in standing stocks of carbon in unmanaged ecosystems, rates of land clearing and abandonment, rates of biomass recovery after disturbance, and changes in the carbon pools as a result of disturbance (Dale and Houghton, in press).

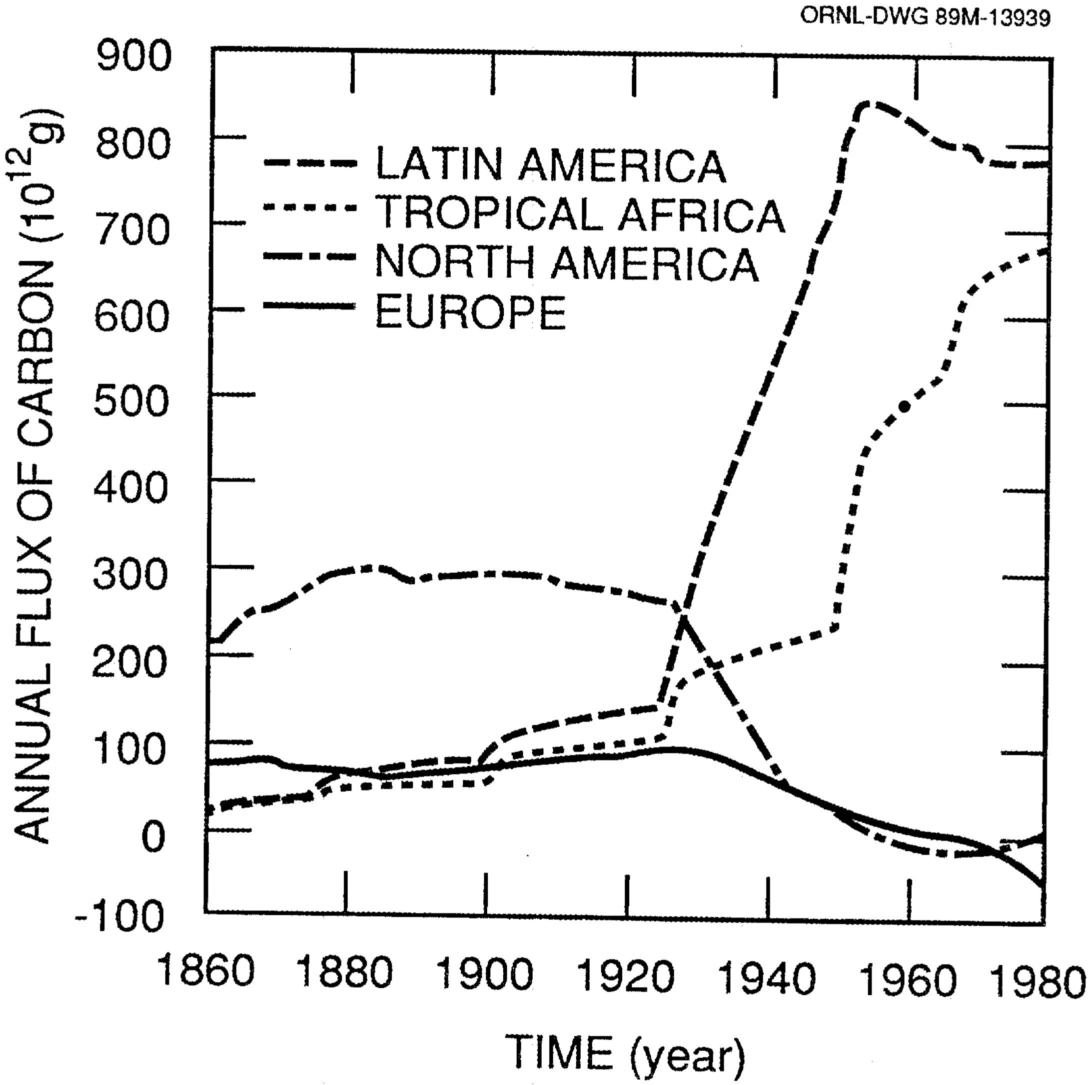

Figure 1. CO_2 flux from different regions (based on Houghton et al. 1983).

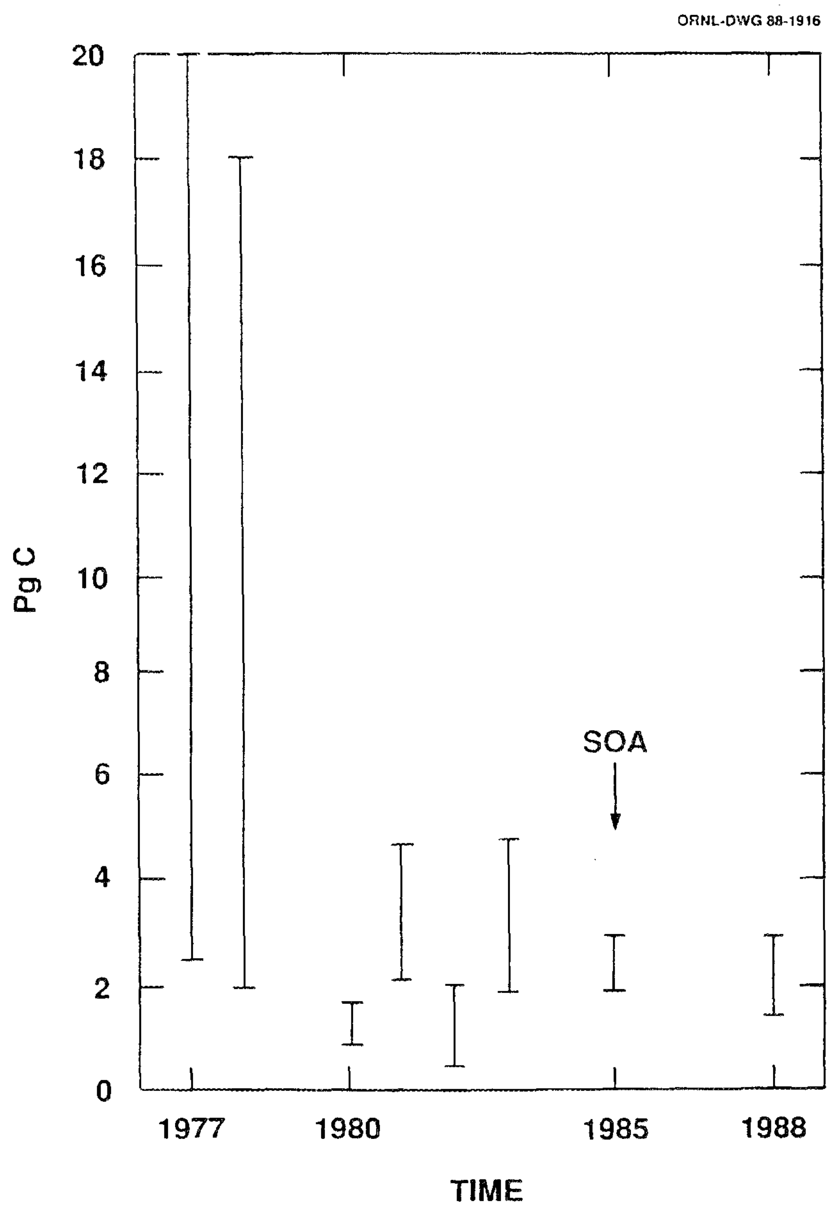

Figure 2. The change in the estimated net annual flux of carbon to the atmosphere from terrestrial ecosystems due to research activities over the past decades (from Dale and Houghton, in press). The estimates, from left to right, are from Woodwell and Houghton (1977), Woodwell et al. (1978), Chan et al. (1980), Moore et al. (1981), Olson (1982), Houghton et al. (1983), Trabalka (1985) [referred to as the State of the Art (SOA) series], and a combination of the studies of Houghton et al. (1987) and Detwiler and Hall (1988).

A major thrust of the terrestrial part of the DOE carbon cycle research in the next few years will be to reduce uncertainties in the flux of carbon between terrestrial ecosystems and the atmosphere. Only when the flux from terrestrial systems is better known will the concentration of atmospheric CO_2 be predictable by using alternative scenarios of fossil fuel use. Validation of the predicted flux of carbon from terrestrial ecosystems can be performed by evaluating the data that go into models used to make predictions and by checking projections from the models. Quantifying rates and effects of conversion of forests to shifting and permanent agriculture and other land uses (e.g., cattle ranching, mining) in tropical ecosystems should be a major focus for reducing uncertainties in rates of land clearing and abandonment.

1.3 VALUE OF REMOTE SENSING DATA

Remote sensing data can be useful in checking projections of atmospheric flux due to land use change from carbon cycle models because they provide an independent, relatively quick, and spatially disaggregated estimate of the amount of clearing that is occurring in tropical forests and other ecosystems. Estimating rates of tropical deforestation with traditional, ground-based measurements is difficult because there is little ground information, the areas within which the change is occurring are very large, the changes are occurring rapidly, and information is not readily accessible. Currently, the ground-based estimates of the biotic release of carbon have to be calculated from 1980 or earlier data because the most recent estimates of deforestation for all the tropics by these methods are for 1980 (FAO/UNEP 1981a, 1981b, 1981c). However, the estimated deforestation of Rondonia, Brazil, has increased greatly since 1980 (Figure 3). If the amount of deforestation has more than doubled in less than a decade, the areas being deforested must be estimated more frequently in order to obtain an accurate projection of the biotic flux of carbon. Remote sensing data must become an integral part of the estimate of biotic flux. In essence, satellite remote sensing offers the scientific community a

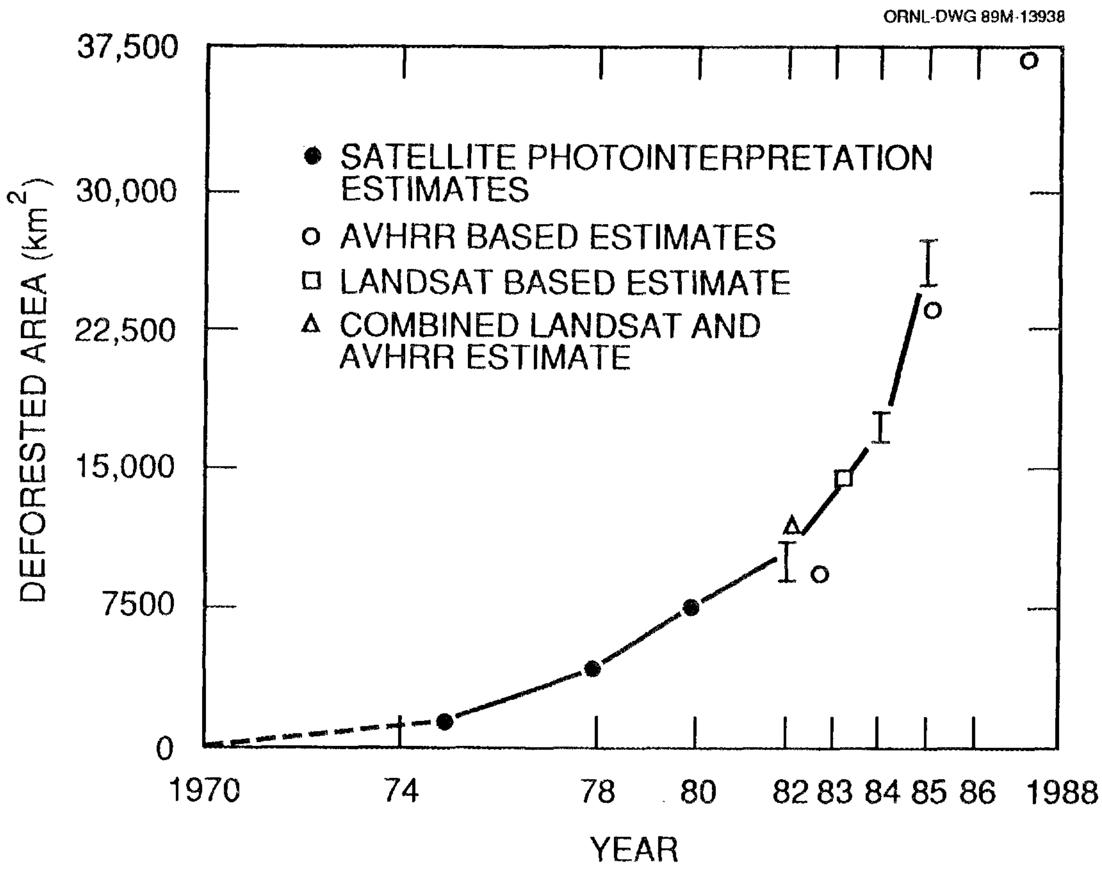

Figure 3. Deforestation in Rondonia, Brazil, from 1970 to 1987 showing the rapid increase in clearing since 1980. The 1970, 1975, and 1980 ground-based data are from Tardin et al. (1980). The 1983 estimate is based on Landsat data (Fearnside 1986). The 1982, 1984, and 1985 estimates are from AVHRR data (Malingreau and Tucker 1988) and include an error estimate of $\pm$ 1000 km^2 based on ground checking the 1985 estimate. The triangular 1982 estimate is from Woodwell et al. (1987). The 1987 estimate is from AVHRR data (Stone et al. submitted).

globally consistent base of data from which the spatial dimensions and temporal fluxes of phenomena such as land cover change can be made within some accepted accuracy limit (Tuyahov et al. 1989).

1.4 WORKSHOP OBJECTIVE

The workshop objective was to formulate a short- and long-term research strategy to estimate changes in land use patterns by using remote sensing. Meeting the objective required that the participants review the current state of a number of issues related to remote sensing and evaluate appropriate sensor systems (considering spatial resolution, frequency of coverage, availability of data, and spectral properties). After some discussion, specific short- and long-term goals were agreed upon. The short-term goal was to estimate land use changes for tropical forests. It was noted that DOE may best promote this goal by focusing on tropical Asia because other research efforts are already under way to use remote sensing to estimate deforestation in tropical America (e.g., Malingreau and Tucker 1988, Woodwell et al. 1987) and because DOE's existing data and modeling efforts are for tropical Asia. The long-term goal was to estimate global changes in land use that cause significant changes in atmospheric CO_2.

2. REVIEW OF CURRENT RESEARCH USING REMOTE SENSING TO ESTIMATE LAND USE CHANGE AND CO_2 FLUX

Efforts to estimate land use change and CO_2 flux with remotely sensed imagery have been partially determined by available technology. Therefore, we review the current status of remotely sensed imagery, present an ideal system, and list the advantages and disadvantages of using remote imagery before recent research results are discussed.

2.1 OVERVIEW OF REMOTE SENSING APPROACH

Remote sensing is an outgrowth of aerial photographic interpretation. The term remote sensing was coined in the late 1950s to cover a new type of image data which was beginning to be acquired. These data represented the spectral response of objects and phenomena beyond the limits of the visible parts of the electromagnetic spectrum. These data from both aircraft and spacecraft have been applied to many types of environmental analysis (Sabins 1986). The combinations of sensors and platform characteristics form the spectral, spatial, and temporal resolution of the data acquired. These characteristics are critical as we attempt to employ remote sensing for the study of land use change.

The approach to the application of remotely sensed data to land cover mapping recommended in this report involves a statistical sampling approach in which data from a number of sensor systems are processed to obtain estimates of land use classes; these classes are then aggregated to provide areawide statistics as described below.

2.1.1 Spatial and Spectral Resolution

The means of deducing global land use changes from satellite observations involve the use of sensor systems with different spatial resolutions (Figure 4). The polar-orbiting satellites in the National Oceanic and Atmospheric Administration (NOAA) series of meteorological satellites (Advanced Very High Resolution Radiometer, AVHRR) provide data of two resolutions. Global data of the terrestrial surface is available at a coarse spatial resolution of 4 km [called global area coverage (GAC) data]. These data have been collected daily since July

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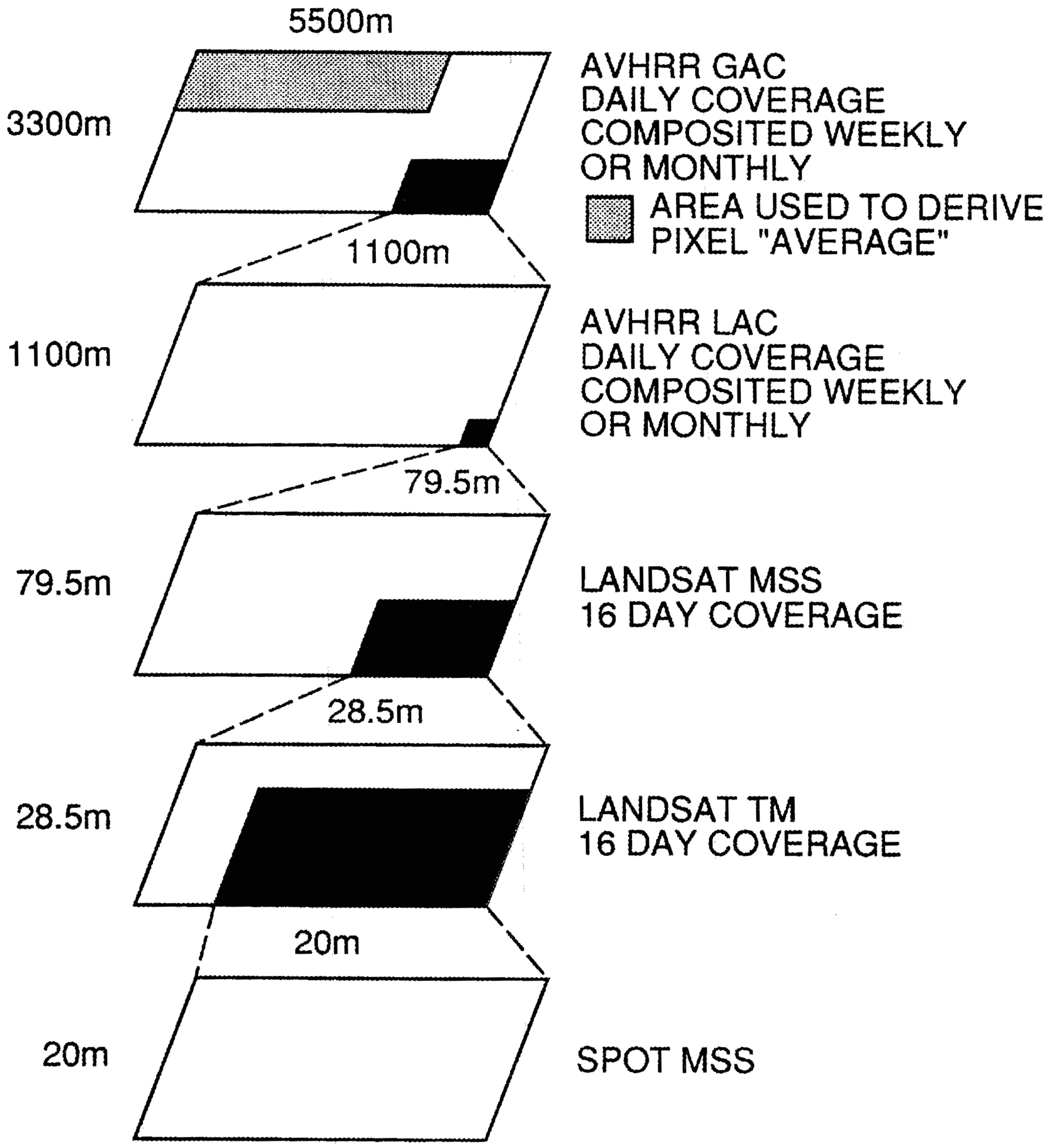

Figure 4. Approximate representations of spatial resolution differences between satellite-borne radiometers.

1981 and will continue to be acquired at least into the middle 1990s (Table 1). The AVHRR sensors also can provide 1.1-km spatial resolution [referred to as local area coverage (LAC) data]. These LAC data have historically existed only for selected areas. Recent studies have shown that large-scale phenomena can be studied with 1.1-km and 4-km satellite data, depending upon the scale of the process(es) under study and the level and land cover class discrimination required (Tucker et al. 1985). The AVHRR sensor on the NOAA satellites has provided the multiyear regional, continental, and global data needed for these studies.

Landsat Thematic Mapper (TM) (30-m resolution) and multispectral scanner (MSS) (80-m resolution) provide higher resolution data which can be acquired in selected areas to provide the means to (1) verify ground-satellite agreement and (2) better understand the spatial patterns which are aggregated in the 1.1-km and 4-km data. The 30-m and 80-m resolution Landsat data can be particularly useful in areas where deforestation is of a fine scale, fragmented, or sporadic. Such is the case in areas of shifting cultivation and small farms. If such areas can be adequately identified by coarse-resolution monitoring, then the fine-resolution data can be used to subsample those areas.

In addition to the different spatial scales at which data are acquired, each sensor system provides different spectral coverages. The NOAA AVHRR provides very broadband spectral coverage with three spectral channels in both the reflected radiation and emissive (thermal) portion of the spectrum. AVHRR has the spectral range to calculate vegetation indices and to detect thermal variations associated with surface changes and fires. The Landsat MSS provides reflectance data only in four broad spectral channels in the 0.5-0.90 ηm spectral region. The Landsat TM provides both reflected and thermal data in seven narrower spectral channels, covering the 0.4-2.5 ηm and the 8.0-12.0 ηm regions of the spectrum. The French SPOT satellite provides a single 10-m panchromatic band in the visible region and two bands (red and near infrared) in the 0.6-0.9 μm region of the spectrum.

Table 1. Source, resolution, frequency, area, and channels of AVHRR data.

		Repeat	Area		
	Source	Resolution	Period	Covered	Channel
LAC	NOAA REQUEST	1.1 KM	~DAILY	SELECTED	ALL
HRPT	LOCAL STATION	1.1 KM	~DAILY	IN RANGE	ALL
GAC	NOAA	4 KM	DAILY	WORLD	ALL
GVI	NOAA	15 KM	WEEKLY	WORLD	NDVI

As can be seen in Figure 5, different vegetation canopy components influence different spectral regions. Thus SPOT data may be used to assess pigment conditions (in the red region) and biomass and cellular condition (in the near infrared), while the TM provides additional spectral coverage of both pigment-dominated reflectance in the blue and green, as well as water content -- dominated reflectance (TM bands 5 and 7) not available in SPOT data. Since CO_2 flux is influenced both by vigor and health as well as by amount and type of vegetation, the additional spectral coverage provided by the TM has proved to be of considerable value in certain studies of land use and land conditions (Rock et al. 1986, 1988c, Vogelmann and Rock 1988).

2.1.2 Ideal Approach to Using Remote Sensing Data

Workshop participants discussed an "ideal system" for vegetation land cover mapping. The discussion was directed toward defining an ideal approach to using remote sensing data for the analysis of land use change--especially in the tropics. Twelve characteristics were identified. (1) Such an approach would allow identification of an area of forest by location. Geographic specificity would allow comparisons of the remotely sensed estimates of forest area with other estimates [e.g., the 1980 or 1990 Food and Agriculture Organization (FAO) assessment]. (2) It would identify the rate of forest clearing or regrowth. This process would require that forest maps be produced at two or more time intervals and subsequently compared. (3) Such a method would be amenable to ground reference checking, perhaps through the use of several test sites located throughout the tropics. This checking would require some high spatial resolution data and some level of international cooperation. (4) The system would have the capacity to store this information in a manner that would be easily updated by either remotely sensed or other types of ancillary data and would require some form of geographic information system (GIS). (5) It would provide the data to modelers in a form most easily used, requiring conversion of the estimates of the area cleared and the rates of clearing into ecological measures such as biomass or forest type units. (6) The system would be based on data that is easily acquired, in a standard format, and has both a history and a future. In other words,

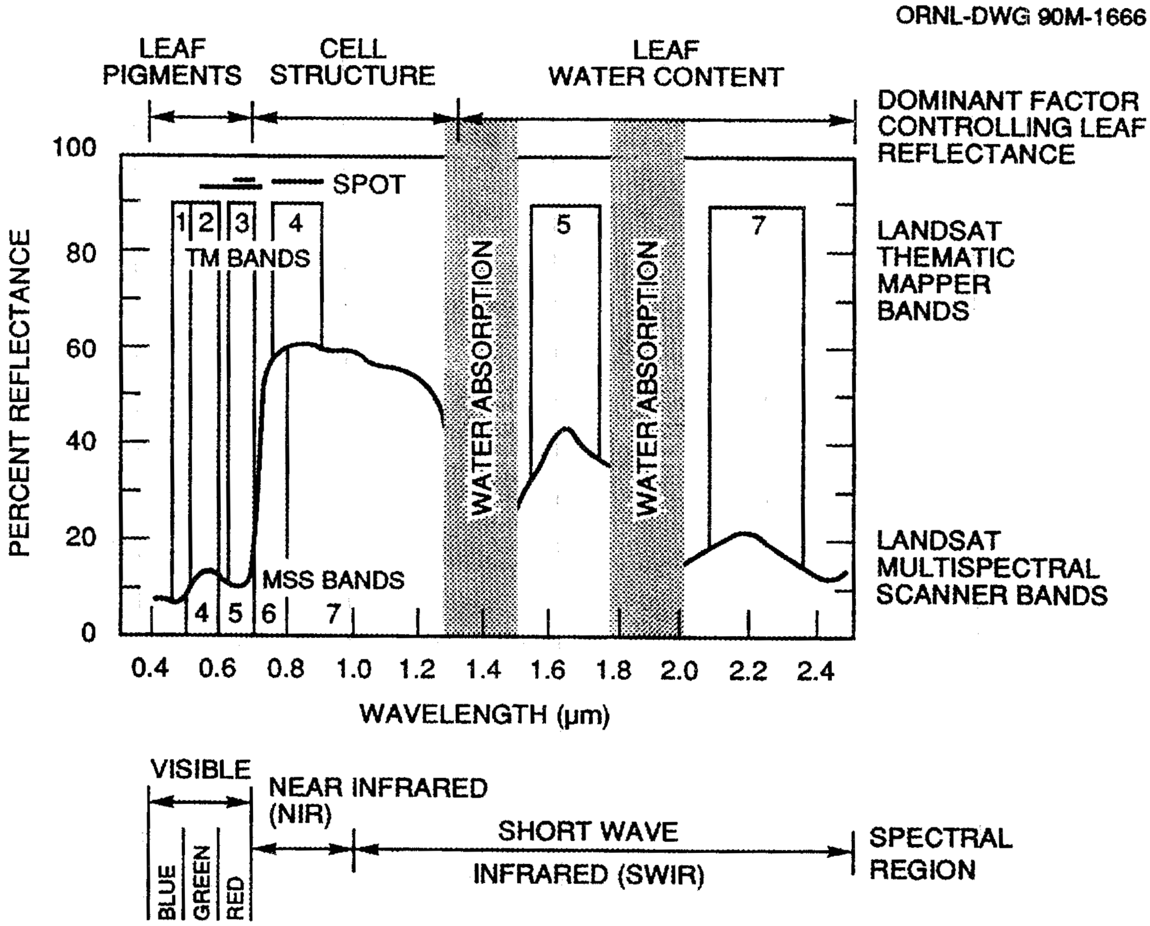

Figure 5. Vegetation reflectance curve.

we should expect this data source to be around for a while. The standard systems are now Landsat MSS and TM and SPOT for high spatial resolution and AVHRR for low spatial resolution. (7) Extended spectral coverage is important because it can be coupled with various levels of spatial resolution to assess both amount and vigor of vegetation, an important aspect of land use evaluation. (8) The data should be able to be easily scaled up. Such scaling up requires a method of converting higher-resolution data into the equivalent of 1.1-km and/or 4-km data after coregistration. (9) It should be able to define repetitiously the same area. This requires that the location of the image be identified using a standard geo-referencing system [e.g., Universal Transverse Mercator (UTM), latitude-longitude, etc.]. Then, standard, widely distributed, and accepted algorithms for classification or change detection should be applied to two or more scenes from the same area. (10) The thematic data should be available at least seasonally (which requires that the raw data be available on a daily basis so that cloud cover can be avoided). (11) Global coverage should be possible with the ability to focus on active change areas. (12) The data should be inexpensive to acquire, store, and analyze so that no research group or agency should be denied access simply because of cost. Some of these characteristics are obviously self-exclusive; synergy between instruments and approaches will have to be sought.

2.1.3 Advantages and Disadvantages of Remote Sensing Approach

The strengths of the satellite remote sensing approach are that it provides (1) unbiased data (which may, at times, be difficult to interpret), (2) the possibility of high positional accuracy at the hectare level, (3) high temporal frequency accuracy, (4) ease of incorporation within a broader GIS approach to land use analysis, (5) extended spectral coverage that allows detection of vegetation features not seen by the human eye, and (6) a base for checking other types of data (i.e., FAO 1983, Myers 1980). Comparisons are, however, difficult because of classification incompatibilities.

The problems in using remote imagery are that (1) data gaps exist--particularly for high-resolution data; (2) clouds, smoke and the atmospheric conditions may contaminate the image; (3) the earliest satellite data are from 1972, and a portion of that material has already been discarded (Marshall 1989); (4) high-resolution data is expensive; (5) processing the data requires a large investment in computers and image processing equipment and software; (6) direct information on forest biomass cannot be obtained by using remote sensing; and (7) the availability of future MSS/TM data sets for monitoring purposes is questionable. Even with these problems, remote imagery is useful because it offers broad-scale data and total global coverage that are not available from any other source. This potential highlights the need for an international acquisition program including receiving stations around the globe.

2.2 APPLYING REMOTE SENSING TO FOREST ECOSYSTEMS

Applications of satellite remote sensing to forested ecosystems have been recently reviewed by Iverson et al. (in press) -- the following discussion is based on that paper. Recent applications of remote sensing to forests have reached a high degree of sophistication because of (1) the use of higher spectral and/or spatial resolution sensor systems, (2) improvements in hardware and software systems designed to process spatially referenced digital data, and (3) the increased availability, standardization, and compatibility of other spatially referenced digital data sets.

Using remote sensing data to classify forest types is subjective. Classification accuracies are improved by using a GIS to integrate digital biogeographical data with satellite imagery. Maps of forest type have been generated with satellite data at a variety of spatial resolutions. Forest type classifications established with the use of AVHRR data are useful primarily for maps of large areas. These maps can then be verified by using a sampling approach with higher-resolution images or map data. For example, Townshend et al. (1987) used multitemporal AVHRR data to produce a vegetation map of South America that differentiated 16 vegetation classes, several with accuracy greater than 90%.

2.3 USING REMOTE SENSING TO DETECT CHANGES IN FOREST AREA

The basic procedure for detecting change in forest cover is to compare two or more satellite images of the same area which have been acquired at different times (preferably during the same season). For example, Sader and Joyce (1988) compared digitized air photo interpretation maps of Costa Rican forest area for 1940, 1950, and 1961 with MSS-derived forest cover maps for 1977 and 1983 and found that the forest cover had decreased from 67% to 17% of the country, with the greatest change occurring between 1977 and 1983. Studies of deforestation in Rondonia, Brazil, using AVHRR band 3 thermal data indicate that the deforested area has increased from 4,200 km^2 in 1978, to 10,000 km^2 in 1982, to 27,000 km^2 in 1985 (Malingreau and Tucker 1987), to 37,200 km^2 in 1987 (Stone et al. in press). Combining AVHRR data with selected MSS scenes of smaller areas of Rondonia corroborates the doubling of deforestation rates between the 1976-1978 and the 1978-81 intervals (Woodwell et al. 1987). Westman et al. (in press) have used Landsat MSS to detect forest change in tropical rain forests of Uganda.

2.4 USING REMOTE SENSING TO ESTIMATE CO_2 FLUX

Recent developments in the study of fires by using AVHRR thermal data have shown the possibility of measuring gaseous emissions from biomass burning (Kaufman et al. 1988). For example, Setzer and Pereira (in press) estimates that 0.5×10^{15} g C/year were released by forest biomass burning in 1987 in Brazil.

Woodwell et al. (1983) evaluated three methods of using Landsat data to improve estimates of carbon flux due to deforestation: an inventory based on a single scene, a comparison of inventories from two scenes from different times, and a change detection approach that uses two scenes from different times. The change detection method gave the most accurate estimate of deforestation that was used to estimate CO_2 flux.

High spectral resolution remote sensing data may be useful in assessing photosynthetic capacity of vegetation (i.e., total chlorophyll levels, chlorophyll a/b ratios), given adequate spectral resolution

(Rock et al. 1988a, 1988b). Because variation in photosynthetic capacity within and between species will influence CO_2 uptake, CO_2-flux limited high spectral resolution for remote assessment of subsets within larger AVHRR pixels may provide valuable input for CO_2-flux modeling efforts.

3. RESEARCH STRATEGY FOR ESTIMATING LAND USE CHANGE AND CO_2 FLUX BY USING REMOTE SENSING DATA

Estimating land use change and its effects on atmospheric CO_2 concentration is a complex process requiring both a short- and long-term research strategy. Over the long term (10 years), emphasis should be on a global estimate of carbon flux from terrestrial systems to the atmosphere. In the short term, information is needed on the carbon flux from the tropical forests. This information is important because forested ares in the tropics are experiencing the most rapid land use changes and contain high levels of carbon. Given the enormity of the task of monitoring the entire tropical biome as well as the currently available funds, work accomplished to date has developed piecemeal by region.

3.1 SHORT-TERM RESEARCH AGENDA

The research strategy is defined by the research priorities, the choice of forest versus nonforest as an initial classification of land use, the spectral properties of tropical forests, the specifics of monitoring for tropical Asia, the sampling procedures, and the database requirements.

3.1.1 Research Priorities

Two priorities were identified as immediately important and achievable: (1) estimation of regional tropical deforestation rates and (2) global land cover vegetation distributions. Suggested approaches were developed for each priority.

Regional deforestation monitoring requires a multilevel approach. AVHRR 1.1-km resolution data can provide the first level. Higher spatial resolution satellite data (TM, MSS, SPOT etc.) would be selectively sampled to provide calibration of the AVHRR data. The initial phase of such a study would distinguish between forest and nonforest land use. Multiyear analyses would then permit annual estimation of land use change.

Currently, efforts are under way in selected areas of the tropics for determining rates and extent of tropical deforestation or forest alteration (Malingreau 1984, Woodwell et al. 1987, Nelson et al. 1987, Malingreau and Tucker 1988, FAO 1983, Stone et al. in press). However, these efforts are not adequately funded, are not coordinated, and employ a variety of techniques. Research is under way in the Amazon Basin of South America, Central America, West Africa, Central Africa, East Africa, Queensland, and Madagascar.

The experts assembled at the workshop recommended that DOE focus its research effort on forests of tropical Asia. Criteria for selecting this geographic region for the DOE-funded effort are as follows: (1) the region is important to the global carbon cycle, (2) a regional approach could build upon DOE's existing studies of land use change in tropical Asia, (3) general methodologies are independent of the region of focus, and (4) a new research program for tropical Asia would complement other efforts in tropical America and Africa.

The second goal of improved estimates of the distribution of global land cover vegetation can be achieved by using 4-km AVHRR data to broadly map vegetation types. This approach would use the temporal and seasonal characteristics of the vegetation as the basis for classification (Tucker et al. 1985, Townshend and Justice 1986, Townshend et al. 1987, Goward et al. 1985). It would also integrate these classifications with other data bases such as maps of life zones and bioclimatic indices to give more detailed resolutions for use with the biomass data. Data sets are currently available for such a classification, but the work is not being funded by any national or international agency. This approach could provide the vegetation type on a global basis as well as the means for determining seasonal characteristics of vegetation; however, the method would not be suitable for detecting spatial change. The map of vegetation type can be used with estimates of biomass by vegetation type derived from ancillary data (e.g., Brown and Lugo 1984) to produce a map of biomass distribution by vegetation type. Research is currently under way to estimate regional net primary production (NPP) of forests directly from AVHRR data (Goward et al. 1985, Townshend et al. 1987). Estimates of biomass of wetland areas have been acquired from remotely sensed data (e.g., Hardisky et al. 1984). A global biomass map would provide (1) an estimate of carbon distribution (carbon content is correlated with biomass) and (2) a basis for extrapolation to predict deforestation by using land use conversion models. DOE should encourage other agencies to support this work.

3.1.2 Classification of Land Use From Remote Sensing Data

The distinction between forest and nonforest is the most important land use consideration to be defined by remote sensing because the conversion between these two land use types represents the major source of CO_2 to the atmosphere from the terrestrial biota. Furthermore, this land use division is compatible with the present status of the processing capabilities associated with remote sensing data available for global-scale studies of deforestation. Overall, the accuracy of using a forest or nonforest classification would be sufficient for initial carbon flux estimation for current models. (Note, however, our later discussion of degraded forests.) Using a series of analytical techniques, it is possible to derive forest/nonforest information at the global scale within a reasonable time frame and at reasonable cost using primarily 4-km AVHRR GAC data. Once a cloud-free data set has been acquired and processed by compositing two or more data sets, these data can be used to derive information that characterizes each data cell as forested or nonforested (related to some land use other than forest) by relatively simple techniques. These techniques are based on the spectral difference between forest vegetation and other land uses. The accuracy of this distinction will depend on the season, the state of the land surface interfacing with the forest, and the land use pattern. By using 4-km AVHRR data that either exist or are being acquired, the forest/nonforest information can be derived at a reasonable cost, considering both purchase and processing costs. Data acquisition, even if "yet-to-be acquired," and processing could be accomplished within a year for any given region (e.g., tropical Asia). The AVHRR GAC data needed for the analysis are currently available for the Earth's entire tropical zone. AVHRR GAC data will also be acquired from a series of satellites that are already planned to operate through the middle 1990s.

The rate of change from forest to other land uses could be determined for a given area as soon as two sets of data encompassing a sufficient time lag are processed and compared. It is possible to acquire and process AVHRR LAC (1.1-km resolution) within a reasonable time frame to obtain the rate of change between forest and nonforest for selected areas. AVHRR LAC data must be acquired through special arrangements with NOAA or the particular regional receiving station if that station is "other than a NOAA station". However, it is reasonable that such data could be acquired and processed for all of the Earth's tropical regions within 5 years or less if a good data set is made. The procedures used to derive the forest/nonforest information are relatively simple and resemble those used to derive similar information from GAC data.

The forest/nonforest classification level is compatible with integrating AVHRR data with finer-resolution remotely sensed data (e.g., Landsat MSS and TM, SPOT). Information derived in determining the forest-versus-nonforest classification and in examining forest change from AVHRR LAC or GAC data would constitute a means of stratification whereby strata could be defined in a geographical sense. Finer-resolution satellite data or aerial photography of limited areas could be acquired to derive information for each AVHRR stratum. This process would assess only those geographic areas constituting significant change. More accurate forest-versus-nonforest data could be derived for the entire area within strata with significant change, or these strata could be sampled through a technique in which an appropriate part of the area is covered by the finer-resolution data. Furthermore, the inclusion of data indicating the percent forest within a given pixel would greatly enhance the accuracy of land use change estimates since this would allow a more precise definition of the terms forest and nonforest.

The simple classification system proposed herein may be sufficient because more refined land use divisions to meet the needs of carbon modelers may be obtained by integrating remote sensing data via GIS with other global data bases already available (e.g. soils, life zones, topography and fine-resolution remote sensing data). As fine resolution remote sensing data become available, further subdivisions of the forest category should be attempted to reflect more accurately differences in standing biomass among forest areas as a result of disturbance.

A key component and source of uncertainty in terrestrial carbon models is the magnitude of the biomass of the forest being converted. Disturbed forests contain less biomass than primary forests. This fact needs to be reflected in CO_2 flux calculations. The distinction of forest types based on degree of disturbance and, hence standing biomass is available for a few areas (Stone and Woodwell 1988; Westman et al., in press). The ability to distinguish between forests of different levels of disturbance would greatly improve the accuracy of results from current terrestrial carbon models. At a minimum, this further division should include the following forest categories: undisturbed, highly disturbed, and moderately disturbed. This topic should serve as the basis for a longer-term research project and should be done in cooperation with forest biomass projects.

Biomass burning is common in the process of tropical deforestation. Forest burning is usually associated with land-clearing activities for agricultural expansion. Fires associated with forest clearing represent a direct phase transformation which injects terrestrial organic matter into the atmosphere. Fire patterns connote human activity, and spatial distribution of fires defines those areas undergoing major changes in land use. Changing patterns of burning can indicate changing relationships between vegetation, climate, and humans (e.g., feedbacks), and the effects of fire can be gradual, repetitive or catastrophic. Fire detection is implicit in the current methodology of AVHRR deforestation monitoring; indeed the thermal data derived from that instrument can reveal the presence of active fires during a satellite overpass. Such data can be used to identify active deforestation fronts, to characterize their pattern, and to assess the magnitude of disturbance. Research issues still pending relate to these areas:

1. spatial and temporal sampling of fires by using the AVHRR data,

2. use of the information derived from fire data in a GIS context in order to better interpret the significance of these data in terms of disturbances to the forest, and
3. information on gas emissions from the fires over the entire burning season.

More appropriate instrument design is called for to better measure fire characteristics (e.g., temperature) and improve the sampling.

3.1.3 Spectral Characteristics of Tropical Forests

Spectral differences between species are often the basis for using remotely sensed data to distinguish between deciduous forest associations or forest types. Usually one or two species predominate in the upper canopy of temperate forests. Even in the most complex deciduous temperate forests, the common upper-canopy trees may be of only three or four species. However, spectral differences between species are usually not the basis for distinguishing forest types or strata in undisturbed tropical forests.

With some notable exceptions, such as the dipterocarp forests in some regions of tropical S.E. Asia, the upper canopies of undisturbed tropical forests have a heterogeneous mixture of 10 to 12 species or more. Although four or five species of dominant and codominant trees in the upper canopy of undisturbed tropical forests frequently may constitute 40 to 50% of the aboveground biomass, the species themselves or the ratios are likely to change with subtle changes in the environment. Furthermore, many of the upper-canopy trees have epiphytic plants that are entwined with the foliage of the trees; and, in some cases of tightly closed canopies, the foliage of adjacent trees may be intermingled. The spectral characteristics of the species compromising various successional stages can afford the basis for identifying areas associated with each stage, provided the spatial resolution of the sensor is compatible with the dimensions of the area affected. Sensors on aircraft and spacecraft platforms could be used to detect the time at which transitions to subsequent successional stages occur. If such information is stored in the context of a geographically referenced system, it could provide a basis for subsequent biomass estimates even though a forest area loses its spectral uniqueness as it succeeds to mature forests.

Structural characteristics of the older forests such as the height variation in the upper canopy and the presence of large, overtopping species give rise to spectral differences in the overall forest. These spectral and spatial differences could be the basis for detecting forest strata in a geographical sense (Holdridge et al. 1967). If such strata correlate with biomass, they can be the basis for improving the accuracy of subsequent biomass estimates. The most relevant information that would correlate with biomass is the degree of disturbance caused by man's intervention. Such a stratification could be performed by using the spectral and spatial differences that relate to the percentage of the ground area covered by tree crowns. The number and nature of these strata would depend on the spatial and spectral resolution of the sensor employed (Joyce et al. 1980). Data from the AVHRR LAC sensor (1.1-km resolution) is likely to be influenced in this manner only by clearings of 10 or more hectares which occur over at least 30 to 40% of each square kilometer, whereas data collected by the Landsat TM (30-m resolution) or SPOT HRV's (10- and 20-m resolution) would be satisfactory for the delineation of "disturbance strata," which include clearings with much smaller dimensions such as relate to indigenous shifting agriculture (Sader and Joyce, 1988).

Once that "disturbance strata" or other strata derived from the data were geographically referenced in a GIS, other data resulting from the digitization of mapped information on soils, topography, life zone, etc., could be integrated with these data to form "ecological units" that constitute different biomass levels. Biomass estimates could be made through an extrapolation of ground-based biomass data to the area of each strata. The subsequent monitoring of the forest could be conducted to detect changes that constitute fluxes in biomass (e.g., Rock et al. 1986). Another approach, whether or not other data were integrated, would be to use a stratified sampling design employing finer-resolution remotely sensed data and/or ground sampling for biomass

(Sader, in press; Joyce and Sader 1988). In this case, large-scale aerial photography and other aircraft-acquired data could be used to derive more detailed information than can be derived from sensor data acquired from satellite platforms (Sader et al. 1985). Information of this nature may include upper-canopy tree counts and crown diameter measurements that may correlate with basal area and other parameters used for biomass estimates (Holdridge 1967).

With additional research, techniques could also be developed to make other measurements of forest parameters used for biomass estimates. The use of laser profilers has great potential for measurement of canopy height and may produce data that correlates directly with total aboveground biomass or that portion in the upper canopy that is difficult to estimate from the ground (Sader 1987a; Sader and Joyce 1985, Nelson et al. 1984). Synthetic Aperture Radar (SAR) data also have potential for measuring forest parameters related to biomass (Sader 1987a, 1987b; Wu 1986). Furthermore, using SAR data has an added advantage over using scanner data because SAR data are not influenced by the persistent cloud cover over topical forest areas. Finally, the increased spectral resolution of imaging spectrometers, such as that proposed for the Earth Orbiting System (EOS), offers potential for more information related to the spectral characteristics. Research on enhanced use of spectral data probably falls primarily under the National Aeronautics and Space Administration's (NASA's) auspices.

3.1.4 Sampling

A global assessment (even limited to the tropics) calls for a multistaged, stratified sampling approach in order to focus attention and effort on areas where the rates of change are high or erratic. There are many well-documented and well-developed techniques in the sampling literature (see references in Cowell 1983). The synoptic view provided by AVHRR data can form the basis for the first stratification.

Initial investigations should concentrate on acquiring, compositing, and processing AVHRR LAC 1.1-km data over the study area(s) of interest. Fine-resolution satellite (MSS, TM, or SPOT) or aerial photo products may be acquired as needed in order to verify ground conditions. The high-resolution data products would also serve as ground reference data to improve the accuracy of the 1.1-km AVHRR classification products. The fine-resolution photo products would not be incorporated into any sort of statistical design in the short-term studies.

For the long term, consideration should be given to using multilevel sampling approaches which integrate multiresolution satellite data to estimate forest area and forest conversion rates at continental and global scales. Multilevel sampling designs which incorporate fine-resolution satellite data (10-100 m; e.g., SPOT, TM, MSS) or aerial photographs permit extrapolation of detailed results across large areas. The fine-resolution data may be processed to accurately discriminate general land cover classes (e.g., forest and nonforest) or to differentiate more detailed land cover classes (e.g., conifer and hardwood; plantation, secondary, and primary forest) of particular interest to carbon modelers (e.g., Woodwell et al. 1983). Inclusion of fine-resolution sensor products in a rigorous statistical design (1) increases the accuracy, repeatability, and reliability of the areal estimates and (2) decreases the variance of these estimates. The specific sampling design depends on the questions being asked, the availability of data, and the level of accuracy desired.

Consideration should be given to the development and evaluation of the use of pixel mixture models to estimate forest/nonforest resources at spatial resolutions of one and four km. The co-registered data sets developed for multistage sampling may be applied directly to the development and evaluation of these models. Mixture modeling, which allows one to infer the land cover composition of individual pixels, would initially be a research and development component of an applied project. If robust mixture models can be developed to evaluate forest resources at a continental scale, they may, in turn, be used to refine forest estimates at the second stage and, as a result, make the use of finer-resolution data unnecessary. It is anticipated that NASA will support this basic type of research.

3.1.5 Data-Base Requirements

The large volume of data required for a global forest assessment argues for multisite processing, multisite data acquisition, and optical disk technology for data storage. The ultimate use of the data requires incorporation of thematic data in a standard GIS, a coordinated data analysis program, knowledge of accuracy requirements prior to data acquisition and processing, and knowledge of the data content and format requirements of the carbon modelers and data analysts. In addition to global coverage at 4-km spatial resolution and local/regional coverage at 1.1-km resolution, it is desirable that the data base be able to accept data at finer resolutions and over longer historical time periods than those offered by the satellite systems. This need arises because of the nature and existence of critical ecological sites which

1. are changing very rapidly (e.g., rapid deforestation and changes in biomass),
2. have a longtime data base available (e.g., aerial photos obtained at regular intervals since the 1920s), and
3. are used as detailed test sites for "calibrating" AVHRR data.

Therefore, the data base must accept imagery at finer resolution than AVHRR [e.g., TM (30 m), SPOT (20 m) or aerial photos (10 m)]. The high spatial resolution data would significantly improve trend estimates in small yet rapidly changing areas, especially if historic aerial photos are available. It is now possible to rapidly digitize aerial photographs and co-register the data with satellite imagery (Dr. Peter Lade, Salisbury State College, Maryland, personal communication, July 26, 1989). Since the satellite data base will be limited in time to less than two decades, it is important to include, if possible, historical aerial photo data to obtain a long-term base, even if only for small critical test sites. The further the data base can be extended in time, the easier it will be to interpret changes and differentiate natural from anthropogenic causes of such changes.

The ability to accommodate data at different spatial and temporal scales can be expensive and add complexity to the system. As demonstrated by NOAA's/National Ocean Survey (NOS) Strategic Assessment Branch, however, such a data base can be implemented at reasonable cost.

3.1.6 Summary of Research Strategy and Considerations For Tropical Asia Forest Monitoring

In summary, the research strategy for using remotely sensed data to estimate deforestation rates and vegetation distribution involves several components. Vegetation classifications should initially focus on forest versus nonforest, but methods of estimating the biomass of degraded forests should also be explored. Spectral characteristics in combination with spatial differences of various sensors may be combined to delineate various forest types. This approach requires a multistaged, stratified sampling scheme and consideration of data storage, manipulation, and coordination from the outset of the research. Attempts to apply the research strategy to tropical Asia would raise some problems. There is currently no LAC (1.1-km) data archived for tropical Asia. There are several High-Resolution Picture Transmission (HRPT) stations in Southeastern Asia that would have to be contacted and set up to acquire and archive the necessary data. This process would require some form of international collaboration on agreement. Furthermore, although the methodology described herein is generic, we cannot expect to apply techniques learned and used in other regions of the world directly to tropical Asia. Consequently, some research may be needed to develop new techniques, although the same general procedures will be relevant.

3.2 LONG-TERM RESEARCH AGENDA (10 YEARS)

The long-term goal of this research program should be to use remote sensing to estimate the global flux of CO_2 from the terrestrial system to the atmosphere. The first global estimate should be based on the use of 4-km AVHRR data to produce a global vegetation map (e.g., Tucker et al. 1985) and a land use change map. Image differencing will be used to identify and estimate the area of land use change (Woodwell et al. 1987). A prime objective is to reduce the margin of error acceptable in the initial stages from approximately 50% to as low as 10%. The methods for doing this may include the following activities:

1. Increase the number of intensive study areas. For example, study sites may be established in forests of tropical Africa and America, or the number of sites already established in tropical Asia may be increased.

2. Refine methodology. Based on sensitivity analysis of the initial inventory, the principal factors contributing to error (e.g., registration, classifications, data limitations) can be identified and approaches developed to reduce the contribution of these factors to errors in the global inventory. For example, additional procedures may be added to classification schemes (e.g., texture analysis, mixed pixel modeling, incorporation of microwave satellite data). Other protocols for using low- and high- resolution satellite data may also be developed.

3. Refine classes. In time, we are likely to find that additional categories other than forest and nonforest will be of interest in the overall research program. For example, the stage of forest growth may be important for carbon flux modeling and biomass inventories. Discriminating these classes may require ancillary data, such as local statistics, digital elevation models, and historical maps.

4. Integrate GIS capabilities. Integrating multilevel data sets (remotely sensed data, vegetation maps, elevation, roads, etc.) will require advancements in data management procedures.

5. Continue improvement of historical data bases to link with remotely sensed/GIS analyses.

6. Interact with carbon modelers to identify sensitive parameters or results from carbon models.

7. Support continued assessments of the spectral signature approach to large-area estimation of land use and vegetation condition (vigor, species composition, photosynthetic capacity, etc.) as input variables for long-term modeling and monitoring efforts.

4. RELATION OF REMOTE SENSING TO OTHER RESEARCH

A major value of remote sensing data is that it provides broad-scale information and total spatial coverage that can be related to information obtained at other scales or by other approaches.

4.1 RELATION TO HISTORICAL ANALYSIS

Tax and revenue records and geographical reference materials such as gazetteers provide high-quality historical data on land use--agriculture, forests, etc. This is true especially for Southeastern Asia, where these records were maintained for tax purposes during colonial times. They provide regional (district, state, country) data that can be cross-checked against other sources like aerial photographs, remote sensing data, etc., from both national and international agencies. The records, which in most cases are kept on a yearly basis and go back several decades, are good indicators of rates of land use change and therefore useful for carbon modeling and overlaying purposes. The historical data can be linearly extrapolated--as was done, for example, for the 1880, 1950 and 1980 data in India (Richards et al. 1985)--and used to validate remote sensing estimates. The percent change of carbon content of land use categories can be assessed by assigning "land degradation" multipliers to the ecological data, thereby providing an indication of flux.

4.2 RELATION TO CONTEMPORARY DEFORESTATION SURVEYS

Current biomass estimation techniques for the tropics use regression to estimate biomass by forest types and extrapolate to large areas by using the Holdridge life zone system. The estimation of biomass per hectare for primary forest is independent of remote sensing. Remote sensing becomes very important in two respects:

1. It can provide estimates of total area. When this quantity is then multiplied by biomass per hectare, the total number of hectares of a particular forest type can be estimated.

2. It may be able to provide estimates (indices) of disturbance, allowing adjustment of biomass estimates to allow for human disturbance (e.g., see Krummell et al. 1987).

Eventually, it may be possible to estimate biomass directly from remote sensing data. For now, we must rely on ground-based forest inventories for estimates of biomass per hectare and use remote sensing data to estimate total areas occupied by particular vegetation types and changes in those areas.

The FAO (1983) forest volume assessment is done by units within country, but forest types are in tabular form rather than geographically located. Remote sensing may allow determination of forest types on a map by providing geographic reference for the FAO data. Satellite imagery also offers the potential for cross-checking and calibrating current surveys of deforestation. Particular emphasis can be made with regard to the FAO forest assessments (Lanley 1982). FAO has produced a survey in which estimates of deforestation were developed from national- or regional-level reports. While this has been an extremely valuable addition, more information is required to disaggregate the national data to finer resolution (e.g., 50 km). Satellite data provide one means of making this kind of revision in the data set. FAO is now in the process of developing a 1990 assessment with subnational information. This, however, will not provide data at a resolution fine enough for most current modeling efforts, and a supplement of satellite data would provide the needed data.

FAO data can support remote sensing by providing ground baselines for verification and validation of remote sensing products. The FAO inventory designs are statistically sound (as much as possible), and inventory results are cross-checked within FAO and with individual countries. The FAO estimates provide a useful ground reference data base which should be used by the remote sensing community.

4.3 RELATION TO GEOGRAPHIC PATTERNING OF LAND USE CHANGE

The spatial patterns of land use change are highly related to other aspects of the landscape such as elevation, slope, soil type, original vegetation types, and proximity to road networks, hydrography, and centers of population. For example, dramatic visual documentation has been shown the very close relationship between proximity to newly constructed roads and deforestation in Brazil (Malingreau and Tucker 1988, Stone et al. in press) and Costa Rica (Sader and Joyce 1988). Rapid deforestation of a more catastrophic nature has been recorded in Borneo (Malingeau et al. 1985). Equally astounding was the extremely rapid conversion of prairies to agricultural use in the United States in the decade following the introduction of the mortarboard plow in 1837; in this case, the nearly level, highly organic, and extremely fertile soils beneath the midwestern tall-grass prairies prompted rapid conversion once the technology for sodbusting was in place (Iverson and Risser 1987). Most land use changes, however, are much more spatially disaggregated in nature and not as visibly dramatic, though they are still extremely important to global carbon budgets when considered across the globe.

Understanding the relationship between pattern of landscape features and land use changes is critical for elucidating the basis for historic land use trends and for building predictive models of future trends. Here we suggest three avenues of research which need to be explored to enable a better understanding of this relationship.

First, we need to investigate the role of landscape characteristics in determining where, how much, and how rapidly deforestation (especially the subtle fragmentation or degrading types of deforestation) will occur. Little research has focused on this topic. In one U.S. study, deforestation was found to be most closely related to the topography of the landscape since virtually all forests that did not frequently flood and that were not excessively sloping were converted to agriculture during the 1850-1910 period (Iverson 1988); currently Illinois forests are confined to "marginal" lands. Similar studies of the land use trends in Georgia reveal the importance of economic and edaphic controls on changing landscapes (Turner 1987, Odum and Turner 1987). Virtually the same thing is now happening in the tropics. Using a GIS approach, with remote sensing providing the land cover data, we could assess the patterns of landscape attributes for recently deforested areas, identify those geographic factors most closely related to the deforestation and the rate of deforestation, and construct maps estimating the probability for future deforestation over various time intervals.

Second, spatial patterns of land use which occur at the subpixel level (1.1-km or 4-km AVHRR pixels) need to be assessed for their influence on the individual pixel spectral characteristics. As an extreme example, would one expect to find similar spectral reflectance values between two pixels that are 50% forested--one undisturbed for half the pixel and barren the other half, and the other with total forest cover but the density of stems being systematically halved? Such land use patterns occur in the tropics when fine-scale cultivation intermingles with large commercial enterprises (e.g., cattle ranching or systematic logging). Therefore, it is important to distinguish regions where deforestation is fragmented as compared to areas where large-scale and uniform forest clearing is occurring. Once these areas are identified, error estimates can be determined by region.

Additionally, more work needs to be conducted using mixed model approaches (combining AVHRR data with high spatial resolution data) to determine the amount and quality of forests contained within partially deforested AVHRR pixels. For example, Iverson et al. (1989) found a good relationship between AVHRR spectral characteristics and the forest percentage occupying AVHRR LAC pixels for ten midwestern U.S. states. In areas undergoing interspersed deforestation over broad regions, it will be important to know the proportion of AVHRR pixels forested because detection of change is otherwise unlikely until the collective forest loss falls below a critical threshold (e.g., 70-80%) for a given pixel to be classified as nonforest. Therefore, forest cover would be overestimated in zones of 30-100% forest cover and underestimated in areas of interrupted woods (<30% forest cover).

Third, indices of spatial heterogeneity, texture, and scale need to be evaluated in terms of their capability to enhance remote sensing strategies to monitor the globe. For example, it may be possible to use one of these indices of landscape heterogeneity (e.g., O'Neill et al. 1988) or texture (Musik and Grover 1990) to stratify large regions using remotely sensed data. Specific classification procedures to delineate change might be tailored to each stratum based on selected spatial attributes. In this case, thresholds of landscape indices may determine the necessary sampling intensity of high-resolution data, whether subpixel mixed model assessments should be invoked, or whether the area should be targeted as one needing a closer look. Scaling issues are obviously paramount when dealing at the global level. How far can biological, climatological, or human-disturbance phenomena occurring at the landscape level be scaled up with meaning? Do we need to be concerned with global data layers of varying resolution and accuracy for calculating global carbon fluxes? These, plus many other research questions, need to be addressed by using methods from the growing body of landscape ecology literature.

4.4 RELATION TO MODELING

Satellite data provide the best contemporary measure of changes in land cover. Other methods are required to obtain historical information, but these approaches must infer changes in land cover from changes in factors that influence patterns of land use. Remote sensing provides an objective appraisal of land use change and provides an accurate definition of actual vegetation cover. These are two critical parameters for global carbon models. Land cover change occurs as a continuum, from the very obvious (e.g. deforestation) to the subtle (forest thinning from fuel wood or timber harvest). The landscape is represented as a mosaic of these types of disturbances, and all are important to modeling CO_2 flux. However, for the near term it is likely that only the most obvious forms of land cover change can be readily detected from space.

Although satellite data provide useful and necessary information for contemporary time frames, experiments with existing carbon models suggest the need for at least 20 years of "backcasted" data. Without such ancillary data, a remote sensing study will overestimate the current CO_2 flux in regions in which there is considerable regrowth (e.g., because of shifting cultivation) and will underestimate CO_2 flux in regions in which there is not considerable regrowth (due to the time lag of slow-decay pools). It must also be noted that remote sensing will not readily provide some other data needed to parameterize carbon models, such as soil organic matter or information on the fate of carbon after disturbance.

However, remote sensing will provide a valuable input to carbon models by accomplishing the following objectives:

1. providing information on the spatial and geographic pattern of land use change (e.g., one could use uncorrected fire data from the AVHRR thermal bands),
2. providing rates and magnitudes of obvious forms of land use change,
3. directly measuring photosynthetic capacity by using limited high spectral resolution data sets as subsets of larger sampling units (pixels) and thus providing validation of model projections, and
4. providing actual measures of land cover (e.g., past efforts using the Holdridge life zone system have had to rely on "potential vegetation").

With regard to the final point, it must be noted that vegetation cover maps derived from remotely sensed imagery provide the base picture of ecosystem distribution and, if appropriately classified, can be parameterized with information pertinent to carbon models (e.g., vegetation type to biomass).

Remotely sensed data of land cover and land use change may best be used as a way to check projections of carbon models. For example, models can project changes in land use as a function of socioeconomic factors such as population growth, tax systems, or road development. The projections can be tested by independently acquired estimates from remotely sensed data for the same area.

5. COLLABORATIVE ASPECTS OF REMOTE SENSING RESEARCH

The scope of the problem of estimating global CO_2 flux dictates that the research involve collaboration among agencies and countries. In particular, the research should be funded by various sources over several years. This must be an international effort for acquisition of satellite data and ground reference data.

5.1 INTERNATIONAL FORUM

The workshop participants recognize the importance and urgency of developing an international forum for advancing major issues raised by current trends in land cover.

5.1.1 The United Nations Environment Programme

The role of the United Nations Environment Programme (UNEP) was noted, especially with respect to global tropical deforestation. At present, however, UNEP has not strongly addressed such issues in an international forum. It is recommended that this agency, through its Global Environmental Monitoring System (GEMS) Programme, consider playing a more active role in the following areas:

1. identifying the means whereby thematic data produced by individual projects (such as the DOE effort) can be incorporated into the existing global data sets, and
2. bringing the attention of the world community to the issues related to current trends in deforestation.

The importance of a central depository for the relevant thematic data (as opposed to the raw data) is recognized. The UNEP/Global Resources Information Database (GRID) Programme was established with this purpose in mind and should now take increased responsibility for promoting the compilation of such data. It appears however that the precise role and mechanisms of GRID in this arena have yet to be clearly defined. Similarly, it is unclear whether, at present, this program can carry out the task.

To reach these proposed objectives, it will be necessary for the United Nations to establish both short- and long-term strategic plans for assessing tropical deforestation and to integrate the growing amount of research data being produced in this field. In the short term it would be useful to

1. identify a technical officer in charge of issues related to tropical deforestation with whom the researchers can communicate,
2. organize the GRID facilities to answer data needs related to the international community's concerns relating to tropical deforestation,
3. strengthen the role of the newly created Standing Committee of Experts (Geneva, January 89) in promoting an internationalization of the issues and in providing technical support to GRID, and
4. identify potential donors to support the efforts of the deforestation research community.

In the longer term (5 to 10-year plans), UNEP should increasingly play a watchdog role in monitoring the tropical forests of the world; to do so, the Agency will have to rely principally on remote sensing approaches of the kind proposed in this document. Since FAO is already doing some of this work, it is vital that UNEP interact with FAO. Long-term support to space observation programs should now be expressed by the United Nations (UN) agencies most concerned with environmental trends.

5.1.2 The International Geosphere-Biosphere Programme

The International Geosphere-Biosphere Programme (IGBP) plans to establish pilot studies in a range of "representative" environments for collecting land cover and land use data relevant to the study of global change issues. These issues pertain to

1. the physical interactions between land surfaces and atmosphere,
2. chemical interactions,

3. the impact of climate change upon vegetation processes and distribution, and
4. complex interactions including feedbacks among humans, climate, and vegetation.

The methodology of the studies will be designed so that it can be extended from local to global issues by using a hierarchy of scales and nesting of different instruments. The minimum data set to be collected includes the distribution of land use and cover, seasonal dynamics of land use and cover, and long-term trends in change. This concept is being developed in test sites.

5.2 REGIONAL FORUM

Several institutions in the tropical belt are devoted to the examination of regional problems. They should be involved with any effort at reaching regional perspectives on land cover changes.

For example, in tropical Asia, the following regional organizations are recognized:

1. Economic and Social Commission for Asia and the Pacific (ESCAP),
2. remote sensing project in Bangkok,
3. UNEP/GRID Bangkok node,
4. Southeast Asian Ministers of Education Organization (SEAMEO), and
5. Asian Institute of Technology (AIT), Bangkok.

Other international institutions working in the area of interest should also be involved, such as FAO, United Nations Educational Scientific and Cultural Organization (UNESCO), United Nations Development Programme (UNDP), International Bank for Reconstruction and Development (IBRD).

It is also pointed out that large amounts of historical data on tropical natural resources can be found in the former "colonial" countries (i.e., France, the United Kingdom, the Netherlands, Belgium, Germany). More recent data (from the last two to three decades) can be obtained from international donor agencies [e.g., the United States

Agency For International Development (USAID), the Canadian International Development Agency (CIDA), the United Kingdom's Overseas Development Administration (ODA)] or from intelligence gathering agencies (e.g., the U.S. Central Intelligence Agency).

5.3 NATURAL RESOURCES

Information on natural resources may be obtained from the following sources:

1. governmental agencies such as ministries of agriculture, ministries of environment, ministries of transport;
2. technical institutions specializing in geodetic and cadastral studies and in space and remote sensing, as well as receiving stations and agricultural experimental stations, etc;
3. national research institutions or individual scientists;
4. banking institutions such as the World Bank, the Asian Development Bank, the Inter-American Development Bank, and the African Development Bank

5.4 FACILITATING DATA EXCHANGE

The remote sensing data needed to estimate land use changes and their effects on atmospheric CO_2 are often produced and/or maintained by agencies or countries different from those that use them. Currently, the data are very expensive to acquire. The problems to which the data are applicable, however, transcend individual agencies and countries. Therefore, the different agencies are encouraged to work together to facilitate data exchange and research progress. Procedures for facilitating research might best be developed by a planning group that consists of representatives from DOE, EOSAT, NASA, NOAA, SPOT, and other agencies and countries. Discussions should include the Interagency Working Group on Management of Global Databases, the Landsat Operational Ground Station Working Group (LOGSWG), and regional station representatives.

6. CONCLUSIONS

This report presents a new agenda for global monitoring which cannot be ignored. Remote sensing data provides the opportunity for global measures of vegetation cover and land use change. These measures are critical to understanding the effect of human activities on atmospheric CO_2 increases and climate change. Deforestation is also having major impacts on global biodiversity, hydrologic patterns, and available resources.

Making use of remotely sensed data requires planning and collaboration. Appropriate use of remotely sensed data requires considering the desirable level of vegetation classification and spectral characteristics of the vegetation, sampling to make the best use of available spatial resolutions of data, and achieving data-base needs. Furthermore, the complexity and broad scale of most projects necessitate collaboration between scientists in various universities, agencies, and countries. Lack of collaboration will impede research by slowing progress and increasing the expense of data acquisition and processing.

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APPENDIX

USING REMOTE SENSING TO ESTIMATE CHANGES IN LAND USE

Workshop Agenda

Wednesday, February 22, 1989

8:00-8:30	Coffee and Registration
8:30	Introduction to Workshop Dr. Michael P. Farrell Dr. Virginia H. Dale
9:00-3:20	"Methods and Examples of Using Remote Sensing to Estimate Land Use Changes"
9:00	Dr. Jean-Paul Malingreau, "Assessing Land Use Changes in the Tropics: Contributions of Remote Sensing"
9:30	Drs. Chris Justice, Yoram Kaufman, and Compton J. Tucker, "Using Remote Sensing to Estimate Vegetation Patterns and Forest Burning"
10:00-10:20	Coffee
10:20	Mr. Tom Stone, "Land Use and Remote Sensing"
10:50	Dr. Ole Hebin, "The Global Resources Information Database of the United Nations Environment Programme"
11:20	Mr. Ross Nelson, "A Statistical Framework for Estimating Land Cover Change Using Satellite Data"
12:00-1:30	Lunch
1:30	Mr. Alan Cross, "Use of AVHRR for Vegetation Classification"
2:00	Dr. Alberto Setzer, "Using Remote Sensing to Estimate Biomass Burning and Land Use Change in Brazil"
2:30	Dr. Jack Estes, "The National Science Foundation National Center for Geographic Information Analysis"
3:00-3:20	Coffee
3:20	Dr. John Richards, "An Historical Approach to Estimating Land Use Change in Bihar, India"
3:40	Discussion

5:00	Adjourn

Thursday, February 23, 1989

8:00-8:30	Coffee
8:30	Dr. Louis Iverson, "A Technique for Extrapolating and Validating Forest Cover Across Large Regions"
9:00	Mr. David Skole, "Using Remote Sensing to Estimate Forest Cover in Brazil"
9:30-5:00	Discussion groups
5:00	Adjourn

Friday, February 24, 1989

8:00-8:30	Coffee
8:30-12:00	Discussion and synthesis of workshop
12:00	Adjourn

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