ACT Publication No. 93-01

Spectral Identification of Successional Stages Following Deforestation in the Amazon

P. Mausel, Y. Wu, Y. Li, E. F. Moran, and E. S. Brondizio

Reprinted from: **Geocarto International 8(4):61-71 (1993)**

Anthropological Center for Training and Research on Global Environmental Change
Indiana University, Student Building 331, 701 E. Kirkwood Ave., 47405-7100, U.S.A.
Phone: (812) 855-6181, Fax: (812) 855-3000, Email: act@indiana.edu, internet: www.Indiana.edu/~act

Spectral Identification of Successional Stages Following Deforestation in the Amazon

Paul Mausel, You Wu and Yinghong Li
Department of Geography, Indiana State University
Terre Haute, Indiana 47809, U.S.A.

Emilio F. Moran and Eduardo S. Brondizio
Anthropological Center for Training and Research on Global Environmental Change
Indiana University
Bloomington, Indiana 47405, U.S.A.

Abstract

Land use and land cover features of a 3,000 sq. km. area west of Altamira, State of Para, Brazil, along the Transamazon Highway was assessed using three dates of Landsat TM data acquired for late July/early August 1985, 1988, and 1991. These data, supplemented by field observations and interviews with land users conducted in 1992, permitted classification of nine features, including three of secondary succession (SS). The research emphasis focused on developing multitemporal field level information through remote sensing that could be used to help assess SS characteristics vital in understanding the area dynamics and processes. Research results indicate that multitemporal TM data can be used successfully to identify three SS land cover classes and their rates of change. Classification accuracy of the features of interest varied from 81 to 98 percent. Information developed from analysis of the classifications included delineation of several patterns of different speeds or rates of SS, rate and spatial nature of deforestation from 1985-1991, and SS areas spectrally nearing or achieving mature moist forest signatures.

Introduction

Deforestation of the Amazon Basin has been a focus of international concern, particularly in the global change community. The Amazon has become one of the critical areas where many of the issues surrounding global-scale environmental change are being addressed (Booth, 1989; Shukla *et al.*, 1990). During the 1980's, South America, principally within the Amazon, average forest loss was 6.2 million hectares a year, which represents an annual rate of 0.6% (Aldhous, 1993). This deforestation has transformed Brazil into the world's fourth atmospheric carbon contributor behind the United States, Russia, and China (Goldemberg, 1989). By 1992, more than 11 percent of the Brazilian Amazonian forests had been altered significantly by deforestation (Skole and Tucker, 1993).

Developing strategies for reducing and/or modifying tropical deforestation practices is needed. Deforestation studies should not only focus on observing the location, amount, and rate of forest destruction but should also ask the following questions: 1) What is the nature of, and reasons for, patterns of land use following initial cutting? 2) What are the characteristics of the soil and terrain in deforested areas and how do these physical parameters impact regrowth? 3) What socioeconomic factors affect initial deforestation and patterns of land use following cutting? and 4) How and why do cut mature moist forest areas take different paths and experience different rates of secondary succession?

Remote sensing, when combined with ground-based data, is a valuable tool to develop information to assess and address problems associated with deforestation. The most common use of remote sensing has been satellite-based estimates of forest losses. Tropical deforestation and related studies have been made using Landsat, SPOT, and AVHRR with varying degrees of success (Baltaxe, 1986; Nelson and Holben, 1986; Woodwell *et al.*, 1987; Malingreau *et al.*, 1989; Berta *et al.*, 1990; Gilruth and Hutchinson, 1990; Green and Sussman, 1990; Sader *et al.*, 1990; Kummer, 1992; Campbell and Browder, 1992). The use of higher resolution satellite data over an extended time period and enhanced with detailed ground-based information to provide multitemporal views of tropical environments at a field level has been rare. Detailed multitemporal views of deforested areas, particularly succession, are required to answer many of the questions posed earlier. Satellite remote sensing research focusing on succession is found for temperate forests (Fiorella and Ripple, 1993) and tropical forests (Sader *et al.*, 1989; Campbell and Browder, 1992), but such research extending over six years or more is uncommon, particularly in tropical moist forests. Low resolution multitemporal views of deforested areas show trends, but the level of detail and the ground truth support for analysis are not adequate to identify features such as field size, changes of land use at the field level, and processes of succession dynamics which are vital to assess many biological, social and economic outcomes associated with deforestation and land cover change.

The objectives of this paper are: (1) to assess the level of land use detail and land use change information achievable using multitemporal Landsat TM data supported by ground-based observations and field histories and (2) to evaluate the feasibility of using the information developed to address deforestation-related questions. Specifically, a 3,000 sq. km study area in the Xingu Basin, which is transected by the Transamazon Highway and which contains the city of Altamira, was used to analyze changes in forest area, changes in patterns of secondary succession, and changes in agricultural patterns between 1985 and 1991.

Study Area

An area approximately 60 km x 50 km along the Transamazon Highway is the focus of this research (Fig. 1). The city of Altamira and the Xingu River, anchor the eastern edge of the study area. Figure 2 is a TM 1991 color composite image of the Altamira site. The area has a local relief often exceeding 60 m. Soils are diverse and, overall, of above average fertility for Amazonia. High quality Alfisols are found, but equally abundant are poorer soils such as Oxisols and Ultisols. The dominant vegetations are mature moist forest and liana forest (Pires, 1983). Annual precipitation is approximately 1700 mm, with a four month drier period occurring June through September. Major deforestation began in 1972 in this region, which was a development coincident with the construction of the Transamazon Highway (Moran, 1976, 1981).

The settlement of this area was strongly based on government grants of land (100 ha) and various types of post-settlement support along the Transamazon Highway and its feeder roads. The feeder roads are perpendicular to the main highway and extend into the interior at varying distances depending on settlement pressure. Larger properties (glebas) devoted to grazing are common toward the end of the feeder roads. Plantation agriculture and other types of commercial agriculture (rice, sugar, cacao, pepper) have been successfully developed by some land owners. The majority population, comprised of farmers with limited resources, plant manioc, beans, corn, vegetables, and tree crops supplemented by pastures for a few animals.

A typical land use sequence after deforestation is cropland followed by pasture. The pasture is invaded with pioneer species of shrubs and trees becoming a "degraded pasture." An abandoned pasture may, eventually, spectrally assume the appearance of original forest. The stages of vegetation from clean pasture to forest regrowth similar to mature moist forest is referred to as secondary succession (SS) stages in this paper.

Data Sources and Methods

Landsat TM data acquired in July or August for 1985, 1988, and 1991 provided the spectral data used in computer classification of features. Detailed ground observations and measurements for this research were acquired during May and June 1992. Land use histories of selected fields back to the 1970's were acquired. Soil maps and soil sample data were acquired as were recent topographic maps (1:100,000 scale) for a majority of the study area.

The methods employed focused on standard unsupervised and supervised classification approaches using the six reflective Landsat TM bands. The focus of classification was development of land cover/land use classes that were indicative of successional stages of vegetation following crop or pasture field abandonment. Foundation classes (i.e. crop, pasture, water, wetland, soil, and mature moist forest) required delineation to provide a spatial-temporal continuum needed to assess absolute change and rates of change in the study area.

Thematic Mapper data used in this study were acquired from the Brazilian Space Agency (INPE) in Brazil. The multidate data used for this research were registered, and the 1988 and 1991 dates were adjusted to be consistent with 1985 digital number (DN) values by utilizing large culturally unaffected rainforest areas in the most remote parts of the study site. These interior mature moist forest areas were the most consistent features in the scene and, their overall spectral characteristics remained relatively constant. These data were classified and geocorrected to the universal transverse mercator (UTM) projection using 1:100,000 scale topographic maps.

The May-June 1992 field data collection expendition made 300 site observations which focused on vegetation type, density, and condition. Twenty-five field histories focusing on land use features dating back ten or more years were acquired through interviews. These detailed observations provided the ground information used to

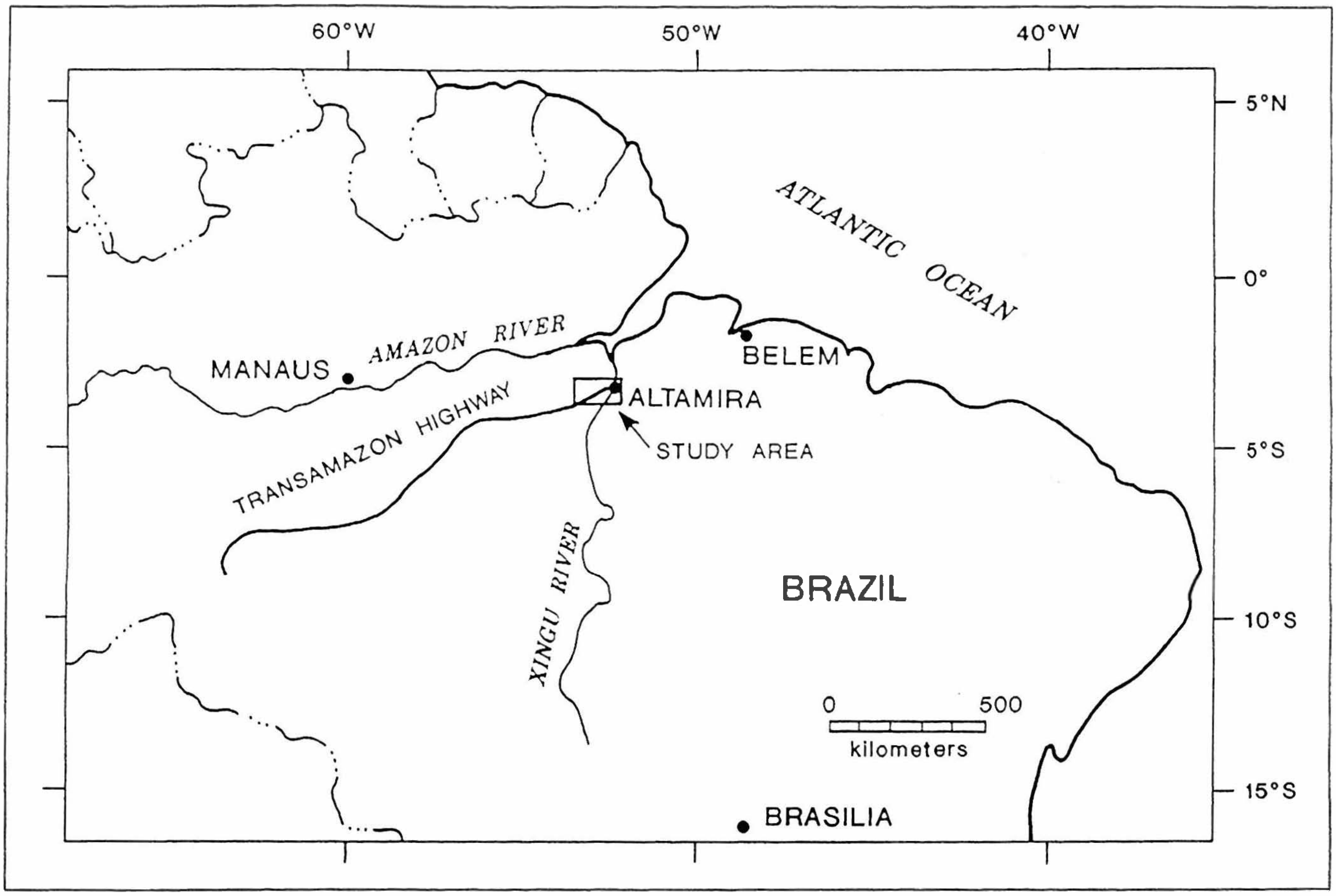

Figure 1 Altamira study area along the Transamazon Highway in an eastern part of the Amazon Basin, State of Para, Brazil.

inform subsequent classifications.

Features of interest in the landscape included soil, water, wetlands, vigorous crop, clean pasture, mature moist forest, and three stages of SS. Two sets of area samples representative of most of these nine features were developed from the ground observations. One set was used to develop the Landsat TM spectral signatures and training statistics for supervised classification and the other set was used to provide insight into classification accuracy.

Spectral signatures of features of interest were developed by implementing isodata clustering using ERDAS on a 486 PC or MULTISPEC (a microcomputer version of elements of LARSYS on a Mac IIc). The cluster statistics associated with a known feature acquired from on-site observations formed the basis for developing key core spectral patterns of the features of interest. The SS cluster statistics supplemented by the spectral statistics of polygons of known character were used in supervised classification.

The spectral pattern of the designated features were developed for the 1991 image and the Gaussian maximum likelihood supervised classification algorithm in MULTISPEC was implemented to identify features throughout the Altamira study area. The classification results of the test fields were analyzed using a confusion matrix approach (Jensen, 1986) and presented in the results section.

Study area classifications of 1985 and 1988 were developed using the methods and spectral signatures described for 1991. Classification accuracy was not determined for the 1985 and 1988 data, because too few test samples were available for those dates using historical data. Inferences were used to provide insight into land use/land cover conditions in 1985 and 1988. For example, (1) a mature moist forest in 1992 was likely to have been a forest or an advanced SS state on the earlier dates since too little time had passed to go from an earlier SS state to mature forest and (2) an 18-year-old successional forest in 1992 would have been a 14-year-old successional forest in 1988, which would still leave it in the advanced SS class. Reconstruction of the past based on known conditions in 1992 introduces errors and cannot account for a significant cultural or physical disturbance which changes the course of natural succession.

The three dates of classified data were used to develop profiles of land use and land cover change for

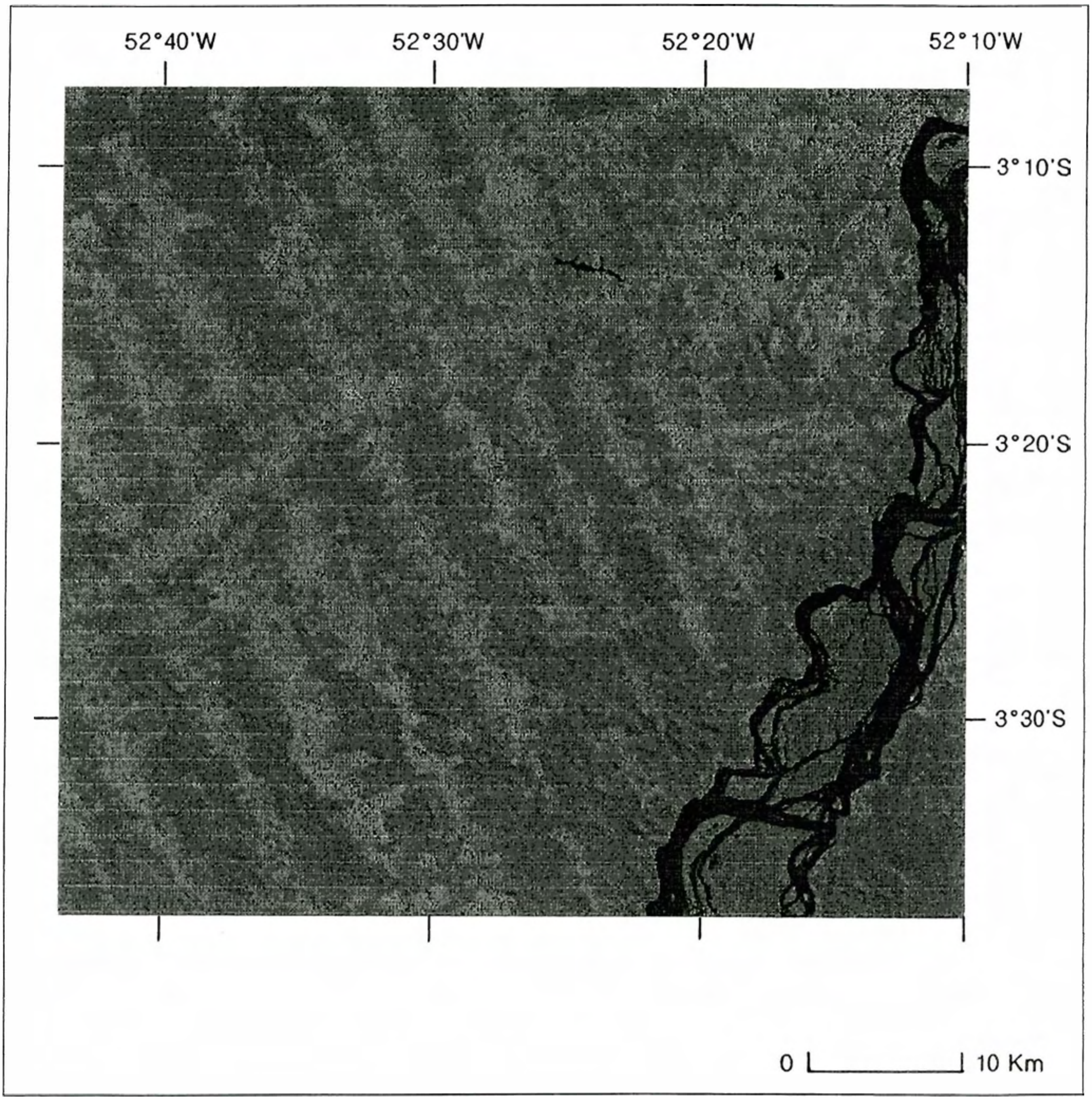

Figure 2 Color composite image of the Altamira study area in August 1991 using Landsat TM bands 5, 4, and 3 in an RGB display.

the Altamira area; however, to best show spatial detail, a 72 km sq. subarea centered at km 23 along the Transamazon Highway was used. Land use distribution statistics were calculated and compared for each one of the three dates. These three dimensional spatial patterns were subjected to interpretation and evaluation.

Spectral Response Characteristics: 1991 Features of Interest

The DN patterns of the features shown in Table 1 were interpreted from a theoretical spectral interaction context to provide an initial model of spectral responses. TM Band 1 was too affected by atmospheric scattering to provide discrimination between features of interest and so was omitted from classification.

The spectral patterns of water and wetland differentiate themselves from the other classes because of their significantly lower responses in the near-IR and mid-IR bands which are related to absorption of these wavelengths by water. Dense green crops with their high chlorophyll content and plant moisture content are differentiated from other classes by their

Table 1 Representative relative TM spectral responses of selected features near Altamira, Brazil: 1991.

TM Band with DN Spectral Responses (Standard Dev)*

Feature	2	3	4	5	7
Water	32(1)	32(1)	34(3)	22(4)	4(2)
Wetland	31(1)	31(2)	38(8)	31(5)	10(2)
Bare	38(6)	45(6)	67(6)	101(9)	35(6)
Green Crop	33(2)	30(1)	103(6)	76(6)	15(2)
Clean Pasture	34(2)	35(3)	71(6)	85(7)	22(4)
Initial SS	32(2)	31(2)	79(8)	81(7)	19(3)
Intermediate	32(2)	30(2)	83(6)	73(6)	16(3)
Advance SS	31(1)	28(2)	80(5)	63(5)	12(2)
Natural Forest	29(1)	27(1)	70(4)	52(4)	10(1)

* The relative spectral responses or digital numbers (DN) in this table give insight into patterns of reflectance of the features indicated. The numbers are relative values in which higher numbers are surrogates for higher reflectance. All values, including standard deviation, have been rounded to the nearest integer. There are variations in the spectral signatures for all classes and the values in the table are typical responses near the center of the feature class. The SS designation in the table refers to secondary succession.

combination of one of the highest (albeit small in sbsolute terms) green minus red values (or highest green/red ratio), one of the highest near IR values and moderate mid-IR values. Bare soil has a pattern in which very high DN values are found in the visible and mid-IR TM bands. This is consistent with relatively high visible reflectance from mineral matter in low organic soils and very high mid-IR DN's in dry soils which have little water to depress mid-IR reflectance.

Clean pasture has a higher visible reflectance than other dense vegetation classes with a green/red ratio usually 1.00 or lower. Its near-IR is variable but usually less than most other vegetation classes excluding mature forest. The mid-IR reflectance is among the highest of the vegetation classes because bare soil is present and impacts on the composite signature.

Initial secondary succession (SS1) has tall grass interspersed with woody/forest growth. The visible band responses drop in value, in part due to greater vegetation density and increased chlorophyll absorption. The near-IR is high due to mesophyll reflectance from dense vegetation. The SS1 mid-IR is moderate but dropping in comparison with clean pasture, primarily in response to absorption of plant water which is more abundant in SS1 compared with pasture.

Intermediate secondary succession (SS2), with its larger trees 8-12 m in height and immature but developing multicanopy, has a biomass and plant moisture higher than that found in SS1. The visible reflectance of SS2 is similar to SS1, but it has a higher green/red ratio, which is consistent with increased biomass. The near-IR reflectance of SS2 is often somewhat lower than that os SS1, and this type of difference becomes even greater in the mid-IR bands in response to an increase in IR spectral traps manifested as shadow which has formed due to complex tree geometry absent in SS1, pasture, and crops.

Advanced secondary succession (SS3), with a maturing multicanopy and trees often exceeding 20 m in height, looks similar to some types of mature moist forest. The visible band reflectance is lower and the green/red ratio is higher than other SS classes which is consistent with increased chlorophyll absorption, but some of this decrease in reflectance might be due to spectral traps/shadow which is greater in SS3 than in the other SS classes. The reflectance of the near-IR and mid-IR bands continue to drop in SS3 comparison with other SS classes, even though biomass and moisture content are the similar, again, is probably in response to increased shadowing.

The mature moist forest is the culmination of the successional continuum and most SS3 should eventually become very similar to it, if undisturbed. The forest is spectrally varied and often distinct from its nearest class of SS3. It has a low visible response with a relatively high green/red ratio, a moderate near-IR response, and a low mid-IR response which is a pattern that appears to require the large amounts of shadow/spectral traps associated with very complex multilayered vegetation.

Classificaiton Results and Discussion

The full 3,000 sq. km area was classified using the training field statistics developed with the support of data acquired in the field. Full area classification statistics are provided in the text. However, it is not possible to display and analyze detailed spatial patterns associated with classification for the full area in a figure; thus a 72 sq. km subsite centered at km 23 along the Transamazon Highway is developed for that purpose. The area developed for detailed spatial interpretation is referred to as "subsite" in the text. Discussions of individual date subsite classification patterns and associated land cover statistics are given followed by subsite multidate classification patterns and their land cover change statistics. A presentation and analysis of the full study area data comparable to that presented for the subsite, excluding display of classification results, concludes this section.

Subsite Individual Classifications

Analysis of Figures 3 through 5 and Table 2 provide the following information. By 1985 approximately 55 percent of the subsite was deforested. An additional four percent of the area was deforested in the following three years; but during the 1988-1991 period, only an additional 1.5 percent of the original forest was cut.

Secondary succession classes collectively were found in less than 20 percent of the subsite in 1985, and most of it was SS1 and SS2. In 1988 and 1991 the amount of secondary succession was approximately 40 and 50 percent respectively. Not only was there an increase in SS, but the more advanced forms became dominant by 1991, indicating that a majority of former crop and pasture lands which reverted to SS were not

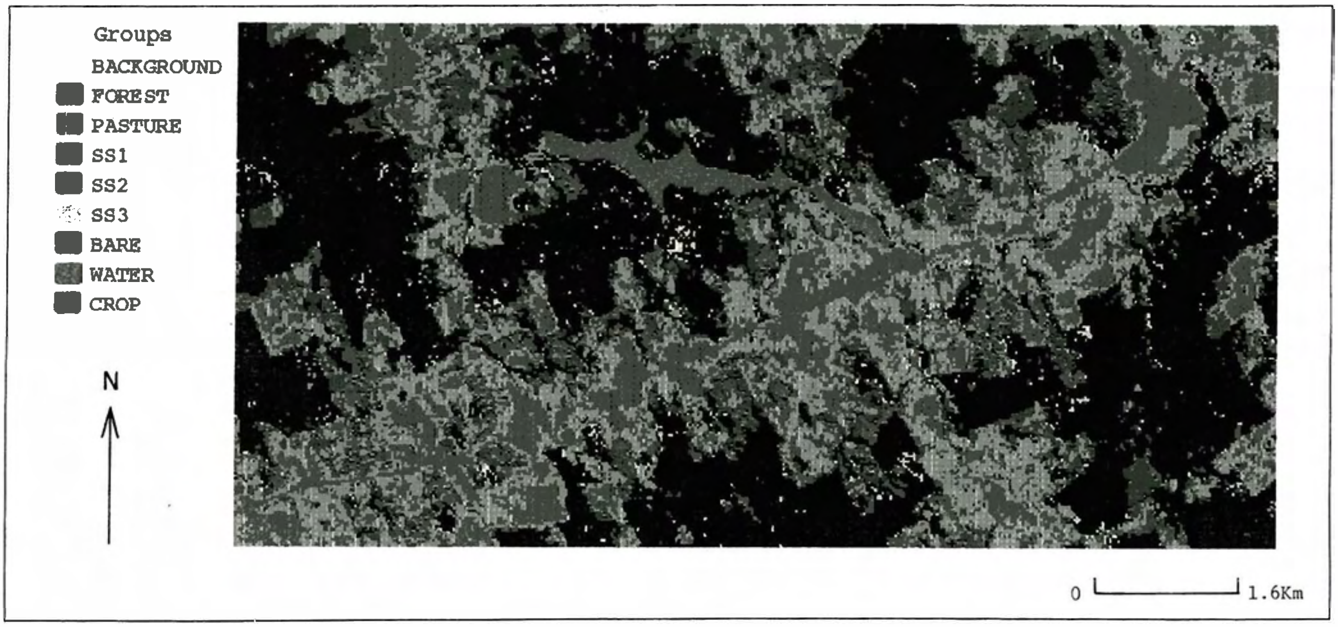

Figure 3 Supervised classification (July 1985) of an Altamira subsite centered at km 23 along the Transamazon Highway using Landsat TM data. The 1985 data were acquired in a drought year resulting in a classification showing a disproportionate amount of dying grass and bare soil. Mature moist forest is the most common land cover and numerous areas of earlier stages of secondary succession are found.

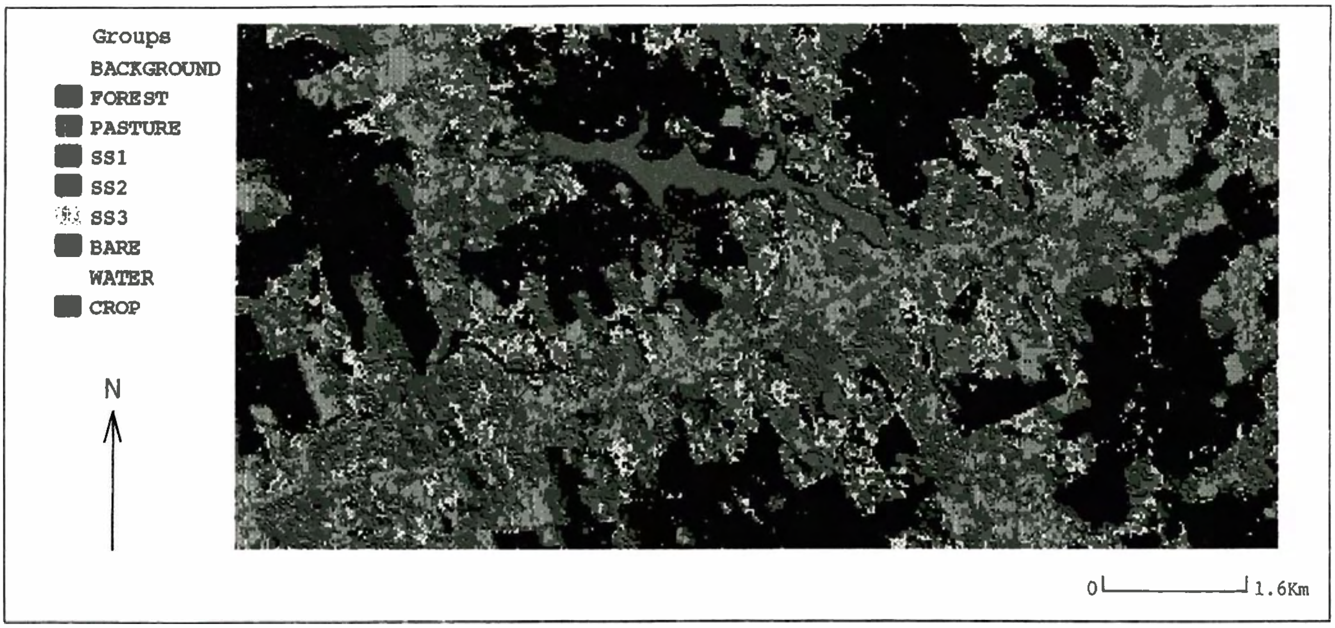

Figure 4 Supervised classification (July 1988) of an Altamira subsite centered at km 23 along the Transamazon Highway using Landsat TM data. Mature moist forest is the most common land cover, but large areas of various secondary succession stages (initial, intermediate, and advanced) are present.

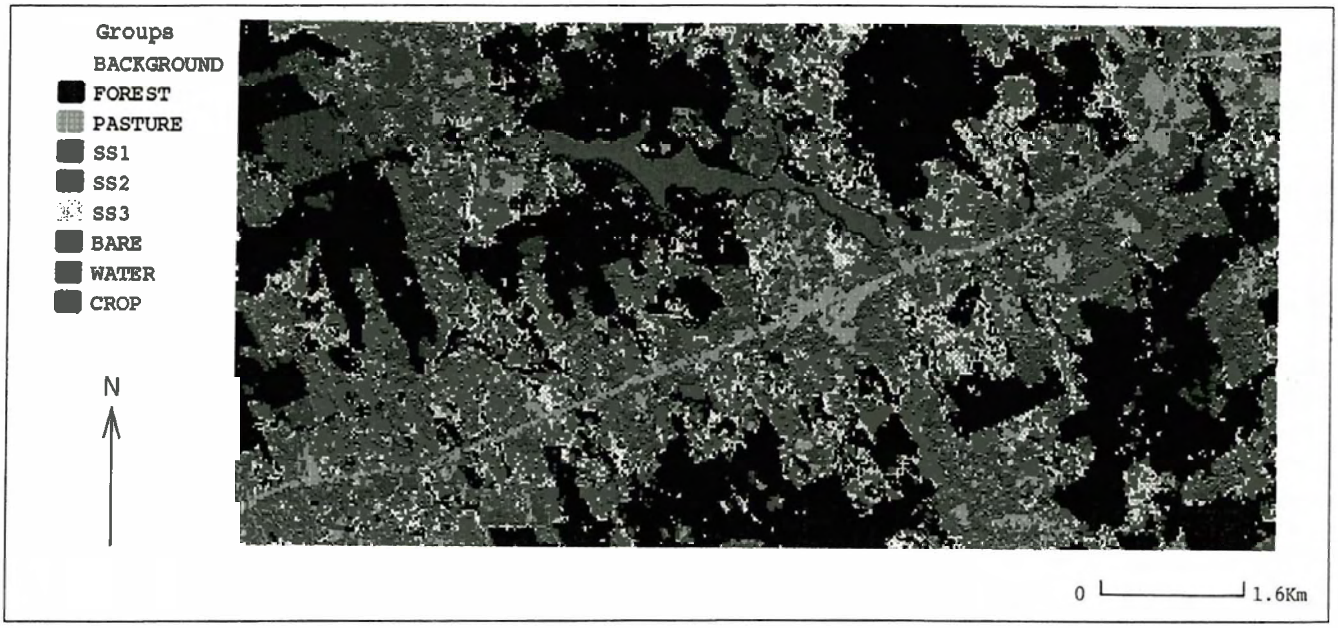

Figure 5 Supervised classification (August 1991) of a Altamira subsite centered at km 23 along the Transamazon Highway using Landsat TM data. Mature moist forest is the most common land cover, but increasing amounts of secondary succession, particularly in intermediate and advanced forms, are present.

Table 2 Land cover changes in the Altamira subsite study site: 1985-1991.*

Land Cover Class	Percent Land Cover		
	1985	1988	1991
Mature Forest	44.32	40.70	39.21
Pasture	18.71	10.88	5.70
Initial SS (SS1)	10.68	13.78	14.67
Interm. SS (SS2)	6.43	18.82	26.42
Advanced SS (SS3)	1.33	6.91	10.65
Bare	14.74	2.72	0.93
Crop	2.38	4.78	1.01
Water	1.41	1.41	1.41
Wetland**	-.-	-.-	-.-

* Figures 3 through 5 show the classifications of this 7,200 ha subsite.

** Only a trace of wetland was classified in this small subsite; thus no percent total was provided for this class.

predominantly being reconverted into agricultural uses but rather left to proceed to advanced forest succession states.

Soil and pasture comprised almost one-third of the subsite in 1985. The presence of almost 15 percent soil greatly exceeded a typical amount of less than two percent and it was a result of an uncommon extended very dry period prior to data acquisition. This drought killed many grasses, crops, and less established threes and shrubs. The soils quickly became covered with pasture, crops, shrubs, and trees after the 1985 drought was over.

Subsite Composite Classification

The individual classifications of the subsite provide insight in spatial patterns of interest, but additional information vital to research objectives requires assessment of change from one date to the other. Thus, the three dates of classification were overlaid and changes in land use patterns derived from analyzing them were assessed. Some of the important multidate patterns derived are shown in Figure 6 and Table 3.

Thirty-four percent of the mature moist forests never changed class, although the individual date classification with the lowest percentage of forest was 39. The other five percent can be accounted for by some mature moist forest areas suffering a physical change such as fire, lightning, disease or minor logging which resulted in a brief return to a SS class. In addition, it appears that more than one percent of the area was reforested back to a mature forest state at least spectrally. A decreasing rate of deforestation between the 1985-1988 period and the 1988-1991 period was evident.

The three date patterns of SS shown on Table 3 were viewed in four ways (slow, fast, very fast, interrupted). Some areas (15 percent) were stable or had very slow SS. Slow SS is defined as an area which had no change or change of no more than one SS unit. For example, a three date sequence of pasture, pasture, and SS1 is representative of this category. Other areas (18 percent)

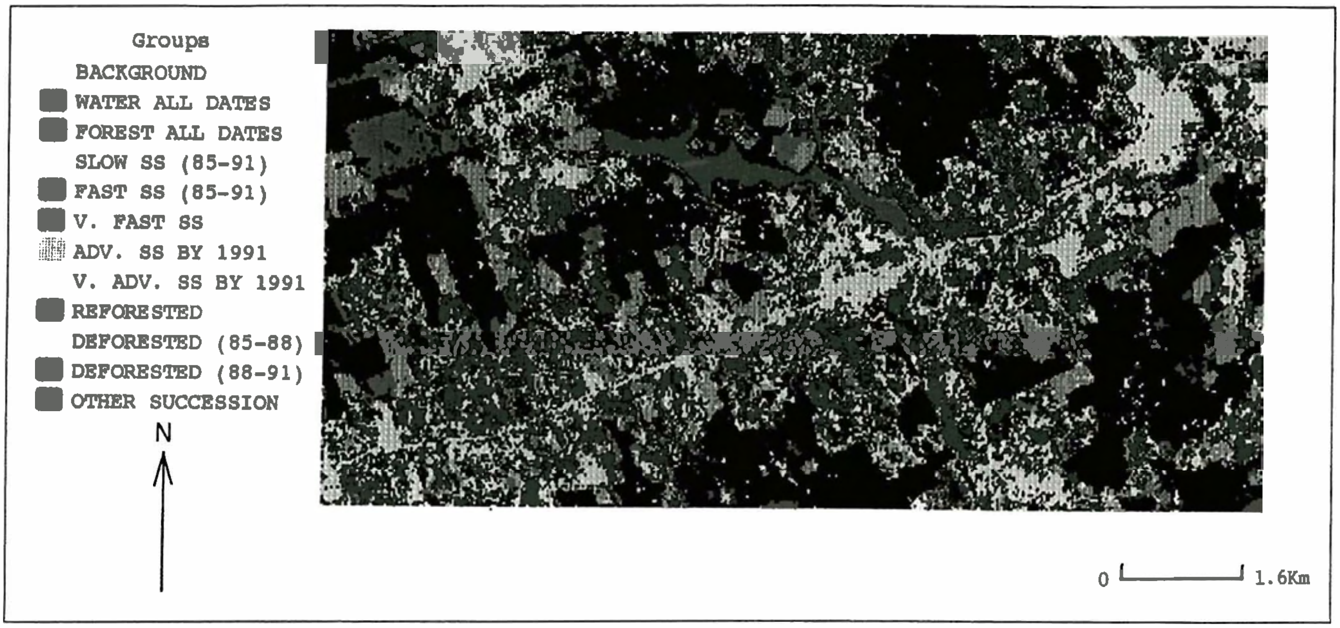

Figure 6 Selected classes in a composite classification of an Altamira subsite centered at km 23 along the Transamazon Highway using three date (1985, 1988, and 1991) Landsat TM data. The rates of succession change classes provide the most important data for this research.

Table 3 Selected composite land cover characterisitcs in the Altamira subsite: 1985-1991.*

Land Cover Class	Percent Land Cover
Water All Dates	1.41
Mature Moist Forest All Dates	34.11
Slow Secondary Succession (1985-91)	15.09
Fast Secondary Succession (1985-91)	17.75
Very Fast Secondary Succession	3.64
Advanced Secondary Succession by 1991	3.90
Very Advanced Secondary Succession by 1991	5.24
Reforested	1.57
Deforested (1985-1988)	6.68
Deforested (1988-1991)	3.81
Other Secondary Succession (Interrupted)	6.80

* Figure 6 shows the composite classification of this 7,200 ha subsite.

had a fast SS in which at least a two unit change in SS was evident. The following three date sequence is representative of the category: SS1, SS2, and SS3. Some areas (five percent) experienced exceptionally fast succession which is defined as change from pasture/ crop or SS1 to a mature forest signature. Another seven percent of the area experienced interrupted succession in which there was no trend or a reverse trend toward maturity. For example, a 1985-1991 sequence of SS1 to SS2 to pasture is representative of this class.

The reasons for SS rates and patterns require analysis of additional data. It is likely that more rapid SS can occur on better soils near diverse seed sources. The areas of slower SS might be growing in poor soils or in areas which are isolated in various ways from seed sources or subject to land use which inhibit fast SS. There is some indication from field observations that a reason for existence of areas with very fast SS to a mature forest signature in less than six years is related to moist areas with good soils. The areas with reversal of succession is very complex with many subcategories, many of which are associated with cultural impacts. For example, a SS1 area in 1985 might become a SS2 class by 1988 but might be cut/burned in late 1988, thus by 1991 could be crop, pasture or a SS1 area.

The composite map (Fig. 6) splits the SS3 classes into those most likely to spectrally attain mature forest status and advanced succession forms that would take somewhat longer to assume a moist forest appearance. How long it will take to go from either of these two SS3 states to mature moist forest is unknown, but it is known that under the most favorable conditions it is possible to go from a deforested state to a mature moist forest spectrally in 15 years or less.

Full Site Individual Classifications

Table 4 presents multidate land use characteristics for the Altamira site. The patterns of land use and land cover parallel the subsite, but the amount in a category may differ.

Table 4 Land cover changes in the Altamira study area: 1985-1991.*

Land Cover Class	Percent Land Cover		
	1985	1988	1991
Mature Forest	64.01	58.73	56.99
Pasture	10.82	7.92	3.06
Initial SS (SS1)	5.58	8.58	10.90
Interm. SS (SS2)	4.19	9.97	15.47
Advanced SS (SS3)	.91	3.96	5.93
Bare	7.59	1.71	1.33
Crop	1.16	2.82	.64
Water	4.87	5.35	5.29
Wetland	.87	.96	.39

* These statistics are derived from classification of the 267,000 ha study area.

The percent of mature moist forest was higher for the full area than for the subsite, but the pattern of a decreasing deforestation rate was similar. The reason for more mature forest is that the full study area contains more remote, less developed areas away from the Transamazon Highway.

There is more water in the full area because of the presence of the Xingu River and its tributaries. Wetland is a small class in the larger study area which is primarily associated with the lowlands of rivers and streams and in small upland topographical depressions.

The percentage of the three SS classes is less in the full site because of a higher proportion of less developed remote areas. The full site pattern of soil and pasture, which accounted for a majority of deforested land in 1985 that converted to advanced levels of SS by 1991, was similar to the subsite.

Full Site Composite Classification

The full site composite classification parallels the Altamira subsite composite classification (Table 5). Variations in the amount of area in a given temporal pattern occur because the full site collectively is less economically developed than the subsite.

Noticeable differences between the full site and the subsite are the higher percentages of mature moist forest, water, and wetland. The full site composite has a small percentage of continually bare which is associated with urban areas not present in the subsite. Deforestation rates and amounts are nearly identical between the full area and the subsite.

The SS classes based on growth rate found in the subsite are also present in the full site, but the percent of area in them is less in the full site than in the subsite because the total amount of area deforested and opportunity for SS is proportionally less. Lowland succession was added in the full area analysis due to the presence of the Xingu River and tributary lowlands which can have a different succession sequence. The patterns of succession rate classes are broadly comparable between the full area and the subsite.

Table 5 Selected composite land cover characteristics in the Altamira area: 1985-1991.

Land Cover Class	Percent Land Cover
Water All Dates	4.09
Wetland All Dates	0.25
Bare All Dates	0.25
Tropical Forest All DAtes	53.50
Slow Secondary Succession (1985-91)	9.63
Fast Secondary Succession (1985-91)	8.86
Very Fast Succession	1.69
Advanced Secondary Succession by 1991	2.54
Very Advanced Secondary Succession by 1991	2.07
Reforested	0.79
Deforested (1985-1988)	6.07
Defforested (1988-1991)	3.84
Other Upland Succession (Interrupted)	4.13
Other Lowland Succession (Interrupted)	1.69

* These statistics are derived from classification of the 267,000 ha study area.

The small percentage of successional reforestation and advanced SS in the full site is less than that in the subsite. The reason is that the subsite is representative of an older more fully developed region associated with the Transamazon Highway and the full site is more of a mixture of developed and undeveloped land.

Preliminary Classification Accuracy Estimates

The proposed use of classification of features identified in this paper depends on achieving high accuracy in order to provide accurate information suitable for developing ecological models. An accuracy above 80 percent for complex classes such as those in SS will likely be suitable for modeling, but additional work needs to be done to improve classification results.

Assessment of accuracy of the classes developed in this paper is in a preliminary stage for selected features. The results (accuracy, omission, commission) presented in Table 6 are preliminary and thus will be modified as more training and test fields are developed and

Table 6 Preliminary assessment of classification accuracy for major features in the 1991 TM analysis of the Altamira area.*

Class	Number of Pixels in Class						Tot	NS	%Om	%Co	%Acc
	1	2	3	4	5	6					
1. Water	178	4	0	0	0	0	182	5	2.2	0.0	97.8
2. Forest	0	482	0	1	13	0	496	8	2.8	1.8	97.2
3. Pasture	0	0	238	18	0	10	266	5	10.5	13.2	89.5
4. SS1	0	0	18	242	14	0	274	5	11.7	15.7	88.3
5. SS2/SS3	0	5	3	20	126	0	154	4	18.2	17.5	81.8
6. Bare	0	0	14	4	0	206	224	5	8.0	4.5	92.0

Overall Accuracy 1472/1596 + 92.2%

* Tot is the total number of Pixels; NS is the number of test fields; Om is omission; Co is commission; and Acc is accuracy.

enhancement techniques (principal component, ratio) are applied in classification. The 1993 field work will fill gaps in ground truth data that are more specifically focused on classification problems identified in this research.

Table 6 provides insight into accuracy which can be supported by ground-based or other published information. The deficiencies which are reflected in the accuracy assessment are:

1. Insufficient samples of known wetland test fields were collected to assess class accuracy even though some training field statistics were developed for classification.

2. A limited number of samples of SS3 were documented during the 1992 field season. After using these few samples for training there were too few left to use for testing. It is likely that the SS3 class is reasonably accurately classified, but more samples are needed to verify this. In the accuracy table, SS3 was combined with SS2 to form a class of advanced SS, but separation of these two will be possible after the incorporation of 1993 field data.

3. The dates of TM data acquisition were not optimal for many types of crop assessment since by July most crops have been harvested. Thus, the number, quality, and representativeness of crop class samples is not ideal for classification.

The classes water, bare, mature moist forest, pasture, initial SS, and combined SS2/SS3 had sufficient ground-based data to permit a preliminary accuracy assessment (Table 6). The relative homogeneity of water and bare features, and to some degree mature forest, resulted in high classification accuracy (92.0 - 97.8%). Pasture is rather distinct, but can have minor confusion with bare soil or young initial succession, thus accuracy was relatively high overall, albeit somewhat lower than some of the more homogeneous classes (89.5%).

Initial and more advanced SS classes are subject to confusion with adjacent classes. The accuracy of SS1 is good (88.3%) but can be confused with pasture and SS2. The SS2/SS3 combined class spectrally can be similar to mature forest and older class SS1 pixels, but nevertheless class accuracy was relatively high (81.8%).

The overall accuracy (92.2%) and individual class accuracies, although preliminary, are encouraging. The addition of 1993 ground-based data should expand the number of classes and their accuracy.

Conclusions

The first objective of this research phase to assess the level of land use and land cover detail using multitemporal Landsat TM data was successfully achieved. Nine features, including three secondary succession forests, were classified with sufficient detail and accuracy that these data are likely to be suitable for implementation into environmental models which is the focus of future research phases.

The second objective to evaluate the use of the data developed to address deforestation and land use change issues in the study site was partially satisfied. Patterns of deforestation and patterns of changing land use following deforestation were identified and evaluated, which provided preliminary insights into the physical and cultural processes associated with these environmental changes. The insights acquired through development and interpretation of this preliminary classification phase of research has identified to the authors the additional data that must be developed in future classifications and field acquisitions as well as to identify potentially useful directions to explore in developing environmental models that integrate cultural and physical processes in tropical forest areas such as those near Altamira, Brazil.

The next phase of research is to maximize classification accuracy by incorporating new spectral data (i.e., TM, ERS-1 radar, digitized photography) and 1993 field acquired data. Additional classification and enhancement approaches will be used. The ecological modeling phases of research will begin using the maximized classification data combined with physical and cultural information and analyzed within a GIS.

Acknowledgements

This study was made possible by a grant from the National Science Foundation (grant 9100526) Program in Geography and Regional Science and the Program in Geography and Regional Science and the Program on the Human Dimensions of Global Environment Change. Supplementary funds were provided by grants from the Midwestern Center of the National Institutes of Global Environment Change. The authors acknowledge the assistance of Lucival Rodrigues Marinho e Jair de Costa Freitas for their help with plant taxonomy and field research-and to the Administrator of EMBRAPA/CPATU in Belem for freeing them from other obligations to collaborate with us. We also thank Dr. Mario Dantas of EMBRAPA's Center for Agroforestry Studies in Acre, for his valuable assistance in the field and in developing an effective field methodology. Responsibility for the views expressed in this paper are the sole responsibility of the authors and do not reflect the views of the funding sources or collaborators.

References

Aldhous, Peter, Tropical deforestation: not just a problem in the Amazon. *Science*, 259:1350 (1993).

Baltaxe, P.A., The application of remote sensing to tropical forest cover monitoring: a review of practices and possibilities. in *Remote Sensing Yearbook* (A. Cracknell and L. Hayes, ed.), Taylor and Francis, 690 pp. (1986).

Berta, M.S., P.W. Mausel, and J.A. Harrington, Multidate image analysis of forest degradation in Equatorial Africa. *Geocarto International*, 5:57-61 (1990).

Booth, W., Monitoring the fate of forests from space. *Science*, 243: 1428-1429 (1989).

Campbell, J.B., and J.O. Browder, SPOT survey of agricultural land uses in the Brazilian Amazon, ISPRS Commission VII, XXIX (Part B-7): 159-165 (1992).

Fiorella, M., and W.J. Ripple, Determining successional stages of temperate coniferous forests with Landsat satellite data. *Photogram. Eng. and Rem. Sens.*, 59:239-246 (1993).

Gilruth, R.T., and C.F. Hutchinson, Assessing deforestation in the Guinea highlands of West Africa using remote sensing. *Photogram. Eng. and Rem. Sens.*, 56:1375-1382 (1990).

Goldemberg, J., *Introduction: Amazonia: facts, problems and solutions.* Sao Paulo: Fundacao da Univ. de Sao Paulo and INPE, (1989).

Green, G.M., and R.W. Sussman, Deforestation history of the eastern rainforests of Madagascar from satellite images. *Science*, 248: 212-215 (1990).

Jensen, John R., *Introductory digital image processing.* Prentice-Hall, 379 pp. (1986).

Kummer, D.M., Remote sensing and tropical deforestation: a cautionary note from the Phillipines. *Photogram. Eng. and Rem. Sens.*, 58: 1469-1471 (1992).

Malingreau, J.P., C.J. Tucker, and N. LaPorte, AVHRR for monitoring global tropical deforestation. *Int. Jour. of Rem Sens.*, 10: 855-867 (1989).

Moran, E.F., *Agricultural development along the Transamazon Highway.* Center for Latin American Studies Monograph, Indiana University, Bloomington, 136 pp. (1976).

Moran, E.F., *Developing the Amazon.* Indiana University Press, Bloomington, 292 pp. (1981).

Nelson, R. and B. Holben, Identifying deforestation in Brazil using multiresolution satellite data. *Int. Jour. of Rem. Sens.*, 7:429-448 (1989).

Pires, J.M., *Tipos de vegetacao da Amazonia.* Belem: Museu Paarense Emilio Goeldi, 20: 179-202 (1983).

Sader, S.A., R.B. Waide, W.T. Lawrence, and A.T. Joyce, Tropical forest biomass and successional age class relationships to a vegetation index derived from Landsat Tm data. *Rem. Sens. of Environment*, 28: 143-156 (1989).

Sader, S.A., T.A. Stone, and A.T. Joyce, Remote sensing of tropical forests: an overview of research and applications using non-photographic sensors. *Photogram. Eng. and Rem. Sens.*, 56: 1343-1351 (1990).

Shukla, J., C. Nobre, and P. Sellers, Amazon deforestation and climatic change. *Science*, 247: 1322-1325 (1990).

Skole, David, and Compton Tucker, Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science*, 270: 1905-1910 (1993).

Woodwell, G.M., R.A. Houghton, T.A. Stone, R.F. Nelson, and V. Kovalick, Deforestation in the tropics: new measurements in the Amazon Basin using Landsat and NOAA Advanced Very High Resolution Radiometer imagery. *Jour. of Geophysical Research*, 92: 2157-2163 (1987).

ACT Publications 1993

No. 93-01
Mausel, P., Y. Wu, Y. Li, E.F. Moran, and E.S. Brondizio. "Spectral Identification of Successional Stages following Deforestation in the Amazon." *Geocarto International* 8(4):61-81.

No. 93-02
Moran, E. F. "Managing Amazonian Variability with Indigenous Knowledge" In *Tropical Forests, People and Food: Biocultural Interactions and Applications to Development*. C.M. Hadlik et al. (eds.). Pp. 753-765. Paris: UNESCO/Parthenon Publ. Vol. 15 in Man and the Biosphere Series.

No. 93-03
Moran, E.F. "Deforestation and Land Use in the Brazilian Amazon." *Human Ecology* 21:1-21.

No. 93-04
Moran, E.F., E.S. Brondizio, P. Mausel, and Y. Li. "Assinaturas Espectrais Diferenciando Etapas de Sucessao Secundaria no Leste Amazonico" *Anais do VII Simposio Brasileiro de Sensoriamento Remoto.* 2: 202-209.

No. 93-05
Brondizio, E.S., E.F. Moran, P. Mausel, and Y. Wu. "Padroes de Assentamento Caboclo no Baixo Amazonas: Analise Temporal de Imagens de Satelite para estudos de Ecologia Humana de Populacoes da Amazonia". *Anais do VII Simposio Brasileiro de Sensoriamento Remoto* 1: 16-26.

No. 93-06
Brondizio, E.S., E.F. Moran, P. Mausel, and Y. Wu. "Dinamica na Vegetacao do Baixo Amazonas: Analise temporal do Uso da Terra integrando imagens Landsat TM, levantamentos florísticos, e etnograficos" . *Anais do VII Simposio Brasileiro de Sensoriamento Remoto* 2: 38-46.

No. 93-07
Moran, E.F. "Minimum Data for Comparative Human Ecological Studies: Examples From Studies in Amazonia." *Advances in Human Ecology* 2:187-209.