Land Cover in the Amazon Estuary: Linking of the Thematic Mapper with Botanical and Historical Data

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Abstract

A Landsat TM scene from July, 1991 was analyzed for an area of the Amazon estuary in Ponta de Pedras, Marajó Island, Brazil. Distinctive spectral signatures were determined for 14 land-cover classes, including upland and floodplain forest, three stages of secondary succession, palm forest, mangrove, pasture, and three types of savanna. Image classification (unsupervised and supervised using a hybrid maximum-likelihood/texture algorithm) of the study area was conducted using the 14 class spectral statistics informed by 1992 vegetation inventories and field studies documenting historical land use. The use of field-based information supportive of classification resulted in individual test field class results which ranged from 81 to 100 percent individual class accuracy. Historically, attainment of good accuracy for many of these classes using satellite data has been difficult, but this research indicates suitable accuracy can be obtained using TM data when carefully integrated with detailed ground surveys. Elements of the classification were focused on addressing the difficult problem of identifying the conversion of "natural" to "managed" floodplain forest. The combination of feature classification using computer-analyzed TM data in conjunction with detailed ground measurements/surveys permitted identification of subtle changes in natural forest that was associated with conversion to managed floodplain forest.

Introduction

There has been growing use of remote sensing to monitor land cover in the Amazon Basin. These studies have been important in bringing to public attention the exponential increases in deforestation that took place in the second part of the 1970s and up to 1987 when the peak rate was reached to date. Estimates of deforestation in the Amazon have fluctuated between 15,000 and 50,000 square kilometres each year since the 1970s (see Skole and Tucker (1993) for the most recent assessment). Up to now, at least 12 percent of the Brazilian Amazonian forests have been affected. Despite the growing use of remote sensing in the monitoring of change in forest cover in the Amazon Basin (Booth, 1989; Riggan *et al.*, 1993; Setzer and Pereira, 1991; Shukla *et al.*, 1990; Tucker *et al.*, 1984; Woodwell *et al.*, 1987), its uses in monitoring *post-deforestation processes* have been limited. The heterogeneity of the vegetation has been commonly thought to make it nearly impossible to monitor land-cover dynamics. Woodwell *et al.* (1987) were unable to differentiate secondary successional forest regrowth from mature forest in Rondonia using MSS or AVHRR. The scale of analysis possible with MSS and AVHRR is too coarse to permit study of local environmental and socio-economic dynamics at the field level. Others have suggested that the use of 30-metre-resolution Landsat Thematic Mapper (TM) images makes it possible to delineate these processes when combined with detailed field studies (Sader *et al.*, 1990; Moran *et al.*, 1994b).

This study explores the extent to which TM data can be used to discriminate between 14 classes of vegetation in the complex tropical forest and savanna area of Marajó Island, Brazil when spectral data are closely linked with structural and floristic surveys of plant cover, and historical/ethnographic studies of land use. Methods were employed which focused on differentiating between classes of interest. Special emphasis was accorded to accurately differentiate between natural and managed floodplain forests in order to specifically illustrate the linking of spectral and botanical/historical data. Historically, the type of land-cover differentiation attempted in this research has been difficult or impossible to obtain in areas with great diversity or no clear dominance of tree species. The problem has been the sole reliance on satellite data, which results in making Amazon-wide statements that are not based on detailed site-specific ground truth at the level of specific fields and households land use. Successful discrimination of the land-cover classes in the Amazon using remote sensing methods could result in GIS databases to address important land-use, economic management, and environmental planning strategies. In addition, multitemporal databases can be used to focus on *land-use* and vegetation dynamics which have important implications in global change/carbon cycle research.

Study Area

The study area is located in the county of Ponta de Pedras, Marajó Island, Pará, Brazil. Marajó Island has an area of approximately 50,000 square kilometres (Figure 1), which is roughly divisible into 23,000 square kilometres of natural grasslands (Pires, 1983) and about 27,000 square kilometres of forests (Prance, 1980). The grasslands are seasonally flooded, whereas most of the forests are flooded daily by the influence of the tides. Patches of upland forest are present

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Photogrammetric Engineering & Remote Sensing, Vol. 62, No. 8, August 1996, pp. 921–929.

0099-1112/96/6208–921$3.00/0

which do not experience flooding. A rich array of vegetation and biotopes are present, including extensive mangroves, palm forests, flooded forests affected by the tides, *Imperata*-dominated savannas, and upland forests. Along the natural grasslands are islands of forests, some of them on mounds of likely prehistoric origin, while others are related to drainage characteristics.

The human population of the region may be found in a small number of urban centers, or scattered along the river banks in a typical pattern going back at least to the rubber boom in 1880 to 1920 (Wagley, 1953; Moran, 1993; Moran, 1974; Parker, 1985). The prehistoric peoples of Marajó have long attracted attention, resulting in a substantive literature (Meggers and Evans, 1957; Roosevelt, 1989; Roosevelt, 1991) that has tried to explain the presence of large-scale settlements and mound-buildings cultures. The dominant explanations posit external occupation followed by devolution, or endogenous developments that antecede even those of the Andes. In contrast, very little attention has been paid to the populations on Marajó Island since contact with Europeans.

In the last two decades, as a result of increased market demand, rural populations settled in the productive floodplain environment have reinforced the use of locally developed agroforestry techniques to intensify management of floodplain forests. Management's main goal is to increase the fruit production of Açaí (*Euterpe oleracea*), a multi-stemmed palm tree that occurs naturally in the floodplain environment. The juice extracted from its fruit is a staple food in the region as a whole, and has become the most important source of income for riverine populations (Brondizio and Siqueira, 1995).

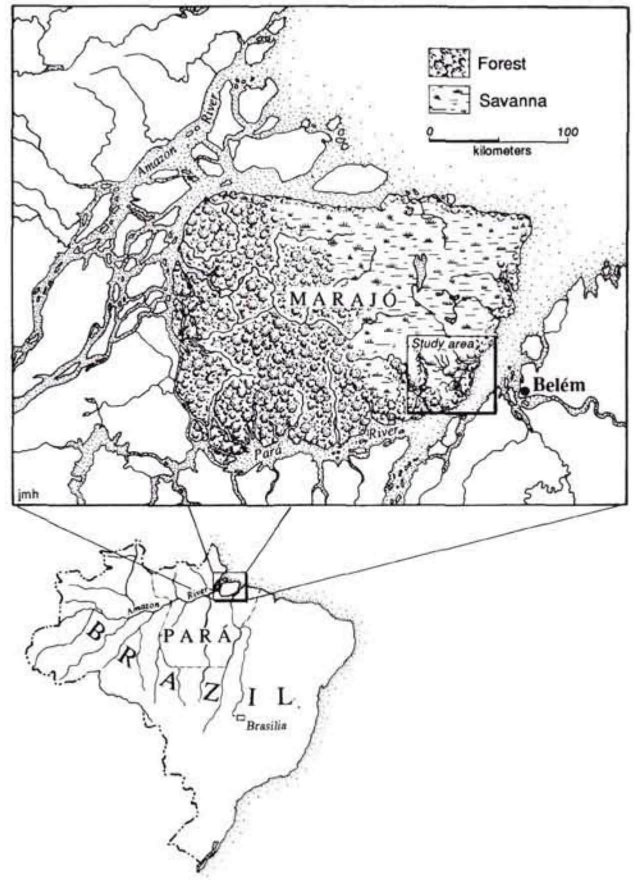

Figure 1. Study area, Marajó Island, Pa, Brazil.

Methods

A July, 1991 Landsat TM image (row/path 224/61 centered at 1° 25' S and 48° 54' W), acquired during one of the few periods with little cloud cover in the study area, was used for analysis after excluding TM band 6. Work proceeded using two software packages, ERDAS 7.5 running on an HP/Apollo 730 Unix workstation and MULTISPEC 6.93 (Landgrebe and Biehl, 1993) running on a Macintosh Quadra 800.

The TM scene was geocorrected to a UTM map projection. Ground control points were taken from available 1:100,000-scale topographic maps (FIBGE, 1984), and the georeferenced image was related to waypoints collected through use of a Magellan Nav 1000 Pro GPS (Global Positioning System) device. By relaying the collection of numerous waypoints in the field, in all areas observed and sampled, it was possible to reliably relate the plant cover observed in the field to the remotely sensed imagery.

Training samples spectrally representative of the 14 land-cover classes were developed by clustering (40 to 60 clusters) several areas of known character identified in the field. All of these clustered areas (each approximately 15,000 pixels in size) contained field checked samples of four or more classes of interest. The cluster patterns and their associated spectral statistics were analyzed in conjunction with specific features identified in the field and located with a GPS. Information about the history of land use and plant cover of the areas was incorporated into the analysis. Relative spectral response statistics in the form of means, standard deviation, and correlation were developed for each of the 14 land-cover classes of interest. Before initiating supervised classification, the six band TM training field statistics were subjected to transformed divergence separability (TDS) analysis to determine if reduction in band dimensionality was appropriate and was likely to provide good supervised classification results using a band subset. A hybrid maximum-likelihood/texture classifier developed at Purdue University and designated ECHO or Extraction of Classes of Homogeneous Objects (Scholz *et al.*, 1977; Landgrebe and Biehl, 1993) was used to identify and discriminate between the 14 classes using the best four bands of data as identified by separability analysis. ECHO is a spatial-spectral classifer. It uses a two-stage process, first segmenting the scene into statistically homogeneous regions, and then classifying the data using a maximum-likelihood approach. It uses the same training fields and statistics as a conventional maximum-likelihood classifier; however, there are three selective parameters which are used to vary the degree and character of spatial relationships used in classification. Because previous research in other areas of humid tropical Brazil indicated that texture information greatly improved classification accuracy, ECHO was used (Li *et al.*, 1994). Classification accuracy was assessed using a test field approach in which fields of known features were classified using the spectral statistics developed from cluster-based training fields. An error matrix was developed and interpreted, providing insights into classification accuracy.

Field studies were conducted in June and July of 1992 to locate representative areas of each class and to select sample areas from which information about plant cover type, vegetation structure and composition measurements, land-use and management history, and patterns of feature distribution was acquired. Household-level interviews were carried out to record the sequence of management steps used in an specific area of floodplain forest. Data collection included the date since the forest had been thinned, prunning of Açaí (*Euterpe oleracea*) clumps, planting of seeds and seedlings, yield through the years, etc.. A fieldwork protocol based on a NASA fieldwork guide was developed (Joyce, 1978). Twenty-seven sample areas (one to four for each land-cover feature) were subjected to detailed observation and measurement, which included floristic composition at the species level, density, frequency, dominance and basal area, percent of soil covered, height of first branch, and total height. Although the selection of areas with differential management was based on interviews with local Açaí producers, a concern with the spatial distribution of the sites on the TM image was also taken into account. During the inventory, four adjacent plots (25 by 25 m) and four nested *sub-plots* (2 by 5 m) were randomly distributed in the managed area. In each plot all the trees (DBH > 10 cm)[1] were identified, and DBH, as well as stem and total height, were measured. In each plot all Açaí (*Euterpe oleracea*) with DBH > 5 cm were counted, taking into account the number of stems per clump. In the subplots all the individuals were identified and counted, and saplings (DBH > 2 cm) were measured for DBH and total height. In the unmanaged floodplain forest site, the number of plots and subplots was doubled (i.e., eight plots of 25 by 25 m). These data were incorporated into a database (Quatro Pro 3.0) and related to image characteristics through the coordinates obtained by the use of the GPS. Relationships between the database and the image was accomplished using ARC/INFO 3.4 software.

Species "Importance Value" data of unmanaged and managed floodplain forest was derived from the field measurements of seven of the 27 sample areas. The transformation of the natural floodplain forest into a managed one can be clearly seen in the change in "importance values." Importance value (I.V.) is an index that combines density, frequency, and relative dominance (Curtis and MacIntosh, 1952). The I.V. index was originally developed by Curtis and MacIntosh as a way to provide a logical arrangement of "dominant" species in a given stand. By taking into account relative frequency, density, and dominance, it balances the different characteristics of a species as it occurs in a plant community. Density indicates the number of individuals of a species, showing the species significance in relation to the community as a whole. Frequency is an expression of the spatial distribution of a species within the stand. Finally, dominance indicates how much a species contributes to the stand in terms of biomass. Basal area, which is the cross-sectional area possessed by the trunk of a tree species, is the most used indicator of species dominance. Therefore, by assigning a percentage index (0.0 to 1.0), I.V. provides a practical classification of species in the plant community, specifically in a heterogeneous habitat, where most species do not have a high level of importance in the stand. These data, in addition to other structural features (e.g., stem and total height, density of understory vegetation), were evaluated with the TM classification to provide an example application in which detailed field measurements support classification results or, conversely, classification is supported by knowledge of the detailed vegetation feature structure.

[1]Diameter at Breast Height

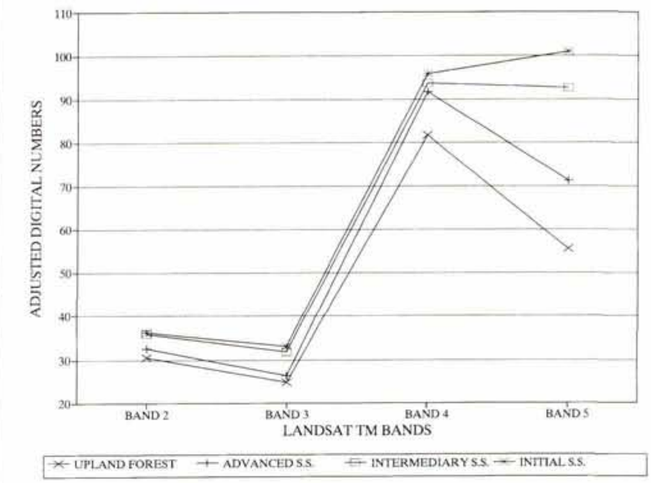

Figure 2. Spectral curves of features representing successional regrowth stages through upland forest using Landsat TM data from July, 1991, Marajó Island, Brazil.

Results and Discussion

Classification

The mean relative spectral response values and associated standard deviations, represented as digital numbers (DN), are shown on Table 1 for all 14 classes of interest. According to separability analysis, TM bands 2 through 5 were determined to be the best band subset which had power comparable to all TM bands to discriminate between the 14 classes. Thus, these four bands were used to develop the training statistics used in the supervised classification. The spectral signature of each of the classes was distinctive, but was rather similar between a few classes (i.e., pasture versus pasture with palms, açaí palm forest versus floodplain forest). Figures 2 and 3 show the spectral patterns of classes difficult to differentiate using satellite data such as stages of forest succession

Table 1. Digital Numbers Representing Spectral Signatures of Land-Use/Land-Cover Classes in Marajó Island, Brazil, Using Landsat TM, Bands 2 through 5, July, 1991.

Classes	Band 2	S.D.	Band 3	S.D.	Band 4	S.D.	Band 5	S.D.
Water	34.8	0.7	35.8	1.2	32.1	4.4	10.1	4.2
Upland Forest	30.5	0.5	24.8	0.4	81.7	1.6	55.4	4.0
Floodplain Forest	30.5	0.3	28.4	0.5	71.0	4.2	46.9	4.7
Açaí Palm Forest	30.9	0.5	28.9	0.6	77.6	3.9	46.3	5.0
Mangrove/Marsh	32.8	0.9	32.9	1.6	52.4	8.0	32.6	0.4
Bare Soil	45.5	2.4	52.5	3.5	60.9	4.2	107.9	7.2
Pasture	39.0	0.8	35.8	2.3	98.0	3.3	115.0	3.5
Pasture w/Palms	37.0	0.2	34.1	0.6	96.7	2.6	112.5	4.1
Initial S.S.	36.1	0.2	33.0	1.1	95.9	6.3	100.9	4.5
Intermediate S.S.	35.9	0.7	31.8	1.3	93.6	3.8	92.6	5.0
Advanced S.S.	32.6	0.4	26.3	0.7	91.7	3.5	71.2	5.4
High Savanna	31.7	0.4	33.9	0.2	44.0	3.7	69.8	3.8
Low Savanna	33.2	0.8	35.0	1.2	55.5	3.5	78.1	2.2
"Imperata" Savanna	32.3	0.6	31.4	1.1	65.6	1.8	61.5	2.1

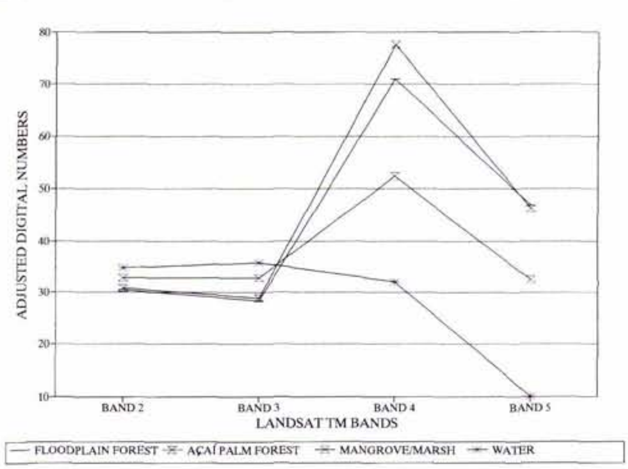

Figure 3. Spectral curves of Floodplain Forest, Açaí palm forest, and associated features using Landsat TM data from July, 1991, Marajó Island, Brazil.

and managed versus unmanaged floodplain forest. Although some land-cover classes have very distinct reflective properties and, hence, spectral signatures, other features of interest had more complex spectral characteristics because of a mix of earth features and were subject to considerable variation over small distances. The spectral definition of these classes is somewhat "noisy" as are any classes that name a land-cover type that represents dynamic plant communities along a continuum. Secondary succession occurs along a continuum that represents numerous factors such as land-use history, age of secondary growth, opportunistic colonization by pioneer and gap species, and landscape features such as soil quality and slope. Late initial secondary succession grades imperceptibly into an early intermediate succession as may be observed on Figure 2, which shows the similarity of spectral signatures except for the ability of near and mid-infrared channels to distinguish between structure and moisture content (which reflects greater shadowing and stratification with time).

The classification using these spectral signatures in the hybrid maximum-likelihood/texture classifier ECHO is shown in Plate 1. Although all 14 classes were classified successfully, only eight are displayed in Plate 1 to improve image interpretability by readers. Three classes of forest succession were combined as a single succession class. Differentiation of succession classes is very important in many types of Amazonian research (Mausel *et al.*, 1993; Li *et al.*, 1994; Moran *et al.*, 1994a) and such difficult discrimination represents a significant achievement; however, these classes are not used individually in application in this paper and thus were combined. A similar merging of three savanna types and two pasture variants, which were classified well individually, results in creating a single class of savanna and a single class of pasture (Brondizio *et al.*, 1994).

The classification accuracy using the test fields derived from field observations are shown in a confusion matrix (Table 2). Individual class accuracies ranged from a low of 81.0 percent for palm forest and a high of 100.0 percent for mangrove, soil, and pasture with palm. The overall accuracy was 94.1 percent, which represents a level of feature classification suitable for applications to Amazonian problems.

The differences in the spectral signatures shown in Table 1 can be related to four basic interactions. TM band 2 (green) and particularly TM band 3 (red) wavelengths are absorbed greatly by chlorophyll; thus, features with large amounts of vigorous green vegetation which completely cover the surface (e.g., mature and advanced successional forests, very dense savanna grasslands) have low spectral responses in these bands. Bare soil or vegetation types which have some bare soil showing through the vegetation (e.g., some pasture and savannas) have increased spectral responses because there is less or no chlorophyll absorption.

Reflectance from plant mesophyll increases spectral response values as healthy green biomass increases. The near-infrared TM band 4 is most influenced by this mesophyll

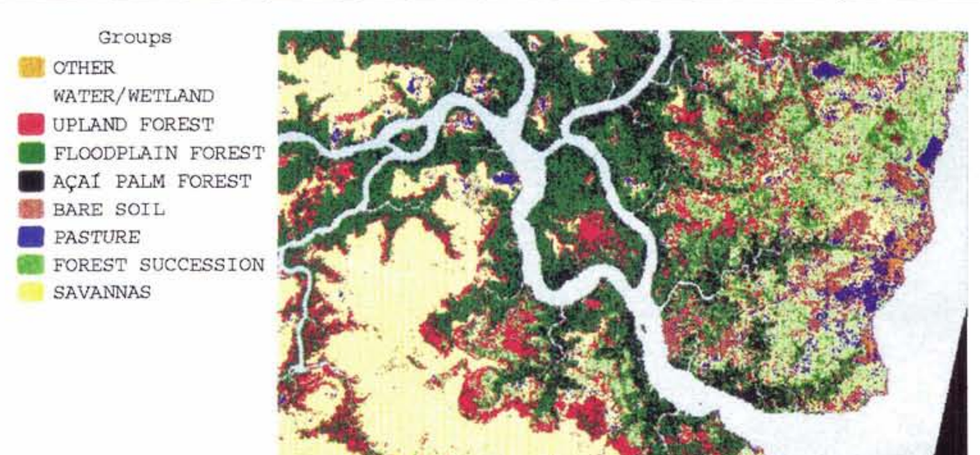

Plate 1. Nine land-cover classes produced from a supervised maximum-likelihood/texture (ECHO) classification of the study area on Marajó Island, Brazil, using Landsat TM data from July, 1991. Successional forests, savannas, and pasture types were aggregated.

Table 2. Error Matrix for Fourteen Features on Marajó Island, Brazil. Classified Using Landsat TM Data from July, 1991.

	Number of Pixels in Class																		
Class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total	NS	% OM	% CO	% A
1	156				1										157	2	.1	.0	99.9
2		137	5	1								3			146	3	6.2	.0	93.8
3			117	3											120	7	2.5	5.8	97.5
4				17	4										21	6	19.0	19.0	81.0
5					43										43	7	.0	11.6	100.0
6						13									13	4	.0	169.2	100.0
7						5	34								39	2	12.8	2.6	87.2
8								8							8	1	.0	.0	100.0
9						1			38	1				2	42	2	9.5	16.7	90.5
10										89	1				90	3	1.1	3.3	98.9
11			2								18				20	4	10.0	5.0	90.0
12						16	1		6			151			174	2	13.2	4.0	86.8
13												4	116		120	1	3.3	.0	96.7
14									1	2				12	15	1	20.0	13.3	80.0
Total	156	137	124	21	48	35	35	8	45	92	19	158	116	14	1,008				94.1

NS = Number of Samples; % OM = Omission Error; % CO = Commission Error; %A = Accuracy

Classes (1 = Water; 2 = Upland Forest; 3 = Floodplain Forest; 4 = Açaí Palm Forest; 5 = Mangrove; 6 = Bare Soil; 7 = Pasture; 8 = Pasture with Palm; 9 = Initial Secondary Succession; 10 = Intermediate Secondary Succession; 11 = Advanced Secondary Succession; 12 = High Savanna; 13 = Low Savanna; 14 = Imperata Savanna)

reflectance. The high green biomass features in the study area such as forests, secondary succession classes, and pasture have higher relative spectral responses than do other classes largely due to their greater biomass and consequently more mesophyll structures that reflect near-IR wavelengths. Many savannas during the time of data acquisition had reduced green biomass due to low precipitation during the dry season. Classes influenced by standing water have a depressed TM band 4 spectral response. It should be noted that near-IR spectral responses are not proportional to the amount of green biomass present. For example, upland forest, floodplain forest, and açaí palm forest have relatively high, but reduced, spectral response values compared with the five pasture and forest secondary succession classes even though the biomass of the three forest classes generally is higher than other classes in the study area. A possible reason for this relates to vegetation geometry and associated shadowing which is discussed later.

TM band 5 is affected by water absorption; thus, classes that are influenced by standing water (i.e., water, mangrove) have naturally low spectral responses. Vigorous vegetation features with high biomass that completely cover the ground have a large quantity of water stored in their biotic system which absorbs much of the TM mid-IR wavelengths. Classes such as the mature forests and advanced succession have their spectral response reduced in TM band 5 due to water absorption. Pasture classes, the less advanced forest succession classes, soil, and to a lesser degree savanna classes have relatively high TM band 5 relative spectral response values, indicating less absorbing effects by water. The high response of soils in TM band 5 is understandable because they were somewhat dry during the date of data acquisition. These vegetation classes with somewhat high relative spectral responses are likely the result of less total stored water in their biotic systems combined in many cases with the influence of dry soil which is responsible for part of the composite signatures of some of the classes such as pasture and early stages of succession.

The effects of chlorophyll absorption, mesophyll reflectance, and water absorption give unique spectral patterns to most of the 14 classes of interest. However, a fourth factor should be considered in order to understand why the spectral pattern of one feature differs from another. A knowledge of plant geometry and the nature of shadowing and/or spectral traps associated with such geometry is needed to help explain why high biomass features such as mature forest have relatively modest reflectance in the near-IR band even though mesophyll conditions encourage high spectral responses. Complex and multicanopy vegetation such as mature forest create large areas of shadow and spectral traps which reduce the amount of energy returning to a sensor. This effect is particularly noticeable in TM band 4 which normally has high reflectance from green vegetation. Moderately high biomass/mesophyll features such as dense pasture will have a much higher relative spectral response in TM band 4 than will mature forest, in part because the plant geometry is less complex, is less likely shadowed, has less moisture content, and is less likely to trap incoming or outgoing energy. The effects of plant geometry also strongly affect TM band 5 wavelengths. Thus, consideration of the effects of plant geometry and its impacts on spectral response needs to be combined with other basic spectral interactions discussed. Distinctive spectral signatures were acquired for the 14 classes in Ponta de Pedras, and a reasonable theoretical explanation of them can be developed through analysis of chlorophyll absorption, mesophyll reflectance, moisture absorption, and plant geometry.

Managed versus Unmanaged Floodplain Application

Once classification accuracy was deemed acceptable, several research themes could be addressed linking TM spectral data in original and classified forms with detailed biotic measurements acquired in the field to address issues of important economic and/or environmental consequence. Several of these themes have been and are being addressed in Marajó Island and other parts of Amazonia using single date and multitemporal imagery. A multitemporal example is assessing rates of forest succession and their relationships with physical and cultural parameters (Mausel *et al.*, 1993; Li *et al.*, 1994; Moran *et al.*, 1994b, Brondizio *et al.*, 1994). One theme of the research explored in this paper is determining whether it is possible to use TM data to discriminate between two dense floodplain forests; one forest in its natural state and the other forest managed to contain a sufficient amount of *Euterpe oleracea* or açaí palm to be economically profitable. Currently, these managed areas are the most important source of

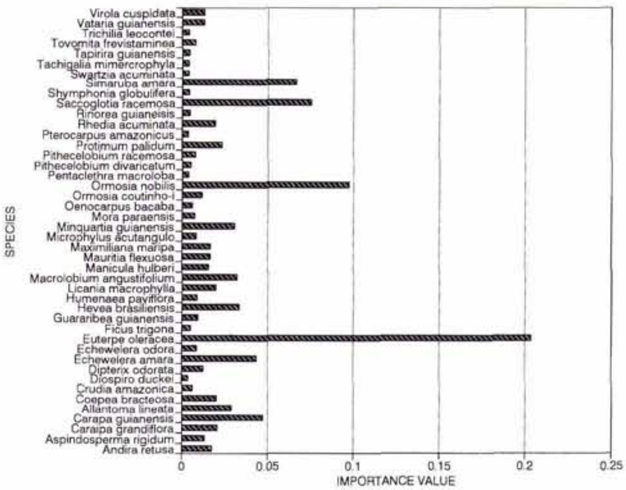

Figure 4. Importance values of common tree species inventoried in an unmanaged floodplain forest study site on Marajó Island, Brazil, derived from June-July, 1992 field data.

income in the region, representing a key element for rural development.

Floodplain forest influenced by the tides (Prance, 1980; Anderson, 1990; Brondizio and Neves, 1992) occurs in Quaternary sites and have a complex structure, with emergent species and a high diversity of palms like açaí (*Euterpe oleracea*), "jupatí" (*Raphia taedigera*), "burití" (*Mauritia flexuosa*), "marajá" (*Bactris maraja*), and many others. This type of vegetation experiences the influence of the daily tides. According to Lima (1956), this type of floodplain forest occupies about 25,000 square kilometres of the Amazon estuary. A second type of vegetation is *Açaí palm forest* — an anthropogenic vegetation resulting from the management of areas where *Euterpe oleracea* is dominant. Calzavara (1972) estimated that these palm forests occupy 10,000 square kilometres in the lower Amazon. Despite their importance, there has not been a systematic survey to establish the areal extent of palm and floodplain forests.

The training field spectral statistics indicate that natural floodplain forest has a spectral signature (Table 1) that is very similar to a managed floodplain forest except in the near-IR region (e.g., TM band 4). The açaí palm-dominated managed forest has a higher near-IR DN value in band 4 than does the unmanaged floodplain forest. Classification of açaí palm and floodplain forest was satisfactory even though spectral signatures are similar in most other TM bands. The managed floodplain forest was 81.0 percent accurately classified. The 19 percent of pixels misclassified were identified as unmanaged or natural floodplain forest. Such a level of discrimination is good considering the spectral similarities between açaí palm managed forest and floodplain forest and represents data acceptable for practical applications. The unmanaged floodplain forest had a classification accuracy of 97.5 percent, with managed floodplain forest as its only class of confusion.

In order to explain the slightly different spectral signatures between the two managed and unmanaged classes, which led to reasonable discrimination between them when a texture-based classifier was used, it was necessary to thoroughly assess the biotic structure of the two forests as well as their land-use history. Detailed measurements were made on seven fields which graded from unmanaged floodplain forest to intensively managed floodplain forest. The measurements included relative density, relative frequency, basal area, relative dominance, stem height, total height, and importance value (an index combining several parameters). Two fields which best illustrated the conversion of "natural" to "managed" floodplain forest were used for analysis. A brief history of recent agricultural events puts the "natural" to "managed" floodplain forest conversions into perspective and indicates the economic significance of such conversions.

Large-scale deforestation in the study area occurred between 1960 and 1980 as a result of agricultural development projects promoted by the local bishop. The use of mechanization in these projects led to rapid land clearing. The relatively poor soils (yellow latosols or oxisols) were unable to sustain production due to low levels of phosphorus and low cation exchange capacity, among many other constraints. High levels of fertilizer inputs were used to sustain annual crops and permanent crops, despite low levels of output. As the price for the fruit of the "açaí" palm (*Euterpe oleracea*) increased in the largest city in the Amazon, Belem, there was a growing conversion of unmanaged floodplain forest to intensive agroforestry management, seeking to increase the density of this palm. Production in Ponta de Pedras increased from 4,000 tons of the fruit in 1975 to 11,158 in 1985 and to 38,450 in 1989 (FIBGE, 1974-1989).

The challenge of distinguishing between the açaí palm and floodplain forest from a satellite platform becomes clear when one notes the nature of this transformation and the diversity of these forests. Local farmers begin management by selectively removing undesirable trees — those likely to compete at the canopy level with the desired palms. Efforts were made to maintain the stratification and overall structure of the floodplain forest considering that maintenance of desirable tree and vine species other than açaí are fundamental to the local economy. Selective cutting of understory species and vines follows. Selective removal of both the offshoots and older high stems of the açaí palm is made to encourage maximum production from those remaining and to decrease canopy height and facilitate harvesting. Finally, there is additional planting of seeds and clones in open areas to increase density. More productive palms are used to generate additional clones and seeds. Despite the considerable modification of species composition, the managed areas largely retain the functional and structural characteristics of the floodplain forest — but with a larger concentration of plants of economic value — especially for *Euterpe oleracea* or açaí (Plate 1) and lower canopy. Additional details on the ecology and management of these palm forests may be found in Calzavara (1972), Anderson and Jardim (1989), Anderson (1990), Brondizio and Siqueira (1995), Balick (1988), Murrieta *et al.* (1989), and Moran *et al.* (1994a).

The "importance value" of a field representing unmanaged floodplain forest is shown in Figure 4 and the "importance value" of managed forest is shown in Figure 5. The forest characteristics that differentiate between natural and managed flooplain forests is the greater dominance of *Euterpe oleracea* in the managed forests and the reduced canopy height of the managed areas. Vegetation stand inventories were developed for seven fields and provided evidence of management effectiveness in floodplain forest. These data are too extensive to present in this paper in tabular form but a summary table of the forest inventories (Table 3), the "importance value" (Figures 4 and 5) and the following descriptive information provides insight into these data. The unmanaged floodplain forest field contained 44 significant tree species for which detailed data were collected, while the managed floodplain forest field had only 15 species. The importance value of the managed forest is dominated by açaí palm with a value of 0.69 while the 14 other significant forest species have values generally 0.05 or less. Açaí palm also dominated the unmanaged or "natural forest" in the study area, but the importance value was only 0.22, and 43 additional forest species were present in amounts with importance values generally less than 0.05. It is evident from a comparison of the two forest forms that measurable structural differences exist that can influence the spectral signature of each. Vegetation composition declines not only in terms of tree diversity, but also in the number of individuals per species in favor of Açaí (*Euterpe oleracea*). Table 3 shows that importance values of açaí increasing as species diversity declines with increased management. The more managed the floodplain forest, the fewer the number of species with diameters above 10 cm DBH and the greater the dominance and importance value of açaí. Following changes in tree composition, there is a decrease in the average canopy height from 19.0 m to 16.5 m and a change in first stem height from 12.4 m to 10.0 m. Considerably taller trees (e.g., emergents) still occur on managed forests. The vigor of biomass, represented by relative dominance (basal area), also confirms the variation between both stands. An important parameter here is the increase in percentage of Açaí basal area (7.2 percent to 51.4 percent) in relation to the total basal area of the stand (Table 3). It is interesting to note that management does not radically change stand biomass, but rather which species contribute to it. It shows that it is possible to achieve intensification in management and production without disrupting structural-functional characteristics of the forest. The reduced canopy height, and the virtual absence of understory vegetation in the managed areas, facilitates spectral separation. Spectral difference between the two forest types is most pronounced in both TM band 4 (near-IR) and TM band 5 (mid-IR) where forests of comparable biomass have different canopy geometry. The unmanaged forest has more shadow associated with its canopy, resulting in lower near-IR reflectance than managed forest.

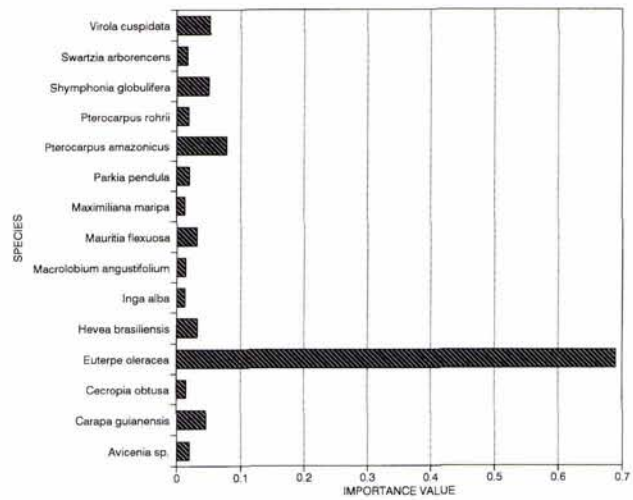

Figure 5. Importance values of common tree species inventoried in a managed floodplain forest (açaí palm forest) study site on Marajó Island, Brazil, derived from June-July, 1992 field data.

Conclusions and Recommendations

Greater detail about vegetation types was achieved in the study area using computer-analysis of Landsat TM data than is usually possible. This degree of success, in which 14 classes were successfully delineated, is attributed significantly to the availability of precise GPS-based location of test and training fields and detailed field observations and measurements which were linked with the TM spectral data. A classification approach which incorporated elements of texture is very important in developing good feature discrimination (Li *et al.*, 1994).

Classification accuracy for individual classes ranged from approximately 81 to 100 percent. The size of some of the test fields, which was the basis of classification accuracy, was smaller than desired for some classes. Additional test fields for selected classes were developed during 1993 and 1994 field work and have been incorporated into the study to further refine and verify accuracy results.

This research indicates that class accuracies are sufficiently high to provide data for application to other research problems such as determining rates of forest succession for implementation into carbon cycle global change research (using multitemporal data). The application addressed in this research using elements of the classified data was based on assessment of elements of physical and economic status of floodplain forests which have varying degrees of açaí palm dominance associated with increasing management.

In the absence of detailed field information such as vegetation structure, vegetation composition, and land-use history, discrimination between managed and unmanaged floodplain forests is unlikely. This study, by incorporating these field data, was able to discriminate between forests which have great economic significance in the region in terms of rural development.

Verification and insights into the differentiation of these two forest classes was made by measuring important physical parameters associated with important tree species found in each forest during the 1992 field data collection expedition. Differences in dominance of açaí palm in the two forest types were determined from the field data. The difference in açaí palm dominance resulted in slight variation in spectral signatures between floodplain forest dominated by açaí palm and floodplain forests containing normal amounts of açaí.

It was determined from analysis of field data that the açaí-dominated forest was shorter overall and had a less complex canopy. These physical characteristics helped to explain theoretically why the relative spectral response of managed forest was somewhat higher in TM band 4 than the unmanaged forest because less shadow and spectral traps were present.

Analysis of field data indicates that in the managed forest açaí palm was dominant and had a high importance value of approximately 0.69. While the açaí palm in the unmanaged forest was the most common species, other forest species were also numerous, resulting in an açaí importance value of 0.22. Additional research needs to be conducted to determine the degree of spectral differentiation possible if the açaí palm importance value falls below 0.69. It may be possible to identify several stages of açaí palm dominance in this area using analysis of TM data. Information derived from discriminating between açaí stages could have important economic applications.

Work has begun on statistical analysis of the detailed measurements of tree species in the seven fields containing variations in açaí palm dominance. It is hoped that statistical indices developed may help to quantitatively describe plant/plant-canopy conditions which can be linked to TM spectral signature patterns.

TM data from 1984, 1985, 1987, 1988, 1991, and 1994 have been or are being acquired to address other land-use, carbon cycling, and ecological management problems or concerns in this part of Amazonia which require or benefit from multitemporal approaches to analysis. This type of research is the focus of other articles that show that a multitemporal

TABLE 3. VEGETATION INVENTORY SUMMARY TABLE OF SEVEN SITES INCLUDING UNMANAGED AND MANAGED FLOODPLAIN FOREST IN PONTA DE PEDRAS, MARAJÓ ISLAND, PA, BRAZIL (INCLUDING THEIR RESPECTIVES COORDINATES).

					Basal Area (B.A.)						
Sites*	# Species	Tot. # Indiv. &	Tot. # Açaí @	% Açaí	Tot. B.A. (m2/ha)	Açaí B.A. (m2/ha)	Açaí % Tot. B.A.	Açaí #Stems/ clump	Açaí Imp. Valu	Site Location Latitude	Longitude
Site 1 (5000 m2)-Unmanaged	43	395	177	44.8	31.77	2.28	7.21	6.3	0.22	1°23'06"S	48°55'00"W
Site 2 (2500 m2)-Managed	28	697	587	84.2	41.9	6.63	15.8	4.8	0.63	1°25'43"S	48°52'11"W
Site 3 (2500 m2)-Managed	13	603	562	93.2	23.5	8.65	36.8	5.1	0.55	1°20'49"S	48°54'20"W
Site 4 (2500 m2)-Managed	18	913	857	93.8	25.7	13.1	50.9	3.9	0.61	1°22'01"S	48°54'27"W
Site 5 (2500 m2)-Managed	11	501	470	93.8	22.8	9.44	41.4	3.6	0.72	1°25'48"S	48°52'18"W
Site 6 (2500 m2)-Managed	15	542	496	91.5	24.6	12.6	51.4	3.4	0.69	1°25'45"S	48°52'18"W
Site 7 (2500 m2)-Managed	14	746	708	94.9	28.7	10.8	37.6	3.1	0.69	1°21'43"S	48°52'46"W

* – Sites located at Ponta de Pedras, Marajó Island, PA, Brazil.
& – Considering Açaí stems with DBH > = 5cm.
@ – Açaí stems with DBH > = 5cm.

approach is important for Amazonian research. The authors are in the process of extending the managed versus unmanaged floodplain forest into a multitemporal mode utilizing two or more dates of TM data in conjunction with recent field data collection and historical data acquired in the field during 1993 and 1994 through interviews and written records. Current research in the area has received support from the NASA Global Change Fellowship Program (to E.B.) to study the local and regional production of Açaí palm forest under different intensities of management, to develop a better understanding about the spectral behavior of Açaí palm forest in intermediary stages of management, and to refine the accuracy of other land-cover classes (e.g., secondary succession regrowth stages).

The combination of Landsat TM data, detailed field measurements, historical data, and a texture-based classifier has the potential to maximize the extraction of information in this part of Amazonia. Understanding the spatial and temporal dimensions of floodplain agroforestry and its integration with other land-use activities will provide information to support future rural development policy for the region that combines local knowledge of management and markets. Floodplain agroforestry presents an outstanding opportunity for intensification of food production in the region without displacement of local populations, without constraining diversification of land use, and without destruction of the resource base.

Acknowledgments

This study was made possible by grants from the National Science Foundation (#9310049 and 9100526) from the Geography and Regional Science and the Program on the Human Dimensions of Global Environmental Change. Supplementary funds were provided by the Midwestern Center of the National Institutes of Global Environmental Change, granted to Principal Investigator Emilio Moran. Earlier field studies in the study area, and informing this study, were made with support from the Wenner-Gren Foundation for Anthropological Research to E. Moran, and grants from the Brazilian National Research Council and the Museu Goeldi in Brazil to E. Brondizio (P.I. Walter Neves, CNPq 403534/90-9; 150043/90-2). A grant from the Indiana Center on Global Change and World Peace supported E. Brondizio during 1993-94 academic year and provided partial support for fieldwork in 1993.

The authors acknowledge the assistance of Lucival Rodrigues Marinho and Jair da Costa Freitas for their help with plant taxonomy and field research, and of the Administration of EMBRAPA/CPATU in Belem for freeing them from other obligations to collaborate with us. We also thank Dr. Mario Dantas of EMBRAPA for his valuable assistance in the field and for developing an effective field methodology, to Dr. J.C. Randolph (SPEA-Indiana University) for his advice on vegetation data analysis, and to Eduardo G. Neves and Mark Ficht for their partnership on the early imaging processing work. Andrea Dalledone Siqueira and Fabio de Castro provided useful comments on an earlier version of this paper when presented at the *VII Brazilian Congress of Remote Sensing*, 10-14 May 1993. The authors especially acknowledge the assistance and friendship of the Açaí producers, the always local support of Valois Delcastagne and Socorro V. Ribeiro, and the people of Ponta de Pedras. 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.

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(Received 13 September 1993; revised and accepted 12 January 1995; revised 13 March 1995)