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Discrimination Between Alfisols and Oxisols in Areas Along the Transamazon Highway (Altamira) Using Landsat TM Data

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ABSTRACT:

There is a paucity of soil maps in the Amazon Basin at a farm-level scale (i.e., 1:30,000). Detailed soil surveys derived from field sampling alone are not feasible in agricultural areas with low population, even though such information would be valuable in agricultural planning. Soil surveys using remote sensing have been rare because a forest cover masks the soil. However, an occasional dry spell, such as that which occurred in July 1985 near Altamira, can be sufficiently severe to kill or reduce vegetation cover in crop and pasture areas thereby exposing soils. This research used such an event to develop soil order information from agricultural areas using computer-analyzed July 22, 1985 Landsat TM data. A NDVI vegetation index band was created from the TM data and it was used to differentiate areas of dense vegetation cover from partially vegetated bare areas. The areas with <50% vegetation cover were analyzed using the Fukuhara soil index (derived from TM data) which subtracts the spectral influence of green vegetation from partially vegetated soils. Unsupervised classification of the TM and TM-transformed spectral data provided detailed information about the distribution of alfisols and oxisols in the non-forested parts of the study areas. Overall a >70 percent correspondence between soils classified by TM data and available published small scale soil maps of selected areas was achieved. Additional field information is planned to assess the methods used and their value for producing soil maps in difficult to reach areas such as Amazonia.

1. INTRODUCTION

The acquisition of soil data through use of remote sensing techniques in humid tropical environments is very difficult even in areas that have a significant portion of the land devoted to agriculture. Areas under natural or successional forests present no possibility to directly detect soil characteristics due to the persistent vegetation cover which completely masks the soil surface. Longer wavelength radar can penetrate a vegetation canopy to some degree, but the potential value of this instrumentation to develop soil maps from vegetated areas has not been conducted (Lillesand and Kiefer, 1994).

Remote sensing can be used to make inferences about soil characteristics in areas covered by vegetation, since some vegetation forms are more commonly associated with one soil than with another (Moran 1977, 1981). However, this approach, which uses vegetation characteristics as a surrogate or predictor of underlying soil characteristics, is more useful at ground-level since vegetation indicators of soils are specific species which cannot be identified from multispectral satellite platforms to date. Generally, vegetation characteristics (species, age, density, etc.)

which may be indicators of soil parameters are difficult to accurately identify using satellite data and technically impractical using high resolution aerial photography or aerial videography data, particularly when large area analysis is required.

A somewhat more promising but indirect approach to developing soil information from densely covered vegetated areas is to monitor land use from one time period to another in order to assess rates of changes in important vegetation parameters which can be associated with soil quality characteristics. For example, if over time one forest succession area was experiencing much faster biomass accumulation (as determined through remote sensing) than another area, and the initial stage of vegetation of both was nearly identical, then it is possible to hypothesize that the cause for the rapidly increasing biomass area might be due to fertile soil. Such a conclusion requires converging evidence from other sources to be verified, but it could be confounded by factors such as land use histories, moisture levels, and catastrophic events. Soil information gathered in this manner requires use of multitemporal data and often complex multiple classifications/analyses of satellite data. The soils information acquired in this manner is at best partial, thus it can not be used to develop soil maps suitable for planning or resources assessment purposes for large areas.

The most accurate description and delineation of any soil is through a detailed soil survey derived from ground observation and laboratory measurement. Such a soil survey is expensive and very difficult to develop and carry out in the humid tropics due to financial and infrastructure deficiences. Most of the Brazilian and Colombian Amazon Basin has been covered by sideways-looking radar (RADAM, 1974) and resources maps for soils, vegetation, land use capability maps have been produced at 1:250,000 scale. This scale, while a major improvement over most maps available previously in these areas, and better than most maps available for a substantial portion of the humid tropics, is still too coarse for farm level decision-making. A few small areas have been mapped for selected scientific and economic purposes, but such surveys are few and limited in scope.

One of the areas that has attracted growing attention in recent years is the Amazon, in particular since 1970 when roads were built across the Basin by Brazil. This opened up the interfluves to settlers who proceeded to try to farm the region. Given the lack of information available in this area, a number of surveys was conducted to provide baseline information to planners and farmers. One of these was the above mentioned sideways-looking radar (RADAM, 1974). The other was a pedological survey ordered in advance of settlement (Falesi, 1972). This area benefited from an earlier 1:50,000 scale soil survey from Altamira to 15 km west at 1:50,000 scale (IPEAN 1967). Falesi's 1972 survey was a 1:1,000,000 scale map of soils 10 km. on either side of the Transamazon Highway from Estreito to Itauba (Falesi, 1972).

In this paper, this part of Falesi's survey used was from Altamira to Brazil Novo located approximately 50 km to the west Altamira. The soil classes are somewhat broad and contain less detail about soil variation than exists based on Falesi's study or other field observations by one of the authors (Moran, field observations). The soil details provided here are finer grained than the more comprehensive soil survey previously discussed (Falesi, 1972). Because of the need to produce a regional assessment within a short period for road-building and colonization purposes, the 1972 survey of necessity had to limit itself to a roadside sampling frame. Thus, soils located away from the main trunk of the highway, along feeder roads to farms, were not included. Figures 1 and 2 show the relevant portions of these two soil surveys. It is important to point out that Falesi pointed out that the 1972 report was a first draft of the soils of the region that needed to be followed up with detailed soil mapping using aerial photography (1972:8). To the best of our knowledge such subsequent analysis was not undertaken due to scarce funds. Thus, the challenge remains of how to economically provide adequately-scaled soils information to farmers over large areas of an ever expanding frontier. While at first the colonization along the Transamazon Highway was foreseen to be 10 km wide on each side of the highway, as of 1993 there were places along the road that were as much as 37 km deep on one or both sides. Thus, soils information on these areas is not available (Moran, 1993; Moran et al., 1994; Mausel et al., 1993).

It is possible to view soils for very brief periods in agriculturally developed parts of the Amazon when land is initially being prepared for crops or pasture, immediately following harvest, and sometimes during planting following burning. However, the amount of soil exposed in a condition conducive for remote sensing analysis is extremely small at any given time because of the speed with which vegetation reoccupies bare areas, and the interference in interpretation associated with vegetation stubble, and in some instances ash from burned fields. These problems have discouraged the use of remote sensing, particularly that from satellite platforms. Remote sensing of soils in these areas is difficult, but techniques are available which provide soil data in areas where the vegetation cover comprises less than half of the surface. The use of remote sensing to develop soil information in humid tropical environments, while not a major method of acquiring such information, holds considerable potential in providing timely information in hard to reach areas, under the right conditions.

The land adjacent to the Transamazon Highway from Altamira west is a study area (approximately 55 km x 50 km) representative of a tropical moist forest environment partially developed for agriculture during the past 20 years (Figure 3). Some soil maps (previously identified) are available, but soil surveys are restricted in scope to areas near the roads and rivers, and the high cost of these field-based surveys leads to the dating of such information, especially in areas experiencing rapid agricultural development. This interest in soil has resulted from the authors' primary research in assessing the role of soil fertility, land use history and size of ares cleared in determining successional rates (Mausel et al., 1993: Moran et al., 1994). Soil is one of the vital parameters in this assessment. We have been trying to increase the data available primarily through soil sampling, but the areal limitations of this approach have also led us to experiment with satellite remote sensing methods of soil surveying.

On relatively rare occasions, perhaps once every 20 years, the mature moist forest regions suffer an extended dry period centered on the months of May through August. Specifically such a dry climatic event occurred near Altamira during 1985. This area normally receives 2001 mm. of precipitation (mean for 1979-1988)[the 1931-1967 mean was reported to be 1697 mm] with 48-51 mm/mo falling during the drier four months of June to Sept. In 1985, while the annual total precipitation was 2950 mm, only 257 mm fell during those four months, and more significantly only 10.4 mm fell in July (25% of the mean for that month) when the Landsat image for 1985 was acquired. In well-drained oxisols and alfisols, which dominate this landscape, this extreme dry period brought about marked changes in the shallow rooted vegetation. It should be noted that the water deficit in Altamira in these months is respectively minus 35 mm, minus 79 mm, minus 91 mm, and minus 83 mm when rainfall is in the normal range (figures based on Thornwaite's method for estimating water balance).

The climate conditions of July 1985 (and the no less stressful 64.8 mm of August, and 12.8 mm of September) were sufficient to kill or wilt vegetation growing as crops and many pasture grasses. These types of land cover became bare or partially so. The soils of many areas could be directly analyzed through remote sensing during one period in 1985 for which data were acquired (July 22) when there was insufficient precipitation to permit new vegetation to cover the ground. The late July, 1985 Landsat TM data used by the authors in land use change analysis near Altamira viewed the region when approximately 20 percent of the area had its soils exposed to varying degrees.

The secondary successional forest as well as the mature moist forest itself remained green, although they undoubtedly experienced some drought related stress. Land with a tree dominance remained covered with vegetation. Nevertheless, a 20 percent exposure of soil represented an opportunity to acquire a larger sample of soil data. Successful identification of these exposed soils through analysis of satellite remotely sensed data, when combined with existing soil and physical characteristics of the area, could provide a basic soil map useful at a scale of larger than 1:50,000. The identification of soils of vegetated areas would require interpolation from the data developed above, but even in these areas insight into their likely soil characteristics is possible.

2. METHODS

Remote sensing techniques can be applied to Landsat TM data to develop information from bare or partially vegetated soil such as that exposed during the 1985 drought. Specifically, two ratios of TM data were applied to discriminate between soils of different character, particularly color and moisture. A ratio called NDVI or normalized difference vegetation index can be used to help differentiate between classes of biomass density thereby separating areas of dense vegetation from those areas that are bare or partially vegetated (Jensen, 1986). A soil ratio called the Fukahara Index is useful in eliminating the contribution of vegetation to a spectral signature from partially vegetated areas (Fukuhara et al., 1979). The original TM data can discriminate soil colors in bare soil. This combination of original and ratio TM data permits assessment of selected soil features in many bare partially vegetated areas.

There is a good correspondence between light-colored soils (yellow or brighter red-yellow) and oxisols/ultisols and a good correspondence between darker soils (red, red-brown or darker red-yellow) and alfisols. The objective of this study is to assess the basic patterns of oxisols and alfisols in the 2750 sq km study area using analysis of original and enhanced Landsat TM data. If this research is successful it may be possible to derive soil suborder information utilizing the techniques proposed, However, delineation of basic soil orders is the sole focus in this paper. Improved knowledge about the spatial distribution of soil orders would be valuable in rural planning and for forest succession studies.

Seven band Landsat TM data acquired July 22, 1985 were purchased from the Brazilian Space Agency (INPE). Band 1 (blue-green) was not used due to excessive scattering and band 6 (thermal infrared) was not used to poor spatial resolution thus TM bands 2,3,4,5, and 7 were the original bands used in this research. These original band data are very useful for extraction information from bare or very nearly bare (approximately < 10 percent vegetation cover) areas, but are less useful as the ground cover increases.

A NDVI or normalized difference vegetation index was developed and added as a sixth band to the data set. The specific form of this band was:

$NDVI = a + ((TM4-TM3)/(TM4+TM3))* b$ where:
$a =$ constant (to prevent negative values)
$b =$ constant (multiplier to stretch data)
$TM3 = .63 - .69$ um DN (digital number)
$TM4 = .76 - .90$ um DN

Analysis of data from this band in association with ground-based information and spectral patterns of the area permitted differentiation between areas that were bare or partially vegetated (< 50 percent vegetation cover) and those in which vegetation covered a majority of the soil. This discrimination is important because a soil ratio capable of extracting selected information from areas with less than 50 percent vegetation cover was used in this study. The NDVI's function was primarily to identify those areas in which a soil index could not be successfully applied.

Analysis of original band TM data can provide soil information from a bare or nearly bare surface, but many of the stressed crop and pasture areas were not rendered totally bare, but rather were reduced to sparse vegetation through which some soil could be observed. Many of these areas had vegetation cover exceeding 10 percent. In these areas of mixed soil and vegetation, where 50 to 90 percent of soil could be observed, a ratio named the Fukuraha Index (Fukuraha et al., 1979) was used to provide soil information that was difficult to derive using original bands. This soil index theoretically removes the spectral influences of green vegetation from a soil vegetation mixture up to a 50 percent vegetation cover. When vegetation is the dominant feature in a pixel mixed with soil and vegetation then the index is ineffective. The form of the Fukahara Index used is given below.

$FI = a + ((X-TM4)/(TM3-Y)) * b$ where:
$a =$ constant (to prevent negative values)
$b =$ constant (multiplier to stretch data)
$X =$ DN of TM4 (.76-.90 um) of the most green pixel in the scene
$Y =$ DN of TM3 (.63-.69 um) of the most green pixel is the scene
$TM4 =$ DN of TM4 of the pixel being transformed
$TM3 =$ DN of TM3 of the pixel being transformed

The DN is the digital number or digitized value from 0-255 representing relative spectral response from a pixel.

The FI was added as an additional band to the original five bands and the NDVI band to create a seven band data set which was used for unsupervised classification of the study area. A two stage unsupervised or cluster classifier was implemented on a MacIntosh Quadra 800 using MULTISPEC image processing software (Landgrebe and Biehl, 1993). The classifiers' first step was to determine initial clusters utilized a covariance-based eigenvector option. Initial clusters were refined in a second stage using an isodata approach resulting in development of 59 seven band clusters of the study area.

The spectral statistics from each cluster, as well as the spatial distribution of the pixels represented by each cluster were analyzed using spectral knowledge developed about the area from previous three date classifications from 1985, 1988, and 1991 (Moran et al., 1994; Mausel et al., 1993). A 1991 classification of the study area was developed that was supported by detailed ground observation and historical land use information acquired during two field sessions conducted during May-July in 1992 and 1993. Representative spectral signatures of major forest, water, wetland, pasture, and several classes of secondary succession were developed. All TM data used in this research, were adjusted to the 1985 data to make spectral responses comparable between dates. The procedures used for spectral adjustment between dates are described in a recent article (Mausel et al., 1993). Some historic data acquired during 1992 and 1993 field work were used to support the interpretation of cluster spectral signatures developed. The spectral statistics associated with each cluster were interpreted and assigned to one of the following classes: water/wetland, forest, secondary succession (and non-forest vegetation covering more than 50 percent of the ground), lighter colored soil (oxisols), and darker soils (alfisols). The two soil classes were analyzed most since they are the research focus. Subdivisions of the two basic soil classes are possible to develop, but they are nor presented in this paper. Analysis of individual clusters was conducted by interpreting the statistics (spectral response means and standard deviations) associated with them in conjunction with visual interpretation of the location of cluster pixels in the image and incorporation of available ground information. The individual 59 cluster classes were merged into three classes to develop an unsupervised classification image suitable for interpretation. Figure 4 shows a portion of the merged classification results for a narrow area along the Transamazon Highway from Altamira to 15 km west. Figure 5 shows merged classification results of the western part of the study area from km 23 to km 50 along the Transamazon Highway.

The soil patterns shown on the final unsupervised classification image were compared with three sets of ground-based soil information in order to assess correspondence between known and classified soils. The portions of the two very general soil survey maps previously discussed (Figs. 1 and 2) which were located in the study area were the primary ground sources used for comparison. It is likely that the patterns shown on these maps were developed to provide broad indications of soil conditions and not to indicate the intricacies of soil complexes inherent in these patterns. In addition, seven light-colored oxisols soils were identified from 1992-193 field work and compared with classification. A much larger and detailed soil survey was conducted by cooperating Brazilian scientists. These data have not yet been fully compiled for use in this study, but it will be added in future soils remote sensing research.

The two soil classes in the unsupervised classifications were compared with ground-based information to assess correspondence of subregional soil patterns. A pixel by pixel accuracy assessment was not deemed to be reasonable considering the general nature of the soil survey data at a point or pixel level. It is likely that the ground-based soil survey data are more reliable in identifying soil characteristics for larger areas represented by grouping of pixels. For example, soil surveys might indicate that the soils adjacent to kilometers 2 to 4 along the Transamazon highway are light colored oxisols. If the unsupervised classification results indicate that lighter colored soils in this area are in the majority, then a correspondence is assumed. Thus, a semiquantitative assessment of accuracy commensurate with the quality of ground-based data was utilized.

3. RESULTS AND DISCUSSION

3.1 Spectral Characteristics of Soils

Table 1 provides the seven band spectral statistics of the cluster classes developed and shown in Figures 4 and 5. Many features were defined by numerous cluster classes; however, only one (or two) representative cluster(s) is given for the classes mature moist forest, succession, and water. These three classes are given to provide a background or framework for soils and details about their variations or subclasses is not needed in this paper. These three classes were merged into a single non-soil class dominated by vegetation when displayed in Figs. 4 and 5. The spectral statistics for each major soil cluster is provided in this table and interpreted. Figure 6 shows representative spectral curves of oxisols and alfisols as well as other basic features classified.

Mature moist forest classes have low spectral responses (represented by digital numbers or DN-values) in the two visible TM bands (TM 2 and TM 3) due to strong chlorophyll absorption. Near infrared responses (TM 4) are moderate representing a mixture of high response due to reflection from plant cell mesophyll walls and low response from shadowed areas found within the canopy. Mid-infrared bands (TM 5 and TM 7) have low spectral responses due to plant water absorption and shadow effects. The Fukuhara Index is meaningless for forests, but NDVI has a high response indicating the presence of high biomass.

The cluster classes representing forest succession are varied since this category includes not only succession, but any vegetation form that covers more than half the surface and is not mature moist forest. Spectral responses in the visible bands are relatively low due to chlorophyll absorption, but not as low as mature moist forest. The near infrared responses are higher than forest because of high reflectance of energy from the plant mesophyll with less energy trapped within shadow areas of complex canopies associated with mature forest. The mid-infrared bands have moderate spectral responses due to absorption by plant water and some shadow effect for the more mature successional features. The Fukuhara Index is meaningless for succession features. The NDVI responses for succession classes are high like the mature moist forest because features in this category also have high biomass.

Water features have somewhat low spectral responses in the visible bands and very low response in the three infrared bands where water almost completely absorbs incoming energy. The Fukuhara Index is meaningless for water. The NDVI, which is a index of or surrogate for biomass amount is extremely low because of the absence of biomass in water.

The basic spectral patterns of soils in the study area have moderate to high spectral responses in the visible bands due to lack of absorbing materials such as chlorophyll, high organic content, and abundant water. Many minerals in soils are relatively reflective of visible and near/mid-infrared energy. The responses of soils in the three near/mid-infrared bands are distinctly higher than that found in forest, succession, and water features because of the dominance of mineral matter in reflectance and the relatively insignificant influence of vegetation, humus, and water.

Several spectral subdivisions within soils can be identified but for this research the various soil cluster classes were divided into basically lighter-color soils (yellow and red-yellow primarily) dominated by the oxisol order and darker-colored soils (darker reds and brown primarily) dominated the alfisol order. Soils transitional between light and dark exist because soil color is along a continuum and individual soil cluster classes in the middle of this continuum were assigned to one of the two basic classes based on spectral similarity.

Table 1 shows the spectral patterns associated with cluster classes assigned into oxisol and alfisol orders. All clusters designated as soils had NDVI of 150 or less which represents features that have at least one-half of their surface comprised of bare soil. The more densely vegetated areas typically had NDVI values near or above 180. The oxisols were differentiated from the alfisols by having higher visible, mid-infrared, and Fukuhara Index spectral responses than alfisols. The near-infrared band provided no reliable discrimination between the two basic soil features.

The oxisols generally are older and more weathered with a mineralogical emphasis on light-colored minerals while the alfisols are generally younger, and less weathered with a higher proportion of darker-colored minerals (U.S. Soil Conservation Staff, 1975). The different mineralogical character of the two soils encourages higher reflectance from oxisols, but other soil parameters reinforce the higher reflectivity of oxisols. Oxisols tend to have lower water holding capacities, thus are drier than alfisols. The mid-infrared reflectance is increased by drier soils since little water is available to absorb these wavelengths. Oxisols tend to have less organic content than alfisols, thus a source of energy absorption is reduced more in oxisols than alfisols. Collectively, the differing mineralogy, water content, and organic content of these two soil orders usually result in different multispectral patterns of response as shown in Table 1 and displayed in Figure 6.

3.2 Accuracy Estimates

Accuracy estimates for individual pixels (30 m x 30 m areas for TM data) are not worthwhile due to the general nature of the soil surveys. Nevertheless, this survey data is the primary source of information with which to compare the unsupervised classification results shown in Figures 4 and 5. Specific soil samples recently acquired from field observations were supportive of accuracy evaluation, but they were too few and did not represent a cross section of soils found in the study area. The accuracy estimates developed were appropriate for the detail of the survey data used. It is assumed that the soil surveys were correct at a small regional scale, but different soils comprising a significant minority were likely present within a region. For example on the 1:1,000,000 scale soil survey a 5 km x 25 km region was identified as red-yellow (oxisol). It is very unlikely that such a large region, shown as a rectangle on the map, is entirely oxisols: however, for purposed of accuracy or correspondence estimates the authors are assuming that it is the dominant soil type of the region. Thus, if the unsupervised classification results in this region are oxisols then the classification is considered correct for the region.

Regional classification accuracy or correspondence was conducted for an area along the Transamazon Highway, two to seven km on either side, using the 1:50,000 scale soil survey. Figure 2 shows the soils in five basic regions from Altamira to 15 km west of Altamira. Figure 4 shows the unsupervised classification which includes this area. The soil survey indicated that oxisols were found in the first region from Altamira to two km west; however, urban development made it impossible to compare this region with the classification results. The second region from km 2.0 to km 6.0 along the highway was indicated as alfisol. The amount of exposed soils classified as alfisols was 81 percent, thus the dominant soil indicated by analysis of TM data was the same as indicated by the survey. The third region, from km 6.0 to km 8.5 along the highway was oxisols according to the survey and the TM classification indicated that 62 percent oxisols were present. The fourth region from km 8.5 to km 12.5 along the highway was a mixture of alfisols and oxisols according to the survey, but it was too covered with vegetation for the classification to identify a significant amount of soils. The fifth region, from km 12.5 to km 15.0 along the highway was dominated by oxisols as indicated by the survey. The classification of this area indicates that 61 percent of the exposed soils were oxisols. It is evident that the classification results corresponded well with the soil survey results in the three regions of the survey which had large amounts of bare or nearly bare soils suitable for analysis.

A large area 10 km on either side of the Transamazon Highway from km 25 to km 45 was identified as alfisols on the 1:1,000,000 soil survey. Figure 5 shows the unsupervised classification of the area from approximately km 23 to km 50 along the Transamazon Highway which includes the alfisol region. The classification statistics of the alfisol subarea shown on the survey were developed and 63 percent of this region was determined to be alfisols. Although a large minority of the soils in the region were classified as oxisols it is evident that the alfisol majority corresponded to the dominant soil order identified on the soil survey.

Soil observation from eight fields were made during 1992-1993 field work. All these fields contained sandy yellow or red-yellow soils which were oxisols. Unsupervised classification results from these fields were analyzed. Three of the eight fields were too covered with vegetation to determine the nature of the soil. The remaining five fields of oxisols that were sufficiently bare to be identified as soils were classified as oxisols in four fields and a transition the soil samples observed in the field were correctly classified.

4. CONCLUSIONS

Use of Landsat TM data in original and enhanced forms, analyzed using appropriate computer techniques, can provide soil information at the order level in areas in which at least one-half of the soil surface is exposed. This conclusion was supported by Landsat TM classified data identifying soils that corresponded accurately with soil patterns shown of two published soil surveys and from observation made in the field by some of the authors. Selected soil suborder information is likely to be developed using the methods described in this research, but this hypothesis was not sufficiently explored to determined to what extent it was true. Future research to determine more detailed soil information from analysis of satellite data is warranted based on the initial results presented. More precise applications of the techniques implemented require additional research. For example, the effect of brown biomass on the spectral signature of soils was not determined. Also, what are the spectral characteristics when vegetation cover exceeds 50 percent? What degree of soil misclassification occurs at different biomass covers from 50 percent to bare is another question of interest. Nevertheless, in spite of some unanswered questions, this research suggests that use of satellite or other remotely sensed data can provide basic soil information, the amount of which is greatest during drier years when more bare soil is exposed.

Ground-based soil survey are undoubtedly the most comprehensive, but the areas likely to be cover by them in the foreseeable future is very limited, thus use of the soil information developed from remote sensing can expand knowledge about the soil data base needed for planning and analysis of succession mechanisms.

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Table 1. Representative Spectral Statistics of Soils and Other Feature Cluster Classes near Altamira, Brazil using Landsat TM Original and Ratio Transformed Data.

Average DN for Bands used in Clustering * Standard Deviations in ( )							Cluster Feature
TM2	TM3	TM4	TM5	TM7	FI	NDVI	
48(3.1)	71(5.7)	70(5.2)	127(6.4)	38(6.0)	59(2.4)	118(5.4)	Oxisol
44(4.8)	65(8.4)	63(8.7)	110(9.4)	35(9.1)	63(6.4)	117(9.2)	Oxisol
45(2.8)	61(7.4)	76(4.5)	104(6.7)	28(6.1)	59(2.8)	136(5.2)	Oxisol
42(2.8)	56(5.3)	67(5.3)	114(7.0)	26(5.0)	64(2.7)	133(6.6)	Oxisol
39(2.9)	55(5.7)	53(5.4)	94(9.4)	30(7.4)	73(6.6)	118(6.4)	Alfisol
41(2.3)	55(3.4)	64(4.4)	98(5.6)	28(5.6)	66(4.6)	132(4.9)	Alfisol
39(2.3)	49(3.5)	69(4.2)	99(6.5)	29(4.5)	67(3.3)	145(4.9)	Alfisol
37(2.3)	48(3.9)	60(4.7)	84(7.6)	23(5.4)	73(5.7)	137(6.0)	Alfisol
29(1.4)	27(0.5)	76(1.5)	59(3.3)	11(2.1)	96(2.8)	190(2.0)	Mature Forest
29(1.5)	27(0.3)	74(2.7)	47(6.1)	9(3.2)	101(9.6)	188(2.9)	Mature Forest
33(2.6)	32(3.4)	99(6.3)	73(7.4)	15(3.8)	44(9.3)	196(6.1)	Succession+
36(1.7)	39(1.6)	82(3.5)	77(6.8)	18(5.1)	62(5.2)	172(6.3)	Succession
35(6.4)	39(11.2)	10(3.6)	7(6.0)	3(2.9)	149(31.8)	32(16.0)	Water

* TM or thematic mapper bands indicated are given in their standard terminology. FI and NDVI represent Fukuhara Index and Normalized Difference Vegetation Index.

\+ Succession includes all vegetation types other than mature forest that has more than 50 percent ground cover.

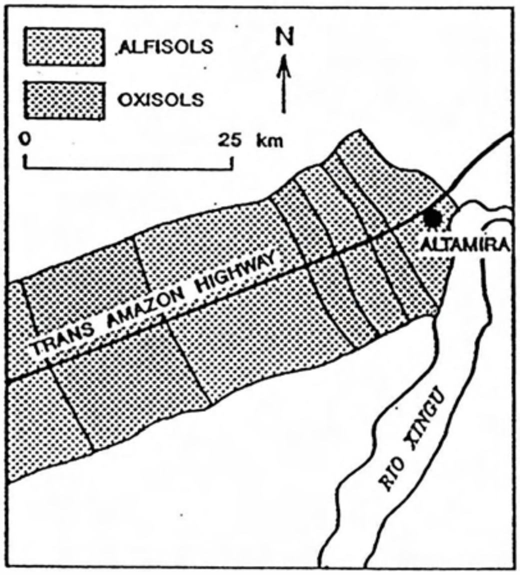


Figure 1. Soil Distribution (1:1,000,000 original scale) along the Transamazon Highway from Altamira to Brazil Novo. Source: Falesi, 1972.

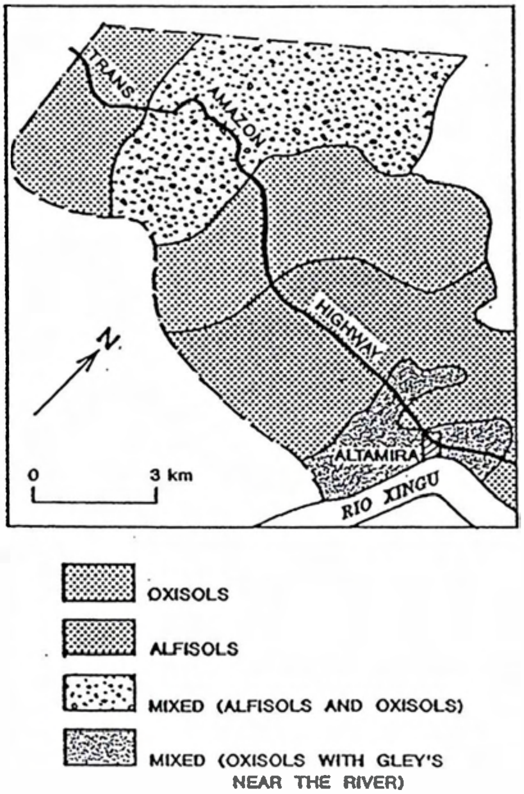


Figure 2. Soil Distribution (1:50,000 original scale) along the Transamazon Highway west of Altamira. Source: Ipean, 1967.

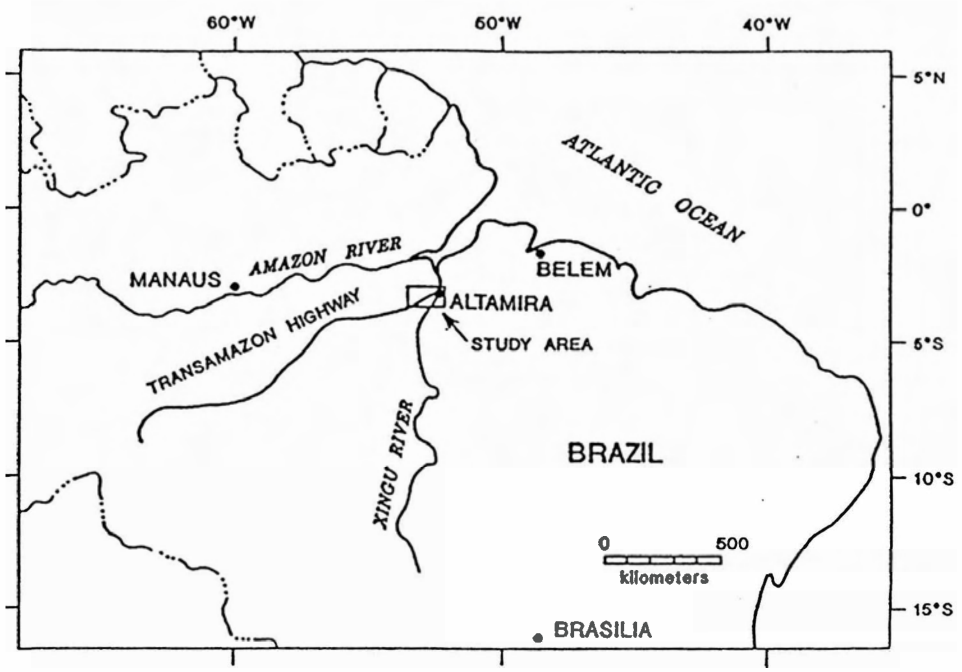


Figure 3. Altamira study area and surroundings.

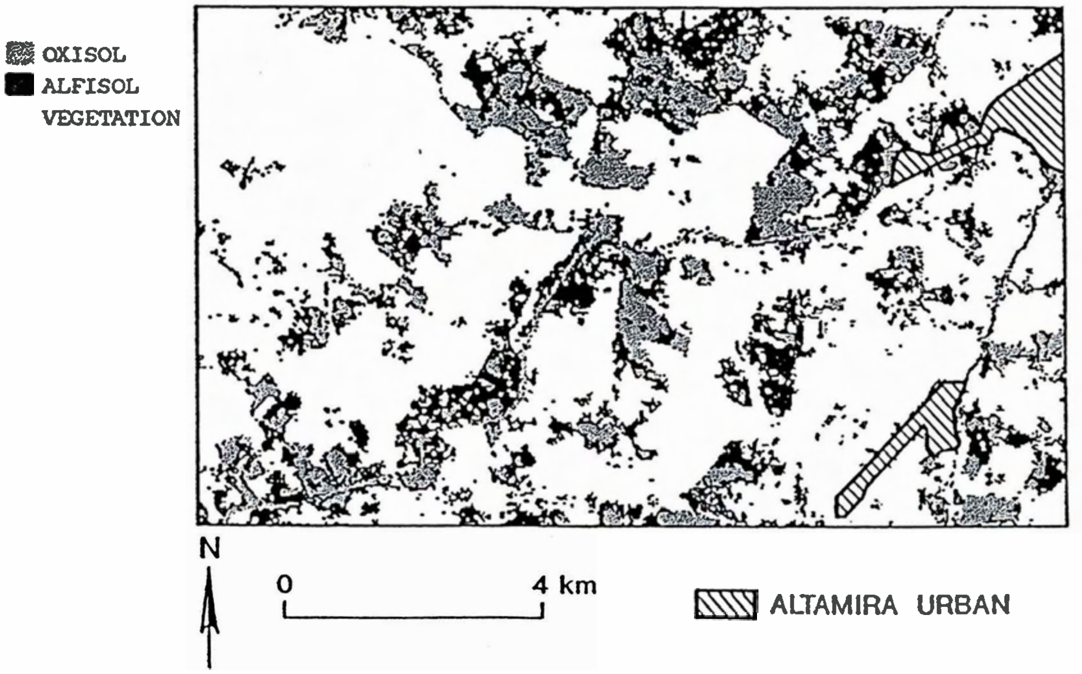


Figure 4. Distribution of Oxisols and Alfisols as determined from computer analysis of July 22, 1985 original and enhanced Landsat TM data in bare and partially vegetated areas along the Transamazon Highway (Km 2-7) west of Altamira.

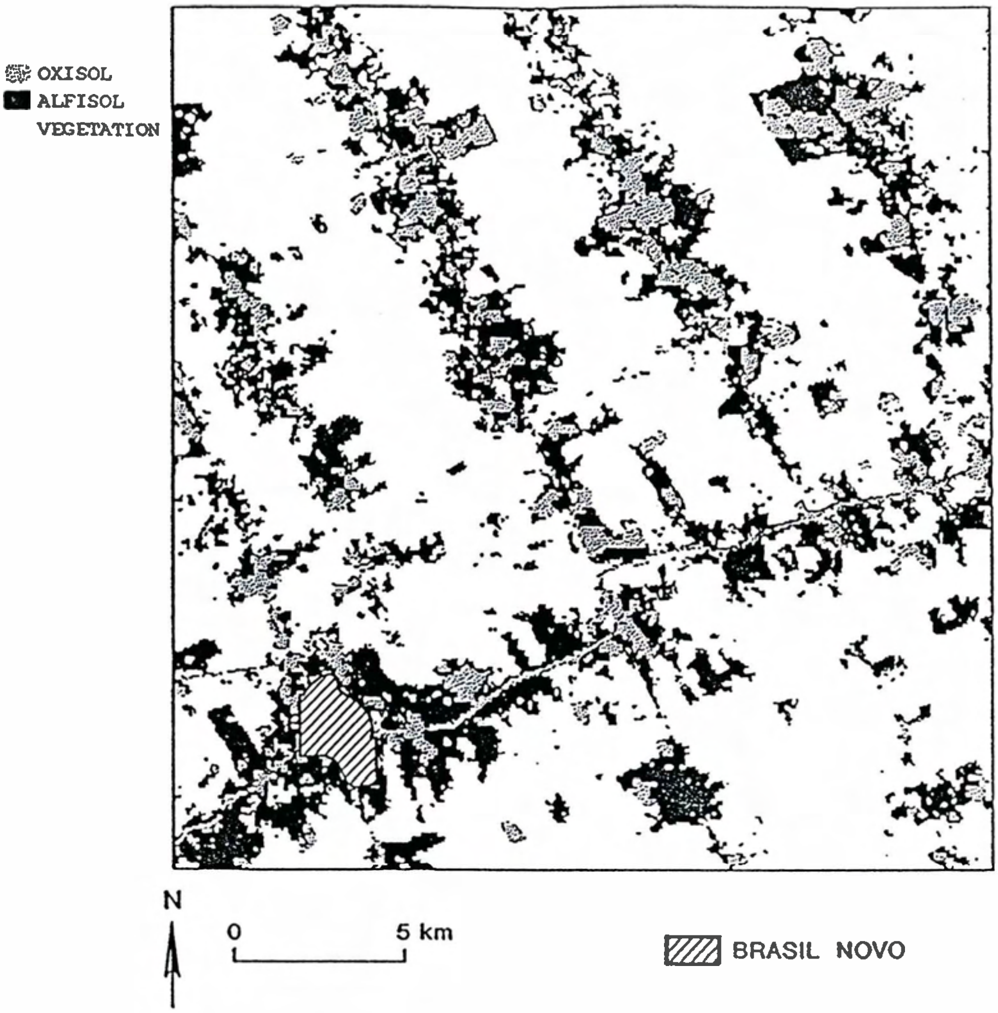
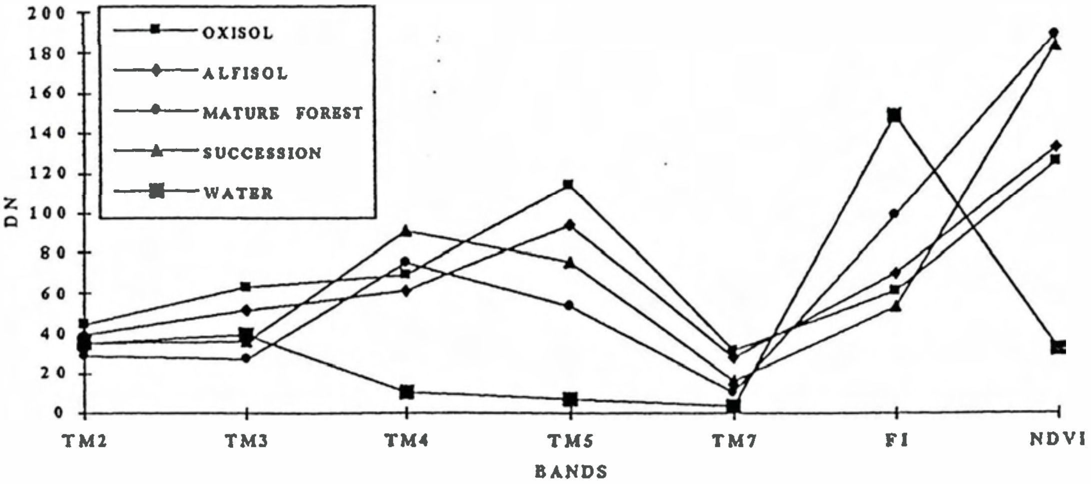


Figure 5. Distribution of Oxisols and Alfisols as determined from computer analysis of July 22, 1985 original and enhanced Landsat TM in bare and partially vegetated areas along the Transamazon Highway west of Altamira from approximately Km 25-Km 50.

FIGURE 6: REPRESENTATIVE SPECTRAL GRAPH OF SELECTED FEATURES NEAR ALTAMIRA BRAZIL USING JULY 22, 1985 LANDSAT TM DATA



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