A NEW LANDSAT VIEW OF LAND USE IN AMAZONIA

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ABSTRACT

A new method of classifying land use in Amazonia was tested in an area north of Manaus. Landsat TM images acquired in August 1988 and 1989 were calibrated by spectral mixture analysis and converted into fraction images of four spectral endmembers: shade, unshaded green vegetation, wood and soil. Mixtures of these endmembers accounted for the spectral variation in the TM images of the study area to within the TM system noise level. Combinations of the endmembers in various proportions described the main types of land use, including undisturbed forest, cleared areas with slash, cleared areas without slash, pasture, and second growth forest. Gradations from one landuse type to another were expressed as changes in the relative fractions of the endmembers. Differences between the fractions of the endmembers in the 1988 and 1989 images were used to infer changes in land use, including clearing and regrowth of vegetation. All of the land-use types showed spatial and / or temporal transitions to the other types. Field observations were made in the study area in 1988 and 1989. Land-use and changes inferred from the fraction images were correct at all of the sites visited. Spectral endmembers similar to those found in the Manaus area occur throughout Amazonia; therefore, spectral mixture analysis may be a reliable way of monitoring changes in land use over the entire region.

INTRODUCTION

Changes in the land surface can be detected on images in two ways: by spatial pattern and by spectral signature. The most obvious and widely used approach is to identify familiar spatial patterns that correspond to known cultural or natural processes. For example, clearing of the forest in Amazonia typically progresses outward from roads, and may result in areas that have straight boundaries and regular patterns. Cleared areas also are lighter in tone than the forest in most reflected light images. Recognition of patterns, however, is critically dependent on spatial resolution. AVHRR, with kilometer-scale pixels, can reveal only the most bold patterns (e.g. Tucker et al., 1983), whereas Landsat TM with 30 m pixels and SPOT with 10m pixels can record considerably more detail. The price for this detail is that the coverage of each scene is small relative to the amount of area to be surveyed.

Although the main patterns of forest clearing can be recognized on Landsat and SPOT images it is difficult from spatial analysis at this scale to determine the condition of the cleared areas and how they are being used. For example, spatial analysis alone cannot distinguish between pasture and second-growth forest, or between slash-covered areas and bare soil. To make such distinctions it is necessary to classify pixels on the basis of their spectral properties. For spectral analysis the best results are achieved with many bands. Thus, Landsat TM is preferable to AVHRR or SPOT.

Conventional methods of image enhancement and of spectral classification (e.g. Singh, 1987) such as color composites, ratios (including various vegetation indices), principal components, and other multivariant classifiers can discriminate between areas that are vegetated and those that are clear of vegetation when applied to multispectral images of Amazonia. However, we find that these methods are not reliable indicators of vegetation type and stature. Vegetation indices reveal cleared areas, but incorrectly classify regrowth and forest. Conventional image-processing methods were unable to distinguish between soil and slash, especially at the subpixel scale, which we will show is important for classification of land use.

In this paper we use a different approach to image classification that we term "spectral mixture analysis" (Adams et al., 1986, 1989; Smith et al., 1990a). Natural surfaces measured by satellite commonly are spectrally variable at the sub-pixel scale, and conventional classes may differ only in the proportions of the spectral components that comprise the scene. In spectral mixture analysis these fundamental spectral components (endmembers) are defined in terms of laboratory or field reflectance spectra of well characterized materials, and pixels are modeled as mixtures of the endmembers. Based on field observations the main classes of land use in the area studied are forest, cleared areas, pasture, and second growth vegetation. However, each of these classes is highly variable. For example, pasture may be all grass or a mixture of grass, soil and slash. In addition, each of the classes is transitional into the other. For example, abandoned pasture becomes transitional into second growth forest.

Our analysis of TM images and comparison with field observations demonstrates that when the spectral variability in the scene is defined in terms of four spectral endmembers, shade, unshaded vegetation, soil and wood, that the main classes of land use can be reconstructed to within the accuracy limitations of the TM system itself. The analysis takes into account in-class variability and gradations from one class to another at all spatial scales.

MATERIALS AND METHODS

Landsat TM images of the Manaus, Brazil area were acquired from the Instituto de Pesquisas Espaciais (INPE). Two scenes, one for 15 August 1988 and one for 2 August 1989 were studied. A 1077 x 489-pixel subset of a partially forested and partially cleared area north of Manaus was examined in detail (Fig. 1). Spectral mixture analysis (Adams et al., 1986, 1989, and Smith et al., 1990a,b) was used to select reference endmember spectra and to calibrate the images to reflectance. Comparisons were made between fraction images and normalized difference vegetation index (NDVI) images.

Field studies were made in August 1988 and in September-November 1989. Field samples were collected for measurement of spectral reflectance in the laboratory. Laboratory spectra were convolved with the TM bands to permit comparison with the images. Selected sites were visited on the ground and studied on aerial photographs. Fraction images derived from the 1988 TM data were taken into the field in 1989 to test the classification results.

RESULTS

Four spectral endmembers were selected from a larger set that included laboratory and field spectra of samples from the study area north of Manaus. The endmember spectra are those of shade, unshaded vegetation, soil and wood. Spectra are shown in Fig. 2. The shade endmember was synthesized, and it incorporated a component of light transmitted through green leaves.

Fraction images were made of each of the endmembers for both the 1988 and the 1989 scenes (Figs. 3a,b-6a,b). Lighter tones on the fraction images correspond to higher fractions of the endmembers. The highest fractions of shade occur in the areas of mature forest. Cleared areas and regrowth vegetation, including closed-canopy *Cecropia* stands, have lower fractions of shade and are clearly distinguished from the forest. In the vegetation-fraction images the *Cecropia-covered* areas show the highest fraction of vegetation, primarily because the relatively flat, unbroken canopy of second-growth *Cecropia* has a low fraction of shade, but also because little soil or woody material is exposed. Elsewhere in the cleared areas vegetation is mixed with the soil and wood endmembers. The soil and the wood endmembers are present throughout most of the cleared areas in various proportions. Woody material is present in most clearings and pastures. Soil is the dominant endmember along roads.

Five classes of land surface were defined using the relative fractional abundances of the four endmembers: 1) mature forest (intermediate fraction of vegetation, intermediate shade, low wood, no soil); 2) woody debris (high wood, low soil, low shade, no vegetation); 3) bare soil (high soil, low wood, no shade, no vegetation); 4) pasture (intermediate vegetation, low to intermediate wood, low soil, low shade); 5) shrub/tree regrowth (high vegetation, low shade, low wood, no soil). These classes themselves may be treated as endmembers, because they may mix with one another at the sub-pixel scale and may be expressed as fraction images.

The results of classifying the TM images were tested using field observations, ground photographs and aerial photographs. In all areas examined, the classification was found to be qualitatively correct, that is, the relative proportions of the four endmembers were verified. For example, pastures with slash remaining were correctly distinguished from ones that were clear; pastures with partial second growth were consistently separated from ones having only grass; second growth was reliably distinguished from mature forest, etc. No attempt was made to assess the quantitative accuracy of the fractions of the endmembers in this area. Quantitative assessment is difficult and perhaps infeasible, except in small areas. Such measurements must be made close to the time of the satellite overflight, because cutting, burning of slash and regrowth of vegetation may vary significantly on the scale of weeks to months. In addition, the measurements themselves are time consuming and subject to substantial error. For example, we did not consider it feasible to measure in the field the areal fraction of woody material, including trunks and branches, covering areas of recently cut forest. For an evaluation of the accuracy of spectral mixture analysis for measuring fractions of vegetation see Smith et al., 1990a.

Fraction images of each endmember for 1988 and 1989 were differenced (Figs. 3c-6c). In the difference images lighter tones indicate more of the endmember in 1989 than in 1988. No changes were detected in the forest between the two images. In the cleared areas, however, there are significant changes in each of the endmembers. Changes in one endmember must be accompanied by changes in others, because the sum of the endmember fractions is unity.

Changes in two or more endmembers were used to deduce surface processes. For example, at Fazenda Dimona (arrow) a dark spot on the vegetation difference image (Fig. 4c) indicates a loss of vegetation from 1988 to 1989. The same spot is dark on the shade difference image (Fig. 3c) which is consistent with a decrease in shade due to cutting of vegetation. However, the spot is white on the wood difference image (Fig. 5c), indicating an increase in woody material, which also is consistent with cutting of vegetation. The soil difference image (Fig. 6c) is unchanged in this area, suggesting that soil was not exposed at either time. We conducted field work August 1988 and in September 1989 and verified that this area was cleared of second growth vegetation in July 1989.

A second example illustrates regrowth of vegetation during one year. There are three irregularly shaped areas in the lower left corner of the difference images in Figs. 3c-5c. In the vegetation difference image (Fig. 4c) these areas are light, indicating new vegetation present in 1989. The same areas on the wood difference image (Fig. 5c) are dark, indicating that woody material disappeared during the same time. Our interpretation is that these areas were covered with slash in August 1988, but by August 1989 they had been revegetated. Furthermore, the new vegetation has a low shade fraction that is consistent with *Cecropia*. Thus, we conclude that these areas had been cut before 1988 (probably from forest because of the large fraction of woody debris) and secondary succession was occurring.

We defined nine dynamic classes based on changes in the static classes over the one year between the TM images: 1) cut mature forest, slash left on ground; 2) cut mature forest, slash cleared; 3) woody debris removed from cleared area; 4) woody debris overgrown by vegetation (shrub/tree regrowth or pasture); 5) bare soil overgrown (shrub/tree regrowth or pasture); 6) pasture vegetation reduced; 7) pasture overgrown; 8) shrub/tree regrowth cut, slash left on ground; 9) shrub/tree regrowth cleared to bare soil. The change from shrub/tree regrowth to mature forest was not observed in one year. Areas unchanged in one year were mapped separately from the dynamic classes.

Vegetation indices were calculated for both of the uncalibrated TM images. The normalized difference vegetation index (NDVI) image for 1989 is shown in Fig. 7. Lighter tones on the image indicate higher values of NDVI. The NDVI images of the study area for both years are nearly identical with the corresponding vegetation-fraction images. Note that the highest values of NDVI occur in the *Cecropia-covered* areas, and the lowest values are in the areas having high soil and wood fractions. The forested regions have intermediate NDVI values.

DISCUSSION

The static and dynamic classes described above were derived from mixtures of endmembers. The endmembers (excepting shade) were spectra of known materials on the ground; thus, different fractions of the endmembers in each pixel were interpreted within the familiar framework of field observations. In contrast, pixel radiance values were not easily interpreted in terms of materials, especially when the surfaces were illuminated differently. The static classes defined in the study area were inherently flexible in that they graded into one another with changing proportions of the endmembers. The endmembers were invariant. Therefore, they were valid from one image to another, regardless of differences in atmospheric conditions, instrumental response and lighting. The endmembers did not change from 1988 to 1989; however, their relative proportions did for many parts of the scene, permitting assessment of the processes occurring on the ground.

In contrast to the spectral mixture analysis, in which all six TM band are used, the NDVI relies on only two bands (TM3 and TM4). There is strong spectral contrast in chlorophyll at these wavelengths. As a result, the index is sensitive to the abundance of green vegetation and is qualitatively equivalent to the vegetation fraction image (Fig. 4a,b). Because the NDVI does not utilize the four remaining TM bands, it is less sensitive to shade, woody plant material or soil, providing no measure of other components within the image. Neither the vegetation fraction nor the NDVI measures the amount of vegetation cover as it would be determined in the field. However, the fraction images can be normalized with respect to the shade fraction, providing an estimate of vegetation cover which is similar to vegetation cover in the field.

If the NDVI is interpreted as a measure of vegetation cover the results for the study area are inconsistent. For example, the NDVI, interpreted in this way would indicate that the forest has less vegetation than the Cecropia-covered areas. In fact, both areas have 100% cover of vegetation, but the forest has more shade.

From these results we conclude that the NDVI and the other ratio-based vegetation indices are not suitable to measure vegetation cover in the study area. As the study area is representative of many forested and cleared regions these conclusions probably apply generally.

The spectral endmembers, vegetation, wood and soil that were defined in the study area represent broad classes of materials on the ground. There are, of course, spectral variations in green vegetation, woody material and soils, even within the study area. These variations, however, are small relative to the differences between the endmembers, and they are difficult to resolve spectrally with the TM bands. In addition, it may not be necessary to examine a TM scene in such detail. For example, there is a range of spectra for the bark and branches of living trees and shrubs, and for slash in various stages of decay. Even if TM could resolve all of these spectral differences (which the system cannot, within system error) it is not necessarily desirable to distinguish these varieties of woody material for the purposes of a general land use classification. It is important, however, to be able to distinguish the broad class of woody material from soil or green vegetation.

Because the spectral endmembers that apply to the Manaus TM scene represent broad classes of materials (and shade) it may be possible to apply the same, or similar, endmembers to images of other forested areas in Amazonia. Our preliminary work with Landsat images of other regions supports this conclusion, although no field work has been conducted yet. We suggest that the approach described here may be a widely applicable way to monitor cutting, clearing and regrowth of vegetation and of assessing changing landuse.

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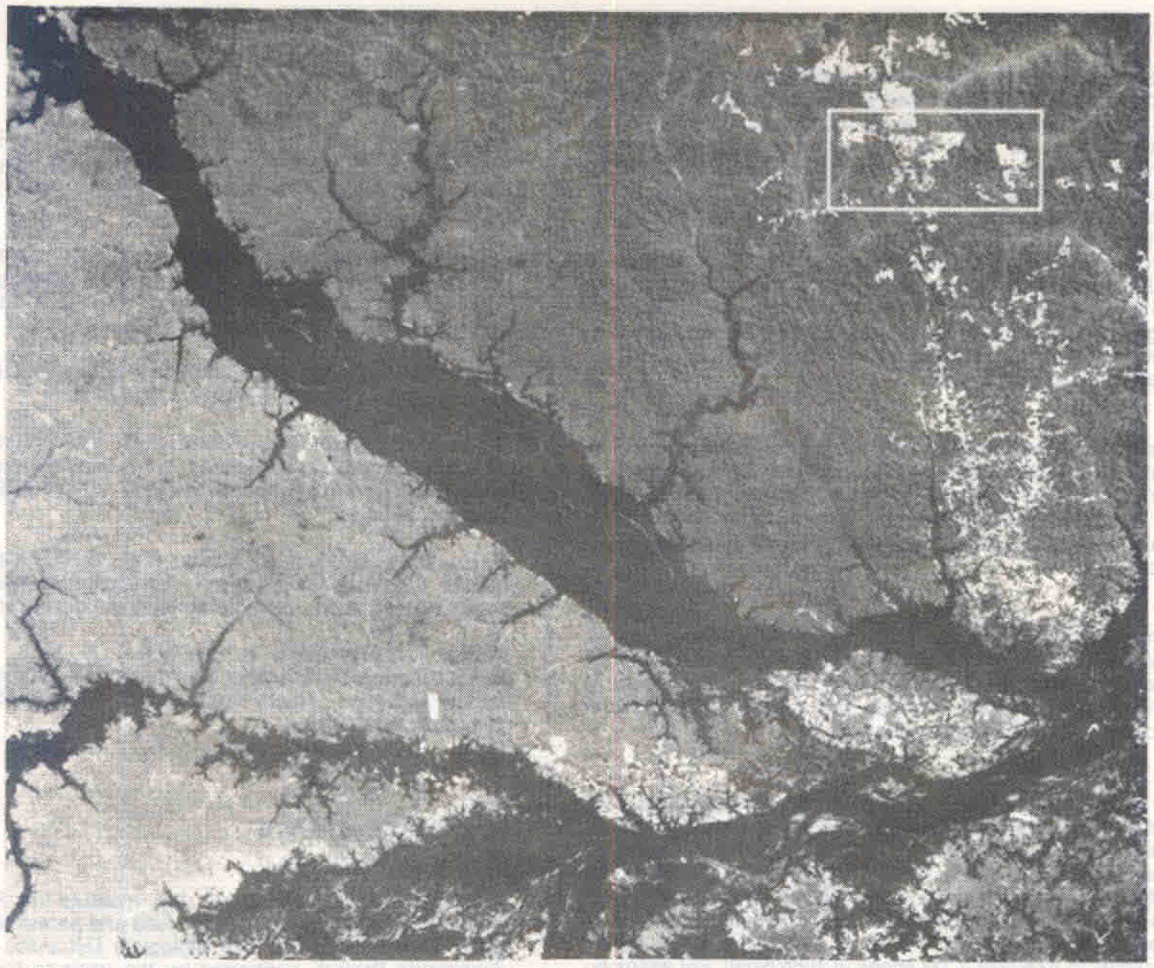
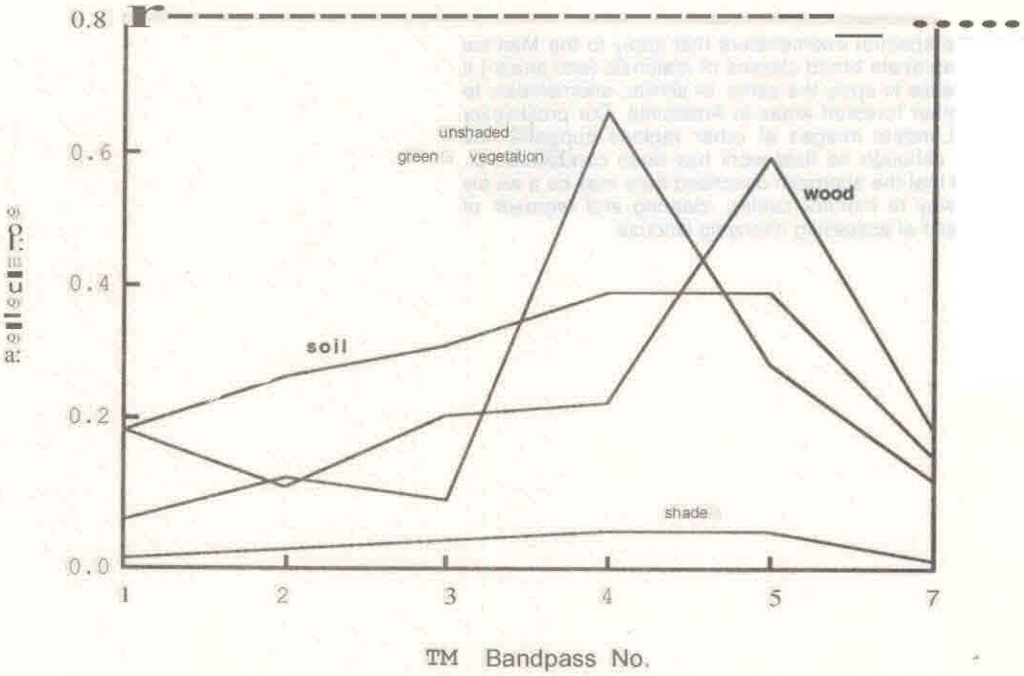


Figure 1. Band 4 of Landsat Thematic Mapper scene of the Manaus area, Brazil, acquired 2 August 1989. The area of study is outlined.



Endmember spectra of shade, unshaded green vegetation, wood and soil. When mixed, using spectral mixture analysis, the spectra reproduce the spectral variance in the study area portion of the TM images to the level of the system noise.