Anais XIV Simpósio Brasileiro de Sensoriamento Remoto, Natal, Brasil, 25-30 abril 2009, INPE, p. 2539-2546.

# Spectral unmixing of forest canopy recovery in selectively logged units in a tropical lowland forest, Costa Rica

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**Abstract.** We examined the use of linear spectral unmixing of airborne hyperspectral imagery to determine potential forest canopy recovery of three selectively logged units in a lowland humid forest in Costa Rica. The units were logged 0.3 to 3 years prior to image acquisition and the logging intensity varied from 4.8% disturbance (comparable to reduce impact logging) to 8.8% (comparable to conventional logging). Because comprehensive field data such as field spectrometer measurements are still scarce for most tropical regions, we employed an endmember selection methodology that combined the calculation of a spectral vegetation index (narrow band NDVI) and visual interpretation of the imagery. We used a number of spectra for each endmember to represent the overall variability of the classes in the scene. Our study suggests that the overall status of the forest recovery is more likely related to logging intensity rather than the time since management. Our results also suggest that in the case of logging practices that are similar to conventional logging, extraction roads had a higher impact of disturbance than tree felling gaps. In field conditions where the forest appears visually to be undisturbed or fully recovered following logging, the spectral properties of the canopy can reveal that certain areas are still damaged or are in a process of structural recovery.

**Keywords:** hyperspectral imagery, NDVI, linear spectral unmixing, selective logging, structural recovery, Costa Rica.

## 1. Introduction

Selective logging is a common practice in tropical regions that may help protect forest areas in the long term, however, a lack of controls and clear guidelines during and after logging operations have shown negative impacts in forest ecosystems (Asner et al. 2006). A comparison between the United Nations Conference on Environment and Development (UNCED) Forest Principles and the Convention on Biological Diversity (CBD) ecosystem approach, illustrates that the two are very similar in their underlying principles (FAO 2005). From the forest management viewpoint, the degree of impact caused by selective logging in the forest ecosystem depends on several factors such as logging intensity, logging methods and collateral damage (Putz et al. 2001). The proportion of both soils and residual tree damage in logging operations generally ranges from 5% to 50% (Putz et al. 2001), with the lower impact being characteristic of reduced impact logging and the highest representative of conventional logging. Canopy recovery or structural recovery of areas affected by logging operations (e.g. gaps, logging roads) is important in order to assess the long term sustainability of forest areas subject to logging even though it is only one component of the natural restoration process in managed areas.

Remote sensing has proven to be a valuable tool for assessing forest changes at different spatial and temporal scales (Skole and Tucker 1993; Hansen et al. 2000; Hayes et al. 2002). Selective logging studies using remote sensing approaches are becoming standard in the scientific literature as multispectral imagery are available in addition to ground truth data. For instance, Asner et al. (2004) combined Landsat 7 ETM+ and field data to study canopy dynamics after selective logging in the eastern Amazon, while Broadbent et al. (2006) used ASTER data to investigate the temporal dynamics of the spectral properties of different gap size areas after selective logging. Nonetheless, the use of hyperspectral data has been more limited in remote sensing studies of selective logging primarily because of a lack of regional and temporal coverage as well as complications that arise from the analysis of these datasets. Also, the size of logging operations is important to consider in these studies; in the Amazon region logging is done on a large scale (> 1000 ha) which may differ from other tropical areas where most of the logging occurs at a smaller scale (< 100 ha) in more fragmented landscapes.

In this study we used hyperspectral airborne data to assess spectral changes in gap areas (tree felling and timber extraction roads) for three management units (> 50 ha) in a lowland tropical wet forest area in Costa Rica using a narrow band NDVI (Asner 2008) and linear spectral unmixing (Asner et al. 2005, Bohlman 2008). The objective of this study is to evaluate the canopy recovery of the disturbed areas (i.e. gaps and extraction roads) in the management units based on their spectral characteristics.

## 2. Methods

### 2.1 Data and study area

We used airborne hyperspectral imagery collected with the HyMap II sensor (15.5-16.9 m spatial resolution) in March 2005 during the CARTA II campaign. The management units, described in Arroyo-Mora et al. (2008), were located on two separate flight lines collected on separate days within the Central Volcanic Cordillera Conservation Area in Northeastern Costa Rica. The imagery had been georeferenced and atmospherically corrected by HyVista Corp. with in-house software prior to data delivery. The forest type in this area is considered to be wet lowland forest where the mature forest has a multistratal canopy with high species richness (McDade et al. 1994). The landscape around the protected forest areas encompasses a mosaic of forest patches that account for varying degrees of disturbance such as logging and management practices surrounded by agricultural crops and grazing pastures (Arroyo-Mora et al. 2008). A fragmentation analysis for the region (Arroyo-Mora 2008) showed that there are a total of 630 forest patches (> 1 ha) with an average forest patch size of 88 ha (± 948 ha). Arroyo-Mora (2008) also found that only eight forest patches were larger than 500 hectares (accounted for 32% of the total forest area) and 38 forest patches each were between 100 and 500 ha (accounted for 14% of the forest area). In addition, forest management activities were carried out mainly in only 21 forest fragments.

### 2.2 Information classes, selection of endmembers and linear unmixing process

Based on our knowledge of the study area and visual interpretation of the hyperspectral imagery, four information classes were chosen for this unmixing analysis: Closed canopy forest, Non-canopy vegetation, Pasture and Soil. The closed canopy forest represents a relatively undisturbed mature forest (McDade et al. 1994). Non-canopy vegetation may encompass several vegetation types of secondary forest or disturbed canopy. The main difference between this class and the closed canopy forest is that the vegetation in the non-canopy class has not reached full maturity or represents disturbance in mature forest. The pasture class is a broad class that encompasses grazing pastures and various grasses and may include patches of exposed soil with a majority of grass / herbaceous vegetation cover. The soil class represents exposed soil with minimal vegetation cover.

Because of a lack of conclusive ground truth data, a narrow band vegetation index (NDVI) (Asner 2008) was calculated for the region around the management units. The NDVI images for each management unit were stratified into twelve uniform classes.These NDVI classes were assigned to one of the four information classes described above based on an examination of their spectral signature and visual interpretation of the spatial context in which each NDVI class was found in the landscape.

Endmembers were chosen from the merged NDVI classes representing the four information classes. The separability of these endmembers was assessed first through an eight dimensional visualization. The eight bands used in this visualization were the best eight bands found by Arroyo-Mora et al. (2008) to separate the overall spectral signatures of the management units. To measure the spectral separability of the endmembers we used the Jeffries-Matusita distance (Richards and Jia 2006). The values for this separability measure range from 0-2, with 2 representing perfect separability. In general values above 1.9 represent good separability but values are scene dependent and with classes that have high variances or are not a good representation of pure endmembers, the separability can be somewhat lower.

For each of the two images a linear unmixing was performed with ENVI 4.3. This method determines the relative abundance of each of the endmember classes based on their spectral characteristics; in this analysis the spectra were constrained to the eight bands identified in Arroyo-Mora et al. (2008). The reflectance in each pixel of the image is assumed to be a linear combination of the reflectance of each endmember present in the pixel (Bohlman 2008). While partial or non-linear unmixing models have been proposed for vegetation, especially if very detailed classes are desired, several studies have successfully used linear models to unmix imagery into broad classes (Asner et al. 2005, Bohlman 2008). The results were normalized to represent a range of 0-1 where 0 would be no contribution from a particular endmember and 1 would be a pure representation of the endmember.

Pixels with predominantly closed canopy reflectance spectra were classified as pixels with a proportional contribution of the closed canopy class of 0.6 or greater (Hansen et al. 2000; Hecht and Saatchi 2007). The remainder of the pixels were assigned to one of the other three classes (non-canopy, pasture or soil) based on the class with the highest proportional representation. For example, a pixel with a canopy spectrum proportion of 0.37, a non-canopy spectrum proportion of 0.53, a pasture spectrum proportion of 0.09 and soil spectrum proportion of 0.01 would be classified as "non-canopy vegetation".The root mean squared error (RMS error) of the unmixing spatially illustrated areas with missing or incorrect endmembers. We determined the overall RMS error for each class in order to assess the overall error in the unmixing results. Because the RMS values are not normalized to the 0-1 range their values are interpreted as relative error.

## 2.3Analysis of gaps and extraction roads

Vector layers from the management plans representing the extraction roads and canopy gaps following logging were used to mask the classified image and determine the proportion of each class that spatially represent known past forest disturbance (Figure 1). Although, we were not able to determine the registration error between the unmixed image and the vector layers, the same spatial location between both layers as determined by Arroyo-Mora et al. (2008) was used.

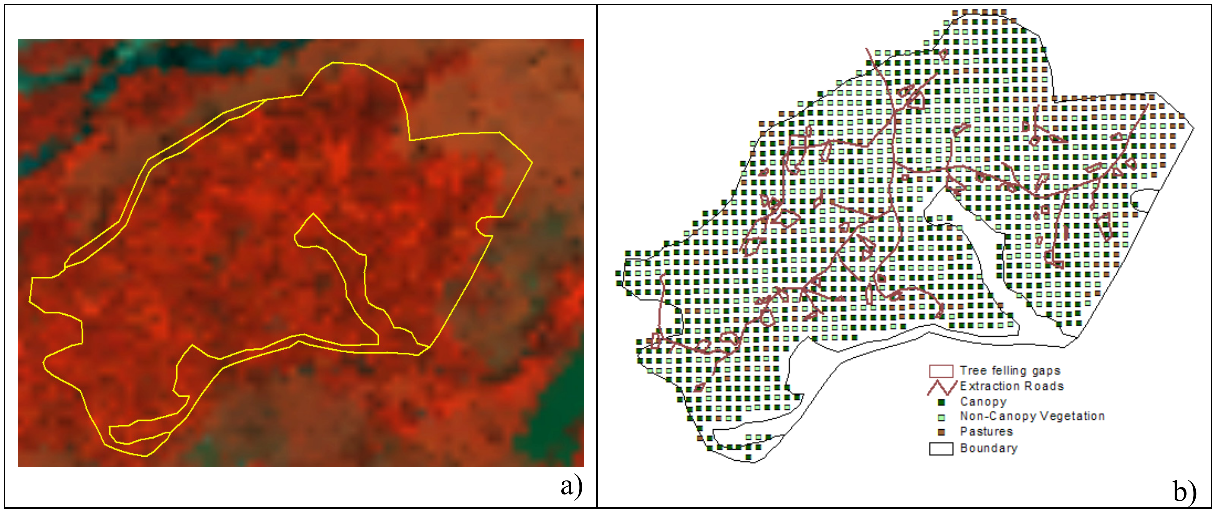

Figure 1. a) False-color composite of LD02, red corresponds to vegetated areas. b) Classification of the LD02 management unit based on endmember proportions with tree felling gaps and extraction road overlaid (logging intensity 5.95%, canopy recovery 57%).

## 3. Results and discussion

Our selection of the endmembers based on NDVI and visual interpretation of the hyperspectral images indicates a high separability of the information classes in the spectral space for both flight lines (Figure 2). This result is supported by the Jeffries-Matusita distance between classes, which has values above 1.77 for all the endmember comparisons with the exception of soils and pastures in flight line 200050327_s6 (1.48) (Table 1).

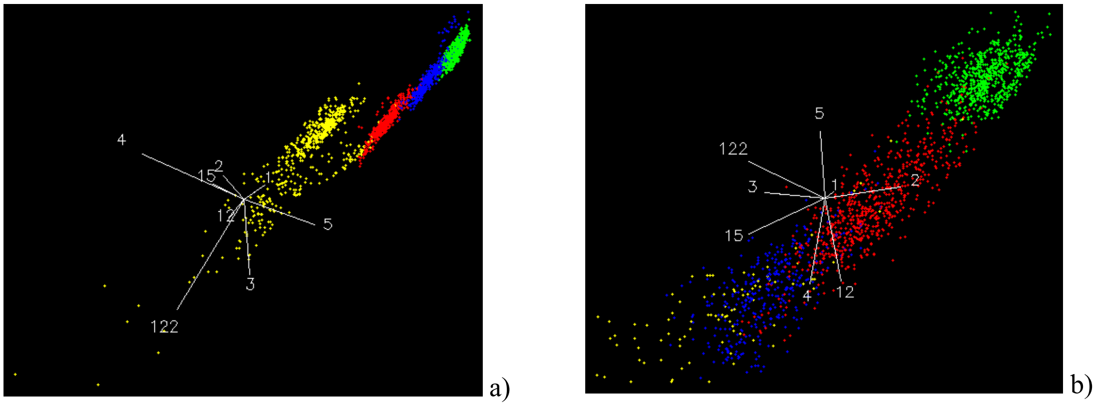

Figure 2. Spectral separability of the endmember classes in an 8-dimensional space for the two HyMap flight lines used in the study. Canopy in shown in green, non-canopy vegetation in red, pastures in blue and soils in yellow). A) Based on flight line for management unit HC01 and HR04. B) Based on flight line for management units LD02.

Examination of the unmixing results indicates a high spatial coherence between the canopy structure extracted from the imagery and the location of the gaps and extraction roads in the selectively logged units (Figure 1). In each unit closed canopy was the predominant class and varied from 39% in HC01 to 100% in HR04 (Table 2). This result suggests that canopy recovery might be related with intensity of the disturbance caused by the logging operations, rather than time since logging (Figure 3). Although most of the HC01 area was selectively logged in 2001, 8.79% of the total forest area had been disturbed, while in contrast only 4.79% of HR04, managed in 2004,had been disturbed (Arroyo-Mora et al. 2008). Moreover, the canopy class represents 57% in the unit LD02 which had a disturbance of 5.95% of the total forest area, indicating an apparent trend where canopy cover is related with overall disturbance rather than with time since the logging operation. The second most dominant class was non-canopy vegetation ranging from 0% in HR04 to 32 and 33% in LD02 and HC01, respectively. Soils were only present in the most heavily disturbed unit (HC01). Overall, the RMS error was relatively low (Table 2), indicating a good representation of the endmembers in the management units. However, the range in the RMS values indicates for all classes that there are some pixels which had additional endmembers we did not account for (e.g. RMS>20). These potential additional endmembers could be related to the influence of the canopy architecture on the spectra (i.e. illumination conditions, shading, canopy topography) (Gamon et al. 2005) as well as the potential contributions of different species of canopy trees or lianas that had not been included in the pixels selected to define the endmembers.

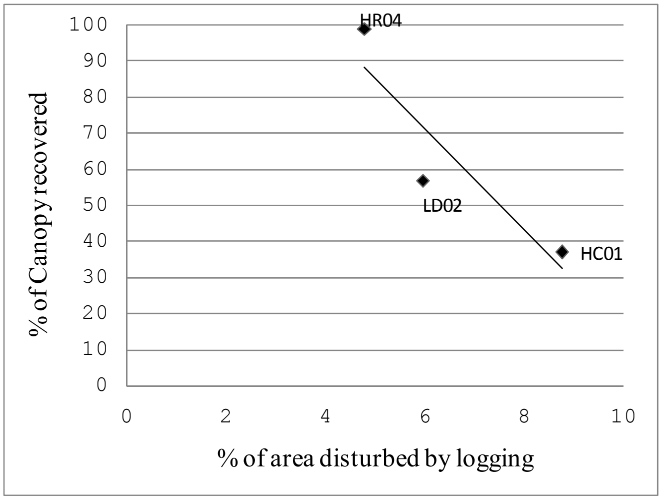

Figure 3. Percentage of area disturbed by logging operations versus percentage of canopy recovered. Canopy recovered refers to the percentage of pixels in gap areas and extraction roads (from selective logging) that were in the ‘canopy’ endmember class.

The endmember proportions in gaps and extraction roads were used as a proxy for forest recovery (Table 3). In the most highly disturbed unit (HC01), 37% of the gap areas were representative of canopy and 38% of roads. In addition, 24 and 32% represent non-canopy vegetation for both gaps and roads, respectively. Moreover, the pasture endmember encompasses 39% of the area in gaps and 31% in roads. In contrast, 59 and 56% (gaps and roads, respectively) appear to have recovered in LD02 in the two years following management. Similarly over 98% for both disturbance classes in HR04 have also recovered to canopy in the four months following management. These results indicate that the overall intensity of the management operations impact the forest recovery for several years in the case of high impact activities such as can be seen in HC01. This trend has also been shown in forest management units in the Amazon, where conventional logging had a greater impact on the canopy compared to reduced impact logging (Asner et al. 2004).

Our results also show that in the case of the conventional logging, the extraction roads have a higher disturbance impact than the gaps (HC01). For example 32% of the area affected by roads is still in the non-canopy vegetation class as opposed to only24% in gaps. Guariguata and Dupuy (1997) showed that logging areas where the topsoil is removed take longer to recover than logged forest areas. For instance, in HC01 the most disturbed areas that still have the spectral signature resembling herbaceous vegetation cover; 39% of the areas affected by gaps and 31% of the areas affected by roads (Table 3). Such a prolonged disturbance in the canopy is indicative of a high intensity/impact disturbance. In contrast the management unit with the lowest overall logging intensity (HR04, 4.79%) shows a nearly complete (98%) recovery in roads and a complete recovery in gaps, even though it is the unit with the least time between logging and the image acquisition (0.3yr versus 2 and 3 years) (Table 3).

Table 1. Endmember separability matrix based on the Jeffries-Matusita distance. The upper part of the matrix corresponds to flight line 20050401_s1 (management units HC01 and HR04) and the lower part (gray shaded) of the matrix to flight line 200050327_s6 (management unit LD02).

| | Canopy | Non-Canopy vegetation | Pastures | Soils |
|---|---|---|---|---|
| Canopy | | 1.80 | 1.99 | 1.98 |
| Non-Canopy vegetation | 1.82 | | 1.77 | 1.96 |
| Pastures | 1.99 | 1.86 | | 1.96 |
| Soils | 1.99 | 1.99 | 1.48 | |

Table 2. Percentage of the endmember classes for each selectively logged unit and relative root means square (RMS) error of the linear unmixing process.

| **HC01** | | |
|---|---|---|
| **Class** | **Total Area in ha (%)** | **RMS (min-max)** |
| Canopy | 4.64 ha (39) | 1.7±3.9 (0.0-19.7) |
| Non-canopy | 3.82 ha (32) | 4.5±5.7 (0.0-22.1) |
| Pasture | 3.46ha (29) | 1.3±3.7 (0.0-22.1) |
| Soil | 0.02 (-) | 17.26 |
| **LD02** | | |
| **Class** | **Total Area in ha (%)** | **RMS (min-max)** |
| Canopy | 24.58 ha (57) | 7.7±5.1 (1.2-36.8) |
| Non-canopy | 12.25 ha (33) | 8.2±5.3 (1.4-35.8) |
| Pasture | 4.06 ha (11) | 8.5±4.4 (2.1-23.4) |
| Soil | - | - |
| **HR04** | | |
| **Class** | **Total Area in ha (%)** | **RMS (min-max)** |
| Canopy | 10.09 ha (100) | 7.1±6.5 (0.0-39.8) |
| Non-canopy | 0.02 ha (-) | (7.9-12.7) |
| Pasture | 0.02 ha (-) | 17.4 |
| Soil | - | - |

Table 3. Endmember percentages in gaps and extraction roads for the three selectively logged units from the HyMap II imagery (year 2005).

| | HC01 | LD02 | HR04 |
|---|---|---|---|
| **Gaps** | | | |
| Canopy | 37 | 59 | 100 |
| Non-canopy | 24 | 38 | 0 |
| Pasture | 39 | 3 | 0 |
| **Roads** | | | |
| Canopy | 38 | 56 | 98 |
| Non-canopy | 32 | 37 | 0 |
| Pasture | 31 | 7 | 2 |

## 4. Conclusions

Our results indicate a good selection of broad endmember classes based on a narrow band NDVI and visual interpretation of the imagery. With these endmember classes we were able to quantify potential recovery of the canopy class in selectively logged areas in this lowland forest in Costa Rica. Nonetheless, our general approach for endmember selection could be improved with ground data such as GPS locations for the classes and field spectra of different vegetation components (Asner et al. 2005). In addition, more sophisticated endmember selection techniques could be applied to enhance the accuracy of the results. A particular aspect of the analysis is that we used as ingle timeframe of data instead of multi-temporal data, therefore, assuming changes in spectra following canopy disturbance are due primarily to selective logging. This analysis illustrates that while the forest may appear to be undisturbed or fully recovered through visual interpretation of the imagery, the spectral information illustrates that effects of logging remain following conventional and mid-impact logging. Refining endmember extraction together with accurate depiction of logging disturbance represents a powerful tool for mapping forest recovery in the tropics, especially small scale logging (< 100 ha) in fragmented landscapes like the one from this study in comparison to large scale forest areas like those characteristic of Brazil and Bolivia, for example.

## 5. Acknowledgments

We would like to acknowledge the financial support of the Center for Environmental Sciences and Engineering (CESE) at the University of Connecticut, the National Science Foundation (Grant OISE-0537208) and the logistical support from McGill University. In addition, we are very grateful with German Obando and Andres Sanchun at the Foundation for the Development of the Central Volcanic Cordillera Area (FUNDECOR) who provided the selective logging data and to Carlomagno Soto at the Costa Rican National Center for High Technology who facilitated the acquisition of the hyperspectral data.

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