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Defoliation and the war on drugs in Putumayo, Colombia

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Analysis of three Landsat Enhanced Thematic Mapper Plus (ETM+) images of the Putumayo region of Colombia, one of the primary regions of coca production in Colombia, demonstrated that aerial spraying of defoliants under the US 'Plan Colombia' programme impacted broad swaths of the landscape and had the unintended consequence of defoliating contiguous and interspersed native plant and food crop parcels. Using fractional coverage, field data collections and a hybrid classification, 106 178 ha of impacted land were found, compared with the United Nations Drug Control Program reported reduction in coca of 71 891 ha, an unexplained difference of 34 287 ha. The complex spatial organization of the Colombian coca-producing landscape appeared to confound the spraying of defoliants, and as demonstrated here, many non-coca land cover classes have been affected adversely.

1. Introduction

Plan Colombia was created by the USA during the Clinton administration to reduce the impact of drugs within the USA (Crandall 2002). The original Colombia-based goals of the plan were: expansion of defoliant spraying into Southern Colombia; support for narcotics interdiction efforts; support for the Colombian National Police; support for development programmes; and support for justice and social sector reform (USDS 2001). Prior to the implementation of Plan Colombia, cocaine was the most widely used narcotic drug, with production concentrated in Bolivia, Peru and Colombia (Ehleringer *et al.* 2000). Aerial spraying of defoliants was used as the primary coca production control method.

The defoliant used, glyphosate, commonly formulated as Roundup$^{\mathrm{TM}}$, is a post-emergent, systemic and non-selective herbicide used widely in both agricultural and non-agricultural applications. Approved by the US Environmental Protection Agency for general use in 1974, in Colombia, it was mixed with water and a locally produced adjuvant, Cosmo-Flux 411F. This formulation increased the persistence and penetration of the defoliant into the waxy leaf structure of the coca plant (USDS 2003). The herbicide mixture was very effective at eradicating coca production. However, the spraying has been reported widely to have also killed basic food crops, such as yucca, avocados, maize and plantains of nearby subsistence farmers (Forero 2002). Cananguchal palm trees, an indigenous staple crop used for food, clothing and roofing material, have also been affected (Anderson 2001). Typically, small-holders intercropped coca with food crops both

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to provide subsistence and to avoid detection and spraying. Drifting glyphosate was also reported to be the cause of some unanticipated defoliation in Ecuador (C. Mena, 2003, personal communication).

During 2001, 84 250 ha of coca were sprayed as part of Plan Colombia (Tenenbaum 2002). This large area spraying event focused on industrial plots and ended in February 2001, when former Colombian President Pastrana limited some missions over negotiation concerns with the 'Revolutionary Armed Forces of Colombia' (FARC) rebels. On 29 August 2002, the USA, with support from the new Colombian President, Alvaro Uribe, initiated the largest and most aggressive effort yet to wipe out coca farms. Limited spraying of 18 000 ha began on 31 July. Coca eradication efforts throughout the whole of Colombia in 2002 were increased greatly to 130 000 ha, 30% more than 2001. The Department of Putumayo, one of the most aggressively targeted regions, and the study site, is located in south-western Colombia and shares borders with the Sucumbios Canton of Ecuador and the Loreto Department of Peru. Over the last few years, two major fumigation efforts have occurred there. The first period of defoliation flights lasted from December 2000 to February 2001 covering 25 000 hectares and the second, from July to October of 2002, covered 60 500 hectares (Vaicius and Isacson 2003). The United Nations Office on Drugs and Crime (UNODC), using remotely sensed imagery, estimated that Putumayo had 32 506 ha fumigated in 2001 and 71 891 ha in 2002 (UNODC 2003).

The research objectives of the work discussed in this Letter are threefold: (1) use remote sensing methodologies to detect the biophysical attribute changes that have occurred as a result of fumigation; (2) quantify the amount of defoliation of vegetation using the field-calibrated data; and (3) identify the primary land cover classes affected by fumigation and attempt to identify whether the spraying has occurred in areas with non-coca land covers.

2. Methods

Three distinct remote sensing techniques were used to meet the objectives. First, fractional coverage of green vegetation (FC), an image processing-based measure, was calculated to quantify the percentage of ground covered by green vegetation. Secondly, the relationship between FC and the vegetation cover on the ground was tested through field measurements and, thirdly, a hybrid classification was used to identify types of ground features most affected by defoliant spraying.

The Landsat Enhanced Thematic Mapper Plus (ETM+) imagery used (path 9, row 60: 09/09/01, 09/12/02, and 10/14/02) cover the coca re-growth cycle after the 2001 eradication event and capture the extent of the defoliation during the 2002 eradication event. Image pre-processing included a radiometric and atmospheric correction of each image resulting in pixel values transformed to surface reflectance (ρ) (Tanre *et al.* 1990; LPSO 2003). Quantitative measurements of defoliation and impacts on non-coca land cover classes were based on two procedures. First, the FC was used to quantify percent change in green leaf coverage between image dates (Qi *et al.* 2000). As FC is expressed as a percent of the pixel area covered with green vegetation, the change detection results were easy to understand and generalize. In each image, the ρ values were first converted to Normalized Difference Vegetation Index (NDVI) values, and then fractional coverage values were generated using the NDVI values. To select the $\mathrm{NDVI_{VEG}}$ value (the NDVI value of a pixel with 100% green vegetation cover), three 25×25 pixel areas were identified and isolated as subsets from the image in places of likely 100% cover such as dense forest and large African Palm plantations. The maximum NDVI pixel value of the subsets was then considered as the pixel value nearest to 100% vegetation cover. A similar method was used to find the $\mathrm{NDVI}_{\mathrm{SOIL}}$ value, except that the subset areas were bare areas, such as the known barren downtown districts of Lago Agrio and Coca. Where the maximum NDVI value was previously used, the minimum NDVI value was used for the $\mathrm{NDVI}_{\mathrm{SOIL}}$.

$$\mathrm{NDVI} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{RED}}) \tag{1}$$

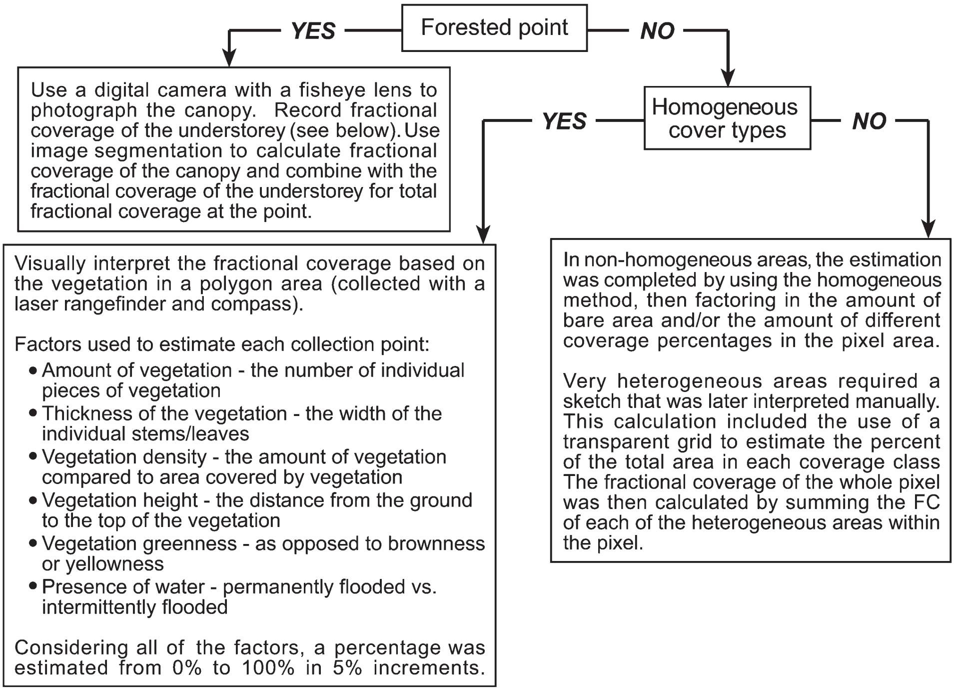
$$\mathrm{FC} = (\mathrm{NDVI} - \mathrm{NDVI}_{\mathrm{SOIL}})/(\mathrm{NDVI}_{\mathrm{VEG}} + \mathrm{NDVI}_{\mathrm{SOIL}}) \tag{2}$$

Second, land use classes were generated using a hybrid classification scheme, which combined unsupervised and supervised methods for classification. The ISODATA-based unsupervised classification was completed first. The spectral signatures generated from this classification were gathered and examined in a transformed divergence matrix. Each signature was compared against all of the other signatures in the set and those signatures with high levels of confusion were eliminated. The resulting signature set contained 90 distinct spectral signatures selected using a transformed divergence statistic of greater than 1950. These signatures were then used as training data in the maximum likelihood supervised classification. Finally, the three Landsat ETM+ images were then geometrically rectified for analysis using a second-order polynomial transformation that resulted in a rms. of less than 1 pixel per image. The respective rectification models were used to rectify all subsequent data products.

2.1 *Field methods*

The imagery-derived FC numbers were examined during field data collection in Ecuador, during June 2003. The points for collection were identified using a stratified random scheme and the 12 September 2002 FC image, which contained significantly less cloud cover than the 14 October 2002 image. The FC image was recoded in 10% increments (0–10, 11–20, etc.) and buffered to keep pixels within 250 m of the roads. For each 10% increment, 30 points were generated, resulting in 300 sample points for primary collection. Once in the field, a hand-held Global Positioning System (GPS) unit was used to navigate to each predetermined FC point location. The FC at each field location was recorded using the decision rule in figure 1 and subsequently differentially corrected.

Land cover data were collected in February 1999, February 2000, June 2003 and June 2004. An adaptive stratified random sample design was used for all collections (Thompson and Seber 1986, Messina and Walsh 2001). The sample design used the class map produced after the supervised classification as the stratifying element and then randomly placed a minimum of 50 sample sites within each strata throughout the landscape. Land cover data collected in 1999 and 2000 were used for attribution of the final class maps. The classification accuracy was assessed through the use of the land cover data collected in 2003 and 2004. The sample design and hybrid classification methods combined to produce land cover maps with an overall classification accuracy kappa statistic of 0.801, which reflects, in part, the dynamism of the landscape.



Use a digital camera with a fisheye lens to photograph the canopy. Record fractional coverage of the understorey (see below). Use image segmentation to calculate fractional coverage of the canopy and combine with the fractional coverage of the understorey for total fractional coverage at the point.

Visually interpret the fractional coverage based on the vegetation in a polygon area (collected with a laser rangefinder and compass).

Factors used to estimate each collection point:

- Amount of vegetation - the number of individual pieces of vegetation
- Thickness of the vegetation - the width of the individual stems/leaves
- Vegetation density - the amount of vegetation compared to area covered by vegetation
- Vegetation height - the distance from the ground to the top of the vegetation
- Vegetation greenness - as opposed to brownness or yellowness
- Presence of water - permanently flooded vs. intermittently flooded

Considering all of the factors, a percentage was estimated from 0% to 100% in 5% increments.

In non-homogeneous areas, the estimation was completed by using the homogeneous method, then factoring in the amount of bare area and/or the amount of different coverage percentages in the pixel area.

Very heterogeneous areas required a sketch that was later interpreted manually. This calculation included the use of a transparent grid to estimate the percent of the total area in each coverage class The fractional coverage of the whole pixel was then calculated by summing the FC of each of the heterogeneous areas within the pixel.

Figure 1. Decision rules used for the calculation of fractional coverage.

3. Data processing and analyses

The FC data from the ground control point locations were compared witho the image-derived FC data at those same locations. Since many of the sample points did not fall within the centre of their respective pixels, a 22.5 m buffer was constructed around each sample point to account for the effects of the surrounding pixels. This distance is slightly larger than half of the distance from a pixel corner to a pixel centre. With the buffer and an overlay process, a sample point falling directly in the corner of four pixels would be represented by FC numbers from each of those pixels. For those points that were within 22.5 m of multiple pixel centres, the average of the pixel values was assigned for the image FC number at that point. In a regression model of the relationship between the FC values from the image and the ground data, 131 sample points were used (figure 2). Given that the region is a very dynamic landscape and that there was a nine-month lag between the date of image acquisition and field data collection, some changes occurred. When changes within the nine-month lag window could be verified by farmer interviews, the points were removed from the sample; otherwise all collected samples were included in the regression model.

Using a subset of the Landsat ETM+ images that captured the areas affected by fumigation, fractional coverage change was computed. Event one captures change between 9 September 2001 and 12 September 2002; event two captures change between 12 September 2002 and 14 October 2002. Confusion between defoliation and small-scale clearings, or tree-falls, was minimized by constraining analysis to areas with more than 10% defoliation. Only pixels with a fractional coverage loss of greater than 10% (thus 10% defoliation) were retained for event comparisons. A 10%

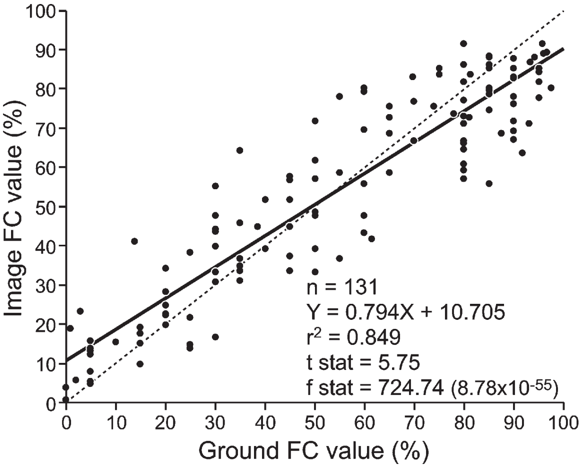


Figure 2. The relationship between the image FC and the ground FC data collected, June 2003.

loss in fractional coverage could be characterized as the reduction of 10% of the area of a pixel covered by green vegetation. This could include 10% of a 100% vegetated pixel being cleared or a reduction of the canopy coverage from 90% to 80%. There were many possible combinations. These pixels were stratified into defoliation classes.

Using the signature set produced earlier, and focusing on event two, a final land cover classification was produced. This classification scheme was based upon experience within the broader region and specifically along the border between Ecuador and Colombia (see table 1, column 1; Messina and Delamater 2003). The accuracy of the land cover classification in Putumayo, Colombia was not assessed directly due to the very large risks to fieldwork in the coca production areas. However, the classification accuracy was assessed through the use of the land cover data collected in 2003 and 2004 in bordering Ecuador. With the exception of coca, the same land cover classes were found widely throughout the region and the field sites visited ranged from less than 1 km from the border to no more than 60 km from the border. The coca land cover class was identified using the decision rule; agricultural classes north of the Rio San Miguel, which divides Colombia and Ecuador, and land cover classes comprising a small percentage of the overall image

Table 1. The intersection of defoliation and land cover classes

Land cover class description	No. spectral classes	% image area	% defoliated area
Dense forest: including primary and high-graded forests	3	38	5
Secondary forest: including young secondary forest and silviculture	1	17	9
Pasture: including grasslands and mixed grasslands with sparse tree cover	2	13	6
Agriculture: including annual and perennial crops	5	13	41
Coca (see text)	5	6	20

area, yet representing a high percentage of the defoliated area. As of 2004, coca cultivation has not been reported in Ecuador, so the rule to limit the coca classes to classes north of the border reduced the chances of mislabelling. The results of the intersection of the defoliation (event two) with these classes are found in table 1.

The sample design and hybrid classification methods combined to produce land cover maps with an overall classification accuracy kappa statistic of 0.87, which reflects, in sum, the simplicity of the broad classification scheme, the coca decision rule and the dynamism of the landscape. The land cover map was then overlaid on the stratified image of defoliation and the number of land cover classes present in each defoliation class tabulated. The results reported here include 16 of the 90 distinct spectral classes identified. These classes represent 87% of the total image area, and 81% of the total defoliated area. The remaining 13% of the image area and 19% of the defoliated area are represented in the remaining 74 spectral classes.

4. Results and discussion

Within the study area, 56 627 ha of 10% or greater defoliation occurred during event one (9 September 2001–12 September 2002) and 49 551 ha during event two (12 September 2002–14 October 2002) of the south-western Putumayo coca eradication effort (see figure 3). The total area experiencing 10% or greater defoliation during 2002 coca eradication effort in the region was 106 178 ha. The linear and noticeably unnatural spatial organizations of the defoliation patterns in both events were striking visual characteristics. The linear patterns are believed to be the result of the flight lines taken by the aircraft while spraying. The scale at which these linear patterns manifest also contributed to unnatural aspect of the patterns. As discussed earlier, the farmers in this area live on very small plots. To have all of them clear their areas at the same time would require a very large and very unrealistic organized effort. The last distinguishing spatial characteristic was the temporal variability that existed between the events. A very noticeable trend was that, while the pattern of defoliation ran north to south, the defoliated areas of event two shifted westward away from the areas in event one.

Impacted land cover classes were identified by comparing defoliated areas with the regional land cover map. Highly constrained spraying of coca would theoretically limit the total number of spectral classes heavily impacted. Thus, the areas of greatest magnitude change in fractional cover would theoretically contain significantly fewer spectral classes. According to the UNODC report, coca production in Putumayo was reduced by 71 981 ha versus this study's measured defoliation of 106 178 ha, an unexplained difference of 34 287 ha. For events one and two, the three dominant spectral classes represent 24% and 36% of the defoliated landscape, respectively, with the top ten classes representing 60% and 69%, respectively. Even assuming that the top ten most defoliated classes captured most forms of coca production, this still left 31% and 40% of the defoliation per event occurring in non-coca or coca intercropped lands. For the 50% and above defoliation class, 57% of the total spectral classes in event one and 63% in event two, including crops and other non-coca producing lands captured in both events, were represented.

5. Conclusions

Multi-temporal analysis of three Landsat ETM+ images of the Putumayo department of Colombia, one of the primary regions of coca production in

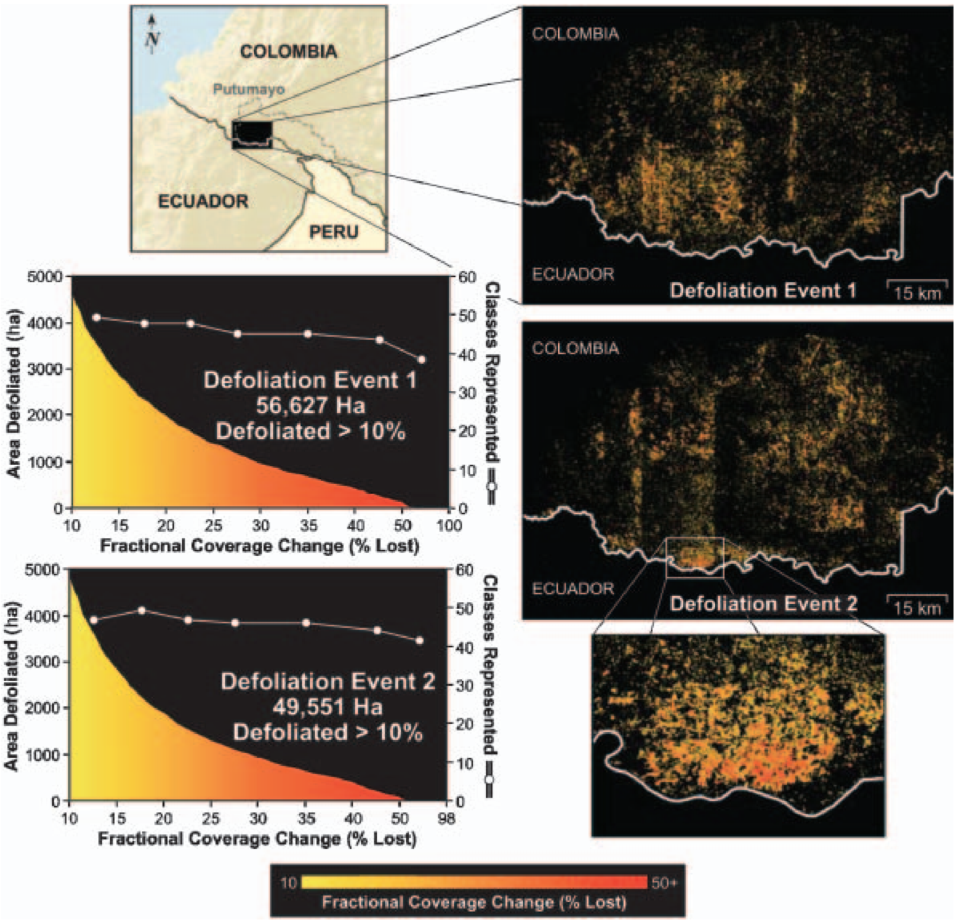


Figure 3. Collateral damage to agricultural and non-coca land cover types in Putumayo, Colombia. Using a common colour ramp between the graphs and the maps (10% defoliated in yellow to 100% in red), the broad-scale vertical striping associated with aerial defoliation and the east–west shift in flight paths are displayed. Area defoliated and percent defoliation is shown with respect to the numbers of classes represented across the defoliation events. The ‘classes represented’ line data indicate the number of land cover classes (out of 90) that contain defoliated pixels in each defoliation class. As percent defoliated increases, a reduced chance that defoliation is occurring due to drift or runoff should exist as heavily defoliated classes should have been coca. With perfect spraying, the ‘classes represented’ line should be strongly negative with the most heavily sprayed areas containing only one spectral class.

Colombia, demonstrated that aerial spraying of defoliants under the US ‘Plan Colombia’ programme has had the unintended consequence of defoliating not only coca but also contiguous and interspersed native forest and food crop parcels. Given restricted access to southern Colombia and dangerous field conditions, remote sensing afforded the only reasonable method to quantify the changes occurring. Data availability, however, has been a significant issue. The region is classic humid tropics, with cloud cover present almost every day. This has made both monitoring the situation more difficult and, conversely, hiding the effects from the public simpler. While this research should not be used to indict the UNODC or the organizations responsible for spraying, it should serve as a warning that the published reports on drug war results are open to interpretation and that some of the anecdotal, and usually dismissed, claims of misapplication of spraying may, in fact, be true. As demonstrated here, significant numbers of other non-coca land cover classes have been affected adversely.

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