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Validation of MODIS annual deforestation monitoring with CBERS, Landsat, and field data

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Abstract: We compare field measurements in central Mato Grosso and coincident CBERS and Landsat imagery to a MODIS-based classification of annual deforestation to evaluate classification accuracy and characterize omission and commission errors. The MODIS 250m deforestation classification had low commission (9%) based on field observations, and no commission errors for identified deforestation areas >20 hectares. Using visual interpretation of coincident CBERS and Landsat imagery, we estimated that the MODIS classification omitted 36% of visually identified deforestation events. Most omitted detections (63%) were at the forest/non-forest boundary, and were excluded based on the MODIS methodology; 82% of omission errors within the MODIS analysis area appeared unburned in coincident MODIS imagery. Omission of clearings <20 ha was high (90%) but very low (9%) for clearings >50 ha. Future modifications to the algorithm to reduce omission of unburned clearings for early detection of large deforestation events appear feasible.

Keywords: MODIS, deforestation, satellite monitoring, field validation, accuracy assessment; MODIS, desmatamento, monitoramento, trabalho de campo, accuracia do produto.

1. Introduction

Deforestation in the Brazilian Amazon is a chronic problem with myriad impacts on regional and global carbon cycling (e.g., Houghton et al., 2000) and climate (e.g., Salati and Nobre, 1991; Werth and Avissar, 2002). Deforestation rates in the Legal Amazon have remained roughly constant or increased over the past two decades (INPE, 2004), elevating the need for frequent and accurate assessment of forest loss. Continued expansion of cattle ranching and mechanized agriculture are important drivers of these consistently high rates of forest clearing (Laurence et al., 2004).

On-going efforts for deforestation monitoring in the Brazilian Amazon require processing and storing large volumes of high-resolution satellite data. The Instituto Nacional de Pesquisas Espaciais (INPE) analyzes more than 220 Landsat TM scenes each year to provide annual high-resolution mapping of deforestation as part of the PRODES project (Estimativa do Desflorestamento da Amazônia). Recent changes in PRODES methodology have reduced the time necessary to analyze this large volume of satellite data (e.g., Shimabukuro et al., 1999), but basin-wide estimates still require many months and thousands of man-hours to complete (INPE, 2002). Analyses of high-resolution data such as Landsat for tropical forest regions also suffer from persistent cloud cover and infrequent repeat coverage (Asner, 2001). In addition, few regional high-resolution data products have been formally validated in the field, leaving data users without a clear understanding of product accuracy.

Data from NASA's Moderate Resolution Imaging Spetroradiometer (MODIS) sensors constitute an important new data source for deforestation monitoring in the Brazilian Amazon. The MODIS instruments aboard the Terra (AM) and Aqua (PM) platforms provide consistent daily coverage of the entire globe at 250m–1km resolution with 36 bands of spectral information (Justice et al., 2002). MODIS instruments acquire images of the Brazilian Amazon up to four times per day, with a swath width of approximately 2,300 km. Raw data are geometrically and radiometrically corrected, processed into products such as surface reflectance and vegetation indices, and distributed at no cost via the Land Processes Distributed Active Archive Center (Justice et al., 2002). Frequent data acquisition and accurate geolocation make MODIS data ideal for deforestation monitoring.

Raw MODIS data are processed into a variety of standard land cover products that can be used for monitoring deforestation. Surface reflectance products (MOD09) are available as daily or 8-day composite images. MOD09 and 16-day composite surface reflectance and vegetation indices (MOD13) products are distributed in near-real time, facilitating more frequent analyses of deforestation. The most appropriate product for deforestation monitoring will depend on the required spatial, spectral, and temporal resolution of input data.

MODIS data products also include a quality assurance (QA) layer that facilitates rapid analysis of forest cover. The QA layer evaluates the quality of input data for each pixel and specifically flags clouds, water, high aerosols, and missing data (Huete et al., 1999). The combination of QA information and product compositing reduces the data volume and processing required for deforestation monitoring and increases the possibility of cloud-free views of the basin.

Several recent studies have used Landsat training data to evaluate MODIS-based mapping of land cover and land cover change in the Brazilian Amazon. In a comparison of methods for identifying annual deforestation increment with MODIS data products, a variety of methods were able to identify >80% of deforestation events larger than 3 hectares for test areas in the Legal Amazon (Morton et al., submitted). A second recent study derived accurate forest and non-forest classes from 250m MODIS data in Pará state using a decision-tree classification (Wessels et al., 2004). Principal sources of classification error were haze or thin clouds and mixed pixels at class boundaries (Wessels et al., 2004). Spectral unmixing of MODIS surface reflectance data at 250-500 m resolution proved useful for classifying land cover (Anderson et al., in press) and identifying recent deforestation in daily and composited land cover products (Anderson et al., submitted). These studies suggest that forest and non-forest discrimination is possible with moderate resolution data, but accurate classification of pixels at the edge of forest/non-forest boundaries or small deforestation events may require sub-pixel classification methods.

The goal of this study was to field validate a simple and efficient method for annual monitoring of deforestation using MODIS data in the Brazilian Amazon. We evaluated results from a recent study of methods for deforestation detection using MODIS in central Mato Grosso (Morton et al., submitted). Field validation data provide reliable information on commission errors in the MODIS 250m deforestation classification. However, it is difficult to evaluate omission error in the field because it is not possible be identify all deforestation events. In this paper, we extend analysis of MODIS detection accuracy through comparisons with coincident high resolution CBERS data (20 m resolution) and Landsat data (30 m resolution). Finally, we separate deforested and deforested/burned polygons based on field observations and evaluate their spectral responses in MODIS imagery in order to categorize omission errors. Lessons from field validation results will help improve methods for MODIS-based deforestation monitoring the Brazilian Amazon.

2. Methods

Mato Grosso state was chosen for field validation of MODIS-based deforestation detections based on consistently high annual forest clearing in recent years (INPE, 2004). Digital PRODES deforestation data from 2003 show a wide range of clearing sizes, with high densities of new clearings in the central portion of the state (INPE, 2004). Building on the results of a previous analysis of deforestation detection with MODIS data (Morton et al., submitted), the single-date threshold method with MOD13 red reflectance was chosen for validation with field observations in central Mato Grosso state between 14-21 July 2004. To reduce commission errors due to variations in MODIS view angle geometry, the edge pixel in the 250m resolution forest mask is removed from consideration in this method; commission errors including the edge pixel were much higher (50%) than after removal (10%) (Morton et al., submitted). For this analysis, deforestation clusters were defined as contiguous 250m MODIS deforestation pixels.

Ground-based teams of observers assessed per-cluster accuracy in the following manner. Using a vector layer of roads in Mato Grosso to stratify the MODIS classification, all deforestation clusters that intersected a road were selected and numbered. Roads, sample clusters, near-coincident Landsat TM and MODIS imagery, and MODIS deforestation classification results were loaded into a GIS and compared with real-time GPS coordinates in the field. To characterize detection accuracy based on cluster size, we observed clusters ranging from single pixels (6.25 ha) to 408 pixels (2,550 ha). For each cluster observed in the field, GPS points were taken along the roaded edges of the clearing and, when possible, at other points along the perimeter. These measurements and observations were compared with near-coincident Landsat TM images in the field. Clusters that contained new deforestation anywhere within the cluster perimeter were classified as deforested. A total of 120 MODIS deforestation clusters were observed in the field.

Following data collection in Mato Grosso, the MODIS deforestation classification was rerun with MOD09 daily surface reflectance at 250m (22 July 2004) to be coincident with field observations of clearing size and burning. MOD13 data were initially chosen to identify the location of new clearings in order to minimize cloud cover, but 16-day compositing, in which pixel choice is biased towards the highest NDVI during the period (Huete, 1999), may mask expansion of clearings or burning events that change on a daily basis. Commission calculations based on field data refer to MOD13 clusters visited in the field. For comparisons between field observations and high-resolution imagery, information from field-validated MODIS clusters was assigned to matching MOD09 clusters.

Field validated forest and deforestation clusters in the MOD09 classification were compared to coincident CBERS images (Scenes 166/113 and 166/114 from 17 July 2004) and Landsat TM (scene 226/68, 23 July 2004) (**Figure 1**). CBERS and Landsat TM images were acquired from INPE and georeferenced to 2002 Landsat ETM+ scenes from the Global Land Cover Facility (www.glcf.umiacs.umd.edu). Using a forest mask from 2003 PRODES digital data, new deforestation events were identified in the CBERS and Landsat data through visual interpretation and hand digitized in a GIS. Digitized polygons from CBERS and Landsat imagery from two expert interpreters showed a high degree of consistency. As a result, polygons from higher-resolution CBERS imagery (20m) were chosen for accuracy assessment comparisons with MODIS. Identifying all new deforestation polygons within the study area through visual interpretation of from high-resolution imagery permits a more robust characterization of omission error than through field data alone.

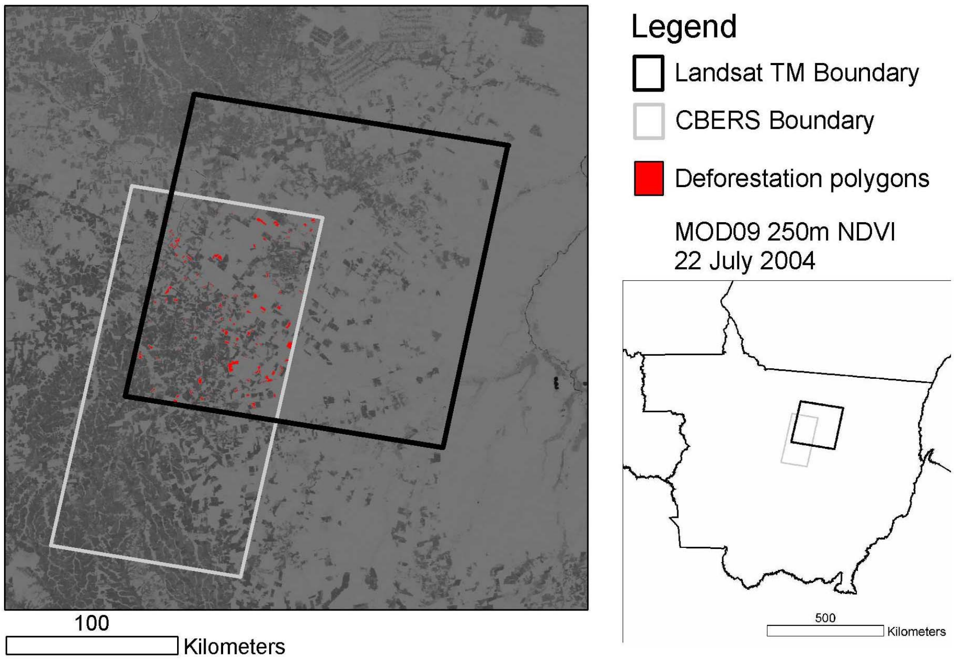

Figure 1. Study area map showing Landsat TM boundary (226/68, 23 July 2004) and perimeter of CBERS images (166/113, 166/114, 17 July 2004) in relation to the state of Mato Grosso (inset). Polygons from CBERS and Landsat interpretation are shown in red over MODIS 250 m NDVI derived from MOD09 surface reflectance data from 22 July 2004.

We quantified MODIS classification accuracy in terms of omission and commission errors separately for field and image-based validation data. Field-visited clusters were first classified as either forested or deforested to assess commission errors. Observations from the field were also used to stratify deforestation clusters as cut (deforested, but not burned) and burned (deforested and burned). Cut and burned strata were then used to generate spectral signatures from MODIS daily surface reflectance. CBERS polygons were compared to MODIS clusters in the CBERS/Landsat image footprint (10,920 km^2) to provide a more robust estimate of omission. Omitted polygons were further classified as 1) within the forest area for MODIS analysis (see Morton et al., submitted) and 2) cut or burned, and summarized by polygon size. Finally, MODIS clusters were compared to corresponding CBERS polygons to characterize deforestation area measurements from the two sensors.

3. Results

Of the 120 MODIS deforestation clusters visited in the field, 109 were observed as deforested (9% commission). MODIS cluster area was 35% of CBERS polygon area for field-validated deforestation events (**Figure 2**). The difference between CBERS and MODIS area was large for all polygons, although differences were somewhat smaller for very larger clearings. All deforestation polygons larger than 20 hectares were observed as actual deforestation in the field. Inter-observer agreement for cluster interpretation in the field was 100%. Omission errors could not be quantified from field observations.

Using polygons from visual interpretation of CBERS imagery, the MODIS classification omitted 36% (88/246) of visually identified deforestation events. Most omitted detections (55/88, 63%) were at the forest/non-forest boundary, an excluded region in the MODIS analysis to minimize false detections from view angle variation. Omitted polygons ranged from 3 to 123 hectares; nearly 40% (34/88) were less than 20 hectares (**Figure 3**).

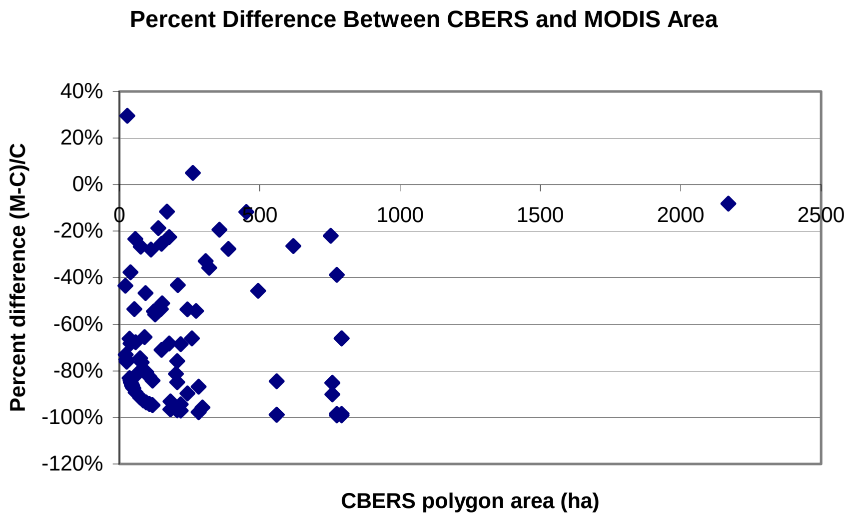

Figure 2. Percent difference between CBERS polygon area and MODIS cluster area for field-validated polygons, defined as (MODIS-CBERS/CBERS).

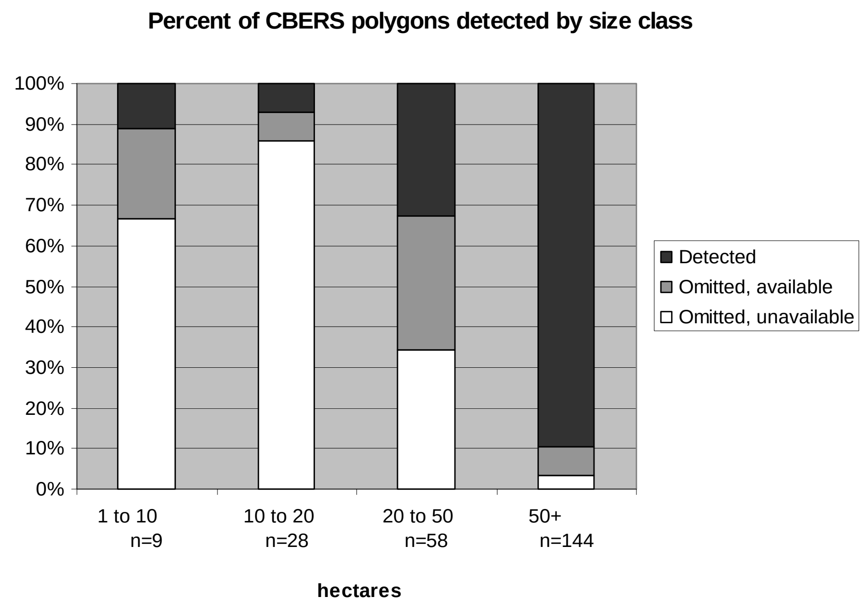

Figure 3. Size distribution of polygons from CBERS and Landsat interpretation detected and omitted in MODIS classification of deforestation. Polygons outside the analysis area for MODIS (omitted, unavailable) comprise 65% of total omission. Polygons that overlap with MODIS analysis area but were not detected are labeled "omitted, available". The number of polygons in each size category is listed.

For field validated deforestation clusters, newly deforested areas ("cut") were greener (mean NDVI = 0.53 ± 0.12) than burned clusters (mean NDVI = 0.31± 0.17) (**Figure 4**). Using the results from field observations of MODIS clusters, it is possible to assess whether CBERS polygons omitted in the MODIS classification were cut or burned. **Figure 5** shows the mean and minimum NDVI for each omitted polygon and the class boundaries as defined in Figure 4. Based on these class boundaries, 27/33 (82%) of omitted polygons within the MODIS analysis area appear cut but not burned.

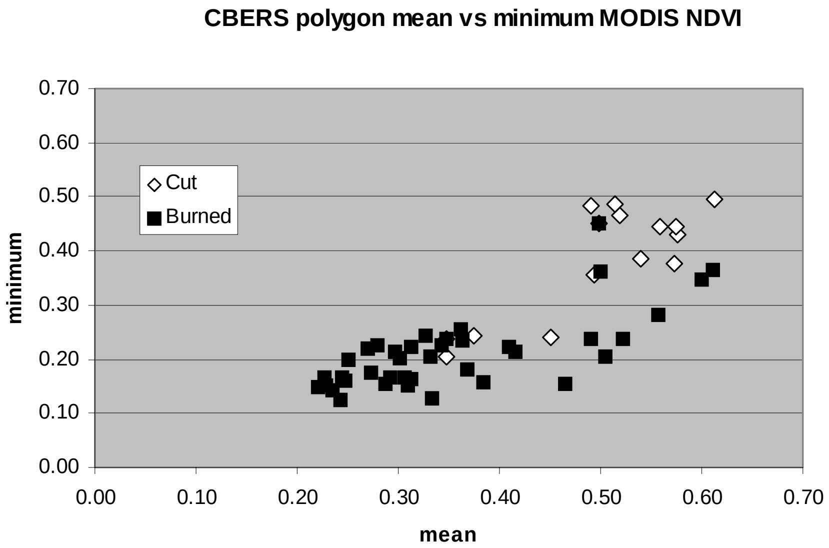

Figure 4. Mean and minimum NDVI for field validation MODIS clusters classified as cut or burned (deforested and burned). Polygons from 20m resolution CBERS data corresponding to MODIS field detections were used to evaluate polygon NDVI characteristics using coincident MODIS surface reflectance data from 22 July 2004 at 250m resolution.

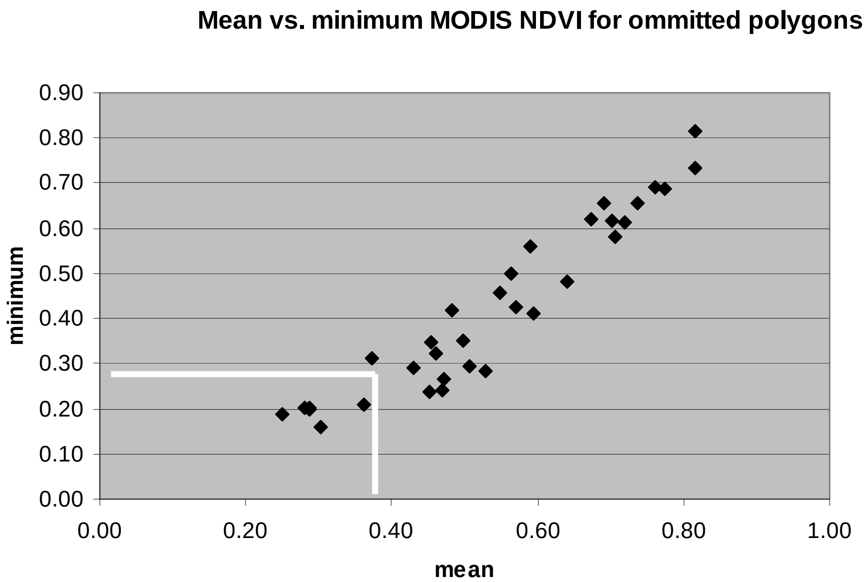

Figure 5. Mean and minimum NDVI from coincident MODIS daily surface reflectance (XX July 2004) for 33 polygons omitted in MODIS-based deforestation detections. White lines indicate the class space for burned polygons based on classification of field-observed polygons. Using these thresholds (see Figure 4), 6 of the 33 polygons would be classified as burned.

4. Discussion

Field validation is essential for accuracy assessment of deforestation monitoring products from satellite imagery. Validation of MODIS classification results with field measurements and high-resolution imagery provide complementary perspectives on product accuracy. Observing MODIS deforestation clusters in the field provides an unrivaled means for verifying deforestation events and assessing commission errors. Image-based validation of MODIS classification results provides a more robust indication of omission error. Without a thorough assessment of classification accuracy, data producers have little feedback on algorithm performance and data users have insufficient information to correctly interpret product results.

Based on field measurements, the MODIS-based classification of annual deforestation in central Mato Grosso proved highly selective for identifying new deforestation events. Commission errors were low, and all MODIS-identified deforestation events larger than 20 hectares were observed as deforested in the field. Based on comparison with coincident CBERS and Landsat imagery, omission errors in the MODIS deforestation classification were higher (36%) due to algorithm design, spectral differences between cleared and burned areas, and difficulties in detecting small deforestation events with moderate resolution imagery.

MODIS viewing geometry and effective pixel dimensions change daily based on the satellite orbit. At nadir, pixel resolution for 250m bands is approximately 250m. At the edge of the 2,300 km swath, effective pixel resolution balloons to over 10 times the nadir resolution, creating additional mixed pixel effects (Schroeder et al., in press). This variability in resolution led Morton et al. (submitted) to eliminate the forest edge pixel from the analysis area to minimize false detections based on viewing geometry. In that study, commission errors commission errors were >50% when edge pixels were included in the MODIS analysis. Controlling for near-nadir viewing geometry, or consistent viewing geometry between observations, is essential for effective deforestation monitoring. Future algorithm modifications that assess detection confidence based on sensor view angle would help reduce spurious detections.

Spectral differences between burned and unburned deforested areas may strongly influence deforestation detection with moderate resolution satellite imagery. In this study, field-validated MODIS deforestation detections within the study area were predominantly cut and burned, and 82% of omitted polygons in the MODIS classification were cleared but not burned. These results suggest that the threshold in the MODIS algorithm may be more sensitive to burned areas than to deforestation. Depending on the monitoring objective, modifications could be made to the MODIS algorithm to separately identify recently cleared forest from cleared and burned areas. This capability may be especially important to advance multiple objectives in a deforestation monitoring system and to adapt to seasonal differences in clearing and burning activities.

MODIS-based deforestation monitoring is not a substitute for high-resolution mapping of the annual deforestation increment. Overall, field validated MODIS detections covered only 1/3 of the total deforestation area identified in coincident CBERS imagery. Differences in MODIS and CBERS area measurements were lower for large deforestation events than for small clearings, where area was underestimated by as much as 100%. This finding supports previous findings that MODIS products accurately identify the location of new deforestation events but do not identify a consistent percentage of the total deforestation area (Morton et al., submitted).

MODIS sensors provide an important data source for deforestation monitoring in the Brazilian Amazon. Standard MODIS products increase the possibility of cloud-free views of the basin, reduce the data volumes and processing required for deforestation monitoring, and are distributed at no cost. In this study, we found low rates of commission based on field validation of MODIS deforestation detections, but higher omission rates based on comparisons with high resolution CBERS and Landsat data. Omission errors were highest for small, unburned polygons at the forest/non-forest boundary. These conditions exacerbate mixed-pixel effects in the moderate resolution data, but may be overcome through additional modifications in the algorithm. Restricting view angle to near-nadir pixels and isolating unburned and burned events could reduce commission errors. MODIS-based deforestation monitoring shows great promise for detecting the location of large clearings across the Amazon Basin with modest data storage and processing requirements.

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