Quantifying Cropland Expansion in Cerrado and Transition Forest Ecosystems with MODIS Satellite Image Time Series

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Abstract

Rapid land cover conversion in the Brazilian Cerrado and transition forest zones for cattle ranching and grain production continues to fragment large tracts of these biomes. The pattern, spatial extent, and nature of these land cover transitions have important ramifications for conservation of biodiversity and ecosystem function. Agricultural census data provide a coarse resolution overview of land cover change in the region, but higher resolution, spatially explicit maps of land cover are needed to analyze the trade-offs in economic benefits and environmental services from changing land use. Using phenological information from time series of MODIS satellite imagery at 250 m resolution, we classified land cover for the state of Mato Grosso from 2000–2004 to quantify land cover transitions to cropland agriculture during this period. Maps of cropland from satellite-based land cover classifications for 2000–2001 and 2003–2004 showed excellent agreement with agricultural census estimates of total area planted in annual crops at the municipal level. We estimate that over 1.6 million hectares were converted to cropland between 2001 and 2004. Conversion of natural grassland areas (e.g., campo limpo) and planted pasture accounted for an estimated 36% of this new cropland area. Direct conversion of Cerrado and forest cover types accounted for 35% and 29% of new cropland area, respectively. The average size of new cropland areas established between 2000 and 2004 was 54 hectares, although more than 800 of the transitions exceeded 300 hectares. The large number and size of new clearings for cropland had measurable impacts on fragmentation and connectivity of remaining natural cover types. Across all municipalities in the study area, the correlation between cropland expansion and increased Perimeter:Area ratio of remaining Cerrado and forest cover types was highly statistically significant ($p<0.0001$). Mapping the spatial extent of agricultural expansion and classifying transitions from Cerrado and transition forest to cropland are critical first steps for evaluating tradeoffs between land use and conservation. Classification and change maps at 250 m resolution provide critical information that can be used to set conservation priorities based on total habitat targets, landscape connectivity, and the location of agricultural frontier zones.

Introduction

Land cover change is the principal driver of habitat loss worldwide. Conversion of natural vegetation for agriculture is one of the most extensive forms of land use change in the global tropics. In Brazil, rapid expansion of cattle ranching, and more recently, highly mechanized grain production, have led to increasing fragmentation of remaining forest and Cerrado cover types (Laurence et al. 2001; Fearnside 2001), alterations in ecosystem function (Hoffmann & Jackson 2000), and potential loss of biodiversity (Ratter et al. 1997). Understanding the dynamics of land cover change is an essential first step towards more informed decision making regarding tradeoffs between land use and conservation.

Surveying methodology has historically been used to ascertain the area planted in various annual and perennial crops, and agricultural censuses remain important sources of information for regional and global characterization of potential food production (Ramankutty et al. 2002, Foley et al., 2005). Agricultural census data are also the primary source of information for monitoring land cover change on a regional basis; consistent methodology and long time records make census data ideal for discerning general trends in land cover change over space and time. Data from the Brazilian Institute of National Statistics and Geography (IBGE) Municipal Agricultural Production census (Produçao Agrícola Municipal) form the basis of many studies of patterns in agricultural practices in Brazil (e.g., Mueller 2003, Brandão et al., 2005). However, coarse resolution census data do not permit more detailed analyses of the spatial distribution of specific cover types needed to understand the conservation implications of land use patterns. Recent efforts to fuse census and satellite data have made progress towards a spatial understanding of cropland distribution in Brazil (Cardille et al. 2002; Cardille & Foley 2003), yet these products cannot characterize the land cover sources of new cropland or assess the spatial patterns of land cover with respect to conservation priorities. Detailed land cover classifications from satellite data at 1 km resolution exist for South America for 2000 (Eva et al. 2004) and 2001 (Friedl et al. 2002), and at 250 m resolution for the state of Mato Grosso, Brazil for 2002 (Anderson et al. 2005). However, comparable maps are not available for other time periods in order to assess land cover transitions.

Satellite remote sensing offers many possibilities for mapping cropland in a spatially explicit fashion independent of census estimates of planted area (e.g., Hill and Donald, 2003). Data from a wide range of available sensors can be used to generate classifications of land cover at various spatial scales. The resulting land cover classification maps can then be used to assess the spatial or temporal patterns of land cover change or predict the likelihood of future land cover conversions (e.g., Soares-Filho et al. 2004; Jasinski et al., 2005).

Landsat data at 60 m or 30 m resolution have been widely used for land cover classification, but these data suffer from two important limitations for mapping cropland. First, Landsat and other high-resolution sensors have infrequent temporal coverage; 16-day repeat coverage from Landsat can limit the number of cloud-free observations, especially during the growing season in the tropics (Asner, 2001), such that definition of a seasonal phenological signature from cropland vegetation is not possible. Second, data volumes and pre-processing methods required to map regional land cover require substantial data storage and processing capabilities, respectively.

Jepson (2005) used Landsat data to map land cover changes in eastern Mato Grosso during 1986-1999; highly dynamic land cover trajectories in the very small study area (4,000 km^2) support the need for frequent statewide assessments to capture temporal and spatial variability among land uses. A higher temporal frequency of observations has also been shown to accurately capture important elements of Cerrado and forest vegetation phenology, even at moderate spatial resolution (e.g., Ratana et al. 2005). A recent comparison between high and moderate resolution satellite imagery for deforestation detection in Mato Grosso also found that moderate resolution data accurately captured the dynamics of land cover change due to the large size of new deforestation events (Morton et al. 2005).

Data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Terra satellite platform with 250 m to 1 km resolution improve cropland mapping capabilities through near daily global observation and regional coverage (swath width ~2300 km) with modest data storage requirements (Justice et al. 2002). MODIS data have been successfully used to map cropland and crop conditions in the United States (e.g., Doraiswamy et al. 2004), Mexico (Lobell & Asner 2004), and São Paulo State, Brazil (Formaggio et al. 2005).

The goals of this study were to derive a simple land cover classification using field measurements and MODIS 250 m Vegetation Indices (MOD13Q1, Huete et al. 1999) for the state of Mato Grosso, Brazil from a decision-tree classifier and to compare the resulting cropland map with agricultural census data from the IBGE *Produçao Agrícola Municipal* (IBGE 2003). We explored the spatial patterns of conversions to cropland between 2000 and 2004 by assessing the dynamics of main land cover transitions (forest-cropland, Cerrado-cropland, pasture/grassland-cropland) with respect to transition size, spatial pattern, and fragmentation of remaining forest and Cerrado cover types. We present MODIS-based maps of land cover classification and land cover changes at 250 m resolution that can be used to assess land use trade-offs and set conservation priorities based on landscape connectivity and the location of agricultural frontier zones.

Methods

Data

Agricultural census data were downloaded from IBGE's census data gateway (http://www.sidra.ibge.gov.br/) for total area planted in annual crops (e.g., rice, corn, soybeans) in 2001 and 2004 for each municipality in Mato Grosso State, Brazil (n=139). Total area planted (ha) represents the cumulative area planted in all crops over the course of the year (IBGE 2003). As a result, the values in the *Producão Agrícola Municipal* census represent nearly two times the size of agricultural fields in production since the same field may be counted during each of two planting seasons (e.g., 1000 ha soybeans and 1000 ha corn).

MODIS Vegetation Indices data (MOD13Q1 16-day composite images) were downloaded from the EOS data gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/) for spatial tiles h12v10, h12v09, and h13v10 for the period May 2000 to March 2005. Three MOD13 bands from each time period were used for this analysis: Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Quality Assurance (QA) (Huete et al. 1999). Data preprocessing to remove cloud and other data quality artifacts was conducted using the entire dataset; only cloud-cleaned MODIS data were used for land cover classifications in this study.

Briefly, QA data were used to identify low-quality pixels (clouds, aerosols, missing data values, etc.) in the time series. Low-quality NDVI and EVI pixel values were replaced with predicted values by fitting a local spline function around missing values in each pixel's time series. Next, cloud-cleaned annual NDVI and EVI time series for the periods day of year 273-2000 to 273-2001 (day of year 273 ~30 September) and 273-2003 to 273-2004 (24 16-day composites) were filtered using an iterative Fourier smoothing algorithm based on the 0th, 1st, 2nd, and 3rd harmonics to remove artifacts from clouds that were not flagged in the QA layer (Roerink et al. 2000). Finally, annual, wet season (12 composites: 273-081), and dry season (11 composites: 097-257) metrics (minimum, maximum, mean, standard deviation, amplitude, and median) were generated separately for NDVI and EVI time series. These metrics (n=36) and the Fourier fit terms (1st, 2nd, and 3rd harmonics) from the NDVI and EVI smoothing procedure were used as inputs to the decision tree analysis for each year.

Field observations of land cover from June 2004 were expanded into polygon training data by digitizing cover type boundaries on near-coincident Landsat TM data at 30 m resolution or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data at 15 m resolution. Training data polygons were then used to select pure pixels for each land cover class at MODIS 250 m resolution to train the decision tree classifier. A total of 24,000 250 m pixels were designated as training data in one of the following 7 classes: cropland, pasture, Cerrado, deforestation, forest, grassland, or water. Metrics values were extracted for each training pixel, and the resulting table was imported into the Splus statistical package (Insightful 2004).

Decision Tree Analysis

A series of decision tree analyses were run using the seven classes of training data and time series metrics from 2003-273 to 2004-273. For all analyses, a random subset of training data (30%) was set aside for validation of the decision tree result. The main portion of the training data (70%) was used to grow the tree. Cost-complexity pruning was used to eliminate nodes with low contribution to both reductions in deviance and misclassification; both methods were used to visually assess the number of functional nodes in the tree. Following pruning, the tree was cross validated using the set-aside training data. The validation tree generated a measure of per-node classification accuracy and a traditional confusion matrix. The decision tree rules were then input into ENVI/IDL to classify the entire MODIS image (RSI 2004). Results for cropland agriculture classes were aggregated by municipality in order to match the IBGE census data. Decision tree rules from 2003–2004 training data were then applied to 2000–2001 time series metrics in a similar fashion.

Analysis of Classification Results

Aggregated cropland classification estimates were compared with census statistics for each municipality with complete MODIS image coverage (n=120) using linear regression. Cropland area was estimated from the MODIS classification by summing the number of pixels in cropland class clusters larger than one pixel (2+ contiguous pixels) and multiplying these counts by the pixel area (5.36 ha). The Pantanal ecoregion and Xingu Indigenous Reserve were excluded from the study area for all calculations. MODIS area estimates should be interpreted with caution, since other studies have shown that MODIS-based classifications routinely underestimate area measurements derived from high-resolution data (Morton et al., 2005). However, the large size of new clearings for cropland may minimize the impacts of mixed pixel edge effects on area estimates. In addition, eliminating single pixel clusters and limiting the types of potential transitions in this study permits a discussion of general trends in transition area.

Transition types were assessed using the following rules. Cropland areas in 2000–2001 werenot allowed to transition to other cover types. New cropland was limited to classification nodes with two crop cycles in a year (nodes 5, 8, 19, and 20); areas of forest, Cerrado, or grassland that transitioned to node 12 (*safrinha*, or single harvest) were not counted in this study. Field edges that transferred from cropland to forest or pasture to forest remained in their original class. Transitions from forest and transition forest, Cerrado, and pasture and grasslands were summed separately to generate estimates of conversion area between 2001 and 2004. Cluster size was assessed independently for each transition type and for all transition types combined.

Fragmentation from cropland expansion was assessed using Perimeter:Area (PA) ratio measurements for each municipality. Cerrado and forest classes were aggregated into polygons for each municipality for 2001 and 2004 (ESRI 2004). Area and perimeter were calculated separately for each Cerrado/forest polygon and then summed per municipality in order to calculate the PA ratio. We calculated percent differences in PA ratios between 2001 and 2004 for each municipality to estimate the contribution of cropland expansion to fragmentation of Cerrado and forest cover.

Results

Decision Tree

The best fit decision tree model for the training data was pruned to 22 functional nodes based on misclassification cost-complexity (Fig. 5.1—replaced with new black&white figure). Five pathways to the cropland classification can be traced in the tree. Leaves 5, 7, and 15 show a typical phenological curve for one wet season and one dry season crop rotation—strong seasonal amplitude during the wet months, lower amplitude in dry months, and low minimum values during the dry season. Leaf 19 collects pixels with a strong green vegetation signature in both wet and dry seasons, typical of cropland with dry season irrigation. Leaf 12 collects pixels with a single crop rotation during the year, often referred to as the *safrinha*. Overall model fit was good (residual mean deviance: 1.01 =16980/16820; misclassification error rate: 0.14 = 2276/16837). This decision tree model based on the training data was consistent when tested with the validation data points (misclassification error rate: 0.15 = 1058/7217). Validation points from the agricultural class showed a moderately high misclassification rate (27%), even though overall classification accuracy was 85% (Table 5.1). Figure 5.2 shows the final 2003–2004 classification for the study region.

Classification and census comparison

The spatial patterns of MODIS-based agricultural classification and IBGE census statistics were similar for the 120 municipalities with MODIS image coverage. When the MODIS classification results were summed for each municipality, the relationships between satellite-based counts and census estimates were linear and highly statistically significant ($p<0.0001$, Fig. 5.3). Area of cropland represents the summation of pixel area for all new cropland clusters that were two MODIS pixels or greater in extent, recognizing that MODIS-based area estimates will underestimate the actual cultivated area mapped with higher resolution data. The linear regression models demonstrated that the MODIS-based estimate averaged 68% and 61%of that from census data for 2001 and 2004, respectively, suggesting that the majority of fields are planted with two crops each year (2001: $y = 0.6831x + 661.5$; $R^2=0.94$; 2004: $y = 0.6099x + 4702.3$, $R^2=0.91$). Regression relationships were similar for the subsets of the municipalities with total cropland area <100,000 ha (data not shown).

Transition dynamics

Over 1.6 million hectares were converted to cropland between 2001 and 2004 (Fig. 5.4—replaced with black&white figure). Cropland expansion in Mato Grosso occurred near three existing agricultural centers and along a new frontier in eastern Mato Grosso abutting the *Parque Indígena do Xingu*. Roughly 36% of the new cropland area was converted from natural grassland areas (e.g., campo limpo) and planted pasture (Table 5.2). Direct conversion of Cerrado and forest cover types accounted for 35% and 29% of new cropland area during this period, respectively. The average size of new cropland areas established between 2000 and 2004 was 54 hectares, yet 880 transitions that exceeded 300 ha accounted for 43% of all new cropland.

Across all 120 municipalities, cropland expansion was associated with an increased perimeter:area (PA) ratio of combined Cerrado and forest cover types (Fig. 5.5). In the nine municipalities with the greatest increase in cropland area between 2001 and 2004 (Sapezal, Querência, Primavera do Leste, Sorriso, Diamantino, Campos de Júlio, Campo Verde, Itiquira, and Campo Novo do Parecis), the PA ratio of remaining Cerrado and forest cover increased by an average of 16%. Negative percent differences in PA ratio between 2001 and 2004 classifications are predominantly a function of variable classification of campo limpo and Cerrado classes in southwest Mato Grosso between subsequent years.

Discussion

Spatially explicit maps of land cover transitions provide critical information regarding the size, pattern, and nature of land use changes that are not available from census-based estimates. Whether new cropland is coming from previously cleared areas such as planted pasture or from intact Cerrado or forest cover has important ramifications for habitat loss and conservation of biodiversity. Although conversion of grassland ecosystems (campo limpo or planted pastures) to cropland is an important transition type in the study area (36%), we suggest that direct conversion of forest (29%) and Cerrado (35%) to mechanized agriculture between 2001 and 2004 must be considered in the discussion of trade-offs between economic and environmental goals.

Tropical forest loss is captured as part of deforestation mapping (Projeto PRODES: *Programa de Cálculo do Desflorestamento da Amazônia*, INPE 2002) and new deforestation monitoring efforts (DETER: *Detecção de Desmatamento em Tempo Real*, INPE 2005). However, these efforts do not track conversion of cerradão or Cerrado land cover types or secondary land use transitions (e.g., planted pasture to cropland). Additional habitat loss from Cerrado and transition forest types may have substantial impacts on biodiversity in these biomes with high endemism (Ratter et al. 1997). In addition, due to the nature of the conversion process and subsequent land use, mechanized agriculture may have longer-term impacts on ecosystem function than previous land cover conversions.

Due to the nature of the conversion process and subsequent land use, large-scale mechanized grain production may have longer-term impacts on ecosystem function than previous land cover conversions (Fearnside 2001). Conversion of Cerrado or forest cover to cropland involves more complete removal of woody vegetation than pasture conversion, with implications for carbon storage, biodiversity, and future habitat restoration. Tractors may be used to pull down woody vegetation and unearth remaining stumps and woody roots. This woody material is then burned, piled into windrows (*leiras*) and burned again, and finally piled into increasingly small mounds and burned until the soil is ready for planting. The burning process to convert forest to bare soil may destroy viable regeneration or seed banks such that abandoned cropland areas may not support natural vegetation without restoration efforts or long recovery periods.

The large size of new cropland areas (average = 54 hectares) may also have important consequences for habitat connectivity. Fragmentation of remaining forest and Cerrado cover was highly correlated with increased cropland between 2001 and 2004; PA ratios of combined Cerrado and forest classes increased by more than 15% for areas with the largest increase in cropland during this period. Irrespective of fragmentation, the size and number of new clearings have important ramifications for conservation objectives in the region. The estimated habitat loss from conversion of Cerrado and forest to cropland was more than 1,000,000 hectares over the study period. Mechanization of both farming and land clearing makes it possible to clear, process, and plant large areas with minimal labor inputs, resulting in a simultaneous intensification of cropland agriculture and accelerated expansion of land cover conversion.

Land cover classification based on vegetation phenology from MODIS satellite data proved highly accurate for mapping cover types in Mato Grosso State, Brazil. Overall classification accuracy from the decision tree model was 87%. The confusion matrix from cross validation of the decision tree model suggests that cropland training pixels were most often misclassified as pasture or grassland, possibly indicating a field that was left fallow for the year, only planted with one crop, or a combination of two growing season peaks into one within the MODIS time series. The complex mosaic of planting times (*safra, safrinha*) and crop types (rice, soybeans, maize, etc.) make the phenological timing of cropland characteristics hard to generalize across the region. However, for fields with two crop rotations during the year, the decision tree classification separated cropland phenology from other land cover types with high accuracy.. MODIS-based results for cropland agriculture showed statistically significant linear relationships with agricultural census data of total area planted in annual crops. The strength of both traditional classification accuracy measures and comparisons with census data suggest a high degree of confidence in the MODIS classification results for 2001 and 2004.

In regions with rapid land cover conversion like Mato Grosso, frequent analyses of land cover transitions are essential to estimate the impacts from land use changes. MODIS data are an important tool for this type of land cover monitoring. Data are provided free of charge from NASA, and are available in raw format or as a range of standard products (Justice et al. 2002). In addition, MODIS 250 m resolution is an appropriate spatial scale for mapping cropland expansion in Mato Grosso because much of the area converted to cropland agriculture between 2001 and 2004 occurred in large patches. The role of MODIS data for monitoring land cover change in other regions depends on the size and nature of the land cover conversion and the resolution required to understand ecosystem impacts from these changes. High-resolution data are currently being used to map legal reserves on private property in Mato Grosso (Fearnside, 2003). Combining MODIS-based classifications with higher-resolution estimates of cropland area could effectively leverage the benefits of these different sensors to create an integrated, multi-sensor approach to both land cover mapping and ecological decision making.

Spatially explicit maps of existing land cover and land cover conversions are an essential first step in assessing trade-offs between economic and environmental goals. Green et al. (2005) suggest a simple model for resolving trade-offs between agricultural production and habitat area based on species-specific relationships between population densities and farming yields. Their simple model does not include measures of landscape condition (e.g., degraded habitat or fragmentation) or species mobility (dispersal, breeding and feeding habitat characteristics, etc.) (Vandermeer & Perfecto 2005). However, this type of maximum-yield/species-area model provides a framework for setting economic and environmental targets. In the case of Mato Grosso, where rapid agricultural expansion is not bounded by yield targets, the onus is clearly on the conservation community to generate estimates of ecosystem impacts from current land cover conditions or future agricultural expansion.

Implication for Conservation

We mapped conversion of grassland, Cerrado, and forest cover types to cropland agriculture in Mato Grosso State, Brazil between 2001 and 2004. Our analysis highlights three components of the dynamics of land cover conversions during this period. First, contrary to recent economic and census-based analyses, we show that large tracts of Cerrado and forest cover were converted directly to mechanized agriculture without initial use for cattle ranching. . Second, mechanization of clearing and planting has enabled farmers to convert an estimated 1.6 million hectares to cropland between 2001 and 2004, including more than one million hectares of Cerrado and forest cover. Finally, land cover conversion to cropland resulted in substantial increases in fragmentation of remaining Cerrado and forest vegetation types. The rapid rates of land cover change and direct conversion of Cerrado and forest to cropland have important implications for conservation of biodiversity and ecosystem function.

This study also highlights the potential to derive spatial patterns of land cover transitions from moderate resolution satellite products. The balance between spatial and temporal coverage from the MODIS satellite sensors captures seasonal phenology more accurately than high spatial resolution sensors with infrequent coverage. We demonstrate how metrics derived from phenological time series can effectively classify cropland, grassland, Cerrado, and forest cover types. In the end, the most appropriate method for land cover mapping or monitoring will depend on the required frequency and spatial and temporal resolution of the classification product. It is possible that an integrated solution of moderate resolution monitoring and high resolution mapping would provide more complete information for conservation decision makers.

The application of methods in this study to the full range of the Cerrado biome or other savanna-woodland ecosystems is promising. Previous work has demonstrated that phenology information from MODIS satellite data can be used to separate Cerrado vegetation types since the fraction of woody cover in various Cerrado physiognomies is related to the timing and duration of peak vegetation greenness (Ratana et al. 2005). We show that other land cover types, principally forest and cropland, are also highly separable from Cerrado based on patterns in phenology. The combined understanding from these studies suggests that MODIS data have high potential for broad applications to monitoring cropland expansion and mapping Cerrado physiognomies. Separation of land cover types with similar vegetation structure and phenology, such as planted pasture and grass-dominated Cerrado types (e.g., campo limpo), may require a different approach such as satellite data at higher spectral or spatial resolutions.

Understanding the spatial extent, pattern, and nature of land cover transitions is an important step forward in assessing the landscape and ecosystem level impacts of land use decisions. Current census-based analyses of land cover change do not provide these important elements for the discussions of trade-offs between land uses. The findings from this study can now be incorporated into discussions regarding conservation priorities, used to set targets to balance economic and environmental trade-offs, and expanded into systems to monitor land cover conversions.

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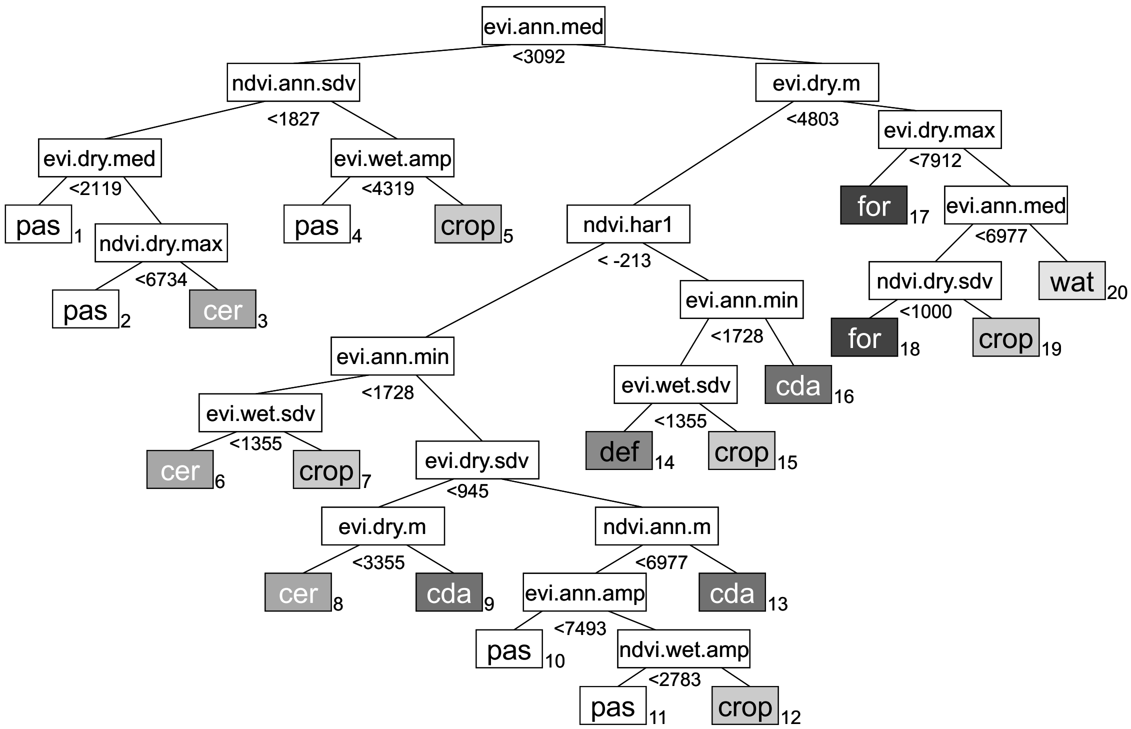

Figure 5.1. Decision tree model for land cover classification based on field training data for 2004. Classes campo limpo (clp), Cerrado (cer), cropland (agr), cerradão (cda), pasture (pas), deforestation (def), forest (for), and water (wat) are labeled by color and node number. Node splits are based on metrics derived from time series of MODIS Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). The labeling scheme uses the following conventions: "n" (NDVI) or "e" (EVI) . "ann" (annual) "wet" (wet season) "dry" (dry season) . metric (m=mean, med=median, min=minimum, max=maximum, sdv=standard deviation, amp=amplitude). The metric "har1" refers to the coefficients for the first harmonic fit to the NDVI time series. This decision tree model was used to classify 2000–2001 and 2003–2004 MODIS data.

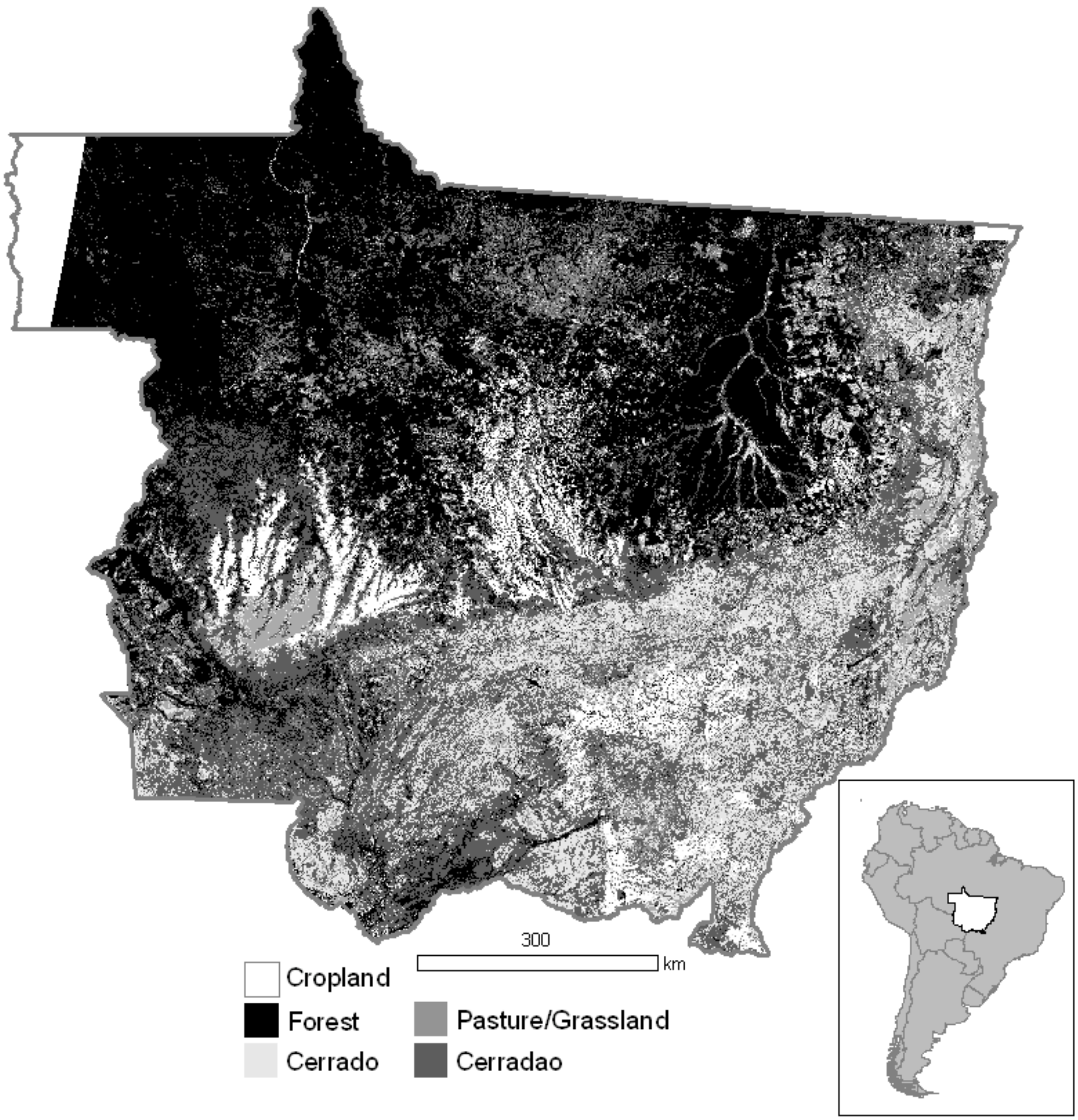

Figure 5.2. Location of Mato Grosso State, Brazil in South America (inset). MODIS classification results from 2003-2004 for image tiles h12 v10, h12v09, and h13v10 covering most of Mato Grosso State. Land cover in the southern half of the state is dominated by a complex mosaic of Cerrado, grasslands/planted pasture, and cropland. The northern half of the state is a mixture of forest cover and planted pasture, while two major cropland centers straddle the cerrado/forest division in central and western Mato Grosso.

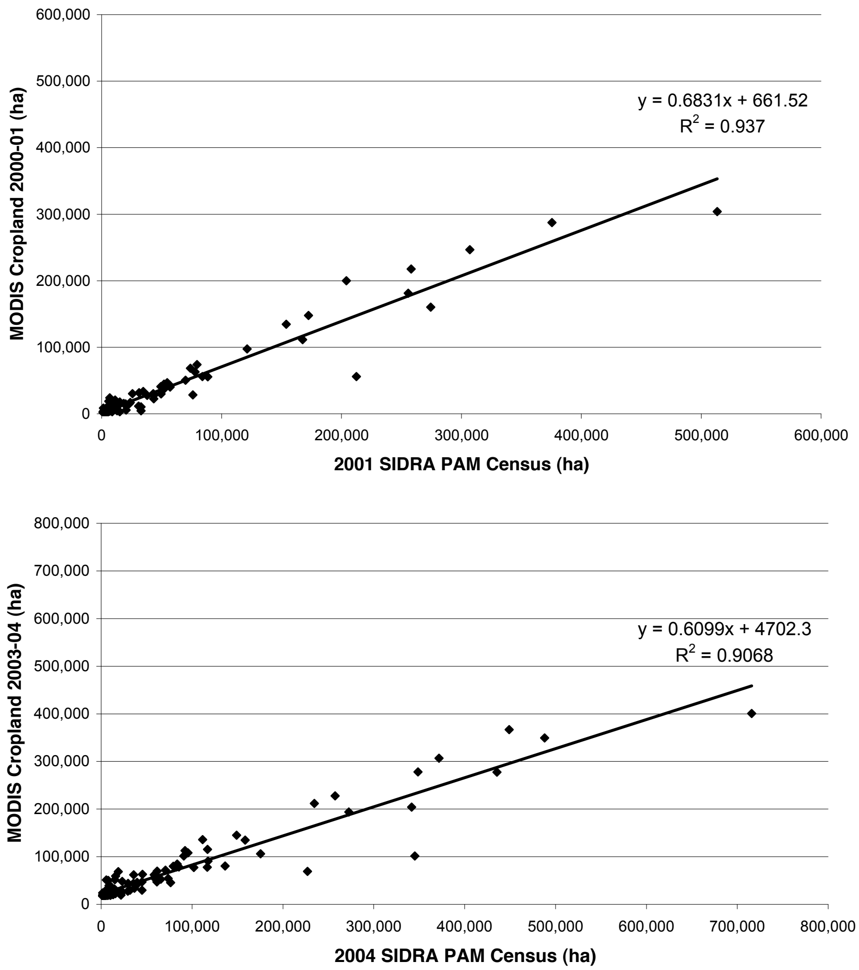

Figure 5.3. Comparison of 2000–2001 (top) and 2003–2004 (bottom) MODIS cropland classification estimates, aggregated to the municipal level, to IBGE agricultural census data for total area planted in annual crops in 2001 and 2004, respectively. Each plot shows the linear regression fit equations and R_2 values for the relationship between MODIS and census estimates.

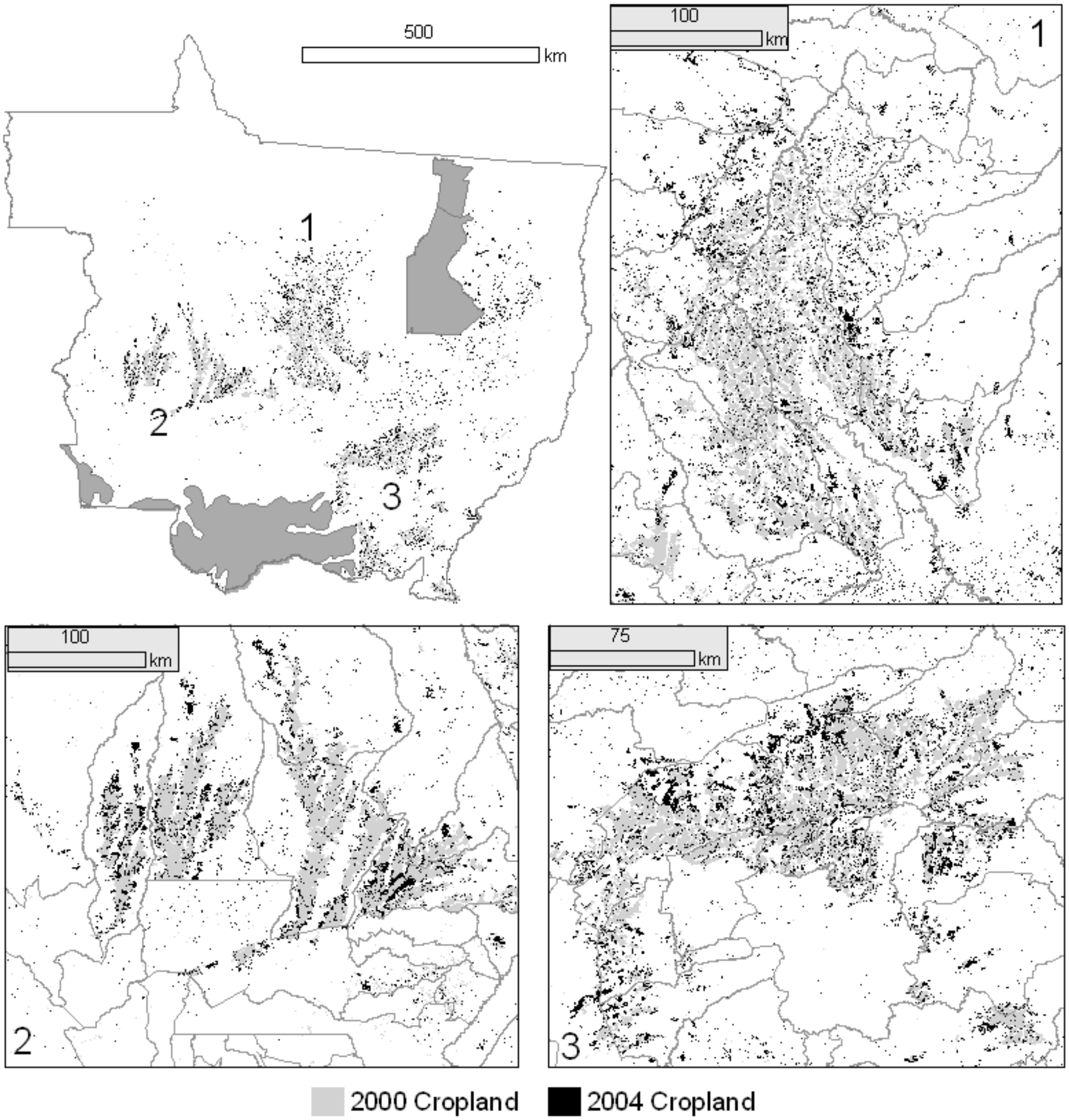

Figure 5.4. MODIS-based estimates of cropland in 2000–2001 (gray) and 2003–2004 (black) for the study area in the state of Mato Grosso (upper left). The Xingu Indigenous Reserve (north, *Parque Indígena do Xingu*) and Pantanal ecoregion (south) are excluded from this study (dark gray polygons). Three subsections of the data are shown in panels 1-3 to highlight cropland expansion in these regions. Panel 1 depicts cropland expansion in central Mato Grosso near the municipalities of Sorriso and Sinop. Panel 2 shows the area near Sapezal, and Panel 3 shows the cropland expansion near Primavera do Leste in south-east Mato Grosso.

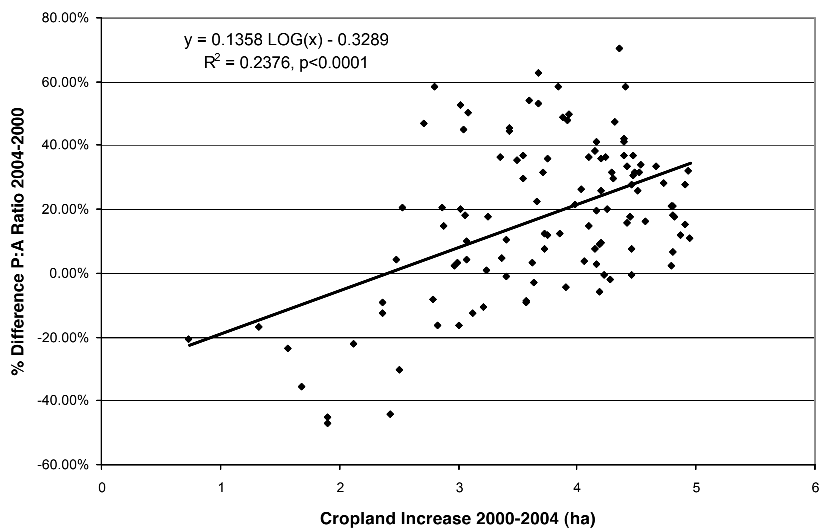

Figure 5.5. Increase in perimeter:area ratio (P:A) for combined Cerrado and forest classes between 2001 and 2004 MODIS classifications as a function of cropland increase during this period for each municipality (*municipio*) in the study area. A decrease in P:A ratio between 2001 and 2004 may indicate a reduction in the total number of cerrado and forest fragments or variability in the classification between the two years (e.g., grasslands and cerrado). Note that increase in cropland is plotted on a logarithmic scale.

Table 5.1. Classification accuracy for each training data class based on cross validation tree. Misclassification rate reports user's accuracy.

Class	Wrong	Total	Misclassification Rate
crop	280	1018	0.275
cerrado	224	573	0.391
deforestation	234	2177	0.107
forest	54	505	0.107
pasture	205	2311	0.011
water	60	632	0.095
Total	1057	7216	0.146
Overall class accuracy			**0.854**
Kappa coefficient			**0.816**

Table 5.2. Estimated cropland increases between 2000 and 2004 based on MODIS land cover classifications. Total area converted and percent of total cropland conversions are shown for each source type of new cropland.

Cover type converted to cropland	Converted area (ha)	% total area
Forest and cerradão	467,000	29
Cerrado	577,000	35
Pasture and campo limpo	593,000	36
Total	1,637,000	