Anais XIII Simpósio Brasileiro de Sensoriamento Remoto, Florianópolis, Brasil, 21-26 abril 2007, INPE, p. 6859-6866.

Secondary forest dynamics and Cerradão loss in Mato Grosso during 2001-2005 from MODIS phenology time series

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Abstract. Mato Grosso State has experienced the highest rates of deforestation and selective logging in the Brazilian Amazon since 2000. We evaluate two additional sources of land cover change in Mato Grosso during 2002-2005, clearing of tall, closed-canopy Cerradão and transition forest vegetation and re-clearing of secondary forests, using phenological information from time series of MODIS NDVI data at 250 m resolution. Overall, conversion of Cerradão and secondary forests during 2002-2005 added 9-14% to the area deforested each year. Re-clearing of secondary forest was partially offset by regrowth on recently abandoned areas, but net loss of secondary forest totaled 1570 km^2 between 2002-2004, or 7.4% of all secondary forest mapped in 2001. Areas recently abandoned to secondary forest were also smaller, on average, than Cerradão and secondary forest clearings. Changes in dry season mean NDVI provided a robust measure of land cover changes in comparison with field and Landsat validation data, suggesting that MODIS-based monitoring of these land cover transitions is possible.

Palavras-chave: MODIS, deforestation, Cerrado, phenology, secondary forests, MODIS, desmatamento, Cerrado, fenologia, florestas secundárias.

1. Introduction

Changes in land cover account for more than 25% of all anthropogenic CO_2 emissions each year (Houghton, 2003). Amazon deforestation contributes one third of the emissions from tropical land use change (Houghton, 2003) due to the high carbon content of forest vegetation (Malhi et al., 2006) and the large extent of new clearing each year (INPE, 2006a). Remote sensing provides a spatially comprehensive estimate of carbon emissions from land cover change (e.g., DeFries et al., 2002; Achard et al., 2002). Recent improvements in satellite detection and data distribution, including detailed annual maps at Landsat resolution (INPE, 2006a) and near-real time assessment with MODIS data (Anderson et al., 2005; Morton et al., 2005; INPE, 2006b), have greatly improved our understanding of the timing and extent of deforestation activities in the Amazon. However, several large gaps exist regarding the fate of carbon from deforested areas and the suite of land cover transitions that occur, often in succession, as part of the clearing process (Ramankutty et al., in press). The net carbon loss from land clearing and abandonment is an elusive, but important, quantity for remote sensing analyses (Foley et al., 2005).

Monitoring the various stages of land cover conversion, from intact tropical forest through clearing for pasture or cropland and abandonment into secondary forest, has been aided by regional observational coverage from the Moderate Resolution Imaging Spectroradiometer

(MODIS) sensors. MODIS sensors provide better cloud-free data than high-resolution sensors due to daily morning (10:30) and afternoon (13:30) observations of the Amazon Basin at 0.25-1 km resolution. High frequency data collection enables the definition of vegetation phenology, and this improved observation capacity has generated novel understanding of tropical forest seasonality (Huete et al., 2006). Morton et al. (2006) use phenology information from time series of MODIS Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) data to evaluate the post-clearing land use as cropland or pasture for recent deforestation in Mato Grosso. A related publication (Morton et al., in press) highlights the contribution of cerrado and pasture clearing to recent cropland expansion. In this paper, we focus on two remaining high-biomass transitions in Mato Grosso: conversion of tall, closed canopy Cerradão that is not included in INPE deforestation mapping and monitoring efforts and re-clearing of secondary vegetation on previously-deforested areas.

Different Cerrado physiognomies exhibit distinct phenological patterns in time series of MODIS NDVI and EVI (Ratana et al., 2005). Cerrado with high shrub and tree cover maintains greener canopy cover during the dry season than grass-dominated areas. Although subtle changes in vegetation cover during conversion of open Cerrado physiognomies to pasture may not be distinguishable using phenology data from moderate resolution satellite sensors, the change from closed-canopy, deep-rooted vegetation to cropland or pasture should exhibit clear changes in time series of NDVI or EVI, similar to conversion of tropical forest.

Analyzing secondary forest cover with optical satellite data is complicated because forest stand age and related parameters such as biomass or canopy height derived from common vegetation indices such as NDVI saturate over young regrowing forests (Steininger, 2000). Although the spectral signature from a pulse of regrowth with uniform height may be distinguished using textural measures from high resolution data, these canopy parameters are not as robust when viewed with moderate resolution data. Closed-canopy, deep-rooted vegetation typical of secondary forest does exhibit a phenological pattern similar to tropical forest, and the stability of NDVI during the long dry season in Mato Grosso provides one method to identify areas of secondary forest and Cerradão.

We map areas of Cerradão and secondary forest in Mato Grosso in 2000-2001 using phenological information from time series of MODIS NDVI. Next, we follow patterns of vegetation clearing in these land cover types during 2002-2005 to evaluate their annual contributions to deforestation dynamics, validating our remote sensing results with field observations and Landsat TM data from 2005. Finally, we examine the creation of secondary forests on previously-cleared lands during 2002-2005 to assess the importance of including these dynamics in carbon estimates from land clearing and abandonment in Mato Grosso.

2. Methods

Time series of NDVI were developed for three MODIS 10° x 10° spatial tiles (h12v10, h12v09, and h13v10) with coverage over Mato Grosso State following methods outlined in Morton et al. (2006) (**Figure 1**). Briefly, 16-day composite NDVI data at 250 m spatial resolution (product MOD13Q1) from October 2000 - September 2005 were screened for clouds, cloud shadows, and high aerosols using the Quality Assessment (QA) layer. For each pixel's time series, contaminated data values were replaced with a predicted value by fitting high-quality observations in each time series with a cubic spline function. A second pre-processing step was needed to eliminate spurious errors in the MODIS product that were not identified by the QA layer. In this step, the cloud-cleaned time series were fit with 1^{st}-4^{th} order harmonic functions, and pixels with a deviation greater than 0.1 NDVI units from the seasonal cycles were replaced with the harmonic-predicted values. The mean dry season NDVI (day of year 113-272) value for each pixel was used to identify forest-like values in previously deforested or non-forest categories in the 2001 INPE PRODES digital product (INPE, 2006a).

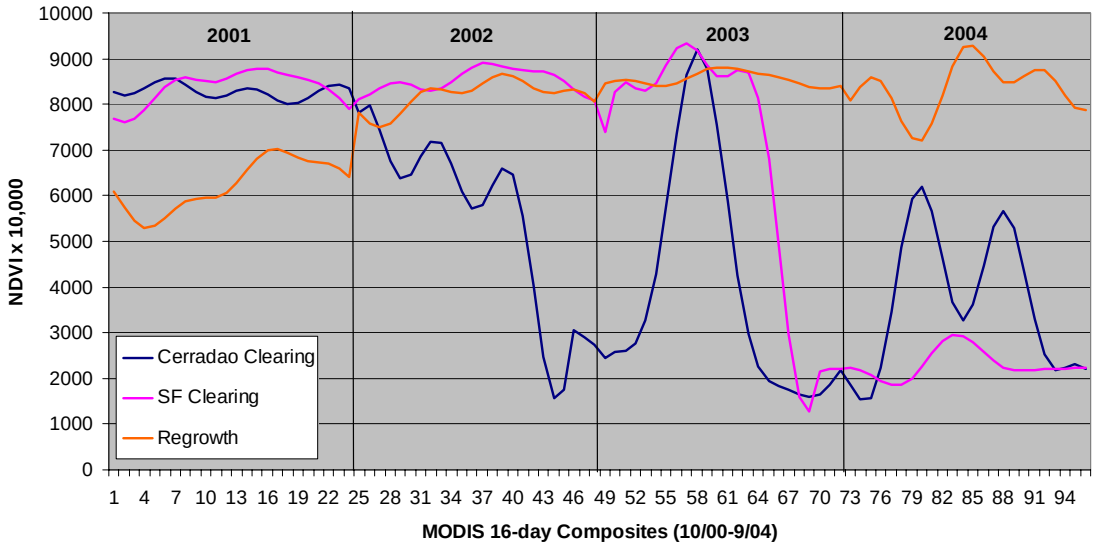

Figure 1. Cloud-corrected MODIS 16-day NDVI time series from October 2000 to September 2004 for Cerradão clearing in 2002, Secondary forest (SF) clearing in 2003, and regrowth of SF in 2002. Composites 13-23 in each year were used to generate the mean dry season NDVI metric.

We identified secondary forest within areas identified by INPE as deforested prior to 2001 using a mean dry season NDVI threshold of 0.8 based on field data and a decision tree classification of forest cover in Mato Grosso (Morton et al., 2006) (**Figure 2**). Re-clearing of secondary vegetation in 2002-2005 was identified using a drop in mean dry season NDVI below 0.8. New secondary forest vegetation from land abandonment in 2001-2004 was confirmed by the development of a persistent mean dry season NDVI $\geq$ 0.8 for two successive years in areas deforested before 2004. Due to data limitations, net secondary forest conversion is only reported for 2002-2004. We do not identify the age or estimate the biomass of regrowing forest vegetation in this study. For secondary forest loss/gain and Cerradão clearing, only changes larger than 3 MODIS 250 m pixels (~16 ha) were included in the final results due to the improvement in map accuracy for large pixel clusters in moderate resolution data (Morton et al., 2005).

Similarly, areas with mean dry season NDVI >0.8 in the INPE PRODES non-forest class were mapped as Cerradão in 2001 (**Figure 2**). Most areas identified as tall, closed-canopy vegetation outside of the PRODES forest mask were located in the headwaters of the Xingu and Juruena rivers and surrounding other topographic features in central Mato Grosso. The map also includes gallery forests along smaller river channels. Pantanal vegetation was excluded from this study using the World Wildlife Fund (WWF) Ecoregion map for inundated savannas to avoid spurious errors from changing water levels. Clearing of Cerradão was identified by the drop in mean dry season NDVI below 0.8.

Results from the analysis of MODIS data were validated using field observations from July 2005 of recent clearing and burning activities along transects through the transition from Cerradão to tropical forest and from visual inspection of four Landsat TM scenes from the same period as field evaluation (July, 2005: Scenes 226/69, 227/69/, 228/69, and 227/70). Field observations provided an estimate of both omission and commission, while Landsat data were only used to assess commission errors in the overall land cover change results. Landsat validation considered only the presence or absence of recent changes, not the size or condition of cleared areas. MODIS results provide general trends in land clearing activities, but area estimates from MODIS data should be interpreted with caution until confirmed with high-resolution data.

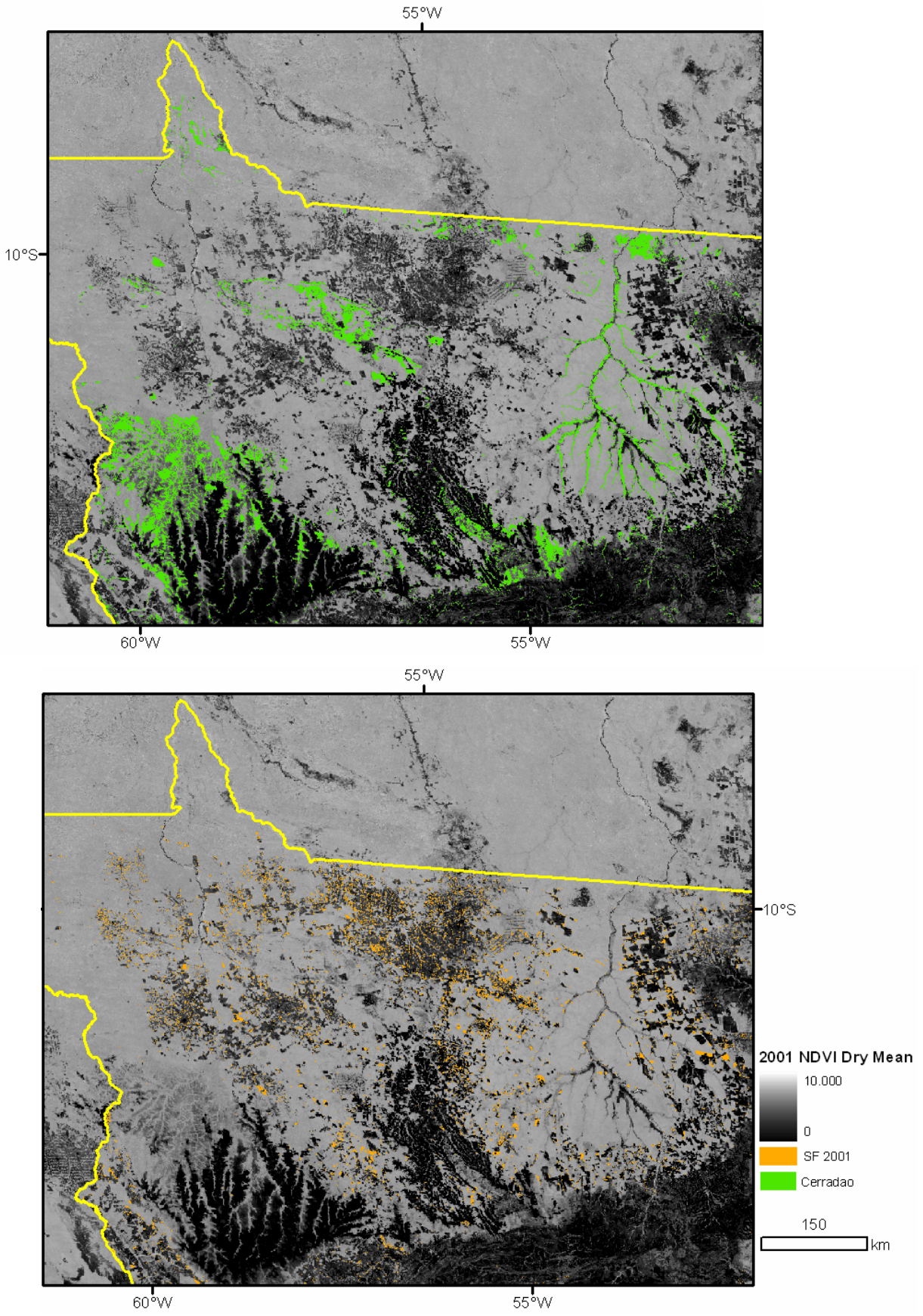

Figure 2. Extent of Cerradão (top) and Secondary forest (bottom) in Mato Grosso State based on high 2001 dry season mean NDVI (>0.8) in areas classified as non-forest and previously-deforested in the INPE PRODES analysis, respectively.

3. Results

3.1 Validation

Maps of Cerradão and secondary forest conversion based on changes in mean dry season NDVI were very accurate when compared with field observations and four Landsat TM scenes from central Mato Grosso State (**Table 1**). Two MODIS results not confirmed by field data were observed as regrowing forest in 2005. In the comparison with 2005 Landsat data, the primary sources of misclassified change were edge effects due to MODIS resolution along class boundaries and burned areas that were not completely cleared. Other minor sources of error were irrigated crop fields (n = 3) and seasonality of Cerradão vegetation (n = 3). Commission errors were more common among small change detection polygons (Cerradão: n = 12; mean = 28.6 ha; s.d. = 16.3 ha, Secondary forest: n = 31, mean = 27.5 ha, s.d. = 6.2 ha). Omission errors also tended to be small; for 50 field observations of recent clearing, 6 omission errors (5 in secondary forest, 1 in Cerradão) were correctly identified in the MODIS results but were disregarded because they were smaller than 4 MODIS pixels in extent.

Table 1. Validation of MODIS results for Cerradão and secondary forest clearing 2002-2005 from field observations and 2005 Landsat TM imagery.

	Correct	Incorrect	% Correct
Field Observations			
Cerradão	10	0	100
Secondary Forest	17	2	89
Landsat			
Cerradão	432	12	97
Secondary Forest	508	31	94

3.2 Cerradão

We identified a total of 34,893 km^2 of Cerradão and gallery forest in Mato Grosso in 2001 (**Table 2**). During 2002-2005, approximately 5.5% of Cerradão mapped in 2001 was converted to other land uses. Rates of Cerradão clearing were highest in 2003 and 2004, similar to peak years of tropical forest clearing in Mato Grosso (**Figure 3**). Recent Cerradão clearings were large, with 58% of the total area cleared in polygons larger than 100 ha (**Figure 4**).

Table 2. Total area in Cerradão and secondary forest in 2001 and clearing/regrowth dynamics during 2002-2005 from MODIS 250 m resolution data. Recent regrowth of secondary forest could not be assessed for 2005 due to data limitations. MODIS-based area estimates provide general trends in land cover change but precise measurements of cleared area should be confirmed with high resolution data.

	Total (km^2)	Area of Clearing or Regrowth (km^2)			
	2001	2002	2003	2004	2005
Cerradão	34,893	398	640	613	250
Secondary Forest	21,240				
Loss		532	738	754	499
Regrowth		297	87	71	x
Net Change		-235	-651	-683	x

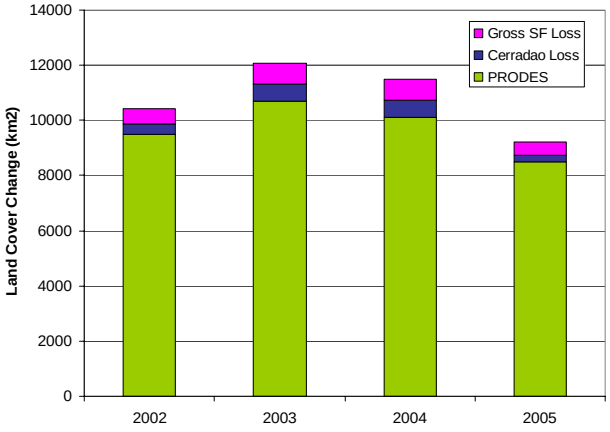

Figure 3. Summary of major land cover transitions in Mato Grosso during 2002-2005. Estimated statewide deforestation extent is from PRODES digital data (INPE, 2006a), SF = secondary forest.

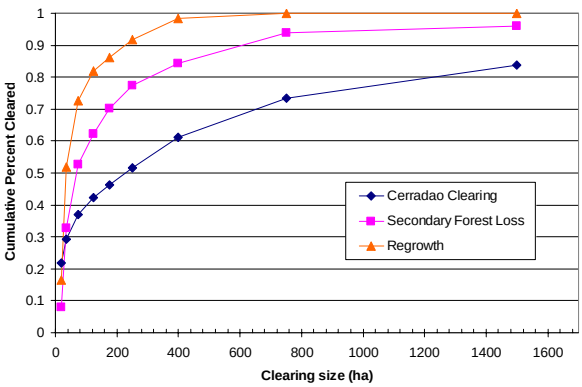

Figure 4. Cumulative percent of 2002-2005 Cerradão conversion, secondary forest clearing, and regrowth of secondary forest (2002-2004) by size of land cover changes.

3.3 Secondary Forest

Only 14% of the estimated 151,831 km^2 of historic deforestation in Mato Grosso exhibited secondary forest phenology in 2001. Rates of clearing for secondary forest were also high, with an average of 3% of secondary forest cleared each year during 2002-2005. Replacement of secondary forest stocks through recent abandonment of cleared lands was insufficient to offset secondary clearing rates; net secondary forest loss during 2002-2004 was 1569 km^2 (**Table 2**). Similar to recent trends for both deforestation and Cerradão clearing, secondary forest loss was highest in 2003 and 2004. On average, secondary forest areas cleared during 2001-2005 were smaller than Cerradão clearings, with only 37% of the cleared area coming from polygons larger than 100 ha. Recently abandoned areas were even smaller, averaging only 44.1 ha (s.d. = 48.5 ha), with only 18% of the total area in polygons larger than 100 ha.

4. Discussion

Deforestation of tall, closed-canopy Cerradão and secondary forest are important contributions to recent land cover change in Mato Grosso, adding 9-14% to the area affected annually by deforestation. Secondary forest clearing was partially offset by regrowth on recently abandoned areas, but new secondary forest areas were smaller, on average, than new clearings of both Cerradão and existing secondary forest. Similar to deforestation patterns in 2002-2005, rates of Cerradão and secondary forest losses were highest in 2003 and 2004, possibly due to high prices for agricultural commodities (Morton et al., 2006) and favorable exchange rates during this period (Brandão et al., 2005) that favored agricultural expansion.

Our estimate of secondary forest in Mato Grosso for 2001 is similar to the finding of 17.1 ±1.9 km^2 in a recent study by Carreiras et al. (2006) based on 2000 SPOT VEGETATION data at 1 km resolution. These estimates differ from previous remote sensing studies (Lucas et al., 2000) and other estimates of the percentage of deforested land now in secondary succession (e.g., (Fearnside, 1996). Part of this difference may result from regional differences in land use patterns. Dynamics of land cover change in Mato Grosso reflect the large property sizes and recent development of infrastructure for both ranching and mechanized crop production that may increase property values and limit the availability of abandoned lands in comparison with other regions of the Amazon Basin.

Net loss of secondary forests during the study period and high rates of re-clearing suggest that regrowing forests are not a long-term carbon sink in Mato Grosso. The carbon content of

secondary forests at the time of re-clearing is difficult to estimate since regrowing forests of different ages may appear similar in optical remote sensing data (Steininger, 2000), and the land use histories are difficult to reconstruct given limited availability of historic satellite data. We expect a large range of secondary forest biomass in Mato Grosso given that the source of secondary forests is quite variable, from selectively logged areas to abandonment of unproductive pastures, and biomass accumulation on cleared and burned areas depends on the intensity of land use and re-clearing activities (Zarin et al., 2005).

Phenology information from moderate resolution satellite data provides a new method for classifying land cover change. Unlike single-date image classifications or image differencing techniques, seasonal vegetation patterns provide a more robust measure for classification of biophysical attributes. The dry season mean NDVI metric provides a direct measure of dry season photosynthesis, thereby identifying deep-rooted vegetation with closed canopies throughout the rainless months. High observation frequency is required to generate cloud-free time series for phenology-based classification; depending on the objective of land cover change monitoring, initial results from moderate resolution studies could prioritize further investigations with high-resolution data to generate detailed area estimates of land cover change. We demonstrate that monitoring changes outside of tropical forest is possible using moderate resolution MODIS data. Variations on the simple method presented here could also provide more information to decision makers, such as generating a confidence layer for change maps based on the difference between pre-clearing and post-clearing dry season NDVI amplitude.

Land cover trajectories, from intact forest through selective logging, deforestation, pasture or cropland use, and eventual abandonment provide a wealth of information about the driving factors of land cover change in Mato Grosso. Our findings on other high-biomass land cover changes augment previous estimates of the fate of logged forest (Asner et al., 2006) and the fate of deforested lands (Morton et al., 2006) to provide a more complete picture of recent land cover changes. Combined, re-clearing of secondary forests and conversion of Cerradão in Mato Grosso is similar in extent to deforestation in Amazonas and more than total deforestation in Acre, Amapá, Maranhão, Roraima, or Tocantins States during 2002-2005.

5. Acknowledgements

This research was supported by NASA and INPE under the Large Scale Biosphere-Atmosphere Experiment in the Amazon (LBA-ECO).

6. References

Achard, F.; Eva, H. D.; Stibig, H.-J.; Mayaux, P.; Gellego, J.; Richards, T. and Malingreau, J.-P. Determination of deforestation rates of the world's humid tropical forests. **Science** 297: 999-1002, 2002.

Anderson, L. O.; Shimabukuro, Y. E.; DeFries, R. S. and Morton, D. C. Assessment of deforestation in near real time over the Brazilian Amazon using multitemporal fraction images derived from Terra MODIS. **IEEE Geoscience and Remote Sensing Letters** 2(3): 315-318, 2005.

Asner, G. P.; Broadbent, E. N.; Oliveira, P. J. C.; Keller, M.; Knapp, D. E. and Silva, J. N. Condition and fate of logged forests in the Brazilian Amazon. **Proceedings of the National Academy of Sciences** 103(34): 12947-12950, 2006.

Brandão, A. S. P.; de Rezende, G. C. and Marques, R. W. (2005). "Crescimento agrícola no Brasil no período 1999-2004: Explosão da soja e da pecuária bovina e seu impacto sobre o meio ambiente." **Texto para Discussão, No. 1103**, from <http://www.ipea.gov.br/Publicacoes/textosdiscussao.php> accessed November 2006.

Carreiras, J. M. B.; Pereira, J. M. C.; Campagnolo, M. L. and Shimabukuro, Y. E. Assessing the extent of agriculture/pasture and secondary succession forest in the Brazilian Legal Amazon using SPOT VEGETATION data. **Remote Sensing of Environment** 101: 283-298, 2006.

DeFries, R. S.; Houghton, R. A.; Hansen, M. C.; Field, C. B.; Skole, D. L. and Townshend, J. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. **Proceedings of the National Academy of Sciences** 99(22): 14256-14261, 2002.

Fearnside, P. M. Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. **Forest Ecology and Management** 80: 21-34, 1996.

Foley, J. A.; DeFries, R. S.; Asner, G. P.; Barford, C.; Bonan, G.; Carpenter, S. R.; Chapin, F. S.; Coe, M. T.; Daily, G. C.; Gibbs, H. K.; Helkowski, J. H.; Holloway, T.; Howard, E. A.; Kicharik, C. J.; Monfreda, C.; Patz, J. A.; Prentice, C.; Ramankutty, N. and Snyder, P. K. Global consequences of land use. **Science** 309: 570-574, 2005.

Houghton, R. A. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. **Tellus Series B-Chemical and Physical Meteorology** 55: 378-390, 2003.

Huete, A. R.; Didan, K.; Shimabukuro, Y. E.; Ratana, P.; Saleska, S. R.; Hutyra, L. R.; Yang, W.; Nemani, R. R. and Myneni, R. B. Amazon rainforests green-up with sunlight in dry season. **Geophysical Research Letters** 33: doi:10.1029/2005GL025583, 2006.

INPE (2006a). Projeto PRODES: Monitoramento da floresta Amazônica Brasileira por satélite, Instituto Nacional de Pesquisas Espaciais.

INPE (2006b). Sistema DETER: Detecção de Desmatamento em Tempo Real, Instituto Nacional de Pesquisas Espaciais.

Lucas, R. M.; Honzak, M.; Curran, P. J.; Foody, G. M.; Milne, R.; Brown, T. and Amaral, S. Mapping the regional extent of tropical forest regeneration stages in the Brazilian Legal Amazon using NOAA AVHRR data. **International Journal of Remote Sensing** 21(5): 2855-2881, 2000.

Malhi, Y.; Wood, D.; Baker, T. R.; Wright, J.; Phillips, O. L.; Cochrane, T.; Meir, P.; Chave, J.; Killeen, T. J.; Laurance, S. G.; Laurance, W. F.; Vargas, P. N.; Pitman, N. C. A.; Quesada, C. A.; Salomão, R.; Silva, J. N.; Lezama, A. T.; Terborgh, J.; Martínez, R. V. and Vinceti, B. The regional variation of aboveground live biomass in old-growth Amazonian forests. **Global Change Biology** 12: 1-32, 2006.

Morton, D. C.; DeFries, R. S. and Shimabukuro, Y. E (in press). Cropland expansion in cerrado and transition forest ecosystems: Quantifying habitat loss from satellite-based vegetation phenology. **Cerrado Land-use and Conservation: Assessing Trade-offs Between Human and Ecological Needs**. C. Klink, R. S. DeFries and R. Cavalcanti. Washington, Conservation International.

Morton, D. C.; DeFries, R. S.; Shimabukuro, Y. E.; Anderson, L. O.; Arai, E.; Espirito-Santo, F. d. B.; Freitas, R. and Morisette, J. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. **Proceedings of the National Academy of Sciences** 103(39): 14637-14641, 2006.

Morton, D. C.; DeFries, R. S.; Shimabukuro, Y. E.; Anderson, L. O.; del bon Espírito-Santo, F.; Hansen, M. C. and Carroll, M. Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data. **Earth Interactions** 9(8): 22, 2005.

Ramankutty, N.; Gibbs, H. K.; Achard, F.; DeFries, R. S.; Foley, J. A. and Houghton, R. A. Challenges to estimating carbon emissions from tropical deforestation. **Global Change Biology**, in press.

Ratana, P.; Huete, A. R. and Ferreira, L. G. Analysis of Cerrado physiognomies and conversion in the MODIS seasonal-temporal domain. **Earth Interactions** 9: Paper 009-003, 2005.

Steininger, M. K. Satellite estimation of tropical secondary forest above-ground biomass: Data from Brazil and Bolivia. **International Journal of Remote Sensing** 21(6/7): 1139-1157, 2000.

Zarin, D. J.; Davidson, E. A.; Brondizio, E.; Vieira, I. C.; Sá, T.; Feldspausch, T.; Schuur, E. A.; Mesquita, R.; Moran, E.; Delamonica, P.; Ducey, M. J.; Hurtt, G. C.; Salimon, C. and Denich, M. Legacy of fire slows carbon accumulation in Amazonian forest regrowth. **Frontiers in Ecology & Environment** 3(7): 365-369, 2005.