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Comparing annual MODIS and PRODES forest cover change data for advancing monitoring of Brazilian forest cover

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ABSTRACT

Annual forest cover loss indicator maps for the humid tropics from 2000 to 2005 derived from time-series 500 m data from the MODerate Resolution Imaging Spectroradiometer (MODIS) were compared with annual deforestation data from the PRODES (Amazon Deforestation Monitoring Project) data set produced by the Brazilian National Institute for Space Research (INPE). The annual PRODES data were used to calibrate the MODIS annual change indicator data in estimating forest loss for Brazil. Results indicate that MODIS data may be useful in providing a first estimate of national forest cover change on an annual basis for Brazil. When directly compared with PRODES change at the MODIS grid scale for all years of the analysis, MODIS change indicator maps accounted for 75% of the PRODES change. This ratio was used to scale the MODIS change indicators to the PRODES area estimates. A sliding threshold of percent PRODES forest and 2000 to 2005 deforestation classes per MODIS grid cell was used to match the scaled MODIS to the official PRODES change estimates, and then to differentiate MODIS change within various sub-areas of the PRODES analysis. Results indicate significant change outside of the PRODES-defined intact forest class. Total scaled MODIS change area within the PRODES historical deforestation and forest area of study is 120% of the official PRODES estimate. Results emphasize the importance of synoptic monitoring of all forest change dynamics, including the cover dynamics of intact humid forest, regrowth, plantations, and cerrado tree cover assemblages. Results also indicate that operational MODIS-only forest cover loss algorithms may be useful in providing near-real time areal estimates of annual change within the Amazon Basin.

1. Introduction

Timely updating of land cover change dynamics is a principal goal of the remote sensing science community. One of the best examples of operational monitoring for quantifying land cover change is the work of the Brazilian National Institute for Space Research (INPE) on mapping deforestation within the Legal Amazon (see Study Area). The main INPE monitoring product is the PRODES (Amazon Deforestation Monitoring Project) (INPE, 2002) data set, which is a high-spatial-resolution map of deforestation produced annually using largely Landsat inputs. The first digital version was created in 1997 and since 2000 has been produced annually. While PRODES captures the spatial detail required to generate area estimates of deforestation, there is some latency in creating the annual update products. Results for the entire Legal Amazon represent August conditions of the current analysis year, but are available several months later, typically by the beginning of the following calendar year. To improve timeliness and meet the needs of other users, INPE has also incorporated the use of imagery from the MODerate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua spacecraft for forest change monitoring through the DETER (Near Real Time Deforestation Detection System) (Shimabukuro et al., 2006) project. DETER data are acquired daily and allow for the near-real time detection of large-scale change events within the Legal Amazon. The DETER products enable quick responses by government agencies in enforcing forest land use policies. However, DETER does not yield deforestation area estimates. In summary, current INPE applications employ MODIS (DETER) for identification of new change hotspots in near-real time and Landsat (PRODES) for the precise areal quantification of change with results made available several months after the end of data acquisition — the nominal reporting period.

Another potential use of MODIS data would be as an intermediate product for provision of an early estimate of areal change covering the entire Legal Amazon. Systematic identification of change at regional scales is feasible and could be delivered operationally at the end date of annual monitoring. Currently, PRODES employs August as the date for updating annual deforestation rates within the Legal Amazon. Subsequent analysis of Landsat imagery requires a few months to derive deforestation change estimates. Methods for automatically

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mapping regional-scale forest cover and change with MODIS data exist (Hansen et al., 2003; Fuller et al., 2004; Morton et al., 2005). While MODIS data do not allow for the direct mensuration of areal change, such regional low resolution products can be calibrated using Landsat-scale data to provide a first estimate of annual change at the August deadline, to be later updated by the PRODES product.

The generation of digitally mapped PRODES data largely coincides with the operation of the MODIS Terra sensor. The temporal overlap is now over half a decade and offers an opportunity to inter-calibrate MODIS and PRODES for forest change monitoring. This paper presents a new approach for mapping forest cover change using MODIS inputs. MODIS per pixel probabilities of forest cover loss products are generated and subsequently calibrated by the existing PRODES data sets to generate forest loss area estimates. The objective is to employ MODIS data to produce an area estimate of forest cover loss immediately at the end of the monitoring cycle, to be updated later by the more precise PRODES product.

Deforestation in Amazônia has been given attention by several organizations (government, researchers, NGOs, etc.), especially in recent decades (INPE, 2002; Moran et al., 1981; Roberts et al., 2003; Skole & Tucker, 1993). Although it has a long history of human occupation, roughly 90% of the deforested areas for agriculture in the Legal Amazon occurred after 1970, as indicated by estimates derived from high-spatial-resolution satellite data (Skole et al., 1994). Other activities also spurred deforestation in the Legal Amazon, including mineral exploration and selective logging of trees with high commercial value (Cochrane et al., 1999). The deforestation in the Legal Amazon is concentrated in the south and east of the region, typically referred to as the arc of deforestation, extending from Acre to Maranhão states (Achard et al., 2002; Cardille & Foley, 2003; Cochrane et al., 1999; Wood, 2002). In recent years, several estimates of deforestation in the Legal Amazon have been produced. However, variations between methodologies have led to inconsistencies in overall change estimates (Fearnside, 1993; INPE, 2002; Skole & Tucker, 1993). Variation relative to the geographical region of study is a potential cause of incompatible estimates of deforestation (Cardille & Foley, 2003; Fearnside, 1993). Another problem relates to the inclusion, or not, of deforestation within the cerrado zone of dry tropical savannas and woodlands. These areas are often ignored, but the magnitude of change within the cerrado is referred to as being similar or greater than in the areas occupied by the humid tropical forest proper (Fearnside, 1993; Kaimowitz & Smith, 2001; Nepstad et al., 1997). The inclusion of secondary forest areas (regrowth) in the deforestation thematic class has been another problem associated with consistently estimating rates of deforestation in the Legal Amazon (Fearnside, 1993). PRODES, for example, does not depict the clearing of regrown forest cover. These issues lead to variations and uncertainty in the regional depiction of forest cover change. A further objective of this study is to examine the MODIS change signal within some of these sub-regions, including the areas of deforestation prior to 2000, the cerrado zone, and the Brazilian humid tropics outside of the Legal Amazon.

2. Data

2.1. PRODES

Since 1970, the Brazilian National Institute for Space Research (INPE) has quantified deforested areas in the Legal Amazon. During this time it initially utilized data from the Multispectral Scanner System (MSS) onboard the Landsat-2 satellite. It performed two estimates using MSS images acquired during the 1973 to 1975 and 1975 to 1978 time periods (Tardin et al., 1980). Since 1988, INPE has estimated deforested areas annually with MSS data replaced by Landsat Thematic Mapper (TM) data onboard the Landsat-4 and -5 satellites. Until the end of the 1990s, the methodology of mapping deforested areas was based on manual interpretation followed by map digitizing to calculate the deforested areas. This procedure did not allow for the production of a digital product for PRODES. The resulting information was available only in a tabular format. In 1997, the first digitally mapped version was created, based on the methodology presented by Shimabukuro et al. (1998). It employs a linear spectral mixing algorithm to generate vegetation, soil, and shade fraction images. The soil and shade fraction images were classified using image segmentation, followed by unsupervised classification and image editing. Since 2000, the digital product has been produced annually. The available PRODES products have used 181, 161, 191, 207, 211 and 211 TM scenes for 1997, 2001–2002, 2002–2003, 2003–2004, 2004–2005 and 2005–2006 respectively and are available at the following website: http://www.obt.inpe.br/prodes/index.html. The deforestation estimates are summarized in Table 1. While cloud cover is an issue, it is largely resolved according to the methodology of Câmara et al. (2006), also available at the PRODES website.

2.2. MODIS

Daily global, gridded, georeferenced MODIS data covering the seven MODIS land bands, NDVI (Normalized Difference Vegetation Index) and land surface temperature (LST) comprised the input data set. The MODIS land data are derived from the MOD09 standard product (Vermote et al., 2002) and the 8-day L3 1-km MODIS land surface temperature product (MOD11) (Wan et al., 2002). The MODIS inputs consisted of 250-m band 1 (620–670 nm, red) and band 2 (841–876 nm, near infrared), and 500-m band 3 (459–479 nm, blue), band 4 (545–565 nm, green), band 5 (1230–1250 nm, mid-infrared), band 6 (1628–1652 nm, mid-infrared), and band 7 (2105–2155 nm, mid-infrared) data. The NDVI was calculated using bands 1 and 2. Data from March 2000 to March 2005 were used for this study.

To avoid the presence of cloud cover, the MODIS daily acquisitions were converted to 32-day composites resulting in 11 roughly monthly composites for each of the 9 inputs (Carroll et al., in press). Compositing is a standard approach to compiling time-series data sets by preferentially selecting cloud-free observations over a given interval. From these 99 composite images, an additional series of 279 annual MODIS metrics was generated. Metrics are time-integrated means, amplitudes and ranks of annual composite imagery that represent salient features of vegetation phenology. These image inputs are not tied to a specific time of year, and have been shown to be more appropriate for mapping land cover at continental and global scales than are time-sequential monthly composite image data sets (Hansen et al., 2000, 2003, 2005, 2008a). For regional studies featuring a synchronized phenology, metrics have been shown to complement time-sequential composites by providing a generalized annual feature space that enables the extension of regional spectral signatures for given vegetation traits of interest, such as forest cover.

Table 1
Deforestation in the Legal Amazon from PRODES (2000 to 2005 in km^2/yr)

State	2000–2001	2001–2002	2002–2003	2003–2004	2004–2005	5 year total
Acre	419	762	1061	729	539	
Amapá	7	0	25	46	33	
Amazonas	634	881	1587	1211	752	
Maranhão	958	1014	993	755	922	
Mato Grosso	7703	7892	10,405	11,814	7145	
Pará	5237	7323	6996	8521	5731	
Rondônia	2673	3067	3620	3834	3233	
Roraima	345	84	439	311	133	
Tocantins	189	211	156	158	271	
Amazônia Legal	18,165	21,237	25,282	27,379	18,759	110,822

3. Study area

The Legal Amazon, administrative unit of Brazil, includes the totality of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima and Tocantins states and partially the state of Maranhão (west of 44°W longitude) comprising approximately 5,000,000 km^2 (IBGE, 2000), between 5°N and 20°S (latitude) and 44°W and 75°W (longitude).

4. Methods

4.1. PRODES annual deforestation mapping

PRODES depicts deforestation within the Legal Amazon. A mask of nominally intact forest is annually updated/reduced by identifying new deforestation events to the exclusion of other change dynamics such as the clearing of secondary regrowth or cerrado. The methodology of image interpretation consists of the following steps: image selection with low cloud cover and acquisition date closest to the reference date for calculating the annual rate of deforestation (August 1st), georectification of the images, transformation of radiometric image data to fraction images (vegetation, soil, and shade) using a Linear Spectral Mixing algorithm, image segmentation, unsupervised classification and image editing to minimize commission and omission errors. The Landsat TM images are selected generally in July, August and September, months with minimum cloud cover, best visibility and adequate radiometric quality. These images are rectified using nearest neighbor sampling to a UTM projection, resulting in a cartographic product with 50-m internal error. For PRODES, TM 3 (red), TM 4 (NIR) and TM 5 (MIR) bands are used to generate the fraction images. The data base created by SPRING software (Câmara et al., 1996) includes the images and output thematic maps. The legend for the maps contains the following classes: forest, non-forest (Savana Arbórea–Arbustiva (Cerrado), Savana Gramíneo–Lenhosa (Campo Limpo de Cerrado), Campinarana, etc.), deforestation (accumulated from previous mapping), year of deforestation, hydrography and cloud.

4.2. Linear Spectral Mixing Model

The Linear Spectral Mixing Model (LSMM) has the objective to estimate the amount of soil, vegetation and shade for each pixel from the spectral response in the TM bands, generating the corresponding soil, vegetation and shade fraction images (Shimabukuro & Smith, 1991). The LSMM can be written as:

$$r_i = a^*\mathrm{vege}_i + b^*\mathrm{soil}_i + c^*\mathrm{shade}_i + e_i$$

where r_i is the response for the pixel in band i of TM image; a, b, and c are the proportion of vegetation, soil, and shade in each pixel; vege_i, soil_i and shade_i correspond to the spectral responses of each component; e_i is the error term for each band i. Landsat TM bands 3, 4 and 5 are used to form a linear equation system that can be solved by any developed algorithm (e.g., Weighted Least Square). The resulting fraction images contain specific information: soil fraction enhances the bare soil areas, vegetation fraction like any vegetation index enhances vegetation cover, and shade fraction enhances water and burned areas. Finally, the resulting fraction images are resampled to 60-m in order to minimize computer processing time and disk space, without losing information compatible to the 1:250,000 final product map scale.

4.3. Segmentation of shade and soil fraction image

Image segmentation is a technique to group the data into contiguous regions having similar spectral characteristics. Two thresholds are required to perform the image segmentation: a) Similarity that is the minimum value defined by the user to be considered as similar and to form a region; b) Area that is the minimum size given in number of pixels in order to be individualized. The unsupervised classification (ISOSEG) method is used to classify the segmented fraction images. It uses the statistical attributes (mean and covariance matrix) derived from the polygons of the image segmentation.

4.4. Image edition and mosaicing

After the unsupervised classification, it is necessary to check the resulting maps. This task is performed by interpreters using interactive image editing tools. Color composites of Landsat bands 5, 4 and 3 are displayed in red-green-blue video. Expert-identified omission and commission errors are manually corrected in order to improve the classification result.

Then the individually classified images are mosaicked to generate the final maps per state and for the entire Legal Amazon. For the state mosaics, the spatial-resolution is kept at 60-m and the scale for presentation is 1:500,000, while for the Legal Amazon the spatial-resolution is degraded to 120-m and the scale for presentation is 1:2,500,000 due to the large amount of information.

4.5. MODIS annual forest cover loss hotspot mapping

As part of a NASA Land Cover and Land Use change program project, annual forest cover loss indicator products are being developed with data from MODIS (Hansen et al., 2008a). The primary use of these data sets is to stratify dominant forested biomes into high, medium and low change strata for sampling with Landsat imagery. The Landsat samples are then used to produce annual and epochal forest cover loss estimates. However, for the Legal Amazon, contemporaneous wall-to-wall annual deforestation data exist in the form of the PRODES data set, enabling the evaluation of MODIS as a direct measure of forest cover loss. Moreover, MODIS data as a direct measurement tool should be of greatest utility in the Legal Amazon due to the level of large-scale agro-industrial clearing within the region, unlike other regions, such as the Congo Basin in central Africa, where change is typically not observable with MODIS on an annual basis (Hansen et al., 2008b).

4.6. Classification tree algorithm

A pan-humid tropical forest cover change indicator map was created using a bagging decision tree algorithm. Decision trees are a type of distribution-free machine learning tool appropriate for use with remotely sensed data sets (DeFries et al., 1997; Freidl & Brodley, 1997; Hansen et al., 1996; Michaelson et al., 1994). They are the primary algorithmic tool used in the standard MODIS land Vegetation Continuous Field (VCF) products (Hansen et al., 2003). Whereas the VCF products depict percent cover per MODIS pixel of basic vegetation traits, such as herbaceous and tree cover, the product described here measures the probability of forest cover loss.

As trees are distribution-free, they allow for the improved representation of training data within multi-spectral space. The relationship between the independent and dependent variables need not be monotonic or linear. This allows for more flexible subsetting of the multi-spectral image space not feasible with many other methods and is most appropriate for large area studies that feature complicated multi-spectral signatures. In addition, the tree structure enables the interpretation of the explanatory nature of the independent variables.

Trees can accept either categorical data in performing classifications (classification trees) or continuous data in performing sub-pixel percent cover estimations (regression trees) (Breiman et al., 1984). For this study, we used the classification tree algorithm of the S-Plus statistical package (Clark & Pergibon, 1992) to depict a forest cover loss category. Methods to avoid overfitting of tree models are available. One such approach entails performing multiple, independent runs of decision trees via sampling with replacement. This procedure is called bagging (Breiman, 1996). When bagging is used with classification trees, a plurality vote is often employed to perform per pixel class assignment. In the approach used here, the median probability of forest cover loss from all bagged trees is retained as the per pixel result. In a two class case, if the median probability map is thresholded at 50%, the result would replicate that of a plurality voting approach. For this study, instead of discretizing the map through voting, the median per pixel forest cover loss probability is retained and compared with the PRODES data.

4.7. Forest cover loss hotspots

The algorithm implementation related reference data from expert-interpreted forest cover loss and no loss categories to the MODIS time-integrated annual image metrics. The training data sets were derived using Landsat browse imagery from 2000 and 2005, overlain on MODIS grid cells. Landsat browse images were accessed at the USGS EROS glovis.usgs.gov website, and have an approximate spatial-resolution of 250 m. The hotspot analysis was implemented only for the humid tropical forest biome, as defined by Olson et al. (2001). A set of 30 bagged trees were created for this time interval, and then applied to each annual interval. Median per pixel change class probabilities from the 30 trees were retained, resulting in the following change probability products: 2000–2001, 2001–2002, 2002–2003, 2003–2004, 2004–2005, 2000–2004 and 2000–2005. Multi-year and annual intervals complement each other by reducing the impacts of residual cloud cover or other artifacts that may deleteriously impact any individual interval. The annual and multi-year forest cover loss maps were thresholded at various forest cover loss probability values to produce per 500 m pixel change/no change maps. For the purposes of this paper, change refers exclusively to forest cover loss.

Two aspects of this approach to mapping change are worthy of note. First, the use of a single set of models is run on all of the time intervals. Due to the robust calibration of the MODIS time-series data (Vermote et al., 2002), it is expected that the change signal being trained upon may be reliably and repeatedly captured over time. Second, the probability outputs produce what amounts to a fuzzy classifier, where the relative probability of a pixel being a member of the change class is output. This leads to a continuous field of change probability and a flexible input to use in change product inter-comparisons.

4.8. Product inter-comparison for calibrating MODIS for area estimation

A sequence of geospatial analyses were undertaken to compare PRODES and MODIS results. The first step was to create a common region of analysis for direct spatial comparison and inter-calibration of the PRODES and MODIS change maps. The PRODES data were reprojected to the standard MODIS Sinusoidal grid using a nearest neighbor resampling to a spatial-resolution that nested within the MODIS 500-m grid cells. Next, a common region of analysis was defined using the PRODES class labels (Table 2). All classes of forest or deforestation occurring between 2000 and 2005 were aggregated to create a region of inter-comparison. All MODIS grid cells covered by 90% or greater of these combined PRODES classes were used to make a mask (Mask A) for comparing the native resolution PRODES and MODIS change data. PRODES depicts clearing of intact forests only, and not clearing of secondary regrowth or cerrado woodlands. However, the MODIS result will capture these other change dynamics in addition to intact forest clearing. Mask A represents primarily intact forest clearing and where change in PRODES is most directly comparable to the MODIS product.

The first step in the inter-comparison was to find a MODIS change probability threshold that best related to the PRODES change products within Mask A. To do this, grid cells within Mask A featuring 50% or greater PRODES change from 2000 to 2005 were discretized and labeled change; those with less than 50% were labeled no change. MODIS probability values from the same time period were thresholded in increments of 10% and compared to the PRODES product using a confusion matrix for assessing agreement. If any of the MODIS annual or multi-year change probability values exceeded the given threshold, that pixel was labeled as change. The MODIS threshold that yielded the highest overall agreement between the two data sets was used to calibrate the MODIS result to PRODES change estimates. Upon establishing a thresholded MODIS change product that best agreed with the PRODES data, a direct comparison between the two was made by summing up the total change of the native resolution PRODES and the thresholded MODIS data sets. The ratio of the two areas yielded a scaling factor for matching PRODES area change to MODIS indicated change.

Table 2
PRODES classes as aggregated for MODIS inter-comparison

ID	Class	Type	Mask A	Mask B	Mask C
1	d2002_5	Change uncertain if w/in 00-05		x	
2	d2001_3	Change uncertain if w/in 00-05		x	
3	d2004_6	Change uncertain if w/in 00-05		x	
4	d2004_2	Change	x	x	
5	d2002_0	Change	x	x	
6	nao_floresta2_2003	Non-forest			
7	nao_floresta	Non-forest			
8	d2003_1	Change	x	x	
9	d2005_7	Change Uncertain if w/in 00-05		x	
10	d1997_0	Non-forest			x
11	d2005_8	Change uncertain if w/in 00-05		x	
12	d2004_0	Change	x	x	
13	d2000_0	Non-forest			x
14	d2005_0	Change	x	x	
15	d2005_4	Change	x	x	
16	hidrografia2004	Non-forest			
17	nao_floresta2_2004	Non-forest			
18	d2005_3	Change	x	x	
19	d2004_7	Change uncertain if w/in 00-05		x	
20	d2002_1	Change	x	x	
21	d2005_1	Change	x	x	
22	hidrografia	Non-forest			
23	d2004_1	Change	x	x	
24	d2003_2	Change	x	x	
25	d2002_4	Change uncertain if w/in 00-05		x	
26	d2000_2	Non-forest			x
27	d2003_6	Change uncertain if w/in 00-05		x	
28	d2003_0	Change	x	x	
29	d2005_2	Change	x	x	
30	nao_floresta2004	Non-forest			
31	d2000_3	Non-forest			x
32	d2003_5	Change uncertain if w/in 00-05		x	
33	d2001_4	Non-forest			x
34	residuo2003	Change	x	x	
35	residuo2004	Change	x	x	
36	d2001_0	Change	x	x	
37	d2004_3	Change	x	x	
38	floresta	Forest	x	x	
39	backg (no data)	No data			
40	n2002	No data		x	
41	n2001	No data		x	
42	n2000	No data		x	
43	n2004	No data		x	
44	n2005	No data		x	
45	n2003	No data		x	
46	n1997	No data		x	

ID and CLASS are provided for users of PRODES data. Type is the definition of each class as employed in this analysis. Mask A consists of MODIS grid cells covered by 90% or greater of the marked classes, including forest in 2005 or deforestation occurring between 2000 and 2005. Mask A reflects the region most directly comparable between PRODES and MODIS results and was used to calculate a change area scaling factor. Mask B consists of the Mask A classes plus all other PRODES classes where change *may* have occurred between 2000 and 2005 (change uncertain if w/in 00-05). Mask B was used to total the flagged MODIS pixels and scaled result until the official PRODES Legal Amazon total was met. Residual change beyond this indicates possible secondary forest clearing. Mask C represents areas deforested before 2000 and where any MODIS detected change indicates secondary clearing.

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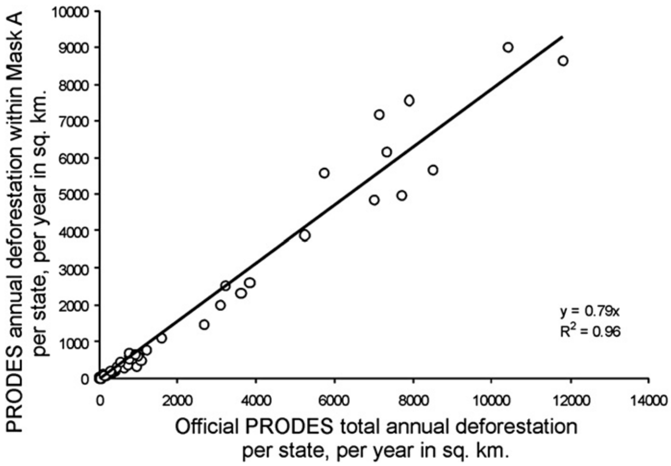

Fig. 1. Annual PRODES results within Mask A versus official PRODES data by state and year.

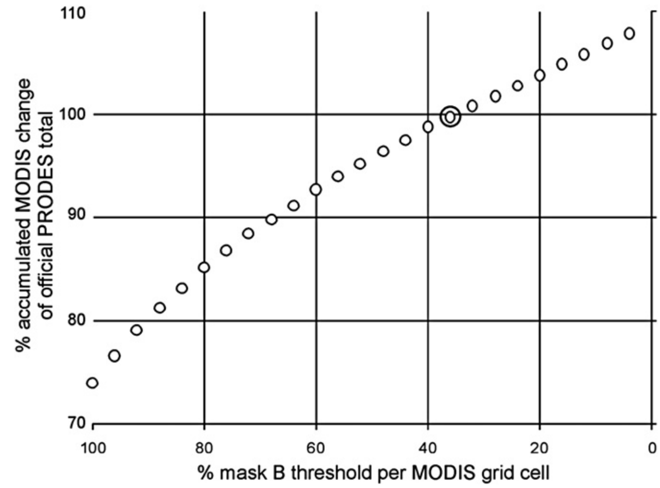

Fig. 3. Ratio of MODIS/PRODES official change as a function of Mask B fraction within MODIS grid cells where Mask B consists of PRODES forest and deforestation 2000 to 2005 along with uncertainty deforestation categories 2000 to 2005 and no data classes (see Table 2). The threshold was lowered until the sum of the scaled MODIS change equaled the official PRODES total.

Next, the scaled MODIS change was totaled using the PRODES forest and deforestation occurring between 2000 and 2005 as well as those PRODES categories in Table 1 that may have been cleared since 2000, but have not been documented as such by PRODES (Table 1 — change uncertain if w/in 00-05). This also included the *no data* classes of PRODES, within which change may have occurred since 2000. The area covered by these classes resulted in Mask B. For this Mask, a direct PRODES/MODIS inter-comparison was not the objective. The objective was to total the flagged MODIS pixels and scaled result until the official PRODES Legal Amazon total was met. This was achieved by calculating the summed area of the Mask B classes as a proportion per MODIS grid cell and accumulating the MODIS change found within. Starting at 90% Mask B per MODIS grid cell and descending, new areas were added and the scaled MODIS change summed until it matched the actual PRODES change estimate over the period. This matching threshold represented the region where the scaled MODIS change matched the total, official PRODES change.

The next step was to examine the MODIS change in excess of the PRODES total. The remaining MODIS change can be depicted within 5 distinct regions. The first represents the change occurring in the area where Mask B coverage is greater than zero, but less than the matching threshold. This region is where PRODES change may occur within intact or secondary forests, but where the MODIS rescaled change estimate has already captured its PRODES equivalent areal change. The second region is where PRODES forest or deforestation between 2000 and 2005 is equal to zero and where PRODES deforestation occurred before 2000 (Table 2, Mask C). This represents a zone of secondary forest cover clearing within MODIS change. The third region is outside of the PRODES mask, but within the Legal Amazon. This is an area of clearing in the cerrado and cerradão savannas and woodlands of the Legal Amazon. The fourth region is where no data have been acquired for the PRODES

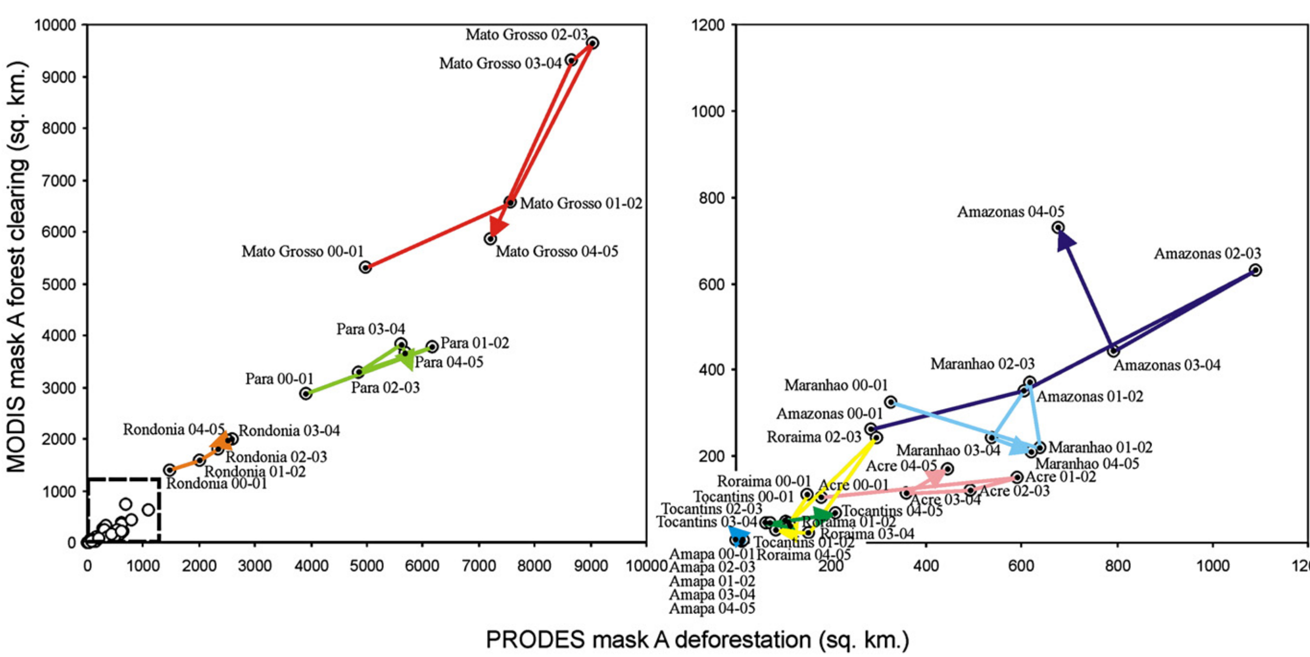

Fig. 2. Plot of PRODES deforestation versus MODIS forest clearing as defined by an 80% probability threshold applied per MODIS pixel. This plot is for Mask A, defined as the MODIS grid cells consisting of 90% or more PRODES forest plus deforestation 2000 to 2005 (see Table 2). The arrows indicate the trend in time. The plot on the right is an enlargement of the dashed box found in the plot on the left.

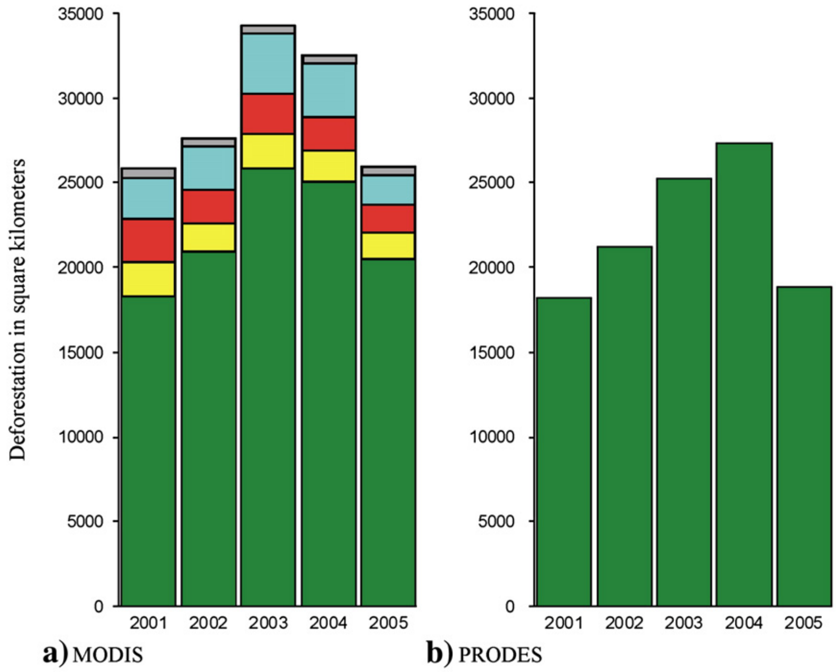

Fig. 4. Legal Amazon annual forest cover loss in square kilometers for a) MODIS, where dark green is MODIS area equal to PRODES official total (Mask B threshold >=36%); yellow is change beyond PRODES official total and includes possible primary and secondary clearing (Mask B>0 and Mask B<36); red is MODIS change for areas deforested prior to 2000, primarily secondary clearing (Mask C>0; Mask B=0); cyan is change outside of any PRODES forest or deforestation class, clearing of cerrado and cerradão woodlands (all PRODES codes, except code 39>0); gray is change for PRODES *no data* classes within the Legal Amazon, and b) official PRODES deforestation data.

analysis. The fifth region is the Brazilian humid tropics outside of the Legal Amazon (Olson et al., 2001). Scaled MODIS change results were calculated for the first four regions by state and the fifth region as a single regional entity.

5. Results

5.1. PRODES-MODIS inter-comparison

To ensure that the area used for the PRODES-MODIS inter-calibration was not biased in under- or over-estimating total change, a plot per state was made for PRODES change inside Mask A versus total PRODES per state, per year change (Fig. 1). The plot reflects that 79% of the PRODES change was inside Mask A, and that on a per state basis, the relative change inside and outside of Mask A was proportionally consistent. Under Mask A, total change estimates using 10% increments of MODIS probability thresholds were compared to the PRODES total. Overall change/no change accuracy was highest (98%) using an 80% MODIS change probability threshold. Of the total PRODES native resolution change within Mask A, 55% was identified by the 80% thresholded MODIS change, while 20% of the MODIS change was outside of PRODES-identified change.

Fig. 2 is a plot illustrating per state, per year change under Mask A for native resolution PRODES and MODIS change probability >=80%.

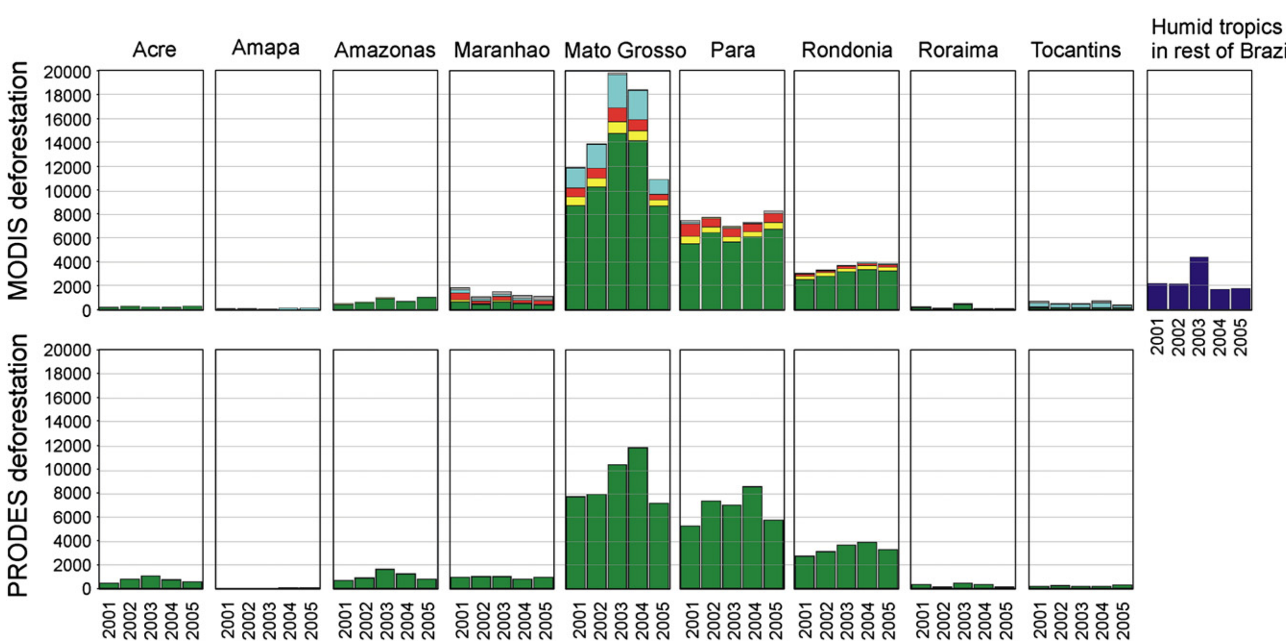

Fig. 5. Per state annual forest cover loss in square kilometers. Colors coded the same as in Fig. 4. Dark blue is for Brazilian humid tropics outside of the Legal Amazon.

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Correlation on an annual and per state basis is strong, with an r^2 of 0.92. The ratio of total PRODES to MODIS change probability >=80% under Mask A was 1.339 (PRODES: 84231.98 km^2: MODIS: 62887.90 km^2). This scaling factor was used to extend the MODIS change estimates beyond Mask A in order to calculate a total MODIS change that matched PRODES over the five year period. This was achieved by using the sliding scale of fractional cover per MODIS grid cell of Mask B. Fig. 3 shows the total scaled MODIS area change as a running total versus fractional Mask B coverage. The running total matched the official PRODES 2000 to 2005 change estimate (110,822 km^2) when the fractional PRODES coverage per MODIS grid cell equaled 36% (Fig. 3), resulting in a MODIS change estimate of 110,490 km^2. This is slightly different than the PRODES estimate due to the use of the MODIS grid cell threshold in determining total change.

All MODIS change where Mask B covers from 0 to 36% of MODIS grid cells is beyond the official PRODES estimate and indicates forest clearing dynamics that are either partially or wholly outside of the PRODES analysis. Fig. 4 disaggregates the change within the Legal Amazon on an annual basis and Fig. 5 does the same for the states of the Legal Amazon. Dark green represents the area of Mask B that matches the PRODES 5-year total. Yellow represents the MODIS change that occurred in grid cells with less than 36% but greater than 0% presence of Mask B categories. Red represents MODIS change occurring in areas where PRODES deforestation occurred before 2000 (Mask C>0%), and that have 0% presence of Mask B categories (likely secondary forest clearing). Cyan is MODIS change outside of PRODES forest or deforestation, and represents areas of the Legal Amazon that largely consist of cerrado and cerradão savannas and woodlands. Gray covers areas for which no PRODES analysis has taken place. Additionally, the annual change of the Brazilian portion of the humid tropical forest biome not within the Legal Amazon (Olson et al., 2001) is also shown in Fig. 5.

From Fig. 4, the MODIS change beyond the matching PRODES total is shown to be significant over the study period. The four classes representing these change sub-categories equal fully 35% of the PRODES total. The largest is cerrado change, which is equal to 12.6% of the PRODES total, followed by Mask C secondary forest clearing (10.2%), Mask B<36% intact forest and secondary clearing (9.6%), and change within PRODES *no data* classes (2.4%). These data illustrate a disturbance regime for the Legal Amazon that is far more complicated when considering a more complete suite of tree cover change dynamics.

However, it must be noted that the MODIS calibration is based on PRODES change that occurs only in intact forest zones. Secondary forest and cerrado clearing are likely to be much more fragmented, and estimates for these change types should be primarily used as

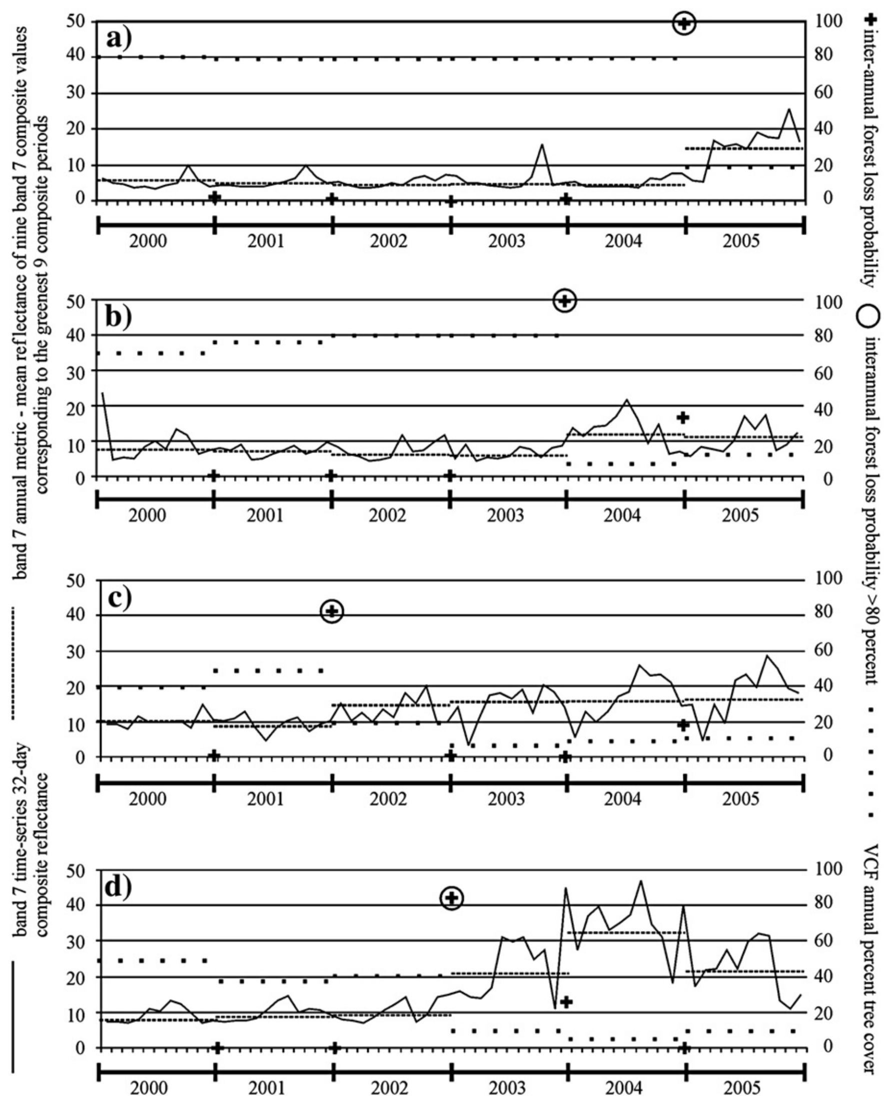

Fig. 6. Time-series for band 7 32-day composites, band 7 annual metric, inter-annual forest loss probability and annual VCF of percent tree cover, for locations in a) upper Xingu River Basin in Mato Grosso state, 54.05 W, 12.58 S, b) lower Xingu River Basin in Para state, 53.61 W, 5.65 S, c) lower Tapajos River Basin in Para State, 54.80 W, 2.61 S, and d) southern Mato Grosso state, 53.83 W, 14.65 S.

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indicators of area change. To highlight this, MODIS VCF data from 2000 were analyzed for all flagged MODIS change pixels within the various change regimes. For Mask B >=36% intact forest clearing, mean 2000 tree canopy cover is 71% +/−14sd 14SD (maximum closure in the VCF is 80%). For Mask B<36% intact forest and secondary clearing, mean tree canopy cover equals 35% +/−25SD. For Mask C secondary forest clearing, mean VCF equals 17% +/−19SD. For cerrado clearing, mean VCF equals 21% +/−20SD. For the no data class, mean VCF equals 23% +/−19SD. As the VCF and MODIS change products do not reflect sub-pixel fragmentation, area of tree cover cleared per pixel within these change classes is not captured, only those pixels that indicate the presence of change.

5.2. MODIS change probability results

The bagged tree algorithms relied primarily on MODIS band 7 and NDVI data to discriminate forest cover loss. The most discriminating MODIS metric was a difference image of the inter-annual mean reflectance of the nine MODIS band 7 32-day composite values corresponding to the greenest 9 composite periods. Almost half (43%) of the total deviance reduction in the bagged trees was attributed to this metric. The bagged trees were then applied to all 5 annual intervals (2000–2001, 2001–2002, 2002–2003, 2003–2004, 2004–2005), and two multi-year intervals (2000–2004 and 2000–2005). Fig. 6 shows time-series plots of band 7, including the annual values of the principal

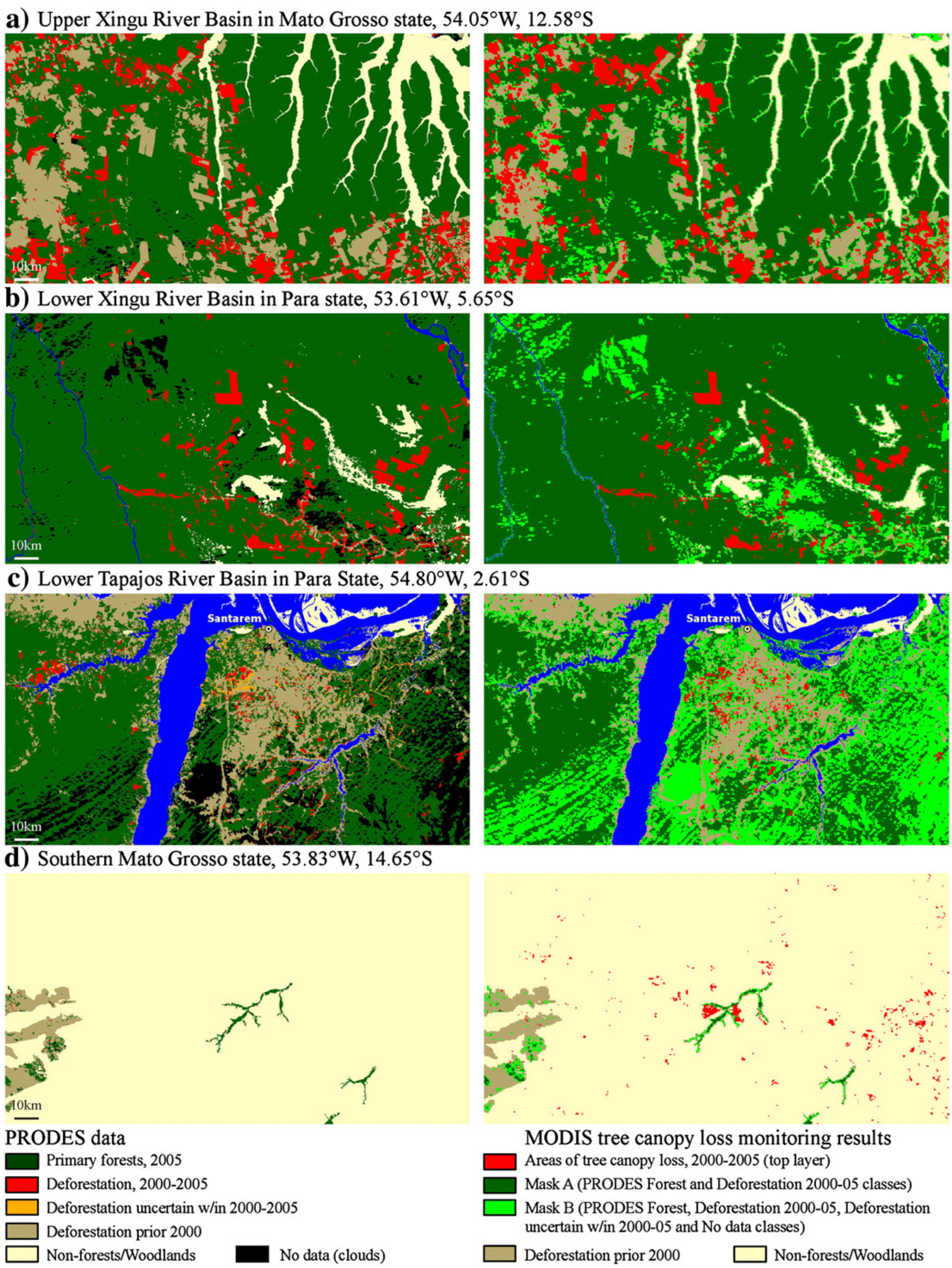

Fig. 7. Areal overviews of forest cover and change, centered on the sites illustrated in Fig. 6. The left column is PRODES, the right column MODIS.

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band 7 metric, along with the resulting forest loss probability values, and the Vegetation Continuous Field percent tree cover data, a standard product of the MODIS Land Science Team estimating annual tree cover (Hansen et al., 2003).

The MODIS result identifies the loss of dense forest cover canopies, regardless of forest type. From Fig. 6, a number of examples are illustrated. Fig. 6a shows the clearing of intact forests within the upper Xingu River Basin in Mato Grosso state. The band 7 phenology is smooth and not affected by atmospheric contamination. These forests are drought deciduous and the annual phenology is clearly observable in the increased ~September reflectance caused by stress of the preceding dry season. Forest clearing occurred for this site in early 2005 and the elevated metric value used by the bagging algorithm results in a high forest loss probability between 2004 and 2005. The VCF cover estimate declines as well from 2004 to 2005. For Fig. 6b, the change is also for an intact forest site, but one closer to the equator in the lower Xingu River Basin of Para state. Sites such as this near the equator have a more atmospherically-impacted phenology due to the greater frequency of cloud cover (Asner, 2001; Ju & Roy, 2008; Roy et al., 2006). However, the forest is still identified as being cleared from 2003 to 2004. Fig. 6c is an example of clearing of secondary regrowth outside of Santarem in Para state. This site is a previously deforested location recently cleared for soy cultivation. Pre-clearing, the mid-infrared time-series is slightly elevated compared to the previous two intact sites, likely due to a fragmented landscape that includes much land without tree cover. However, the mid-infrared signal is sensitive enough to the presence/absence of tree cover to detect a clearing event between 2001 and 2002. Fig. 6d is a change site outside of the humid forest domain and illustrates cerrado clearing in southern Mato Grosso state. The band 7 data for this stand is brighter and more seasonal than the others. The VCF values prior to clearing are in the low 40's for percent tree cover, indicating a woodland canopy. This site is likely more homogeneous regarding tree cover than the secondary forest clearing site of Fig. 6c. The difference in the band 7 mean metric is clearly evident, and change is discriminated between 2002 and 2003.

Fig. 7 illustrates in map form the PRODES and MODIS products centered on the sites of Fig. 6. For Fig. 7a, large area clearing for soy cultivation is clearly identified by both depictions. One area of disagreement is found within a fire-affected area (left-center) that is documented as having been deforested prior to 2000 in the PRODES data. The MODIS time-series does not predate 2000, and partially captures this change post-2000 possibly due to latent affects of canopy mortality from the original fire. Fig. 7b illustrates a forest clearing frontier in Para state where PRODES and MODIS strongly correlate. Fig. 7c depicts an area near Santarem, Para state on the Amazon and Tapajos Rivers. MODIS captures significant clearing inside previously deforested PRODES lands. This area is also an example of data limitations and a corresponding presence of the 'no data' PRODES class. The left portion of the image shows a PRODES change detection omitted by MODIS. Fig. 7d is largely outside of the historical PRODES forest/deforestation mask, but still within the Legal Amazon. Contiguous blocks of clearing are detected by MODIS and point out the possibility of developing a dry tropical, cerrado and cerradão annual monitoring system.

6. Discussion

The total MODIS area change within the PRODES historical deforestation and forest mask is 120% of the official PRODES estimate. This indicates that considerable forest cover change is occurring within the area labeled as deforestation. Clearing of forest regrowth in abandoned pastures, plantations, and other tree cover is not documented in the deforestation class of PRODES. Additionally, change within the cerrado (12.6% of the PRODES total) is significant for many of the Legal Amazon states, including Mato Grosso, Maranhão, and Tocantins. While the MODIS change model applied in this study is not optimized for cerrado change mapping, it is clear that such an approach could be used to document clearing in the drier tropics. A significant proportion of the humid forest biome forest cover change is also found outside of the Legal Amazon (Fig. 5). While the scaled MODIS results for intact forest clearing are not directly translatable to secondary forest or cerrado clearing, results indicating tree cover loss emphasize the need to synoptically monitor the whole of Brazil in quantifying forest cover change and in assessing the various implications for carbon and climate studies.

The use of a scaling factor to convert the thresholded MODIS change indicator maps to an area estimate is limited by the offset in spatial detail between the MODIS and Landsat products. Fig. 5 shows that for states experiencing agro-industrial clearing on a large-scale, such as Mato Grosso, the calibrated MODIS product overestimates change; for states such as Acre experiencing finer scale change, the calibrated MODIS product underestimates change. If the overall ratio of large to fine-scale (agro-industrial to small landholder) changes dramatically, so would the MODIS calibration. By using the latest 3 to 5 years of data only in relating PRODES to MODIS change, such a trend may be captured in the calibration of an annual product. An alternative to this would be to use location-specific relationships either based on administrative unit or past spatial arrangement of fine-scale change (Mayaux & Lambin, 1997).

Due to the discretization of the MODIS product, variations in the timing between the MODIS and PRODES reporting intervals, and the presence of non-systematic MODIS-PRODES misregistration, it is difficult to evaluate the capability of MODIS to detect Landsat-scale change. To improve the integrated use of MODIS and Landsat-scale data, several recommendations can be made. First, the current MODIS annual change indicator products are made on a March to March interval. This could easily be changed to conform to the PRODES timing of August to August. While the overall trends are compatible, Figs. 4 and 5 highlight a different peak year for forest loss as depicted by the PRODES and MODIS products. Establishing a consistent interval for MODIS inputs along with training data that conform to PRODES timing may improve the correspondence of inter-annual trends. Additionally, the PRODES data or other high-spatial-resolution change data could be used directly as training for a *percent* forest cover loss algorithm optimized for the Amazon Basin. The current algorithm results in a continuous change *probability* measure. A percent forest cover map would have greater biophysical meaning and enable a more direct assessment of MODIS in estimating change area.

The most practical use of a well-calibrated MODIS area change estimate would be as a first assessment of change in lieu of PRODES data set updating. In the August–September timeframe, a MODIS forest loss area estimate could be generated automatically and provide state-level data, to be replaced by the higher spatial-resolution, more spatially explicit PRODES map in later weeks. Work on customizing the process for use by INPE with this goal in mind is underway.

7. Conclusion

This paper has demonstrated the use of MODIS for operationally indicating forest cover loss within the humid tropics of Brazil, and for calibrating such maps for estimating area of forest cover loss. INPE currently has a number of operational products providing timely and accurate information on forest cover loss for the Legal Amazon. The MODIS annual change indicator maps may fill a niche in the INPE monitoring program by providing an automated and near-real time, update of area change. This niche lies between the DETER MODIS alarm product and the PRODES Landsat map product. The primary value of the MODIS annual change indicator method is its push-button approach. The product is trained using high-spatial-resolution change/no change samples over a period of years. These data are then related to the MODIS time-series imagery to produce a hard-wired algorithm that enables

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operational end-of-season mapping of change across the Legal Amazon, and that captures change in areas outside of the PRODES forest mask. In addition to their use as a first estimate of area change, the MODIS forest loss maps could also be used to stratify and sample the Legal Amazon using blocks of Landsat data for estimating area of forest loss (Hansen et al., 2008a). This would also be an interim, but highly accurate, estimate of change area, created in the period before PRODES product generation.

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