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Fraction images derived from Terra Modis data for mapping burnt areas in Brazilian Amazonia

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The objective of this paper is to present a method for mapping burnt areas in Brazilian Amazonia using Terra MODIS data. The proposed approach is based on image segmentation of the shade fraction images derived from MODIS, using a non-supervised classification algorithm followed by an image editing procedure for minimizing misclassifications. Acre State, the focus of this study, is located in the western region of Brazilian Amazonia and undergoing tropical deforestation. The extended dry season in 2005 affected this region creating conditions for extensive forest fires in addition to fires associated with deforestation and land management. The high temporal resolution of MODIS provides information for studying the resulting burnt areas. Landsat 5 TM images and field observations were also used as ground data for supporting and validating the MODIS results. Multitemporal analysis with MODIS showed that about 6500 km^2 of land surface were burnt in Acre State. Of this, 3700 km^2 corresponded to the previously deforested areas and 2800 km^2 corresponded to areas of standing forests. This type of information and its timely availability are critical for regional and global environmental studies. The results showed that daily MODIS sensor data are useful sources of information for mapping burnt areas, and the proposed method can be used in an operational project in Brazilian Amazonia.

1. Introduction

Land-cover fires are a global phenomenon that occurs in the tropical forests of Brazil and Indonesia, the temperate forests of the United States and Europe, the boreal forests of Siberia, China, and Canada, the tropical savannas of Africa, and the agricultural lands of the United States and Europe (Levine 1996). These fires play an important role in the emission of greenhouse gases and aerosols affecting the radiation balance, in altering patterns of cloud condensation, and in land-use practices that can result in land-cover changes. Information on the location and extent of the areas affected by fire is necessary to assess the effects of biomass burning on atmospheric chemistry, ecosystem functioning, and human health.

Satellite sensor data have been used in the last decades and provide a unique source of spatial information in detecting, monitoring, and characterizing land-cover fires for global change researchers (Justice and Korontzi 2001). Satellite

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remote sensing is the only technology which allows consistent and extensive data collection at global scales. Its application for the detection and monitoring fires at local and continental scales has been developed over many years, using a number of different sensors and systems such as Landsat Thematic Mapper (TM) (Brustet *et al.* 1992), National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) (Setzer and Pereira 1991), the Defense Meteorological Satellite Program (DMSP) satellite (Cahoon *et al.* 1992), and the Geostationary Operational Environmental Satellite (GOES) (Prins and Menzel 1994).

Satellite images acquired by moderate- and coarse-spatial-resolution systems (where pixel spacing is equal or greater than 250 m), such as the Terra and Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) system, constitute a useful source of information for monitoring the Earth surface over large areas. The MODIS sensor system has enhanced spatial, spectral, and temporal characteristics that provide daily observations of earth surface conditions. It also offers high geolocation accuracy, which is a prerequisite for multitemporal analysis to monitor burnt areas. The rapid changes in spectral signature of burnt areas in some ecosystems, combined with fires occurring over large and remote areas, require a moderate spatial resolution with high temporal resolution for burnt area mapping at regional or global scale.

Using a moderate or low spatial resolution sensor data increases the so-called 'mixture problem', i.e. the pixel value is a mixture of reflectance from different targets within each pixel. Several techniques, such as modelling and empirical estimations, have been applied to depict subpixel heterogeneity in land cover from remotely sensed data (DeFries *et al.* 2000). Fraction images derived from different remote sensing data have provided consistent results for monitoring deforestation (Shimabukuro *et al.* 1998), land-cover change (Carreiras *et al.* 2002), and vegetation classification (DeFries *et al.* 2000). Fraction images, derived from a linear spectral mixing model, constitute synthetic bands containing information on end-member proportions. The generation of these fraction images is an alternative approach for reducing the dimensionality of image data and enhancing specific information for digital image processing (Aguiar *et al.* 1999). The objective of this paper is to present a method for mapping burnt areas using the shade fraction image derived from daily Terra MODIS data.

2. Study area

Acre State, located in the western region of Brazilian Amazonia (figure 1), served as the site for this study. According to IBGE vegetation map (IBGE 1992), the study site is primarily covered by moist tropical forests ('Floresta Ombrófila Aberta') that has been partially deforested during the last decades. The climate in Acre is classified as Am (tropical monsoon with the driest month somewhat below 60 mm) in the Koppen system. Average monthly temperatures range from 24 to 27°C. Yearly rain is about 2100 mm, with a dry season from June to September. Rainfall for the period 1 April–30 September averaged 489 mm for the period of 2001 to 2004 in the region of 8 to 12° S and 66 to 70° W, as derived from the Global Precipitation Climatology Project (NASA 2006). In 2005 the same area averaged only 301 mm, a 38% drop from the previous years. This extended drought provoked a large number of fires, including fires that penetrated into standing forests (Brown *et al.* 2006a).

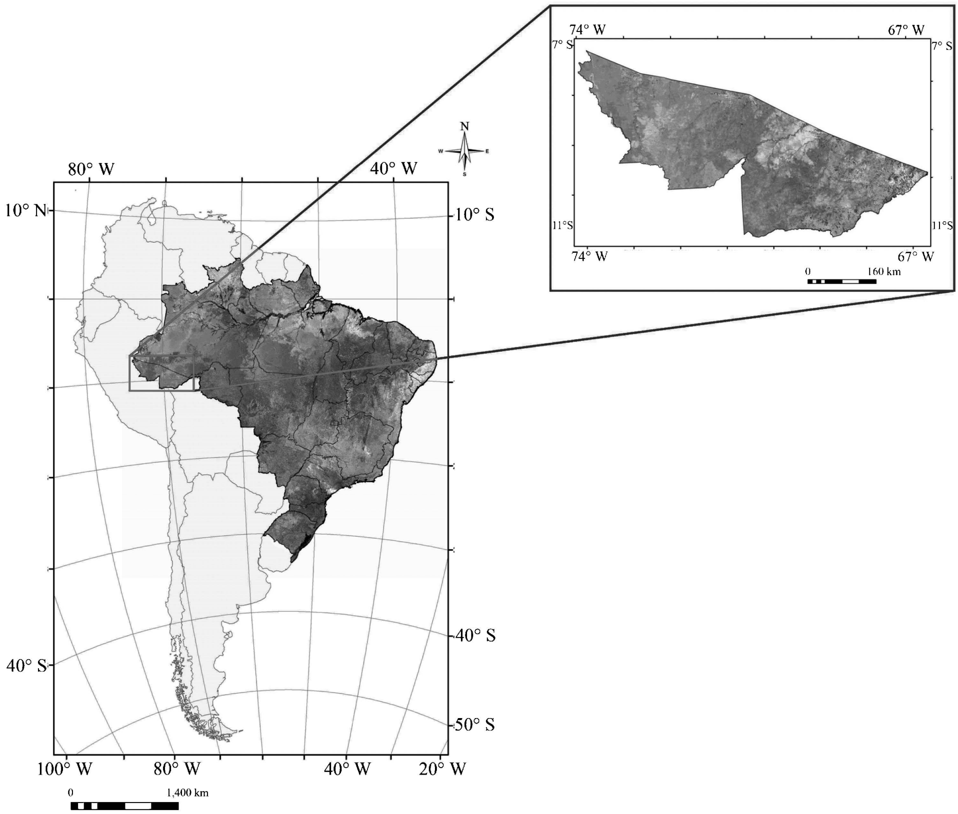

Figure 1. Location of the study site: Acre State, Brazilian Amazonia.

3. Remote sensing data analysis

The satellite images used in this study are the Terra/MODIS daily surface reflectance data (MOD09 collection 4 product), acquired on 3, 5, 15, and 16 September 2005 and on 12 October 2005. The MODIS MOD09 product, is a seven-band images centred at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm wavelengths (Justice *et al.* 2002). The product is an estimate of the surface spectral reflectance for each band, as it would have been measured at ground level if there were no atmospheric scattering or absorption. For this analysis, the atmospheric correction algorithm is applied to the MODIS data. The MOD09 product contains red and near-infrared (NIR) bands with 250 m spatial resolution (MOD09GQK) and blue, green, and three short wave infrared (SWIR) bands with 500 m (MOD09GHK) resampled to 250 m spatial resolution.

To apply this method (figure 2), we used the red (band 1, centred at 640 nm), NIR (band 2, centred at 858 nm), and SWIR (band 6, centred at 1640 nm) surface reflectance bands corresponding to the Landsat TM bands 3, 4, and 5, respectively. The fire points (figure 3) detected by Terra and Aqua MODIS in June through October time period by INPE's PROARCO Project (http://www.dpi.inpe.br/proarco/bdqueimadas/) and MODIS rapid response system (http://rapidfire.sci.gsfc.nasa.gov/) were used to support the interpretation of burnt areas in the study site. It can be observed that both systems present different number of fire

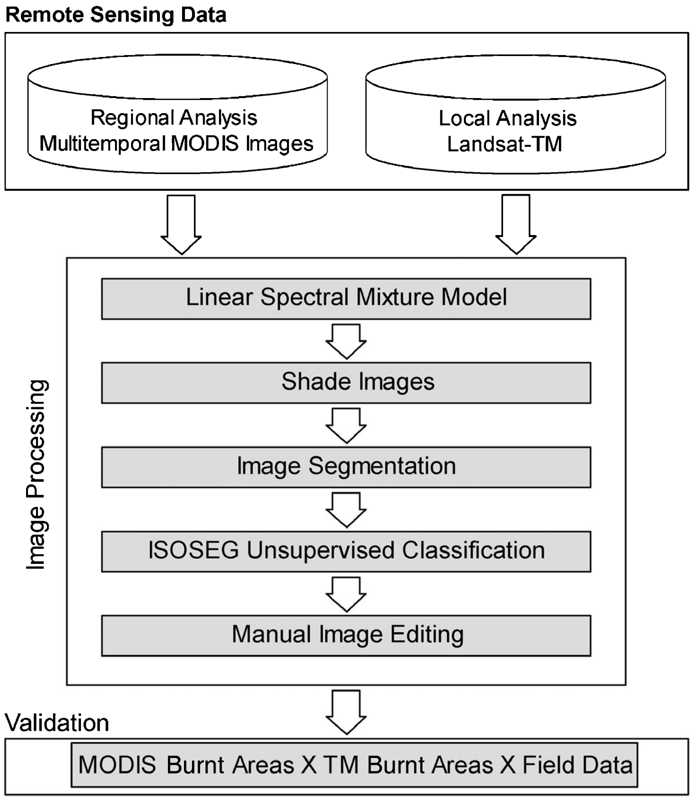

Figure 2. Procedure steps for mapping burnt areas using digital image classification of MODIS multitemporal data.

points due to their methodological approaches. MODIS rapid response system presents higher number of fire points when comparing to PROARCO dataset that is more conservative trying to prevent the commission errors. It means that these datasets can not be considered for burnt areas estimation. However, both datasets show the occurrence of fire points during the period analysed and then any of them can be used as the support for mapping burnt areas as proposed in this study. The INPEs DETER (Detection of Deforested Areas in Real Time Project, Shimabukuro *et al.* 2006) 2004 dataset (http://www.obt.inpe.br/deter/) for Acre State was used to identify the land-cover types affected by the fires. Two Landsat 5 TM scenes (path/row 002/67) acquired on 11 September and 13 October 2005 and field observations performed during the fire season were used as ground data for supporting and validating the MODIS results (Brown *et al.* 2006b).

The proposed approach was adapted from INPEs PRODES digital method that is based on image segmentation of fraction images derived from Landsat TM, using a non-supervised classification per region algorithm followed by manual image editing to minimize misclassifications (Shimabukuro *et al.* 1998). The proposed method focuses on image segmentation of shade fraction images derived from MODIS daily data, using a non-supervised classification per region algorithm followed by manual image editing. The linear spectral mixing model (Shimabukuro and Smith 1991) has been used to analyse the mixture of signatures of vegetation, soil, and shade in each pixel for several remote sensor images. The unmixing methods available in several

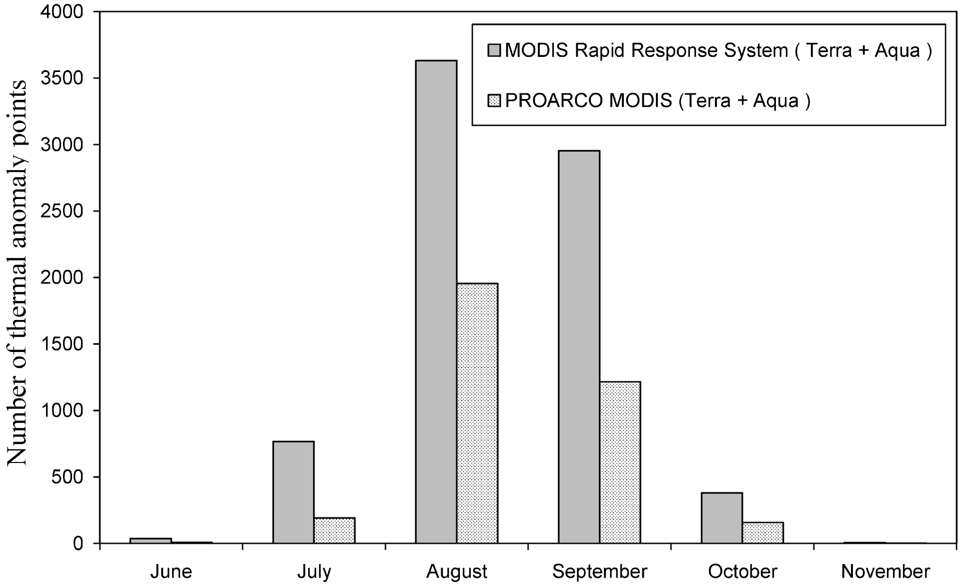

Figure 3. Number of thermal anomaly points detected by INPE's PROARCO and NASA's MODIS rapid response system using Terra and Aqua MODIS sensors data during the period from June to October 2005 over the study site.

software packages estimate the proportion of each component inside the pixel by minimizing the sum of squares of the errors. The soil fraction image highlights mainly non-vegetated areas (clear cuts, bare soil, etc.); the vegetation fraction image shows the vegetation cover condition similar to the well known normalized difference vegetation index (NDVI); and the shade fraction image enhances water bodies, vegetation cover structure, and burnt areas, the last being the focus of this study.

The image segmentation approach used in this study was based on a region growing technique (Bins *et al.* 1993). Two threshold parameters have to be set by the analyst to define segments (regions) that will be used in the subsequent classification procedure: (a) similarity threshold (the Euclidean distance between the mean digital number of two regions, under which they will be grouped together); and (b) an area threshold (minimum area to be considered as a region, set by the number of pixels). For this study, the threshold values were defined as a digital number of 8 (where a value of 255 corresponds to a reflectance of 1) and an area of 4 pixels. Then, segmented images were classified using ISOSEG, a region classifier algorithm based on clustering techniques. This non-supervised algorithm uses the covariance matrix and the mean of the regions to estimate the centres of the classes. The analyst defines an acceptance threshold, the maximum allowed Mahalanobis distance that a mean digital number may be from the centre of a class, to be considered as belonging to that class.

After the classification process, some classes may be regrouped to express more faithfully terrain features. The map editing phase consists of a visual inspection directly on the computer monitor, correcting the commission and omission errors in classified areas.

In this study, the vegetation, soil, and shade fraction images were derived from MODIS daily surface reflectance images (bands 1 (620–670 nm), 2 (841–876 nm) and 6 (1628–1652 nm)) using a linear spectral mixing model. The pure pixel of vegetation, soil, and shade components were selected directly from the MODIS

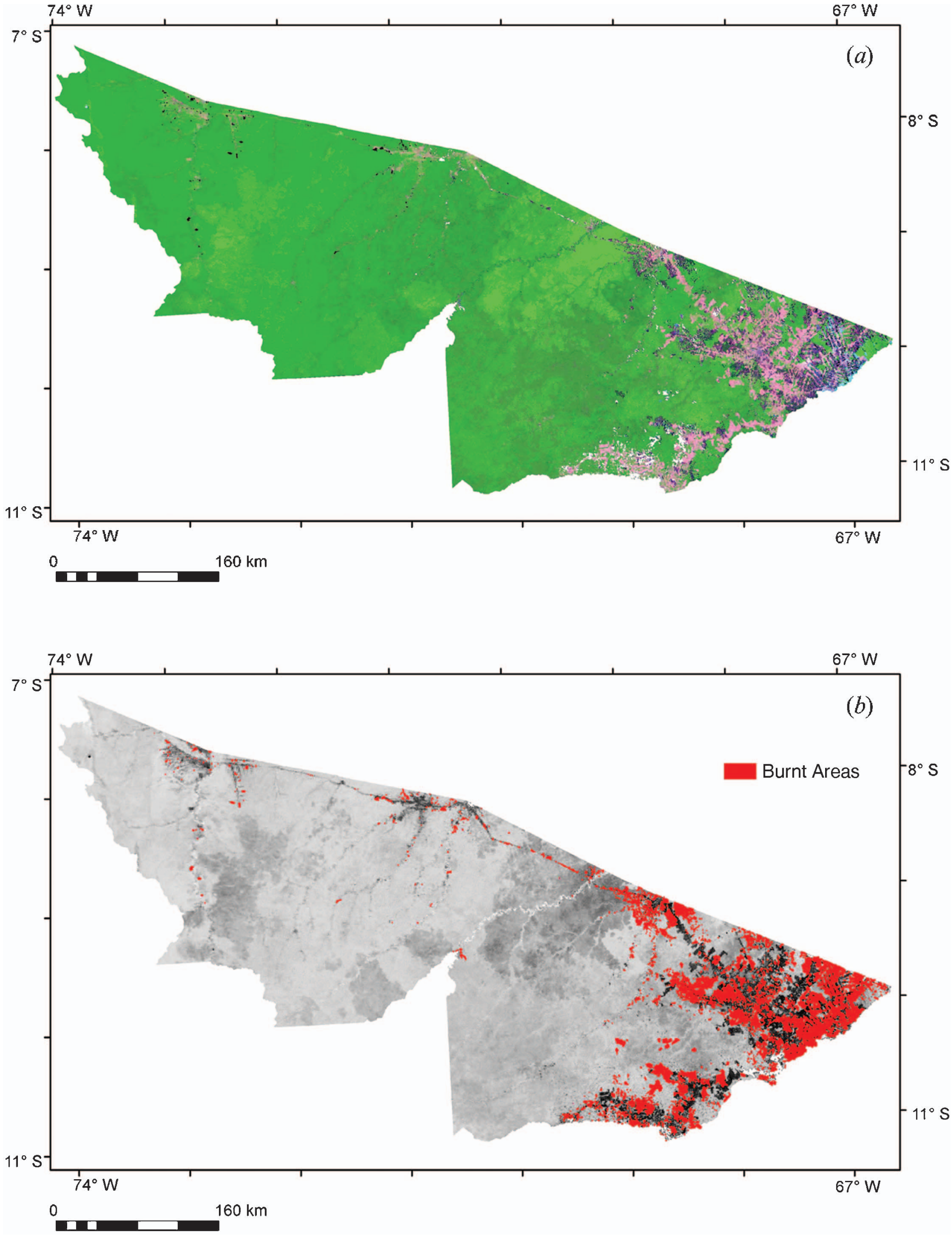

Figure 4. (*a*) Colour composite (R-B6, G-B2, B-B1) of MODIS mosaic formed based on the highest shade proportion values derived from MODIS images analysed in this study; (*b*) classification of total burnt areas (shown in red) in Acre State over the shade fraction mosaic.

images (image endmember procedure) to run the unmixing algorithm in order to generate the corresponding fraction images. The shade fraction image was the main source for mapping burnt areas. This fraction image highlights burnt areas, water bodies, and cloud shadows due to the spectral similarity among these three targets (low spectral responses in all electromagnetic wavelengths). The multitemporal shade images were segmented and classified in order to produce the map of burnt areas. Then, image editing was performed directly in the computer monitor using the MODIS R6 G2 B1 (similar to TM R5 G4 B3) colour composite as a reference to correct the digital classification. This procedure corrects the misclassification of water bodies and cloud shadows that have similar spectral responses and are highlighted in the shade fraction images similar to the burnt areas. Therefore, this procedure minimizes the commission and omission errors produced by digital image classifiers (Almeida-Filho and Shimabukuro 2002). The same procedure was also applied to the Landsat 5 TM images to map burnt areas. Then, a qualitative and quantitative evaluation of MODIS classification was performed by comparing it to the TM classification for a local area. In addition, over a hundred forest and pasture fires were observed during fieldwork campaigns and provided qualitative information as to fire occurrence (Brown *et al.* 2006a).

4. Results and discussion

Figure 4 shows the MODIS composition formed by the MODIS images analysed in this study. It was formed based on the highest shade proportion, highlighting the burnt pixels in the colour composite (R6 G2 B1). These burnt areas are bright areas in the individual shade fraction images. The results of multitemporal analysis with MODIS when compared with the DETER and PRODES (http://www.obt.inpe.br/prodes/index.html) datasets indicate that 6500 km^2 of land surface was burnt in Acre State in late 2005. Of this, 3700 km^2 corresponded to the previously deforested areas, and 2800 km^2 corresponded to the forested areas (figure 5). This method can also help monitor the burnt areas over a short time period.

Brown *et al.* (2006b) used Landsat-5 TM and CBERS 2 imagery from October 2005 to estimate the area of forests affected by fires for eastern Acre State. They observed >2670 km^2 of forests affected by fires with omission errors of 29% dominating commission errors of 4%, using aerial photography for validation. The

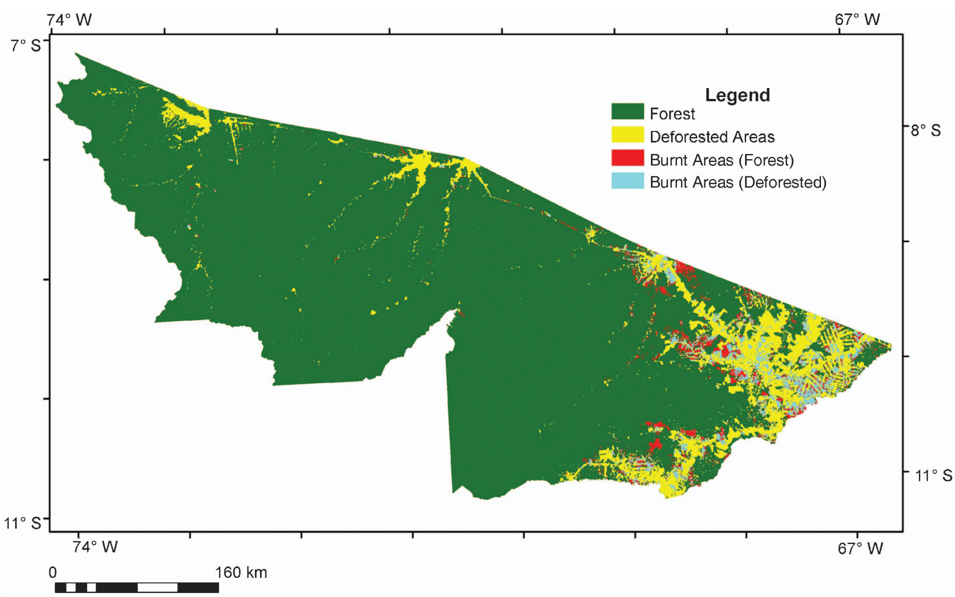

Figure 5. Land-cover classification of Acre State derived from multitemporal MODIS data. The classes mapped are: forest, deforested, and burnt areas.

observed total area is consistent with the estimate from the MODIS imagery, however, large compensating omission and commission errors resulted in this close approximation. While the combination of Landsat/CBERS images can provide more accurate estimates of burnt area than the method using MODIS images described here, the Landsat/CBERS approach required a much greater investment in operator time and was dependent upon relatively infrequent imagery—a 16- and 26-day repeat cycle for Landsat 5 and CBERS 2, respectively—that can be problematic in cloud-abundant, lowland Amazonia. Figure 6 shows the classification of burnt areas using MODIS and Landsat TM shade fraction images. It can be observed a good qualitative agreement between both classifications. The difference of area estimation between the classifications is due to the spatial resolution (30 m and 250 m for TM and MODIS, respectively) of the sensors utilized in this study.

Timely information is critical for evaluation of impacts of disasters, such as the extensive burnt open areas and fire-impacted forests that occurred in 2005 in eastern Acre State. The potential for MODIS imagery to provide nearly real time estimates of burnt areas in tropical forest regions will become increasingly important if predictions of greater climate variability, particularly of droughts, leading to savannization become reality (Salazar *et al.* 2007).

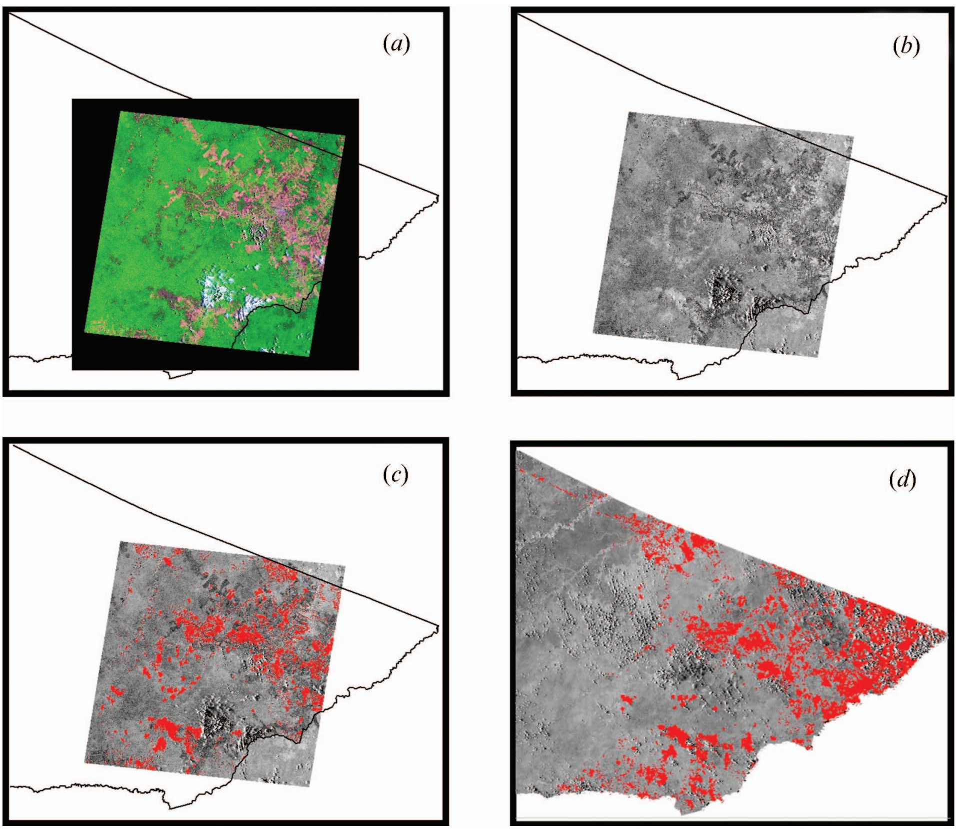

Figure 6. Burnt areas derived from MODIS and Landsat-TM shade fraction images: (*a*) R5 G4 B3 colour composite of TM acquired on 13 October 2005; (*b*) shade fraction image derived from TM highlighting the burnt areas (bright pixels); (*c*) burnt areas (red colour) over the TM shade fraction image; and (*d*) burnt areas (red colour) derived from MODIS multitemporal images over MODIS shade fraction mosaic.

5. Conclusions

The method described in this paper can be used to digitally classify burnt areas in Terra MODIS images of the Amazonian region. The increase in shade proportion present in a forested pixel provides the information to detect the effects of fire on the forest canopy. Similarly, the increase in shade proportion in a grassland pixel indicates the effects of fire over deforested areas. The results of multitemporal analysis with MODIS showed that 6500 km^2 of land surface were burnt in Acre State in 2005. Of this, 3700 km^2 corresponded to the previously deforested areas, and 2800 km^2 corresponded to the forested areas. This information is critical for regional and global environmental studies and for efforts to control such burning in the future. The results demonstrated that MODIS sensor daily data are important sources of timely information for mapping burnt areas and can be used at the regional level in Brazilian Amazonia. The map of burnt areas produced with good total accuracy by the proposed method will be useful for evaluating the future MODIS burnt areas product that will be delivered by the MODLAND Group. The next step of this research is to apply the proposed method for the entire Amazonia as part of DETER (http://www.obt.inpe.br/deter/) and PANAMAZONIA (http://www.dsr.inpe.br/panamazon.htm) projects developed at the Brazilian Institute for Space Research (INPE).

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