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Assessment of tropical forest degradation by selective logging and fire using Landsat imagery

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ABSTRACT

Many studies have assessed the process of forest degradation in the Brazilian Amazon using remote sensing approaches to estimate the extent and impact by selective logging and forest fires on tropical rain forest. However, only a few have estimated the combined impacts of those anthropogenic activities. We conducted a detailed analysis of selective logging and forest fire impacts on natural forests in the southern Brazilian Amazon state of Mato Grosso, one of the key logging centers in the country. To achieve this goal a 13-year series of annual Landsat images (1992–2004) was used to test different remote sensing techniques for measuring the extent of selective logging and forest fires, and to estimate their impact and interaction with other land use types occurring in the study region. Forest canopy regeneration following these disturbances was also assessed. Field measurements and visual observations were conducted to validate remote sensing techniques. Our results indicated that the Modified Soil Adjusted Vegetation Index aerosol free ($MSAVI_{af}$) is a reliable estimator of fractional coverage under both clear sky and under smoky conditions in this study region. During the period of analysis, selective logging was responsible for disturbing the largest proportion (31%) of natural forest in the study area, immediately followed by deforestation (29%). Altogether, forest disturbances by selective logging and forest fires affected approximately 40% of the study site area. Once disturbed by selective logging activities, forests became more susceptible to fire in the study site. However, our results showed that fires may also occur in undisturbed forests. This indicates that there are further factors that may increase forest fire susceptibility in the study area. Those factors need to be better understood. Although selective logging affected the largest amount of natural forest in the study period, 35% and 28% of the observed losses of forest canopy cover were due to forest fire and selective logging combined and to forest fire only, respectively. Moreover, forest areas degraded by selective logging and forest fire is an addition to outright deforestation estimates and has yet to be accounted for by land use and land cover change assessments in tropical regions. Assuming that this observed trend of land use and land cover conversion continues, we predict that there will be no undisturbed forests remaining by 2011 in this study site. Finally, we estimated that 70% of the total forest area disturbed by logging and fire had sufficiently recovered to become undetectable using satellite data in 2004.

1. Introduction

In recent decades, the logging of high-value tree species has became an important land use of tropical evergreen forests in Central Africa (Laporte et al. 2007) and in the Brazilian Amazon (Stone & Lefebvre, 1998; Nepstad et al., 1999; Alvarado & Sandberg, 2001). However, until the 1960s most of this logging in Brazil was restricted to flood plains (*várzeas*) in areas flooded annually. This situation changed drastically after the widespread construction of roads during the 1960s and 1970s which allowed the expansion of selective logging into the inter-fluvial (*terra-firme*) forests in the Brazilian Amazon (Uhl & Vieira, 1989; Uhl et al., 1997).

As a result of the increased access provided by roads, selective logging became a major concern in the Brazilian Amazon due to its potential negative effect on natural forests. Selective logging is a form of timber extraction of a group of trees from selected species where only the most valuable tree species are removed from the forest. Selective logging operations usually leave behind a complex landscape comprised of intact forest, treefall gaps, roads, log-loading patios, and

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damaged forest (Verissimo et al., 1995; Uhl et al., 1997; Laporte et al., 2007). In addition, logging activities increase the amount of dead slash or dried biomass (fuel) and, consequently, forest fire susceptibility is substantially increased (Uhl & Buschbacher, 1985; Stone & Lefebvre, 1998; Nepstad et al., 1999; Souza & Barreto, 2000). Therefore, the impacts caused by logging in tropical forests are significant both in terms of forest degradation and fire susceptibility (Uhl & Buschbacher, 1985; Stone & Lefebvre, 1998; Nepstad et al., 1999; Souza & Barreto, 2000). Selectively logged forests often become highly degraded and usually have 40–50% of their canopy cover removed during logging operations (Uhl & Vieira, 1989; Verissimo et al., 1992). Accordingly, forest fires have increased in the Brazilian Amazon, and became very common in fragmented forests located adjacent to deforested areas, which serve as ignition sources for forest fires (Uhl & Kauffman, 1990; Cochrane & Schulze, 1998; Cochrane, 2001; Cochrane et al., 2004).

Meanwhile, most studies based on remotely sensed data to estimate forest impacts of selective logging in the Brazilian Amazon have relied on study sites mostly located in Eastern Pará, Brazil. For example, Souza and Barreto (2000) used a linear mixture model and Landsat imagery to detect logging patios within selectively logged forests in a study site in the state of Pará, Brazil. Additionally, Cochrane and Souza Jr. (1998) developed a remote sensing technique to detect and classify burned forests using non-photosynthetic vegetation derived from Linear Mixture Analysis for a study site in Tailândia, Pará. Furthermore, Cochrane and Sousa Jr. (1998) and Cochrane et al. (1999) used field studies and a multi-temporal analysis of remotely sensed imagery to understand forest fire dynamics in another study site in Pará. Finally, Souza et al. (2003) developed a methodology to map classes of degraded forest for a case study in Pará using fraction images (vegetation, non-photosynthetic vegetation, soil, and shade) derived from spectral mixture models.

Asner et al. (2002) applied Landsat textural analysis to assess forest canopy damage from selective logging in yet another study site in the state of Para, Brazil. Based on those study results, the authors concluded that although this technique was useful for broad delineation of forests impacted by selective logging, it could not appropriately estimate the extent of canopy damage.

More recently, Souza et al. (2005a) conducted an evaluation of different vegetation and infrared indices and fraction images derived from spectral mixture analysis to assess multi-temporal forest degradation within nineteen transects in the eastern Brazilian Amazon, whilst Matricardi et al. (2005) estimated areas of selectively logged forests using Landsat imagery and fieldwork measurements for a study site in the Brazilian state of Mato Grosso. Souza et al. (2005b) developed a remote sensing approach based on Spectral Mixture Analysis (SMA) to map selectively logged and burned forests for a case study in the state of Mato Grosso.

Asner et al. (2005) also developed an automated remote sensing technique to map degraded forests by selective logging in the five major timber center states of the Brazilian Amazon. The authors used Landsat ETM+ imagery from 1999 to 2002 and the Camegie Landsat Analysis (CLAS) based on atmospheric modeling and spatial pattern analysis to detect forests impacted by selective logging in their study area. By using the CLAS, they were able to classify forests degraded by selective logging on the Landsat imagery with 86% overall accuracy. That study did not include, however, any assessment of forest degradation by forest fires.

These previous studies have contributed to substantial improvements in remote sensing based techniques to assess both extent and impacts caused by selective logging and forest fires. However, a more comprehensive assessment of forest disturbances by forest fire and selective logging and their interactions with other land use and land cover processes is still lacking. Moreover, atmospheric changes caused by smoke from deforested and forested areas have limited multi-temporal analysis using remotely sensed data (Karnieli et al., 2001; De Moura & Galvão, 2003). This research intended to measure extent and to assess impacts of selective logging and forest fire on tropical rain forests using Landsat imagery. Therefore, we conducted a detailed multi-temporal analysis of these impacts on natural forests in the Southern Amazon State of Mato Grosso, one of the major logging centers in Brazil. It included field observations, statistical tests on performances of different vegetation indices and green vegetation fraction (GV) derived from SMA to assess forest canopy degradation in the presence of smoke, and development of a modified vegetation index more resistant to atmospheric conditions in the study site.

2. Methodology

2.1. Study site

This research was conducted using one Landsat scene (path 226 and row 068) that encompassed approximately 30,000 km^2 in the state of Mato Grosso, located in the southern Brazilian Amazon (Fig. 1). The study area included the *municípios* of Santa Carmem and União do Sul and parts of the municípios of Colider, Feliz Natal, Itaúba, Marcelândia, Nova Ubiratã, Paranatinga, Sinop, Sorriso, and Vera, which combined form a territory known as the Sinop region.

The climate in the study area is humid tropical with very distinct dry and wet seasons that extend from June through September, and from December through March, respectively. The average annual precipitation and temperature is 2000 mm and 26 °C, respectively (RADAMBRASIL, 1980). Prior to modern colonization, spurred by the Brazilian Federal Government in the 1970s, the study area was mostly covered by transitional forests, a semi-deciduous forest type, with emergent canopy. However, by 2004 approximately 8500 km^2 of native forest had been converted into extensive soybean plantations and grazing areas. Nonetheless, the Sinop region still is a major timber center in the Amazon in spite of persistent high annual deforestation rates.

2.2. Dataset

2.2.1. Land use and land cover dataset

Multi-annual land use and land cover GIS (Geographic Information System) layers for 1992 through 2004, produced by the Global Observatory for Ecosystem Services (GOES) at Michigan State University for the Landsat path 226 and row 068, were used in this analysis. These layers were generated via standard unsupervised classification of Landsat TM and ETM+ imagery, and subsequent manual editing using GIS. Each layer included seven classes of land use (forest, deforestation, secondary regrowth, savannah, cloud, shadow, and water body). Layers and Landsat imagery were projected in UTM projection, Zone 21 South, Datum and Spheroid WGS84. Since there was no quantitative accuracy assessment of this dataset, we conducted a visual inspection on each GIS layer and Landsat image edited any observed misclassification of the forest and non-forest classes, which were easily distinguished in this analysis. Multiple non-forest land use and land cover classes were lumped together to create a forest and non-forest mask. This masking procedure was performed to separate forested areas, degraded or not, on each Landsat image. Forest masked images were subsequently used to detect selectively logged and burned forests.

In addition, cumulative cloud and shadow layers for the period of analysis were also masked out of all Landsat images, which provided a common area of analysis. However, forested areas affected by smoke, visible on bands 4, 5, and 7, were not masked out.

2.2.2. Selective logging dataset

Selective logging GIS layers previously presented by Matricardi et al. (2005) were used. Matricardi et al. (2005) used semi-automated (texture algorithm) analysis of Landsat band 5 to detect log landings (log storage patios). Subsequently, Matricardi and his colleagues also