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An integrated remote sensing and GIS approach for monitoring areas affected by selective logging: A case study in northern Mato Grosso, Brazilian Amazon

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ABSTRACT

Forest cover disturbances due to processes such as logging and forest fires are a widespread issue especially in the tropics, and have heavily affected forest biomass and functioning in the Brazilian Amazon in the past decades. Satellite remote sensing has played a key role for assessing logging activities in this region; however, there are still remaining challenges regarding the quantification and monitoring of these processes affecting forested lands. In this study, we propose a new method for monitoring areas affected by selective logging in one of the hotspots of Mato Grosso state in the Brazilian Amazon, based on a combination of object-based and pixel-based classification approaches applied on remote sensing data. Logging intensity and changes over time are assessed within grid cells of 300 m × 300 m spatial resolution. Our method encompassed three main steps: (1) mapping forest/non-forest areas through an object-based classification approach applied to a temporal series of Landsat images during the period 2000–2015, (2) mapping yearly logging activities from soil fraction images on the same Landsat data series, and (3) integrating information from previous steps within a regular grid-cell of 300 m × 300 m in order to monitor disturbance intensities over this 15-years period. The overall accuracy of the baseline forest/non-forest mask (year 2000) and of the undisturbed vs disturbed forest (for selected years) were 93% and 84% respectively. Our results indicate that annual forest disturbance rates, mainly due to logging activities, were higher than annual deforestation rates during the whole period of study. The deforested areas correspond to circa 25% of the areas affected by forest disturbances. Deforestation rates were highest from 2001 to 2005 and then decreased considerably after 2006. In contrast, the annual forest disturbance rates show high temporal variability with a slow decrease over the 15-year period, resulting in a significant increase of the ratio between disturbed and deforested areas. Although the majority of the areas, which have been affected by selective logging during the period 2000–2014, were not deforested by 2015, more than 70% of the deforested areas in 2015 had been at least once identified as disturbed forest during that period.

1. Introduction

Forest degradation is a pervasive environmental issue, especially in the tropics, which together with deforestation have important impacts on biodiversity and human well-being, and significant contribution to greenhouse gas emissions (Thompson et al., 2013). In the Brazilian Amazon (BA), the world's largest expanse of tropical forest, forest areas have been significantly impacted by forest degradation due to different anthropogenic forest disturbance processes such as selective logging, forest fires and forest fragmentation (Souza, 2013). It has been estimated that the area of forest affected by selective logging in the BA is as high as the area of deforestation, representing additional harm not addressed in deforestation studies (Asner et al., 2005). In fact, degraded forests (either by fire or logging) identified by INPE's DEGRAD system (INPE, 2008) were almost twice the area of deforestation in the period of 2007–2013 (Aguiar et al., 2016).

Despite the economic importance of the logging industry (e.g. generating revenues and jobs) and the potential it has as renewable resource, logging activity in the Brazilian Amazon has resulted in substantial ecological damage due to the high volume of extraction, poor management practices, and very often illegal (unplanned) activities (Asner et al., 2009). Mapping forest areas affected by these

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anthropogenic disturbance processes (like selective logging) is the first step to understand forest changes leading to degradation. Plenty of definitions for forest degradation and degraded forest have been proposed (Lund, 2009); however, a common definition is still under debate. In this research, we are mainly concerned with human-induced disturbances (e.g. tree harvesting, road construction) causing a change process that can negatively affect the forest functioning and lead to long-term forest degradation (FAO, 2011).

Knowing where and how changes are happening allows for tackling the problem, supporting planning and protective measures and proposing reduction targets, especially within the context of incentive mechanisms such as REDD+ (Reduction of Emissions from Deforestation and Forest Degradation). Consequently, reliable information about the extent of forest cover disturbances is highly needed (FAO, 2011).

Remote sensing products have been a key source of information for monitoring land cover changes in the past decades (Lunetta et al., 2002). Moreover, these products can be considered as the single feasible way of consistently monitor changes in forest cover over time for large geographical regions (Shimabukuro et al., 2014). In the Brazilian Amazon, according to Souza (2013), remote sensing has been used for mapping selective logging, from local to regional scales, and the approaches range from visual interpretation to automated techniques. The author also highlights the differences in possible mapping goals, for instance mapping the total area affected by logging (which includes canopy damaged areas, cleared areas or logging infrastructure, and portions of intact forest), or mapping damaged areas only. Examples of studies using visual interpretation include Watrin and Rocha (1992) and Stone and Lefebvre (1998). A technique often applied in the BA is the Spectral Mixture Analysis (SMA), which is used to enhance the detection of selective logging areas and to deal with the problem of heterogeneous land cover in these environments, especially for medium resolution images such as Landsat (Souza, 2013). Examples for the usage of SMA include Souza and Barreto (2000), Anwar and Stein (2012), and Asner et al. (2004). Souza et al. (2005) proposed a new index based on SMA called Normalized Difference Fraction Index (NDFI), for detecting forest canopy damage due to selective logging or forest fires. This index has been used e.g. by the Mato Grosso State government for mapping logging areas for the 2012–2013 period based on visual interpretation of the NDFI images (SEMA-MT, 2015). Other studies have applied SMA in combination with GIS techniques (buffering), such as Souza and Barreto (2000), Monteiro et al. (2003) and Matricardi et al. (2005). Asner et al. (2005, 2006) used the Carnegie Landsat Analysis System (CLAS) an automated method based on SMA and pattern recognition for assessing forest disturbances for large areas of the Brazilian Amazon. A recent study by Pinheiro et al. (2016) used data mining techniques and cell approach for classifying forest degradation patterns based on a defined forest degradation typology and landscape metrics. Object-based image analysis is a method, which has rarely been applied in this region for mapping selective logging (e.g. Monteiro et al., 2007). The Brazilian National Institute for Space Research (INPE) has estimated forest degradation for the Brazilian Amazon since 2007 through a visual interpretation procedure as part of the DEGRAD project (Forest Degradation Mapping in the Brazilian Amazonia); however mainly areas heavily disturbed (by selective logging and/or fire) with a tendency to be cleared were considered (INPE, 2008). Most of the remote sensing based research, regarding the mapping of logged forests in this region, used Landsat imagery, which is indicated currently as the most feasible data, considering that it is cost-free and regularly acquired (Souza, 2013). Finer resolution images (e.g. IKONOS) can enhance the detection of selective logging but have considerable cost and computational constraints (Asner et al., 2009). It is expected that the availability of time series of finer spatial resolution data such as Sentinel-2 (10 m × 10 m spatial resolution) will improve the assessment of logging areas. However, even using visual interpretation and finer resolution images, defining the boundaries of logged areas is not trivial (Souza, 2013).

Despite many initiatives for assessing selective logging in the BA, mapping the areal extent of logged forests using remote sensing imagery is still reported as a challenge (Asner et al., 2009) especially because of (1) the highly dynamic spatial–temporal patterns of logging activities, which can be detected by remote sensing only for a limited amount of time due to rapid canopy closure after the logging events (Asner et al., 2009), (2) the complexity of these forest environments, encompassing green vegetation, dead trees, bark, bare soil (Souza, 2013), (3) the occurrence of logging associated with other processes, such as forest fires (Souza, 2013), and (4) the fact that logging activities show different intensities and patterns, depending on logging techniques used and on how the activity is performed (planned/unplanned), amongst others. Moreover, the lack of a consensus definition has hampered forest degradation mapping and monitoring in general (Thompson et al., 2013).

In this context, our main goal was to investigate the annual changes in forest areas due to forest disturbance processes (mainly selective logging) in the Brazilian Amazon from a Landsat multi-temporal dataset over a 15-year period. For this aim, we propose a new method based on fraction images and GIS techniques, which allows to map and monitor forest disturbances due to selective logging. Our method can concomitantly assess deforestation and could be later adapted to integrate other forest disturbance processes such as fire.

2. Study area

The study area (Fig. 1) is located in the central-northern part of Mato Grosso State, within the Amazon biome (IBGE, 2004). The size of this area is c. 55 km × 111 km and corresponds to a subset of a Landsat scene (path/row 226–68). For investigations of forest cover changes, Mato Grosso is a key state of the Brazilian Amazon with very high deforestation rates and high occurrence of areas affected by forest disturbances (INPE, 2008). The selected study area is among the main timber production centers of Mato Grosso and encompasses parts of municipalities which hold very high occurrence of illegal logging for the 2012–2013 period such as Marcelândia, União do Sul e Santa Carmem (SEMA-MT, 2015). The forests in this area are described as transitional forest or ecotone areas between ombrophilous and seasonal forests (IBGE, 2004).

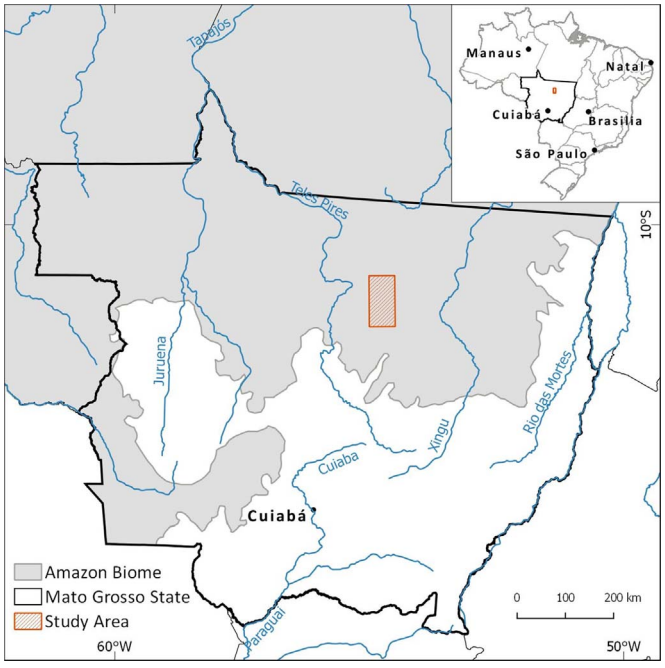

Fig. 1. Location of the study area in the Brazilian Amazon biome and Mato Grosso State.