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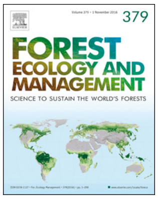

Dynamics of forest fires in the southwestern Amazon

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ABSTRACT

The synergism between climatic change and human action has provided conditions for the occurrence of forest fires in the Amazon. We used annual mapping to reconstruct the history of fire in Brazil's state of Acre to understand the forest-fire regime over a period of 33 years (1984–2016). The burn-scar index (BSI) derived from the fractions of soil and of photosynthetic and non-photosynthetic material was generated by CLASlite© software using Landsat-TM and OLI satellite images. The area of forest-fire scars totaled 525,130 ha in the period analyzed. This total includes forests that fire affected only once (388,350 ha), twice (59,800 ha) and three times (5727 ha). The years 2005 and 2010 represent 90% of the total area of forest fires in Acre, coinciding with severe droughts caused by the anomalous warming of the tropical North Atlantic Ocean. The most heavily impacted portion of Acre was in the eastern part of the state, which has the greatest forest fragmentation, consolidation of agricultural activity and presence of settlement projects. In 2005, the municipalities of Acrelândia, Plácido de Castro and Senador Guiomard accounted for more than 50% of the forest remnants impacted by fire. Of the total extent of forest fires in Acre, 43% occurred in settlement projects administered by the National Institute for Colonization and Agrarian Reform (INCRA) and 16% in conservation units administered by the Ministry of Environment (MMA). The area of forest fires was 36 times greater in the 16 years after 2000, compared to the 16 years before 2000. The frequency of fires increased dramatically from one fire episode roughly every ten years (period from 1984 to 2004), to one fire every five years (period from 2005 to 2016). With the projections of warmer climate and advancing deforestation, the forest fires in Acre will tend be more intense and frequent.

1. Introduction

Forest fires and logging have stood out as the principal causes of forest degradation in the Amazon in recent years (Aragão and Shimabukuro, 2010; Barlow et al., 2016; Bowman et al., 2009; Cochrane and Barber, 2009; Trumbore et al., 2015). Souza et al. (2013) estimated that forest degradation each year represents an area 30% the size of the area deforested annually area in Brazilian Amazonia as a whole.

The normal conditions of the Amazonian climate, with high humidity and rainfall, do not favor the occurrence of natural fires (Fernandes et al., 2011). The Amazon experienced mega El Niño events accompanied by large fires at intervals ranging from 300 to 500 years from 1800 to 400 BP (Bush et al., 2008; Meggers, 1994). However, in recent years the synergism between climatic extremes and human action has provided conditions for the occurrence of large forest fires at much shorter intervals than in the past (Aragão and Shimabukuro, 2010; Cochrane and Barber, 2009; Lewis et al., 2011). Over the past 40 years, forest-fire peaks have occurred every 4–5 years in different parts of the basin (Alencar et al., 2004; Aragão et al., 2018; Silva et al., 2013; Vasconcelos et al., 2013; Xaud et al., 2013).

Vulnerability of Amazonian forests to fires, as well as the spatial and temporal distributions of the fires, have been associated with extreme droughts caused by anomalous increases in sea-surface temperature in the Pacific in the case of El Niño and in the tropical North Atlantic in the case of the Atlantic dipole. The northern and northeastern portions of Brazilian Amazonia are most affected by El Niño (Alencar et al., 2004; Chen et al., 2013; Fearnside, 1990; Schroeder et al., 2009). In the southern and southeastern portions of Amazonia, extreme drought is often associated with warming the surface of the tropical portion of the North Atlantic Ocean (Aragão et al., 2018, 2007; Chen et al., 2013; Marengo et al., 2008; Zeng et al., 2008). There is also a combination of

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these two types of anomalous warming that has an impact throughout the Amazon, as in 1982–83, 1997–98, 2009–10 and 2015/2016 (Aragão et al., 2018; Marengo and Espinoza, 2016).

Mapping forest-fire scars in the Amazon allows integration of temporal resolution with the geographical context of the fire. Alencar et al. (2011) mapped such scars over a 23 year period at a fine spatial resolution (30-m pixels). Morton et al. (2013) monitored forest fires over a period of 13 years in southern Amazonia, but with low spatial-resolution images (250-m pixels). Mapping using political boundaries of states, which represents the level at which decisions to control and prevent deforestation and fires are taken, has been done in a few studies for specific years: Acre in 2005 (Shimabukuro et al., 2009), Mato Grosso in 2010 (Anderson et al., 2015) and Roraima in 1997/98 (Barbosa and Fearnside, 1999; Barni et al., 2015). There has been an evolution in the validation and calculation of uncertainty, which has been possible thanksto the increasing number of mappings of forest fires in Amazonia (Anderson et al., 2017; Foody, 2008; Mack et al., 2014; Padilla et al., 2014).

Acre was the epicenter of the severe droughts of 2005 and 2010 (Lewis et al., 2011) that provided conditions for large forest fires. However, no historical analysis has been done with mapping of areas impacted by forest fires, their frequency and recurrence, and the relationship with human activity and extreme droughts. The objective of this study was to analyze the extent and characterize the spatial and temporal dynamics of forest fires in the state of Acre in the southwestern portion of the Brazilian Amazon. Our study was intended to answer the following questions: (1) What was the extent of forest fires over a period of 33 years? (2) What extreme drought type had the greatest influence on the occurrence of forest fires, years of El Niño or of warm surface water in the tropical North Atlantic? (3) What is the relationship between deforestation and forest fires? and (4) What is the spatial distribution of fires between municipalities and land-tenure types?

2. Data and methods

2.1. Study area

Our analysis covers the entire state of Acre (Fig. 1). Acre is at the western end of the “arc of deforestation” an area that extends from Paragominas, Pará to Rio Branco, Acre; this area is connected by highways and is the location of most deforestation in the Brazilian Amazon (Fearnside, 2005). In Acre, the agricultural frontier is expanding between the municipalities of Rio Branco and Cruzeiro do Sul along Highway BR-364 and in the northern portions of the municipalities of Porto Acre and Sena Madureira, which border on the state of Amazonas.

2.2. Mapping of forest fires based on Landsat satellite data

Forest fires were defined in this study as those in which the crowns of the trees were directly or indirectly affected by fire to the point that they cause a detectable impact on the optical satellite images, representing the scar left by the fire. Many fires were probably not detected because they were not strong enough to reach the canopy, affecting only the understory of the forest.

To identify forest-fire scars in the state of Acre we used Landsat 5 TM (Thematic Mapper), Landsat 7 ETM + (Enhanced Thematic Mapper Plus) and Landsat 8 OLI (Operational Land Imager) satellite images from 1984 to 2016. The images were accessed without cost on the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov/). The dates of the images used for processing are from September to December. Images were used from March to June for years with cloud problems or with very large fires in order to map the fire events in their totality (Supplementary Material, Table S1 and Fig. S1).

Image processing was performed using CLASlite 3.0 free software, a compact version of the Carnegie Landsat Analysis System (CLAS). This software uses a spectral-mixing model associated with a robust spectral library to generate fractions that represent the main biophysical components of the landscape in a pixel (Asner et al., 2009). The gross images in DN (digital number) were automatically corrected radiometrically for atmospheric effects and transformed into reflectance (Fig. 2a).

Fraction images were derived from the linear spectral mixing model. The following fractions were identified: photosynthetically active vegetation (PAV), non-photosynthetic vegetation (NPV) and soil (S). Based on the fraction images (Fig. 2b), the burn-scar index (BSI) (Fig. 2c) was applied following Alencar (2010), as in Eq. (1).

$$\mathrm{BSI} = (\mathrm{PAV}-\mathrm{NPV})/(\mathrm{PAV} + \mathrm{NPV}) \tag{1}$$

In order to analyze only forested areas and reduce errors of commission, a deforestation mask was applied year-by-year to the images used to calculate the BSI. This reduces the interpositions of the NPV fraction between deforested areas and forest-fire areas, mainly where the fire was intense.

For the years 1997–2016 a deforestation mask was applied with data from the PRODES program of INPE (National Institute for Space Research), which monitors Brazil's Amazon rainforest annually (Brazil, INPE, 2016). For the period from 1984 to 1986 the image interpretation for deforestation was done by manual editing. Local knowledge of an interpreter is necessary in order to avoid commission errors with specific punctual events, such as blowdowns, vegetation under extreme water stress and senescent bamboo populations in open forests (Carvalho et al., 2013; Espírito-Santo et al., 2014; Nelson et al., 1994) (Supplementary Material, Fig. S2).

We obtained the final product for forest-fire mapping by the BSI image-slicing method, subjectively defining the thresholds by trial and error using the color composition of the reflectance images as a guide to identify forest-fire scars. For each scene we set an average of 10 thresholds, after which it was possible to standardize the threshold value for the scene. Silva et al. (2013) observed that there is no standard or fixed threshold for this identification, which changes from scene to scene according to fire intensity, vegetation contrast, and image noise. In this study, the average threshold in all years and scenes identified by slicing ranged from −0.15 to 0.4. In years of extreme drought the threshold ranged from −0.3 to 0.53, while in normal years the threshold ranged from −0.1 to 0.38.

After slicing the BSI image, a medium smoothing filter with a window of 5 × 5 pixels was applied to reduce the number of isolated badly classified pixels. The next step was to convert the raster map into a vector map for visual auditing, allowing deletion of poorly sorted polygons.

2.3. Validation of the mapping of forest fires

Remote sensing has been widely used for assessing the dynamics of land use, but field validation is indispensable in order to compare remotely sensed data with ground truth and estimate the margin of error. Validation of mapping in a large area like the state of Acre requires visiting a sufficient number of points in the field – a task that requires substantial financial resources. To supplement our field points we therefore used additional points at randomly selected locations on the images, and the classifications of these points were confirmed by experienced interpreters.

Validation in the field was performed for 139 points, and an additional 2500 random points were identified on the Landsat images (Fig. 3). Verification in the field was performed between 2015 and 2016; 22 points were checked in intact forest areas and 106 forest points were checked at locations mapped as forest-fire scars. In addition, 21 points were observed by Irving Foster Brown in overflights in 2005. Field observations determined whether charcoal was present at