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Variability of vegetation fires with rain and deforestation in Brazil's state of Amazonas

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ABSTRACT

Understanding the variability of fire events and their relationship to precipitation and changes in land use and land cover is essential in order to evaluate the susceptibility of Amazonian vegetation. Time series of hotspots, of deforested area and of rainfall (all derived from satellite data) were used to determine the temporal and spatial distributions of fire in Brazil's state of Amazonas in order to establish the seasonal patterns of each variable and interactions with biomass burning. From 2003 to 2012, 60% of the hotspots detected were in the southern part of the state, with high variability between different months and years. Between 95% and 99% of the hotspots were recorded during the period of greatest occurrence of burning (July to March) with peaks during the months of August, September and October (the months with the lowest precipitation), suggesting that fires in Amazonas are mainly initiated by humans. Deforestation activity occurs approximately three months before the start of the burning activity. The number of hotspots did not show a relationship with the area deforested but showed a strong inverse relationship with rainfall. There is marked seasonal and annual variability, with patterns changing over time. Over the last decade the hotspots detected in Amazonas are associated not only with changes in land use and cover, but also with the use of fire in managing deforested areas.

1. Introduction

Fire is an important agent of disturbance that influences climate and tropical ecosystems through its connection with land-use dynamics, atmospheric composition and the global carbon cycle (Morisette et al., 2005). Deforestation and burning of the forest dramatically reduces biodiversity and can cause a variety of environmental impacts, such as erosion and loss of soil fertility (Jain et al., 2008) and emission of gaseous pollutants (Longo et al., 2009). Forest fires from human activity severely affect the structure and floristic composition of tropical forests by reducing the number of individuals by 20% to 30% (Slik et al., 2002), reducing the diversity of plant species by 15% to 33% (Araújo et al., 2010), and reducing the percentage of canopy cover (Cochrane & Schulze, 1999). Effect on species composition can be observed even 15 years after a fire (Slik et al., 2002). The decline in the diversity of plant species leads to reduction in the availability of fruits and fauna, thus reducing the food supply that supports birds and other animals (Barlow & Peres, 2006). Studies in seven 0.25-ha (10 × 250 m) plots in *terra firme* (upland) forest in the Tapajós–Arapiuns Extractive Reserve in the state of Pará showed that forest fires dramatically increase the mortality of trees with ≤40 cm diameter at breast height (DBH, measured 1.3 m above the ground or above any buttresses) between 1 and 3 years after the fires (Barlow et al., 2002, 2003). Another study done in ten 0.2-ha plots affected by fire in 2005 in the Embrapa Community Forest Management Project in the municipalities of Senator Guiomard and Acrelândia (both in the state of Acre) indicated that tree mortality for this DBH range may reach 83% in the first year after the fire (2006) and 89% four years after the fire (2009) (Vasconcelos et al., 2013). In addition, recurrent fire events slow forest growth (Davidson et al., 2012). Burning of forests in areas that are being cleared for agriculture and livestock, forest fires and burning of secondary forests, pastures and different types of savannas substantially increase biomass losses and carbon emission to the atmosphere (Alencar et al., 2006; Fearnside, 2002). In years with El Niño-Southern Oscillation (ENSO) events, such as 1997–1998, committed carbon emissions due to forest fires in Brazilian Amazonia may reach 0.049 to 0.329 Pg C (1 Pg = 10^{15} g = 10^{9} tons) (Alencar et al., 2006). During extreme droughts in Atlantic-dipole events, as in 2005, the absolute committed loss of carbon due to decreased biomass from tree mortality caused by fires can reach 5.3% one year after the fire and 14.4% between one and four years after the fire (Vasconcelos et al., 2013).

The smoke emitted by burning and forest fires in the Amazon changes the physical properties of clouds and reduces precipitation (Ackerman et al., 2000; Andreae et al., 2004). The concentration of atmospheric aerosols increases (Artaxo et al., 2002; Davidson et al.,

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2012; Koren et al., 2007), as does their average residence time (Ramanathan et al., 2001). These aerosols have a significant negative impact on human health (Brown et al., 2006; Mendonça et al., 2004) and have been positively associated with morbidity (for example in respiratory diseases and in risk of low birth weight) and in mortality of different age groups (Castro et al., 2009; Ignotti et al., 2010; Prass et al., 2012).

The differences in the length and severity of the dry season in the Amazon region delineate distinct periods of increased flammability of the vegetation (Schroeder et al., 2005). The duration and the spatial location of burning events reflect the seasonal variation in rainfall and the presence of anthropogenic ignition sources (Cardoso et al., 2003). For example, during the 2005 drought, which was attributed to the anomalous peak in sea-surface temperature (SST) in the tropical North Atlantic Ocean that severely affected the southern region of the Amazon (Cox et al., 2008; Marengo et al., 2008), there was a dramatic increase of hotspots detected by satellites in the southern portion of the Amazon region (Aragão et al., 2008; Brown et al., 2006). "Hotspots" on a satellite image consist of the detection of the signal from the radiance of fire flames with temperatures of approximately 335 K in channel 21 and 330 K in channel 22 of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, whose emission peaks are situated in the mid-infrared region (3.929–3.989 μm) (Soares et al., 2007). The MODIS sensor is practically free of false detections (less than 0.01%) and can detect a fire front 30 m in length by 1 m or greater in width (INPE, 2013a). However, since the picture element (pixel) of this sensor is 1 km × 1 km for data available on a daily basis, a fire measuring only a few tens of m^2 can be identified as occupying 1 km^2 under nadir conditions and up to 3 km^2 if viewed from other angles (e.g., INPE, 2013a). A hotspot can indicate a single small area of burning, several small fires, or one very large fire inside the pixel (França, 2004; INPE, 2013a). This means that a fire needs to occupy only a small fraction of the total area of the pixel to saturate the mid-infrared channel and thus be detected (Belward et al., 1993; Schroeder et al., 2009).

In recent decades, the number of polar-orbiting satellites with active-fire monitoring capacity has increased, thus increasing the capacity of organized civil society to delineate the variability and the spatial and temporal patterns of fire distribution in remote, hard-to-reach areas like the Amazon. Over the past two decades Brazil's National Institute for Space Research (INPE) has had an excellent system for monitoring fire, with results now freely available by Internet (http://www.inpe.br/queimadas). Data on hotspots have been used satisfactorily in monitoring fire events at local and regional scales (Aragão et al., 2008; Brown et al., 2006; França & Setzer, 2001; Morisette et al., 2005; Morton et al., 2008; Schroeder et al., 2005) and at the global scale (Giglio et al., 1999; Justice et al., 2002; Malingreau, 1990).

A large number of hotspots is detected by satellites annually in the tropics (Dwyer et al., 2000), primarily due to the widespread use of fire for land management in these regions. In Brazil, the highest numbers of hotspots detected every year are in *cerrado* (central Brazilian savanna) and in forest along the southern and eastern edges of the Amazon biome (Schroeder et al., 2005). This crescent-shaped region of forest is known as the "arc of deforestation" (also called the "arc of fire"). Information on the location and extent of instances of burning in deforested areas and of forest fires is important for defining strategies to control the use of fire and for real-time alerts that permit fighting and preventing fires. This information is also important in ecological and economic damage assessment and as an input to both climate models (Justino et al., 2011) and models of fire (Alencar et al., 2006; Nepstad et al., 2004; Silvestrini et al., 2011).

In the present study we used a time series of hotspots (2003 to 2012) derived from satellite data with the goal of determining the temporal and spatial distributions of fire events in Brazil's state of Amazonas. In addition, we used time-series data on precipitation and deforestation (2004 to 2012) to quantify seasonal patterns and to assess the influence of these variables on fire activity in the state.

2. Material and methods

2.1. Study area

The study was done in Brazil's state of Amazonas (Fig. 1). The state covers 1,559,161 km^2 and has an estimated 3,483,985 inhabitants, 21% of whom live outside of urban areas (IBGE, 2012). The southern part of the state of Amazonas has recently become part of the arc of deforestation.

2.2. Data on fire, precipitation and deforestation

Data on hotspots from MODIS Collection 5, which has higher radiometric accuracy than previous collections (Roy et al., 2008), were used to determine the temporal and spatial distribution of fire in the state of Amazon as during the period from 2003 to 2012. The MODIS sensor we used is carried aboard the NASA's AQUA satellite, which INPE has chosen as one of its "reference satellites" to produce daily data on hotspots. These data are used to compose a time series that extends over the years since 2002, thus allowing an analysis of trends in the number of hotspots in the regions and years of interest.

The data on hotspots generated by INPE are made available in near real time (approximately three hours after being generated) (INPE, 2013a). Over the ten years for which we analyzed fire data, the AQUA satellite maintained a stable time of passage: 16:38 to 19:00 Greenwich Mean Time (GTM) or 12:38 to 15:00 local time in Amazonas.

To determine the dry period in Amazonas (cumulative precipitation ≤100 mm/month) a time series was used for the period from January 2004 to December 2012, of the cumulative monthly precipitation (mm/month) derived from the MERGE product from INPE, which is the combination of observed precipitation data at meteorological stations that are reported on a regular basis by the Global Telecommunication System (GTS), Data-Collection Platforms (PCDs) and regional centers in Brazil with the data on precipitation estimated by the 3B42RT algorithm of the Tropical Rainfall Measuring Mission (TRMM) satellite. The validation of this dataset showed that the combination of TRMM results with observed data provided significant improvements in obtaining the precipitation field in a regular numerical grid for a region that has a low density of observations like the state of Amazonas (Vila et al., 2009). MERGE efficiently represents the main atmospheric systems that cause precipitation in Amazonia and throughout South America, making this the best available source of precipitation data reflecting the high spatial and temporal variation of this parameter (Marengo, 2005, 2006; Reboita et al., 2010).

The database of INPE's Detection of Deforested Areas in Real Time (DETER) project was used to quantify the cumulative monthly deforested area in km^2 from January 2004 to December 2012 (INPE, 2013b). In addition, the time series from 2003 to 2012 for the annual deforestation rate in km^2 was obtained through PRODES (Program for the Calculation of Deforestation in Amazonia) (INPE, 2013c). DETER uses MODIS (on NASA's TERRA satellite) and WFI (on the Chinese/Brazilian CBERS-2B satellite) data with high temporal frequency (two and five days). The availability of monthly data (http://www.obt.inpe.br/deter/), but with a limited spatial resolution of 250 m, only permits detection of completely deforested (clearcut) areas larger than 25 ha, as well as similar areas that reach a state of "deforestation" through a process of forest degradation. Additionally, not all clearings are identified by DETER because of the low resolution of the images and sensors used and because of the limitations imposed by cloud cover. PRODES uses data from the TM [Thematic Mapper] (LANDSAT satellite), DMC (Disaster Monitoring Constellation satellite) and CCD (CBERS satellite) sensors (and their successors for recent years) with high spatial resolution of 30 m that is degraded to 60 m in the database, but with low temporal frequency. PRODES measures the annual rate of deforestation by clearcutting, detecting clearings of at