Ecological Indicators 78 (2017) 270–281

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Drivers of fire occurrence in a mountainous Brazilian cerrado savanna: Tracking long-term fire regimes using remote sensing

Swanni T. Alvarado[a,b,*], Tamires Fornazari[a], Andresa Cóstola[a], Leonor Patricia Cerdeira Morellato[b], Thiago Sanna Freire Silva[a]

[a] Ecosystem Dynamics Observatory, Universidade Estadual Paulista (Unesp), Instituto de Biociências, Phenology Laboratory, Rio Claro, Av. 24A, 1515, Rio Claro, SP, 13506-900, Brazil

[b] Phenology Laboratory, Universidade Estadual Paulista (Unesp), Instituto de Biociências, Campus Rio Claro, Av. 24A, 1515, Rio Claro, SP, 13506-900, Brazil

ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form
25 November 2016
Accepted 24 February 2017
Available online 27 March 2017

Keywords:
Burned area
Seasonality
Fire frequency
Ignition season
Moisture limitation
Fuel limitation
Biomass

ABSTRACT

Fire is a natural disturbance in savannas, and defines vegetation physiognomy and structure, often influencing species diversity. Fire activity is determined by a wide range of factors, including long and short term climatic conditions, climate seasonality, wind speed and direction, topography, and fuel biomass. In Brazil, fire shapes the structure and composition of cerrado savannas, and the impact of fire on vegetation dynamics is well explored, but the drivers of variation in fire disturbance across landscapes and over time are still poorly understood. We reconstructed 31 years of fire occurrence history in the Serra do Cipó region, a highly-diverse cerrado landscape, located in the southern portion of the Espinhaço mountain range, state of Minas Gerais, Southeastern Brazil. We mapped burn scars using a time series of Landsat satellite images from 1984 to 2014. Our questions were 1) How does fire occurrence vary in time and space across the Serra do Cipó cerrado landscape? 2) Which climatic drivers may explain the spatial and inter-annual variation in fire occurrence on this landscape? 3) Is fire occurrence in this cerrado landscape moisture-limited or fuel-limited? We evaluated the inter-annual variation and distribution of burned areas, and used linear models to explain this variation in terms of rainfall amount (determinant of fuel load production), seasonal rainfall distribution (determinant of dry fuel availability), abnormality of precipitation (Standardized Precipitation Index – SPI), and vegetation type (Enhanced Vegetation Index – EVI). Contrary to our expectations, annual rainfall volume was weakly and negatively correlated with burned area, and the strongest predictor of burned area was drought during the ignition season. The length of the dry season and the distribution of rain along the season determined ignition probability, increasing fire occurrence during the driest periods. We conclude that the mountain cerrado vegetation at Serra do Cipó has a moisture-dependent fire regime, in contrast to the fuel-dependent fire regimes described for African savannas. These findings imply that savannas at different continents may have different recovery and resilience capabilities when subjected to changes in the fire regime, caused by direct anthropogenic activities or indirectly through climatic changes. The possible effects of these changes on cerrado landscapes are still unknown, and future studies should investigate if currently observed fire regimes have positive or negative impacts on vegetation diversity, recovery, resilience and phenology, thus helping managers to include fire management as conservation measure.

1. Introduction

Savannas are characterized by a continuous grass layer with scattered trees and shrubs, growing under hot and seasonally dry climatic conditions. Covering 20% of the terrestrial surface, savannas are present in Africa, Asia, Australia and South America (White et al., 2000). The structure and diversity of savanna vegetation are determined by the interaction of moisture availability, soil fertility, temperature, and an equilibrium between the proportion of woody and grass biomass and the fire regime (Lehmann et al., 2014). Fire is a natural disturbance in savannas, and is considered the key component in defining their physiognomy and structure, influencing species abundance and diversity (Bond et al., 2005; Bond and Keeley, 2005). Fire activity in savannas is determined by a wide range of factors, including long and short term climatic con-

* Corresponding author at: Ecosystem Dynamics Observatory, Universidade Estadual Paulista (Unesp), Instituto de Geociências e Ciências Exatas, Departamento de Geografia, Campus Rio Claro, Av. 24A, 1515, Caixa postal 178, Rio Claro, SP, 13506-900, Brazil.

E-mail address: swanni_ta@yahoo.es (S.T. Alvarado).

http://dx.doi.org/10.1016/j.ecolind.2017.02.037
1470-160X/

ditions, climate seasonality, short-term variations in wind speed and direction, topography, and fuel biomass (Cochrane and Ryan, 2009; Trollope et al., 2002). In all savannas across the world, these natural fire regimes have been increasingly altered by human activities, either through direct land use practices or indirectly through changes in climate (Archibald, 2016).

Annual rainfall seems to be one of the main drivers of inter-annual variability in fire occurrence, and is often one of the main input variables in predictive fire models (Aldersley et al., 2011; Archibald et al., 2009; van der Werf et al., 2008). In a gradient from mesic to arid ecosystems, fire activity can have predictable spatial patterns according to the interaction between climate conditions (moisture) and fuel availability (biomass) (Bradstock, 2010; Krawchuk and Moritz, 2011; Meyn et al., 2007; van der Werf et al., 2008). In biomass-rich areas, where fuel is always available for burning during the fire season, fuel moisture conditions rather than fuel amount represent the main limitation of fire activity (Krawchuk and Moritz, 2011). On savannas, fire activity is more complex and can vary across continents (Lehmann et al., 2014). In South America, where savannas are found in regions with up to 2500 mm of annual precipitation, fire activity is closely associated with climate seasonality (Lehmann et al., 2011). Conversely, African savannas usually receive less than 1000 mm of annual precipitation, and fire is less frequent (Lehmann et al., 2011) and associated with fuel biomass availability and connectivity (Krawchuk and Moritz, 2011).

In Brazil, the cerrado savannas originally covered an area of ~2 million km^2, corresponding to about 25% of the Brazilian territory (Durigan and Ratter, 2016). Recent estimates show that only 41% (~833 000 km^2) of the original cerrado cover still remain as native vegetation cover (Soares-Filho et al., 2014). Overbeck et al. (2015) estimate a loss of 92,712 km^2 of natural cerrado areas to agricultural uses, between 2002 and 2009, showing that current deforestation rates are still high, and increasingly leading to landscape fragmentation and loss of ecosystem function. The cerrado is currently one of the most threatened vegetation types in South America, with only 7% of its present cover under legal protection (Soares-Filho et al., 2014). These threats are mostly derived from direct human activities, especially from the dramatic changes in land use promoted by large-scale agriculture (soybean, rice, corn, and cotton monocultures), livestock ranging, and mineral extraction (Klink and Moreira, 2002; Overbeck et al., 2015). Recent research has underscored the importance of the cerrado, emphasizing its high diversity. Over 13,127 plant species have been recorded within this biome, on par with the 13,216 plant species reported for the Amazon region (Overbeck et al., 2015). Moreover, a high degree of endemicity has been observed for plants and animals (Silva and da Bates, 2002; Silveira et al., 2016).

In Brazil, fire shapes the structure and composition of cerrado vegetation (Coutinho, 1982; Loiola et al., 2010; Silva et al., 2013). Fire can affect the reproductive success of cerrado plant species by influencing seed germination (Fichino et al., 2016; Fidelis et al., 2016) and flowering (Fidelis and Blanco, 2014; Hoffmann, 1998), and also determines trait variability in cerrado plants (Dantas et al., 2012; Hoffmann et al., 2012a). Nevertheless, human-induced fire is considered one of the most significant threats to this ecosystem (Pivello, 2005). Changes in the natural fire regime can lead to increased woody encroachment (Hoffmann, 1999) and invasive grasses (Durigan et al., 2007; Gorgone-Barbosa et al., 2016), which in turn change fire behavior and increase their severity (Gorgone-Barbosa et al., 2013).

The role of fire as the main driver of vegetation dynamics in the Brazilian cerrado, maintaining the equilibrium between grasses and trees, has been demonstrated elsewhere (Dantas et al., 2013; Hoffmann et al., 2012b, 2009). However, studies of the drivers of temporal and spatial variation in fire occurrence have been limited to coarse global models, seeking to explain the drivers limiting savanna and fire occurrence across continents (Krawchuk and Moritz, 2011; Lehmann et al., 2014, 2011; van der Werf et al., 2008). Quantifying fine-scale and long-term changes in the temporal and spatial patterns of fire occurrence in the cerrado, and its attributes (intensity, seasonality, size, and return time), is therefore crucial for understanding the driving forces of changes in fire dynamics, and assist land management and conservation practices for cerrado landscapes.

Retrospective studies based on historical remote sensing have allowed the reconstruction of fire history on ecosystems for most parts of the world (Csiszar et al., 2004; Wittkuhn and Hamilton, 2010). Two basic types of information can be derived from remote sensing to estimate fire affected areas: a) the presence of active fires, using thermal remote sensing, and b) the identification of burn scars or burned areas, using optical data. The near-continuous Landsat data record, available since 1984 with a spatial resolution of 30 m and temporal resolution of ca. 16 days, offers the best trade-off between temporal coverage and spatial resolution, making it ideal for mapping fire scars in savanna landscapes from local to regional scales (Hudak and Brockett, 2004; Russell-Smith et al., 1997).

In the present study, we reconstructed 31 years of fire occurrence history in the Serra do Cipó region, a hyperdiverse mountainous cerrado landscape in Brazil, based on the spatial and temporal analysis of burn scars mapped using Landsat satellite images from 1984 to 2014. We also related observed fire frequencies to the possible drivers of fire occurrence in cerrado to explain fire patterns and their variation across time. Our questions were 1) How does fire occurrence vary in time and space across the Serra do Cipó cerrado landscape? 2) Which climatic drivers may explain the spatial and inter-annual variation in fire occurrence on this landscape? 3) Is fire occurrence in this cerrado landscape moisture-limited or fuel-limited?

2. Methods

2.1. Study area

We studied the area comprised by the Serra do Cipó National Park (SCNP) and the enclosing Morro da Pedreira Environmental Protection Area (MP-EPA), located about 100 km northeast of the city of Belo Horizonte, state of Minas Gerais, Brazil (Fig. 1). Both areas are usually referred together as “Serra do Cipó”, and comprise the southern portion of the Espinhaço range, the largest interior mountain range in Brazil (Giulietti, 1997). The SCNP has an area of 316.3 km^2, and was created in 1984. The MP-EPA has an area of 1001.1 km^2, and was created in 1990, to provide a buffer zone to the protected ecosystems within the park. Between 2002 and 2004, conservation policies resulted in the progressive reduction of livestock herding in the SCNP, culminating with a virtually livestock-free status in 2008 (França and Ribeiro, 2008).

The climate of the region is warm subtropical with dry winters and hot summers, and markedly seasonal. Average annual rainfall is ca. 1400 mm, with a rainy season ranging from 75 mm to 340 mm, from October to April (monthly rainfall >60 mm), and a dry season ranging from 7 to 32 mm, from May to September (monthly precipitation <40 mm) (ANA 2016). Average daily maximum and minimum temperatures are 33 °C and 28 °C for the hottest month (February) and 13 °C and 7 °C for the coldest months (July). The topography of the study area is rugged and predominantly mountainous, with elevations ranging from 750 m above sea level (a.s.l) to 1670 m a.s.l. (Ribeiro and Figueira, 2011).

Within the SCNP and MP-EPA, vegetation occurring below 900 m altitude includes a mosaic of forest-like formations (“Cerradão”), lowland cerrado vegetation with varying proportions of herbaceous and woody cover (“Cerrado *sensu stricto*”, “Campo Cerrado” and