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How can we advance the knowledge on the behavior and effects of fire in the Cerrado biome?

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ABSTRACT

The indiscriminate use of fire represents one of the most significant environmental threats to the Cerrado, the second largest biome in South America. However, the impacts of fire on ecological, cultural, and economic processes remain poorly understood, making it difficult to create effective action plans for fire prevention, control, or management.

We extensively reviewed the literature on fire behavior and effects in the Cerrado biome to identify current knowledge gaps and ways to advance research on fire ecology to improve the efficacy of current policies for fire use in this biome.

The knowledge gaps reflect the absence of a systemic and integrative approach linking fire behavior and its effects. To fill current knowledge gaps, there are three major challenges related to interactive effects and spatial and temporal scales of the analyses: (1) predictive scale (change from single to multiple drivers); (2) spatial scale (change from site to biome); and (3) time scale (change from short- to long-term dynamics).

Considering the difficulty of studying all three scales in a single experiment, we propose the following priorities: (1) increasing the scientific effort, even if independently, to include at least one of the three proposed scale changes; (2) interdisciplinary proposals that integrate different study tools; (3) studies that assess which ecological processes are more sensitive or more resilient to fire and consequently have major impacts on ecosystem services.

The continuation of existing long-term studies could be an opportunity to address these priorities in addition to new sites, which can represent different landscape configurations or environmental changes.

1. Introduction

Fire is a disturbance with a long history of occurrence and plays a fundamental role in the patterns and processes of the ecosystems globally (Beerling and Osborne, 2006; Bond, 2015). Fire influences the structural and floristic dynamics of vegetation (Kraft et al., 2015), the carbon cycle (Bond and Midgley, 2012), and climate (Bowman et al., 2009; Jin, 2010). Over paleoecological time scales, fire has shaped biotic characteristics and ecosystem processes of savanna biomes (Beerling and Osborne, 2006; Cerling et al., 1997), but in recent history, anthropogenic activities, such as the use of fire for agricultural purposes, have changed its natural frequency (Bowman et al., 2009). Thus, it cannot be presumed that all species will be able to adapt to current fire regimes (Pausas and Keeley, 2009).

The Brazilian Cerrado, the savanna with the richest flora in the world (Myers et al., 2000), is severely threatened by the indiscriminate use of fire (Durigan and Ratter, 2015). Between 2002 and 2010, the area burned in the Cerrado represented approximately 73% (545,000 km^2) of the total burned area in Brazil (Araújo et al., 2012). The Forest Code (Law number 12651), the main environmental law in Brazil that has been in effect since May 2012, addresses fire management in protected areas of the Cerrado (Article 38), declaring illegal the burning of native vegetation outside reserves. However, the national policy on Integrated Fire Management proposed by the Ministry of the Environment is still under discussion. The challenge is to create action plans for fire prevention, control, and management that promote balanced prescription of fire regimes that considers the trade-offs of fire impacts on ecological, economic, and cultural processes (Box 1).

Efficient use of fire depends on understanding the relationships between fire and its drivers, and relationships between fire and the multiple ecological processes affected by fire (Archibald et al., 2017). Experimental studies evaluating these relationships in the Cerrado biome (Fig. 1; Table 1) include the "Fire Project"[1] (Miranda, 2010), which was implemented in 1991 and is considered the largest project

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Box 1
Fire use trade-offs

In the Cerrado biome, anthropogenic fire has been an efficient and inexpensive tool (Pivello, 2011) for removing native vegetation before pasture or crop cultivation, stimulating the regrowth of native grasses for cattle grazing, hunting and dispersing venomous animals, and indigenous rituals (Mistry, 1998). However, these practices result in large emissions of carbon and other trace gases, contributing to the increase in greenhouse gas emissions and global warming (Pivello, 2011). The Cerrado represents approximately 50% (1.69 Mt CO_2eq) of the total CO_2 emissions for pasture management in Brazil (Bustamante et al., 2012). In addition, fire used for these purposes can escape control and burn surrounding natural areas, exemplified by the large and catastrophic fire that burned 93% (1236 km^2) of Emas National Park in 1994 (França et al., 2007).

Between 2002 and 2010, the burned area of the Cerrado was concentrated mainly in the northern part of the biome, especially at the "Arc of Deforestation" in the Amazon-Cerrado transition (Araújo et al., 2012). The highest proportion of natural vegetation remaining in the biome is also concentrated in its northern part (Sano et al., 2010). This region also has a high concentration of recent land conversions (2002–2009) (Rocha et al., 2011), which involve biennial or triennial burns to clear the area within a period of 10 to 20 years. The extensive use of anthropic fire and its threat to the remaining native vegetation are apparent at the level of spatial pattern.

Cerrado vegetation occurs heterogeneously in space, forming vegetation mosaics due to the high environmental heterogeneity (soil and climate) and transitions with other Brazilian biomes (Caatinga, Mata Atlântica, Pantanal, and Amazônia) (Coutinho, 1990; Felfili et al., 2008). The specific effects of fire on native Cerrado vegetation depend on the type of vegetation (Fig. 2). Open savanna and savanna formations are more flammable and fire-tolerant than forest formations (Hoffmann et al., 2012b). The higher flammability of open savannas and savannas is attributed mainly to lower tree cover, which promotes a microclimate with higher temperatures and sun exposure, and high grass cover, which acts as a fuel source and allows fire to spread rapidly (Hoffmann et al., 2012b; Miranda et al., 2010). Because of the shorter residence time of the fire front, trunk temperature does not significantly increase resulting in less damage to trees (Kayll, 1968). Higher fire tolerance is attributed to morphological adaptations, such as thick bark that protects vascular tissues against high temperatures and a greater investment in root biomass as a source of carbohydrates for regrowth (Hoffmann, 2005). These adaptations are less evident in forest formations, making these environments highly vulnerable to changing fire regimes (Hoffmann and Franco, 2003). Despite the lower flammability of forests, fire occurrence is not inhibited, especially where ecotones are formed with open savanna and savanna formations (França et al., 2007) or during severe droughts (Brando et al., 2014).

Despite the relative fire tolerance of open savanna and savanna formations, fire can threaten these formations, especially where the natural fire regime has been altered (Miranda et al., 2010). For example, unlike natural fires that occur during the dry-rainy season transition, anthropogenic fires that occur during the dry season cause greater damage to vegetation; because they are more intense and burn larger areas because of the abundance of fine fuel load and the absence of rainfall (Miranda et al., 2010; Ramos-Neto and Pivello, 2000). Anthropogenic fires are also more frequent, which prevents the recovery of individual plants to heights sufficient to avoid the direct effect of the flames. This increases mortality rates, especially of smaller individuals (Sato, 2003); decreases recruitment of woody species, species richness, and diversity (Hoffmann et al., 2012a; Medeiros and Miranda, 2005); and promotes the invasion of exotic grasses (Silvério et al., 2013). These changes may convert forest formations to savanna formations (Henriques, 2005) (Fig. 2, Arrow 1). Increased fire frequency also causes an imbalance between CO_2 emission and consumption by vegetation, since a shorter burn interval does not allow vegetation to reabsorb carbon released during the fire (Sato et al., 2010).

Conversely, total fire exclusion is also a potential threat to open savanna and savanna formations, since they depend on the fire regime to maintain their structure, microclimate, diversity, and function (Medeiros and Fiedler, 2011). Thus, without fire, savanna formations might become denser (Abreu et al., 2017; Pinheiro and Durigan, 2009), and forest formations may encroach on savannas that have the climate and soil able to support forests (Henriques, 2005) (Fig. 2, Arrow 2). The increased vegetation density can reduce species richness and diversity (Abreu et al., 2017; Cardoso et al., 2009; Pinheiro and Durigan, 2009). Fire also stimulates reproductive mechanisms of some Cerrado species, including flowering (Fidelis and Blanco, 2014) and fruiting (Conceição and Orr, 2012). Thus, fire is one of the factors maintaining coexistence between savanna and forest, which are considered alternative stable states (Dantas et al., 2016). Damage caused by the indiscriminate use of fire not only alters plant and climate processes but also affects economic and cultural processes (Durigan and Ratter, 2015). Therefore, criteria for the use of fire in the Cerrado must consider the type of vegetation cover and the natural fire regime. It is necessary to determine efficient techniques to control and fight fire, when it is needed, to prevent its use from threatening surrounding areas.

involving prescribed fires in Latin American savannas (Dias and Miranda, 2010). More recent projects include "Fire as a management tool in Cerrado conservation units"[2] (Gorgone-Barbosa et al., 2015; Rissi, 2016), which was implemented in 2011 as well as the "Prevention, control and monitoring of irregular fires and forest fires in the Cerrado"[3] project (Schmidt et al., 2016b) and the "Effects of fire and its suppression on the structure, composition and biodiversity of the ecosystem in the Cerrado physiognomic gradient"[4] project (Durigan, 2017; Hoffmann, 2018), both implemented in 2014. Although these studies have achieved major advances in the understanding of fire ecology in the Cerrado, gaps remain due to the absence of a systemic approach that links the behavior, effects, and drivers of fires.

A fire event involves complex interactions and feedbacks between biotic and abiotic processes (Harris et al., 2016). Mathematical models are useful to simulate these multiple and complex ecological processes (Rothermel, 1972), select primary predictors, and predict fire behavior and its impacts (Alexander and Cruz, 2012). However, fire modeling studies for the Cerrado are rare and need to be improved to develop a more systemic approach (Pereira et al., 2014). In addition, most of the models that have been tested for this biome were originally developed for temperate regions with different vegetation and physiological characteristics (White et al., 2013, 2016), which reduces the accuracy of their predictions (Mistry and Berardi, 2005).

Compared with studies in Australia, Europe, and North America, the literature about fire in South America is less abundant (Prichard et al., 2017). In this context, we performed a broad literature review of studies evaluating the relationships between fire behavior and predictive environmental variables (biotic and abiotic) and between fire behavior

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