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FILIPE VIEGAS DE ARRUDA

O MANEJO DO FOGO NOS BIOMAS CERRADO E PANTANAL: UMA ABORDAGEM CIENCIOMÉTRICA E EXPERIMENTAL

Anápolis - GO

Fevereiro de 2020

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Tese apresentada ao programa de Pós-Graduação Stricto Sensu em Recursos Naturais do Cerrado da Universidade Estadual de Goiás para obtenção do título de Doutor em Recursos Naturais do Cerrado.

Orientador: Prof. Dr. Fabrício Barreto Teresa

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Na ladeira de pilar é tombador.
Bota fogo no sapê.
Que pra nascer a fulô.

SUMÁRIO

Resumo

O fogo é um importante agente em relação a biodiversidade global e o manejo do fogo é uma questão nova extremamente importante para o Cerrado, apesar de relativamente recente. Tanto os incêndios antropogênicos de alta intensidade, quanto a sua supressão completa podem reduzir a biodiversidade neste bioma. Os diferentes históricos de queimadas podem prover uma heterogeneidade de habitats e consequentemente aumentar a biodiversidade. Apesar de haver um grande número de estudos com fogo no Cerrado não registramos nenhum que apontasse as tendências e a lacunas dos mesmos. No entanto, compreender o atual estágio que se encontram as publicações científicas com fogo no bioma Cerrado pode ser fundamental para os avanços científicos nessa área. Assim, tivemos como primeiro objetivo localizar as tendências e as lacunas, dos estudos sobre fogo no Cerrado, o que auxiliou no direcionamento dos próximos objetivos. Entre as lacunas identificadas estão: i) a realização de estudos em diferentes escalas espaciais, principalmente em grandes escalas; ii) estudos que demonstrem os impactos das áreas queimadas com diferentes históricos; iii) estudos que abordem os efeitos da interação das queimadas associadas com outros distúrbios. Consequentemente nosso segundo objetivo avaliou como diferentes tipos de queimadas podem influenciar a colonização de ninhos experimentais por formigas no Cerrado e o potencial de bioindicação das espécies de formigas em relação aos diferentes tratamentos. Nossos resultados demonstraram que os diferentes tipos de queimadas impactam de diferentes formas a colonização. Ou seja, o tipo de queimada também deve ser levado em consideração pelo manejo de áreas de preservação. Além disso, observamos que três espécies diferentes de formigas atuaram como indicadores de diferentes intensidades de queima. Em nosso terceiro capítulo buscamos analisar o efeito da interação das queimadas com outros distúrbios (inundação) em diferentes escalas espaciais. Para isso amostramos formigas de solo em uma planície de inundação em áreas com diferentes históricos de queimadas e com diferentes altitudes (*proxy* para tempo de inundação). Nós observamos que as queimadas exercem um efeito dominante sobre a inundação, ou seja, apenas as queimadas impactaram a riqueza e a composição de espécies. No entanto, embora o fogo cause grandes impactos sobre as espécies de formigas, esses efeitos tendem a desaparecer com o tempo. Além disso, não encontramos impacto do período de inundação nas espécies de formigas, que mostram resistência às inundações e resiliência ao fogo pelas formigas.

Palavras chave: cienciometria, distúrbios ambientais, formigas, planície de inundação, riqueza de formigas, composição de formigas.

Abstract

Fire plays a crucial role in global biodiversity and, despite relatively recent, fire management is of extreme importance for the Brazilian Cerrado. Both high-intensity anthropogenic fires and the complete fire suppression can reduce the biodiversity of this biome. The different fire histories can cause habitat heterogeneity and as a consequence increase biodiversity. Although the large number of studies on fire in the Cerrado, we have not found any study addressing trends and gaps in these studies. However, understanding the current stage of scientific publications with fire in this biome can be fundamental for scientific advances in this area. Therefore, our first object was to identify the trends and gaps of publications about fires in the Cerrado, which helped in aiming the next objectives. Among the gaps identified are: i) studies on different spatial scales, mainly at large scales; ii) studies showing the impacts of burned areas with different fire histories; iii) studies addressing the effects of the interaction between fire and other disturbances. Consequently, our second objective was to evaluate how different types of fires can influence the ant colonization of experimental nests in the Cerrado and the bioindication potential of ant species in the different fire treatments. We found that different types of fires impact colonization in different ways. In other words, the type of fire should also be considered when managing preservation areas. Besides, we observed that three different ant species acted as indicators of different fire intensities. Finally, our third objective was to evaluate the effect of the interaction between fire and other disturbances (flood) at different spatial scales. For this, we sampled soil ants in a floodplain area with different fire histories and elevations (a proxy for flood time). We found that fires have a dominant effect over flooding, that is, only fires impacted the ant species richness and composition. Nonetheless, although the fire causes major impacts on ant species, these effects tend to disappear over time. Furthermore, we found no impact of the flood period on the ant species, which show flood resistance and fire resilience by the ants.

Keywords: scientometrics, environmental disturbances, ants, floodplain, ant richness, ant composition.

Introdução geral

Distúrbios são componentes chaves de sistemas ecológicos terrestres e aquáticos e provocam impactos em diferentes escalas (WHITES; PICKETTA, 1985). Entre os distúrbios, o fogo aparece entre um dos principais agentes moduladores da diversidade (HE; LAMONT; PAUSAS, 2019), direcionando as dinâmicas das comunidades e populações animais e vegetais, funcionando como um agente essencial na evolução da biodiversidade (KOLTZ et al., 2018; PAUSAS; PARR, 2018; PAUSAS; KEELEY, 2019). As queimadas podem ser caracterizadas por seus históricos (tamanho, intensidade, estação sazonal e frequência de queimadas (HE; LAMONT; PAUSAS, 2019)) e influenciando as comunidades animais e vegetais (ABREU et al., 2017; MARAVALHAS; VASCONCELOS, 2014; PAOLUCCI et al., 2017). As queimadas de áreas com diferentes históricos, podem gerar um mosaico de áreas com diferentes características (ABREU et al., 2017) e essa diferenciação das áreas provocadas pelo fogo é conhecida como pirodiversidade (MARTIN; SAPSIS, 2012). A pirodiversidade pode afetar a dinâmica populacional de muitas espécies, determinando a extinção local ou a invasão de espécies e, por fim, os padrões de riqueza e composição observados (BEALE et al., 2018; MARAVALHAS; VASCONCELOS, 2014).

As queimadas são eventos frequentes nas savanas tropicais (BOWMAN et al., 2009; PYNE, 1997; SIMON et al., 2009), inclusive no Cerrado (savana brasileira) que é um bioma constituído por complexa vegetação e por uma rica e diversa fauna. Este bioma está localizado principalmente nas porções centrais do país e possui cerca de dois milhões de km2 (23 % do território nacional). No bioma Cerrado ocorrem formações florestais que não são consideradas pertencentes ao cerrado *sensu lato,* como por exemplo, as matas estacionais decíduas e semidecíduas, as matas sempre verdes, as matas de vale e as matas de galeria (Oliveira-Filho e Ratter 2002). Os principais fatores que diferenciam as formações de cerrado *sensu lato* e florestais são a resistência ao fogo, a disponibilidade de água e os níveis de macronutrientes no solo (Coutinho, 1990). Apesar da importância do fogo no manejo do cerrado, ainda existem grandes lacunas nos estudos com fogo no Cerrado e entender a atual situação da produção científica com a temática fogo no Cerrado e analisando os aspectos temporais e tendências espaciais pode direcionar de forma mais precisa os estudos futuros.

As formigas estão entre os organismos mais abundantes do mundo (HÖLLDOBLER; WILSON, 1990) e são consideradas excelentes bioindicadoras (HOFFMANN; ANDERSEN, 2003; MAJER, 1983; TIEDE et al., 2017). Elas são impactadas diretamente (morte de indivíduos) e indiretamente (locais de abrigo, disponibilidade de alimentos) pelas queimadas (ANDERSEN, 2018; FAGUNDES et al., 2015; FRIZZO; CAMPOS; VASCONCELOS, 2012). As queimadas realizadas no Cerrado em períodos sazonais diferentes (início, meio e final do período seco) possuem características e intensidades diferentes (RISSI et al., 2017) e as comunidades de formigas podem responder de diferentes formas a essas queimadas. Porém, apesar do manejo do fogo realizado nas áreas de preservação e nas áreas indígenas e quilombolas utilizarem queimadas com diferentes técnicas (i.e. contra vento, a favor do vento, queimada e faixas, queimadas em foco, queimadas em L, queimadas em U e circular), ainda não se sabe o grau de intensidade dessas diferentes técnicas e quais são os impactos diretos e indiretos das mesmas sobre a fauna e flora.

Apesar do fogo ser um distúrbio importante, muitas vezes seus impactos podem estar associados a outros distúrbios naturais ou antrópicos e a interação entre esses distúrbios raramente são analisados (KÉFI et al., 2019). Além disso, os distúrbios podem apresentar diferentes resultados de acordo com as escalas temporais e espaciais analisadas (TURNER, 2010; WHITES; PICKETTA, 1985). No Pantanal que é uma das maiores planícies de inundação do mundo e possui ciclos de inundações naturais anuais (HARRIS et al., 2005) as queimadas vem se tornando cada vez mais frequentes. Isso ocorre principalmente devido ao manejo de plantas invasoras que prejudicam a pastagem e consequentemente a criação de gado (JUNK et al., 2006; SEIDL; SILVA; MORAES, 2001). Ou seja, as ações antrópicas estão intensificado a queimadas que atingem até as áreas que ficam alagadas durante o período chuvoso. As formigas de solo podem ser impactadas tanto pelas inundações (MAJER; DELABIE, 1994; VASCONCELOS et al., 2010) como pelas queimadas (ANDERSEN, 2018; VASCONCELOS; MARAVALHAS; CORNELISSEN, 2017), o que faz das mesmas excelentes organismos para analisar o efeito da interações entre esses distúrbios nas comunidades animais.

Nesta tese, investigamos os aspectos temporais e espaciais dos trabalhos científicos com fogo no cerrado, o impacto das queimadas realizadas com diferentes técnicas na mirmecofauna arborícola e os efeitos das interações entre as queimadas e inundações sobre as formigas de solo. Sob a premissa que essas perguntas são importantes para o manejo com fogo em áreas protegidas, analisamos: i) o atual estado em que se encontram as publicações científicas sobre o fogo no bioma Cerrado; ii) os efeitos das queimadas com diferentes técnicas e consequentemente com diferentes intensidades na colonização de ninhos artificiais por formigas arborícolas; iii) como as formigas respondem a interações de diferentes distúrbios (fogo e inundação). Cada um desses objetivos foi desenvolvido em um capítulo da tese. Dessa forma, a tese está estruturada em três capítulos:

Capítulo 1: Trends and gaps of the scientific literature about the fire effects on Brazilian Cerrado. Esse capítulo apresenta os dados obtidos através de uma análise cienciometríca de 228 artigos científicos publicados entre os anos de 1991 a 2016 relacionados com fogo no bioma Cerrado. Verificamos que existe uma tendência de aumento no número de publicações e que a maioria dos estudos estão relacionados ao efeito das queimadas nas plantas. Também foi possível observar que as regiões que apresentam os maiores números de estudos não são as áreas que apresentam maiores números de queimadas. Enquanto as áreas com maiores concentrações de incêndios estão relacionadas com o desmatamento nas áreas popularmente conhecidas como Arco do Desmatamento (MATOPIBA) e os estudos estão concentrados em áreas com maiores produtos brutos (São Paulo e Distrito Federal). Este artigo foi publicado em março de 2013, no periódico *Biota Neotropica*.

Capítulo 2: Different burning intensities affect cavity utilization patterns by arboreal ants in a tropical savanna canopy. Esse artigo demonstra como as queimadas com diferentes técnicas utilizadas no manejo possuem intensidade (velocidade e altura do fogo) diferentes. Além disso demonstramos que as queimadas com diferentes intensidades impactam de diferentes formas a colonização de ninhos artificiais por formigas no Cerrado. Apesar das queimadas com maiores intensidades possuírem maiores riquezas de espécies, maiores números de ninhos e árvores colonizadas, os ninhos colonizados nessas áreas possuem um menor número indivíduos, o que demonstra o efeito indireto do fogo nas comunidades de formigas. Esse artigo está em revisão no periódico *Ecological Indicators*.

Capítulo 3: Fire and flood: How the Pantanal ant communities respond to multiple disturbances on different temporal scales. Esse artigo apresenta os que a interação entre os diferentes distúrbios (fogo e inundação) na comunidade de formigas do Pantanal apresenta diferentes resultados de acordo com a escala temporal analisada. Em relação a riqueza de espécies o fogo foi um distúrbio dominante (o único que afetou a comunidade de formigas) a curto prazo, enquanto a inundação não afetou a comunidade de formigas em nenhuma escala temporal (curto, médio e longo prazo). Em relação a composição de espécies apenas o fogo modificou a comunidade a curto e médio prazo. Esses resultados demonstram a resistência do fogo em relação a inundação e a resiliência das formigas do Pantanal em relação ao fogo. Esse artigo está formatado nas normas do periódico *Ecology Letters*.

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CAPÍTULO 1

TRENDS AND GAPS OF THE SCIENTIFIC LITERATURE ABOUT THE EFFECTS OF FIRE ON BRAZILIAN CERRADO

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Abstract

Fire management is an important issue in the Brazilian Cerrado, since both anthropogenic high intensity fires and complete fire suppression can reduce the biodiversity in this biome. In this paper, we highlight the trends in scientific literature about fire effects in the Cerrado, aiming to detect possible gaps and to indicate directions of future scientific research. We searched for articles in the periodic database Web of Knowledge from 1991 to 2016, and observed an increase in the number of publications throughout the years. Most articles were associated with Brazilian institutions (58%), followed by those with collaboration between Brazilian and international institutions (33%), and those published by authors exclusively from international institutions (9%). Most articles addressed the effects of fire on biodiversity (77%), followed by articles about abiotic environment (19%), and then biotic interactions or interactions between organisms and environment (4%). The most studied taxonomic group was plants (75%), followed by mammals (8%) and insects (6%), with the remaining taxa comprising about 11% of publications. The Federal District was the federative unit with the greatest number of researches (31%). The majority of studies was conducted in areas with fewer fire events, whereas areas with major incidence of fires are poorly studied. Our data shows that studies on the effect of fires on the Brazilian Cerrado are geographically and taxonomically biased. This lack of knowledge limits the extrapolations about the effects of fire on this biome. Therefore, we emphasize the need for investment in research in areas with high fire frequency and also for an increase in knowledge about these effects on the biota, especially on the fauna. This action is fundamental to support the development of public policies for effective and directed fire management in the Cerrado.

Keywords: Burning, Scientometrics, Biodiversity Hotspots, Savanna, Perturbation.

Introduction

The Brazilian Cerrado comprises an area of 2 million km^2 and is home to a rich and diverse fauna and flora (Ribeiro & Walter 2008). In this biome, there are more than 1,000 terrestrial vertebrates and 12,000 plant species (Myers et al. 2000, Mendonça et al. 2008), and about 80% of those plant species are endemic (Lenthall et al. 1999). Given its wide range, the Cerrado is constituted by different phytophysiognomies that vary from open areas to forest formations (Oliveira-Filho & Ratter 2002, Lenthall et al. 1999). Therefore, we cannot assume that the Brazilian Cerrado is homogeneous since it hosts a large variation in soil structure, geomorphological formation, drain basins and associated vegetation (Silva et al. 2006, Furley 1999).

The Cerrado exhibits remarkable characteristics such as (i) poor, acidic soil with a high concentration of aluminum (Queiroz-Neto 1982, Reatto et al. 1998), (ii) climatic seasonality with well-defined rainy and dry seasons, and (iii) resistance to fire (Coutinho 1990). In fact, fire has been considered the prevalent force driving the evolution of biota in this biome (Simon et al. 2009). Fire can influence community composition (Oliveras et al. 2012, Vieira & Briani 2013, Silvério et al. 2015, Abreu et al. 2017), soil properties and regional climate (Bustamante et al. 2012, Wendling et al. 2014). In fact, fire can act as either a natural or an anthropic disturbance in the Cerrado. In non-protected areas, the frequency and intensity of fires has increased due to recent expansion of agriculture and livestock, with potential negative effects on the biota (Bowman et al. 2011). However, this issue is controversial since some studies have shown that fire frequency is reduced in protected areas of the Cerrado, with negative consequences for biodiversity (Moreira 2000, Roitman et al. 2008, Cardoso et al. 2009, Pinheiro & Durigan 2009, Pinheiro et al. 2010). Thus, not only the increase but the changes in the frequency of fires are of great concern for the conservation of the Cerrado's biodiversity (Pivello 2011, Abreu et al. 2017).

Several studies have been conducted to understand the effects of fire on different environmental aspects of the Cerrado (e.g. Tubelis et al. 2009, Fagundes et al. 2015, Abreu et al. 2017). Indeed, the understanding of the effects of fire and also of fire suppression on biodiversity and ecosystem function is fundamental to a satisfactory establishment of public policies focusing on natural resource management (Durigan & Rattter 2016). Nevertheless, due its wide range, the Cerrado is also a spatially heterogeneous biome (Silva & Bates 2002). Considering that fire or fire suppression can have different effects in different regions, there should be studies conducted across a wide geographical range, and spatially replicated across the biome. The predominance of studies in the vicinity of traditional research centers (Nabout et al. 2015), or the non-equitable spatial distribution of infrastructure providing unequal access to many areas, may generate a geographic asymmetry on the development of studies in the Cerrado. Also, the occurrence and frequency of wildfires are not spatially homogeneous (Pereira Júnior et al. 2014). Thus, the spatial variation in fire events may also benefit the development of studies, given the urgency in obtaining parameters for fire management in those environments.

In this study, we performed a scientometric evaluation of the studies related to fire in the Cerrado biome, seeking to understand the temporal and spatial trends in publications about this theme. Specifically, we (i) evaluated the temporal increment of the number of articles; (ii) highlighted the main taxonomic groups or themes addressed in the studies; (iii) determined the journals with the most publications about fire in the Cerrado; (iv) evaluated the possible biases in the location where studies were conducted and the fire frequency in the Cerrado; and (v) indicate directions for future studies.

Material and Methods

We used the Web of Science database (www.isiknowledge.com) to access articles about the influence of fire in the Cerrado biome. We considered publications from 1991 to 2016, since abstracts are only available in this database from 1991 to 2016, and this research is based on abstracts. The search was restricted to articles using the words (“fire*”) AND ((“savanna*”) OR (“cerrado*”)) AND (“Brazil*”) in the topics.

For each article, we evaluated the title, keywords and abstract, to collect the following information: (1) publication year; (2) the institution, the nationality and state of the institution where the authors were associated at the time the manuscript was written; (3) taxonomic group (i.e. humans, mammals, amphibians, birds, reptiles, fishes, insects, non-insect invertebrates, microorganisms, plants and fungi); (4) journal in which it was published; and (5) geographic location(s) of the research.

To assess the temporal trend in the number of articles, we used Pearson correlation between the year of the publication and the number of articles published in that given year. The same test was performed separately for each taxonomic group to check the temporal trend in articles by taxonomic group. We also used Pearson correlation to test separately the relation of the number of authors and first authors by state with the frequency of fire occurrences in that given state. In this case, the states were considered as sample units since data on fire occurrence are easily available on the *Instituto Nacional de Pesquisas Espaciais* (INPE) website (https://queimadas.dgi.inpe.br/queimadas). The Federal District is not a formal state, but was considered a sample unit in the present study. These data refer to fire events from 1992 to 2015. We then built maps with the number of fire events as well as with the number of published papers within this period for each state. One limitation of the INPE dataset is that it does not distinguish fire occurrences between natural vegetation and crops or pastures. We recognize this limitation but we acknowledge that fire events in crops and pastures pose a high risk for the natural vegetation of the Cerrado. Therefore, these limitations do not detract our inferences about the relation between fire frequency and number of studies in the states of this biome.

Results

We found 288 articles from 1991 to 2016 addressing fire in the Brazilian Cerrado. Among these articles, 166 (58%) have authors associated only with a Brazilian institution. We counted a total of 96 articles with collaboration between Brazilian and international institutions (33%) and a small part (26 articles, 9%) published only by authors affiliated with international institutions.

We found an increasing temporal trend in the number of articles published over the years ($r = 0.86$; $P < 0.001$) (Figure 1). Most articles (223, totaling 77%), addressed the effect of fire on biodiversity. Another 53 (18%) focused on the association between fire and abiotic variables. Among the studies about abiotic factors, the highlighted factor was the effect of fire on soil and nutrients. Only 12 articles (4%) reported interactions (biotic interactions or interaction between organisms and the abiotic environment).

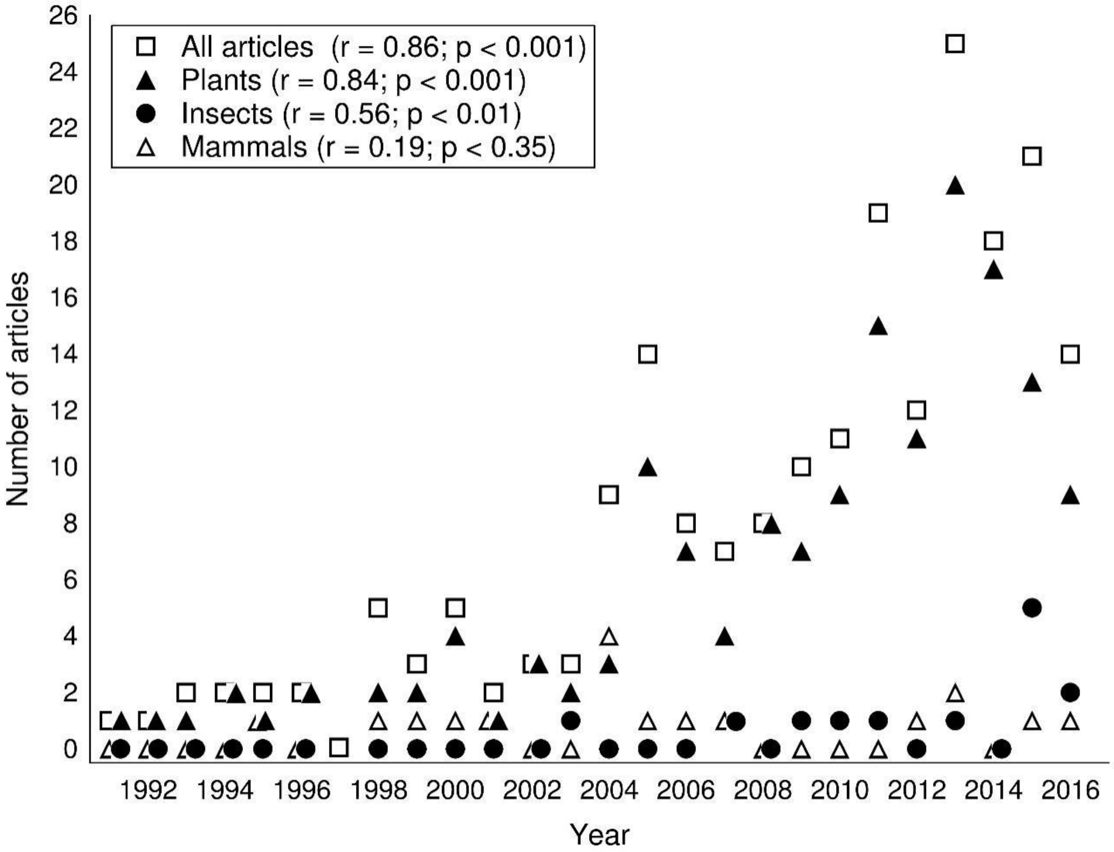

Figure 1. Temporal tendency of the total number of articles and number of articles involving insects, mammals and plants related to fire in the Cerrado from 1991 to 2016.

We identified the studied taxa in 207 articles and observed the predominance of studies involving plants, 155 publications (75%), followed by mammals with 17 (8%) and insects with 13 (6%) publications (Figure 2). The remaining taxa comprise 22 publications (11%) and each one has less than 10 publications (Figure 2). Among the taxa with the highest number of publications, plants (r= 0.84; p<0.001) and insects (r=0.56; p <0.01) showed an increase in the number of articles across the years (Figure 1). We did not observe any temporal trend in the number of publications for mammals (r = 0.19, p = 0.35) (Figure 1). Due to the low number of studies, we did not perform inferential analyses to microorganisms, lichens, reptiles, humans, invertebrates (except insects) and birds.

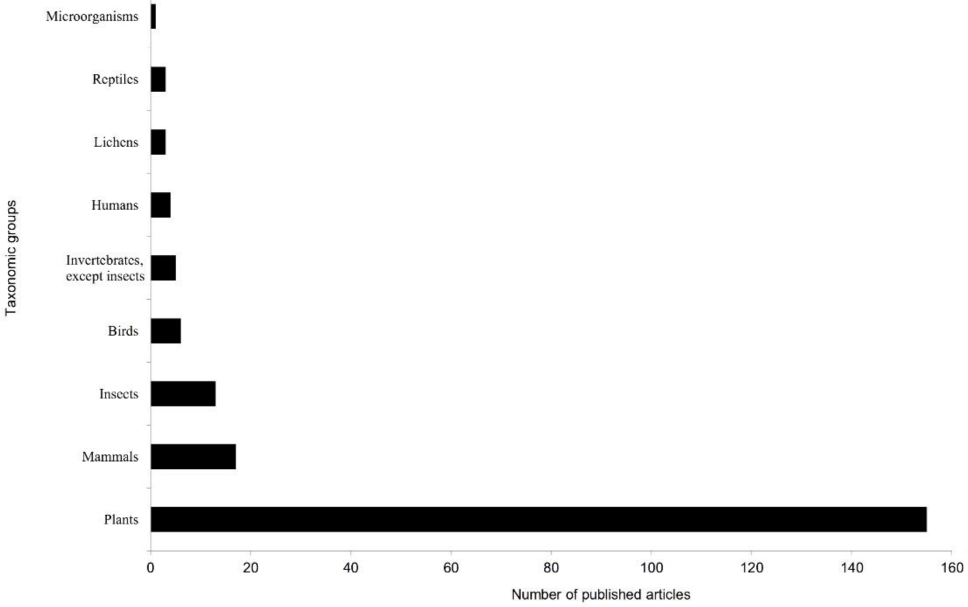

Figure 2. Taxonomic groups addressed in scientific articles about fire in the Cerrado from 1991 to 2016.

We found 115 journals with articles addressing fire in the Cerrado. However, the number of articles published in these journals is asymmetric, since about 40% of them were published in only 13 journals. The journal *Acta Botanica Brasilica* published the highest number of articles (20 articles) about this theme, representing 7% of the total (Figure 3).

Figure 3. Journals with the highest number of articles about fire in the Cerrado from 1991 to 2016.

We identified the state in 285 articles and 14% of these studies were performed in more than one state (39 studies). For studies restricted to just one Brazilian political unit, the major part of them (89 or 31%) was done in the Federal District (Figure 4). The states of Minas Gerais and Goiás (35 studies or 12% each), Mato Grosso and São Paulo (28 or 10% each) are where most of the research was conducted (Figure 4). About 11% of the publications were performed in the remaining states (Tocantins, Roraima, Pará, Mato Grosso do Sul, Bahia, Amapá, Maranhão, Piauí and Rondônia) and each State has less than 5% of all publications (Figure 4).

The number of studies performed in each state was positively correlated with the number of first authors with an institutional address associated with that state ($r = 0.80$, $p < 0.001$). The fire frequency in each state was not correlated with either the number of articles per state ($r = 0.08$, $p = 0.73$) nor with the number of first authors affiliated to an institution located in the state ($r = -0.13$, $p = 0.59$). The spatial distribution of these three variables demonstrates asymmetry in the distribution of fire occurrence, studies location and researchers' institutional affiliation (Figure 4). Fire occurrence is more frequent in the Cerrado areas bordering the Amazon rainforest (Figure 4), while location where research was conducted and affiliation of researchers are mainly in the southeast and central-west states of Brazil (Figure 4).

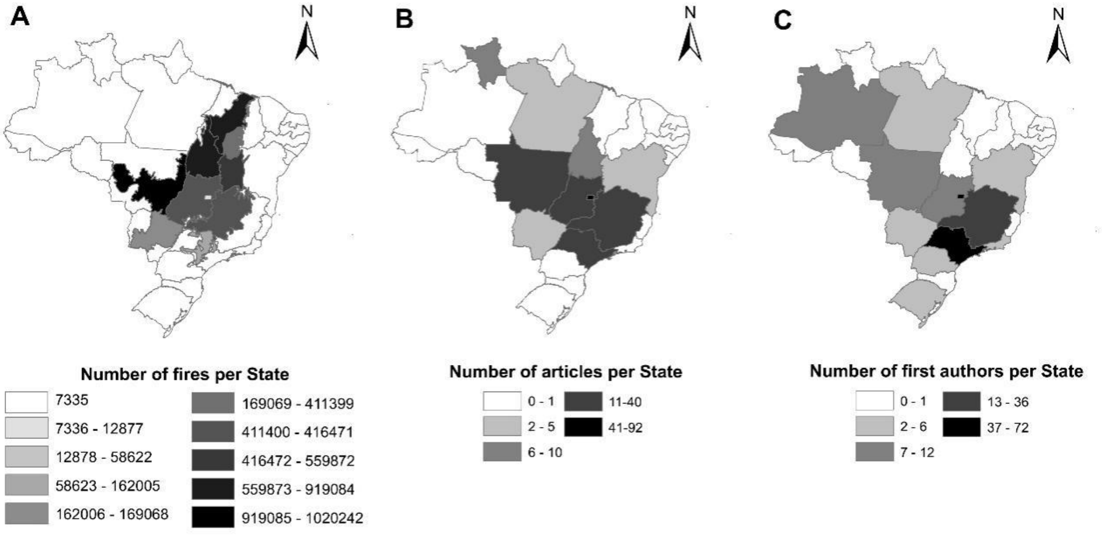

Figure 4: Geographic distribution per Brazilian State of (A) number of fires events (from 1992 to 2015 available at https://queimadas.dgi.inpe.br/queimadas), (B) number of articles and (C) number of first authors affiliated.

Discussion

We found that the number of publications about fire in the Cerrado has increased over the years and this trend was about the same for the literature involving the Cerrado (r = 0.86 in the present study *vs.* r = 0.89 in Borges et al. 2015). Thus, the interest about fire in the Cerrado reflects the interest in the biome by itself. Additionally, the growing interest in the effects of fire in the Cerrado may be due to the biome complexity: both high and low frequencies of fire can have negative effects on biodiversity (Anjos et al. 2016, Maravalhas & Vasconcelos 2014, Abreu et al. 2016), and proper fire management programs based on scientific knowledge are still in development **(**Durigan & Ratter 2016). Our results also indicate that most publications were about the effects of fire on plants, and were performed in states with fewer fire events. These asymmetries limit generalizations of the observed patterns that may not be applicable to the whole biome. In Brazil, there is a growing demand to create fire policies to conserve the Cerrado (Durigan & Ratter 2016). Thus, an unbiased knowledge about the effects of fire on different taxa and regions of the biome is desirable to create clear guidelines for future fire management policies.

Even though fire has become an international issue due to its biodiversity and atmospheric consequences (Miranda et al. 2009, Bustamante et al. 2012), most studies were conducted by researchers from Brazilian institutions. These results demonstrate the importance of Brazilian universities and research institutions in this field. Thus, the recent cuts in Brazilian research investments (Fearnside 2016, Gibney 2015, Angelo 2017) may directly impact the generation of knowledge applied to Cerrado preservation, especially due to the lack of scientific background in fire management policies and consequences of both fire effects and fire suppression.

Although the number of journals publishing articles related to fire in the Cerrado biome is high, the distribution of the theme among them is clearly asymmetrical. A small number of journals is responsible for the great majority of publications. The Brazilian journals *Acta Botanica Brasilica* and *Brazilian Journal of Biology* stand out. Nevertheless, besides these two journals, international journals dominate the articles publication assessing fire in the Cerrado. This demonstrates the global interest in this subject, which is directly related to greenhouse gas emissions and climate change, which are currently two of the greatest issues facing humanity (Moraes et al. 2011). Moreover, similar to the Cerrado, there are other biomes where fire exerts a constant pressure. This demonstrates that the issue of fire is not only applicable to a regional context.

Among the different studied taxa, plants were the most frequent in articles about fire in Cerrado (Borges et al. 2015). Since the journal *Acta Botanica Brasilica* has a botanical perspective, this may be a possible reason for the higher number of publications about fire and vegetation in the Cerrado in this journal. Furthermore, the great vegetation diversity, the high endemism rates and the high risk of species extinctions (Myers et al. 2000) seem to explain the higher interest about the effects of fire in plants. Also, the plant's adaptations to fire are diverse and attract interest in this field (*e.g.* Eiten 1972, Ratter et al. 1997, Simon et al. 2009). Moreover, there are fewer studies performed on other taxa, which demonstrates the insufficient knowledge regarding the effects of fire on the general biodiversity. By reviewing the studies regarding the effect of fire on the Brazilian savanna fauna, Frizzo et al. (2011) found a great shortage of studies, which according to them, besides limiting knowledge, might induce generalizations that do not reflect the real effects of fire on animal communities. The fact that some animal taxa have a different number of specialists, demands more complex logistic and infrastructure to be studied, may have an influence on the low number of published articles about them (Agostinho et al. 2005, Borges et. al. 2015). Therefore, investment in research on other animal groups in the Cerrado is necessary for a better comprehension about the effects of fire on biodiversity.

We gathered evidence showing that the studies involving the effects of fire in the Cerrado are not evenly distributed. There is a tendency for studies to be regionally concentrated, with a particular concentration in the Federal District. A great part of this production occurred in the IBGE (Brazilian Institute of Geography and Statistics) Ecological Reserve – RECOR. Created in 1975, the RECOR has been established as an important research center of the Cerrado biome, mainly by the creation of a Long-Term Ecological Research – LTER (PELD in Portuguese) developed in collaboration between the IBGE and the University of Brasilia – UnB (http://recor.org.br). This concentration of studies brings some limitations to summarize what we currently know about the effects of fire on the Cerrado. Although a large number of species have broad distributions, the plant communities of the Cerrado *sensu stricto* harbor a high number of locally restricted species, as a consequence of climatic and geomorphological heterogeneity (Felfili & Silva Júnior 2005, Françoso et al. 2016). In fact, different studies have confirmed high beta diversity among regions within the Cerrado (Lindoso & Felfili 2007, Lopes et al. 2011). Furthermore, the Cerrado is surrounded by Pantanal, Amazon rainforest, Caatinga and Atlantic Forest biomes with distinct floristic composition in the transition areas (ecotones) (Maracahipes et al. 2011, Lima et al. 2015).

Fire can also affect the strata of the flora in different ways. Frequent burnings can damage the woody strata and make the areas more open, decreasing diversity over time (Libano & Felfili 2006). Absence of fire in turn may reduce the diversity of herbaceous savanna specialists plants due to the low light availability promoted by forest canopy (Abreu et al. 2017). The fauna can also be affected in different ways, depending on the taxonomic group and the intensity of the fires. For instance, arthropod abundance can be lower in burned rupestrian fields over two years after a fire event (Anjos et al. 2016). On the other hand, Xenarthrans (*e.g.* armadillos and anteaters) probably use burned areas to obtain food resources such as termites and ants (Prada & Marinho-Filho 2004). Ant diversity is reduced in a fire suppression scenario (Abreu et al. 2017) and lizard abundance responds negatively to both fire suppression and high intensity fires (Sousa et al., 2015). Considering the great heterogeneity within the Cerrado, caution is needed when generalizing conclusions about the effects of fire on the whole biome from studies carried out in restricted regions. This issue is particularly important once studies that evaluate the effect of fire on biotic and abiotic components can promote public policies of fire management within and nearby legally protected areas.

Lastly, the most studied locations are not those where higher fire frequency is observed. Most study sites are in the region of the study author's institution, usually far from the agricultural frontier (e.g., Deforestation Arch and region called MATOPIBA), where the major proportion of fires is observed. This geographic bias in research is concentrated in regions with higher Gross Domestic Product (GDP), such as São Paulo and Federal District, where universities are concentrated (Moerman & Estabrook 2006, Pautasso & McKinney 2007, Boakes et al. 2010, Nabout et al. 2012). Nevertheless, in states where fire events are more frequent (e.g. Tocantins e Maranhão) studies are scarce. Therefore, we assert the need for investment in research in areas with high fire frequency and the need for an increase in knowledge about these effects on the biota.

Conclusion

Despite the increase in the number of articles published about the effects of fire on the Cerrado over the years, the main focus of these studies is on the impacts of fire on vegetation, with an evident gap in knowledge related to animal groups. Most studies are concentrated in few states, particularly those with a lower fire incidence. This shows a clear imbalance in our knowledge about the effects of fire on the Cerrado. In addition, evidence from the literature has shown that the response of biodiversity to fire is context-dependent. In this scenario, the development of public policies for effective and specific fire management would depend on research efforts driven to overcome the spatial bias in knowledge about the effects of fire on the Cerrado.

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CAPÍTULO 2

DIFFERENT BURNING INTENSITIES AFFECT CAVITY UTILIZATION PATTERNS BY ARBOREAL ANTS IN A TROPICAL SAVANNA CANOPY

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Abstract

Fire is a natural disturbance in many ecosystems worldwide, including tropical savannas, where it drives the assembly of animal and plant communities. The effect of fire is often indirect, impacting the availability of essential resources like food and shelter. The Brazilian Cerrado is the largest tropical savanna in the world, and ants comprise a very high proportion of its animal biomass. About one-third of the Cerrado ant fauna actively forages in the canopy. These ants use trees not just in search of food but also as their main shelter resource, as most arboreal ants nest mainly in cavities produced by wood-boring beetles. While it seems clear that fire can have important direct and indirect effects on arboreal ants, the number of studies using an experimental approach focusing on such impacts is relatively few. Here, we aimed to understand the impacts of fire on arboreal ants' usage of shelter resources. Moreover, we also evaluated the potential influence of different fire intensities on these resources' usage. For this, we assessed the colonization rates of experimental cavities under four different burning intensities (in order of intensity): 'control', 'low-intensity', 'intermediate-intensity', and 'high-intensity'. We hypothesized that fire would have a detrimental effect on cavity occupation. This effect would be stronger in higher intensity burns, once they can dramatically decrease the availability of natural cavities and, thus, the abundance and richness of arboreal ants. We also predicted that some ant species would be indicative of different fire intensities, due to differences in heat tolerance and colony size. Our data showed that fire had a major positive effect on experimental cavity use by arboreal ants, with more ant species, more colonized trees, and higher cavity occupation under fire treatments. This effect was higher with the increase of fire intensity. Some ant species were found more commonly on distinct fire treatments, which was mainly due to their different nesting site requirements and colony sizes. Jointly, these results show that fire affects arboreal ant cavity colonization patterns, and that fire intensity is extremely critical in shaping these patterns. Altogether, our work offers important insights for a better understanding of the effects of ecological disturbances on resource use patterns of a highly abundant and diverse organism.

Key-words: canopy ants, biodiversity hotspots, Cerrado, ecological disturbance, fire

1. Introduction

Fire is an important natural disturbance in many ecosystems of the world, and some systems, such as tropical savannas, are a product of frequent fire events (Bowman et al., 2009; Pyne, 1997; Simon et al., 2009). In these biomes, fire influences patterns of biodiversity and drives population dynamics and community assembly of animals and plants (Koltz et al., 2018; Pausas and Keeley, 2019; Pausas and Parr, 2018). The effects of fire disturbance on species assembly patterns can operate at different levels. While it can affect population size by direct mortality, it can also have an indirect effect on population dynamics by impacting the availability of essential resources, and especially food and shelter resources (Andersen, 2018; Fagundes et al., 2015; Frizzo et al., 2012). In many cases, both direct and indirect effects can be acting at the same time and identifying the main cause of changes in species assemblies after fire events is notoriously hard to track.

Some insects, like ants and termites, are responsible for a large portion of the animal biomass of tropical savannas (Andersen 1992; Dawes-Gromadzki 2008) and can be used as biological indicators (Andersen et al., 2012; Cunha, 2006; Hoffmann and Andersen, 2003; Majer, 1983; Tiede et al., 2017) since these highly diverse organisms show fast responses to ecological disturbances (Andersen and Müller, 2000; Eggleton et al., 2002; Hoffmann and Andersen, 2003; Majer et al., 2007). Although fire can have crucial effects on the communities of these insects, the main effects are not through direct mortality, but rather through changes in the habitat, and consequently on resource availability (Costa et al., 2018; Fagundes et al., 2015; Kim and Holt, 2012; Swengel, 2001). Thus, it is expected that those animals that rely directly on arboreal resources may be especially sensitive to fire (Frizzo et al., 2012), and their responses may be idiosyncratic, depending on fire intensity, duration and frequency (Vasconcelos et al., 2017).

The Cerrado is the largest south American savanna and is also the most diverse and threatened of all grassy biomes, and is considered a hotspot of biodiversity (Myers et al., 2000). Ants comprise a high proportion of the animal biomass in this ecosystem, and about one-third of the ant fauna of Cerrado actively forage on trees (Camacho and Vasconcelos, 2015). Cerrado arboreal ants feed on other arthropods and on the sugar-rich liquid food resources produced by sap-sucking hemipterans and extrafloral-nectaries (Ribas et al., 2010; Rico-Gray and Oliveira, 2007). Arboreal ants also use trees as shelter, nesting almost exclusively in abandoned feeding tunnels of wood-boring beetles (Novais et al., 2017; Philpott and Foster, 2005; Powell et al., 2011). Indeed, recent research shows that these shelter resources are very limited for arboreal ants, and may be much more important in determining arboreal ant species assembly patterns than previously thought (Debout et al., 2007; Jiménez-Soto and Philpott, 2015; McGlynn, 2006; Peeters and Molet, 2009; Philpott and Foster, 2005; Powell et al., 2011). Thus, Cerrado arboreal ants are ideal organisms to study the impacts of fire events on resource use and ultimately on arboreal ant species assembly patterns.

Here, we aimed to understand the impacts of fire on arboreal ant usage of essential and limited shelter resources. Moreover, we also assessed the potential influence of different fire intensities on arboreal ant shelter use. For this, we assessed the colonization rates of experimental cavities under four different burning intensities: ‘control’, ‘low-intensity’, ‘intermediate-intensity’, and ‘high-intensity’. We hypothesized that fire would have a detrimental effect on experimental cavity occupation by arboreal ants, with less occupied nests per tree and also a lower number of trees with occupied nests in the fire treatments. Importantly, this effect would be dependent on fire intensity, being stronger in higher intensity burns, once they can dramatically decrease the availability of natural cavities and thus, the abundance and richness of arboreal ants. We also predicted that some ant species would be indicative of different fire regimes, due to differences in heat tolerance and colony size.

2. Materials and Methods

2.1. Study area

This study was conducted on the microregion of Chapada dos Veadeiros (13°33' S, 47°31' W), a 235,000-hectare reserve, located in the Northeast region of the state of Góias, Brazil. This region is characterized by a tropical climate with two well defined seasons: a dry winter (May to September), and a rainy summer (October to April). The mean annual precipitation ranges between 1300 and 1500 mm, and the mean annual temperature is around 25ºC (Antonelli-Filho, 2011). The experiments were performed on the typical Cerrado physiognomy (cerrado stricto sensu), with intermediate canopy connectivity for this ecosystem of between 30 and 50% (Oliveira-Filho and Ratter 2002).

2.2. Fire treatments

The study was conducted in partnership with the Integrated Fire Management Project (MFI). The studied area has been managed since 2014 by the Brazilian Environmental and Renewable Natural Resources Institute (IBAMA), and by the *Quilombola* community (a traditional local community consisting of slave descendants). The main influences on fire intensity are wind speed and wind directions (Cruz *et al.*

2018; Tedim *et al.* 2018), and both factors were taken into account when we have chosen the distinct fire treatments. Four 200 x 200-meter areas were selected, being one control (unburned area), and three with different burning methods and intensities: against the wind (low intensity fire hereafter), L-shaped (intermediate intensity fire hereafter), and circular (high intensity fire hereafter) (Table 1). The burning experiments were performed between July and August of 2017. As is often the case in large-scale manipulative studies, the experimental design has some inevitable limitations, including the small number of replicates per treatment. A massive replication of an experiment in such scale implies in spatial, logistical and monetary constraints.

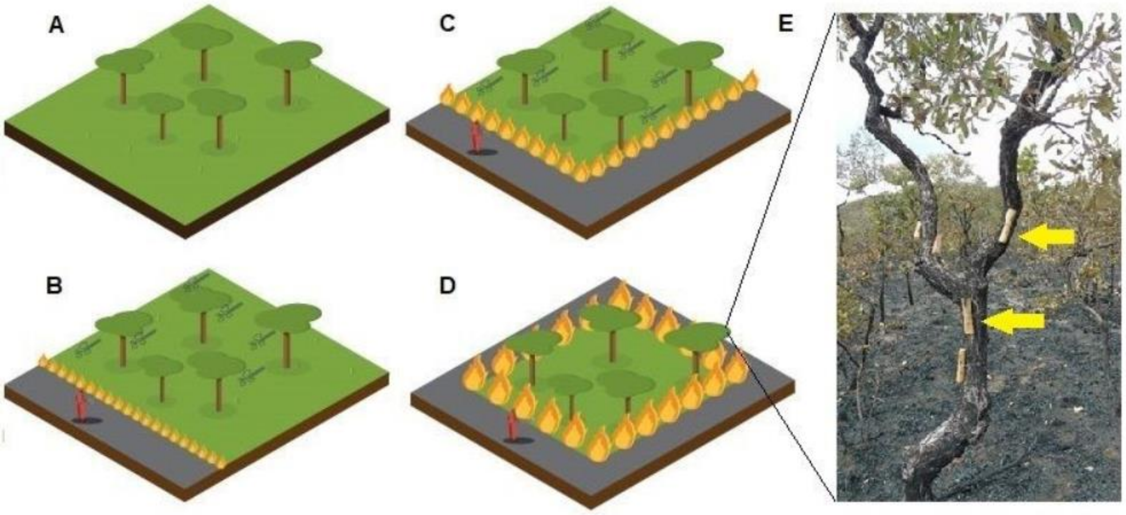

Figure 1: Characterization of the distinct fire regimes (A) Control, (B) Against the wind, (C) L-shaped, (D) Circular, and (E) experimental cavities (arrows) in a burned area.

Table 1: Characterization of the distinct fire regimes by time, height, speed of fires and level of impacts.

Area	Tempo de Queima	Altura	Velocidade	Intensidade
Controle	-	-	-	-
Contra Vento	50 minutos	0,6m	1m/s	Baixa
Em “L”	16 minutos	1,3m	41m/s	Média
Circular	8 minutos	3,05m	83m/s	Alta

2.3. Experimental cavities manipulation

Twenty trees of the species *Qualea parviflora* Mart. were selected in each of the four experimental areas. This tree species was chosen because it is extremely abundant in the study area and is found throughout the entire range of the Cerrado biome (Gonçalves-Alvim et al., 2004). All trees were of medium size (between 20 and 59 cm of breast height diameter) and had a minimal distance of 20 meters between each other, to guarantee the independence between the trees in each treatment.

The experimental cavities consisted of wooden dowels with 10 cm length and a width of 2.5 cm (Figure 1E). Each experimental cavity had an internal cavity of 8 cm in length and 1 cm in diameter (cf. Camarota et al., 2015; Powell et al., 2011), and a lateral entrance hole. Ten experimental cavities of five different entrance sizes (2, 3, 4, 5, and 6 mm) were used on each tree, with two experimental cavities of each entrance size per tree. The different chosen entrance sizes allowed for colonization by species representing a wide range of body sizes (Camarota et al., 2015; Powell et al., 2011). The experimental cavities were wired on the tree from May 2017 to September 2017, totaling four months in the field (two months before and two months after the fire). Ants colonize experimental cavities really quickly, and the period of a few months is more than adequate to capture a high number of nesting species (Powell et al. 2011; Camarota et al. 2015). After the experimental period, the cavities were collected, sealed, and brought to the laboratory, where the ants inside the cavities were counted and identified. The ants were stored in 80% alcohol, and at lab identified at the lowest possible taxonomic level with assistance of specific identification keys (e.g. Baccaro et al., 2015) and by comparison with the collection of Laboratório de Entomologia from Universidade Federal de Viçosa (UFV). At least one ant individual of each occupied nest was pinned and mounted, and these ants are held at the zoological collection of the Universidade Estadual de Goiás.

2.4. Data analyses

To test if there is were differences in ant species richness among the different fire treatments, a Generalized Linear Mixed Model (GLMM) with Template Model Builder and Poisson distribution were used. To assess differences in the number of colonized trees between the different fire treatments, a GLMM was also used, but with a normal binomial distribution. To test if there were differences in the number of colonized experimental cavities per tree and number of ants per experimental cavity among the different treatments, GLMM with binomial distribution was carried out. All analyses above were performed using the R package 'glmmTMB' (Brooks et al., 2017).

In order to identify indicator species for the fire treatments, we performed the Indicator Species Analysis. We used a multilevel approach, where species are tested for their association with each treatment, but also for a set of treatments. The indicated value is the product of two distinct values: *A*, a specificity measure based on species abundance, and *B*, based on species occurrence on each treatment (De Cáceres et al., 2010). *A* is maximum when a given species is present only in one given group, while *B* is maximum when a given species occurs in all different groups. A total of 999 randomizations were performed, and species were considered indicators when $p \leq 0.05$. This analysis was conducted using the 'indicspecies' package in R (De Cáceres and Legendre, 2009). We considered colonization when a minimum of one ant was found inside the wooden dowels. All analyses above were performed in the R software, version 3.4.4 (R Core Team, 2016).

3. Results

A total of 1,281 individuals belonging to 13 species, five genera, and three subfamilies of ants were recovered from the sampled cavities (Table 2). The different burning intensities had significantly different ant species richness (Estimate= 0.257, SE=0.131, p=0.049) (Fig. 2), increasing with the intensity of fire, with the highest number of nesting ant species found in high intensity burn (nine species), and the lowest on the control area (four species).

Table 2: Number of occupied experimental cavities and the species that occupied these cavities on the different fire treatments.

	Cavities occupied by area			
	Control	Low	Medium	High
Formicidae				
Formicinae				
Camponotus arboreus (Smith, F., 1858)	0	7	0	1
Camponotus bonariensis (Smith, F., 1858)	1	0	2	2
Camponotus crassus (Mayr, 1862)	0	0	11	1
Camponotus renggeri (Emery, 1894)	0	0	1	0
Camponostus rufipes (Fabricius, 1775)	0	1	0	1
Myrmicinae				
Cephalotes grandinosus (Smith, F., 1860)	0	0	0	1
Cephalotes betoi (De Andrade & Baroni Urbani, 1999)	9	8	0	5
Cephalotes pallidoides (De Andrade, 1999)	0	1	0	0
Crematogaster sp. 1	0	0	15	20
Solenopsis sp. 1	5	0	2	3
Solenopsis sp. 2	0	1	2	0
Pseudomyrmecinae				
Pseudomyrmex gracilis (Fabricius, 1804)	0	2	0	1
Pseudomyrmex sp. 2	1	0	0	0
Total number of cavities colonized (colonized trees)	16 (7)	19 (11)	33 (9)	35 (14)

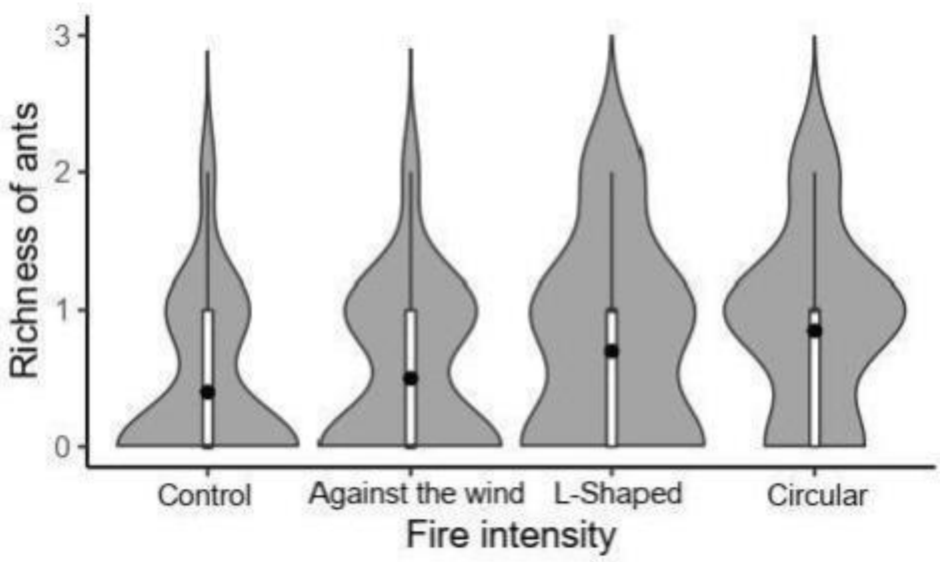

Figure 2: Richness of ant species occupying experimental cavities across the different fire regimes. Surrounding the boxes (shaded area) on each side is a rotated kernel density plot, which is comparable to a histogram with infinitely small bin sizes.

3.1. Colonized trees

We considered as colonization when even a single ant was found inside the wooden dowels. More than half of the experimental trees had colonized cavities (41 trees). However, just in three cases we found larvae and pupae inside these cavities and no queen was registered. Probably, the major part of wooden dowels was colonized by colony partition, when part of a colony moves to a new experimental cavity. The highest number of colonized trees was found in the burned area with high intensity (14 trees), while the smallest was found on the Control area (seven trees). The number of colonized trees was significantly different between the different areas (Estimate=0.478, SE=0.212, p=0.024; figure 3).

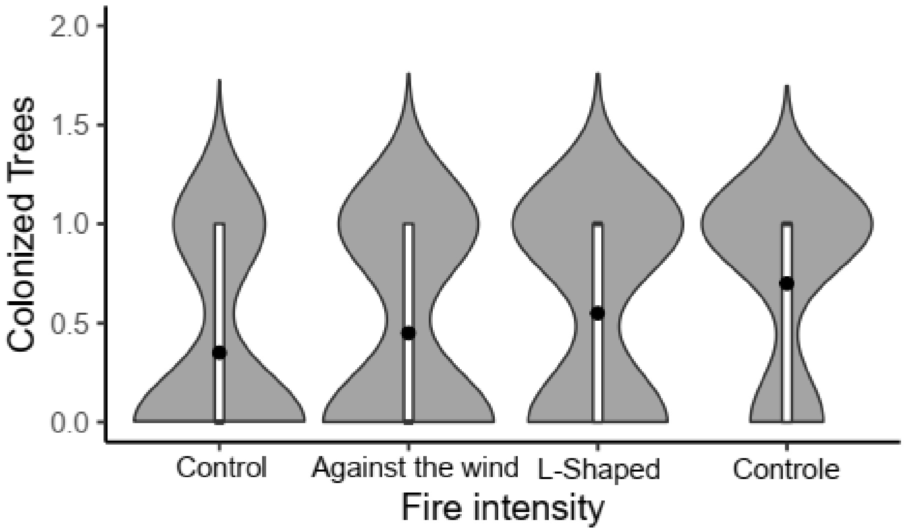

Figure 3: Number of colonized trees across the different fire regimes. Surrounding the boxes (shaded area) on each side is a rotated kernel density plot, which is comparable to a histogram with infinitely small bin sizes.

3.2. Experimental cavities

Of all 800 experimental cavities, 104 were occupied by ants. The highest number of occupied cavities was found in the burned area with intermediate intensity (35 experimental cavities), and the smallest on the control (16). The number of occupied cavities was significantly different between the areas (Estimate=0.294, SE=0.133, p=0.027; figure 4).

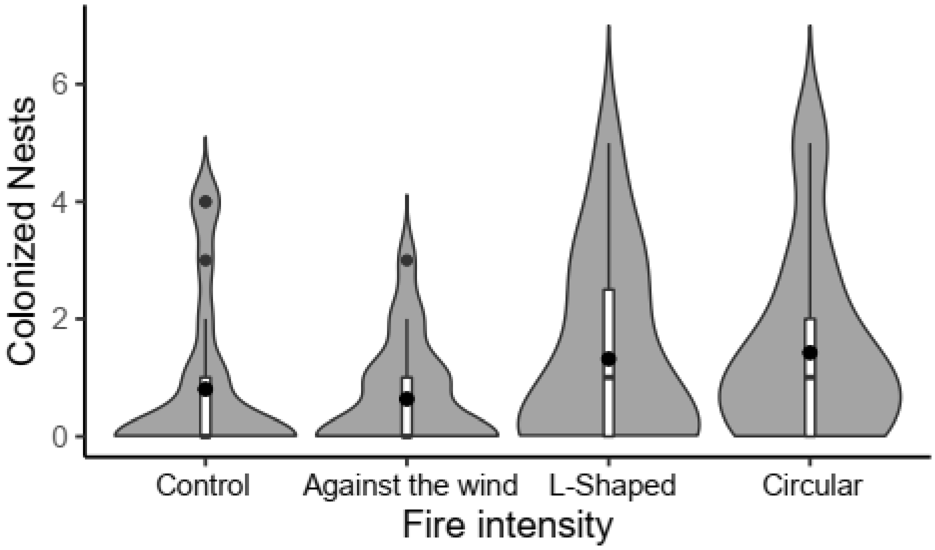

Figure 4: Number of occupied experimental cavities across the different fire regimes. Surrounding the boxes (shaded area) on each side is a rotated kernel density plot, which is comparable to a histogram with infinitely small bin sizes.

3.3. Number of cavity occupants

There was a large amplitude in the number of occupants on a cavity (from one to 120 occupants), with a significant effect of the fire regime (Estimate=0.220, SE=0.825, p=0.007; figure 5). The highest number of number of occupants was found in the burned area with low intensity (421 experimental cavities), and the smallest on the control (169).

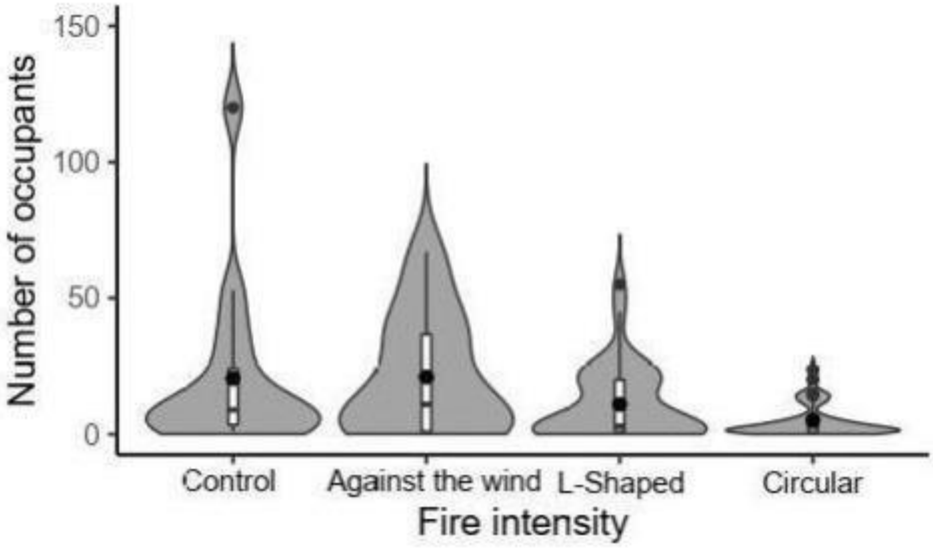

Figure 5: Number of ant occupants on experimental cavities across the different fire regimes. Surrounding the boxes (shaded area) on each side is a rotated kernel density plot, which is comparable to a histogram with infinitely small bin sizes.

3.4. Indicator species

Of all the ants found occupying our experimental cavities, three species had different responses to the fire regimes. The species *Cephalotes betoi* was found significantly more in the Control and low intensity fire areas (A=0.849, B=0.437, Stat=0.61, P= 0.042) *Camponotus crassus* was a medium intensity fire indicator (A=0.928, B=0.363, Stat= 0.581, P= 0.03), and *Crematogaster* sp. 1 of the high intensity fire (A=1, B= 0.375, P= 0.045).

4. Discussion

Here, we have shown that fire has a significant positive effect on experimental cavity use by arboreal ants, with more ant species, more colonized trees, and higher cavity occupation under fire treatment. The positive effect of fire was modulated by its intensity, with higher species richness and number of overall trees colonized in high-intensity fire. Moreover, there were higher cavity occupation rates under fire with intermediate intensity. In the absence of fire, ant species richness and number of colonized cavities were consistently lower. Interestingly, fire had a negative effect on the number of ants per occupied cavity, which was significantly lower as the fire intensity increased. As expected, some ant species were indicative of the distinct fire intensities. Jointly these results show that fire intensity is an important factor affecting arboreal ant cavity colonization patterns, offering a better understanding of the effects of ecological disturbances in ant communities.

The number of studies assessing the effects of fire on ant communities is considerable, and has been increasing over the last decades (Folgarait, 1998; Philpott et al., 2010; Vasconcelos et al., 2017). However, the vast majority of these studies are focused on ground foraging ants, and there is still a need for much more information on the effects of fire on arboreal ant assemblages (Vasconcelos et al., 2017). The lack of information on arboreal ants is especially true for the Brazilian savannas, which have a much higher ant diversity than other tropical savannas (Campos et al., 2011). Despite the consensus that fire is more detrimental for arboreal dwelling ants than ground-nesting ants, it seems that the scenario may be as complicated as it is for ground ants. While some studies found a negative impact on ant species richness and cavity colonization patterns (Frizzo et al., 2012; Morais and Benson, 1988), others failed to detect significant changes on cavity colonization rates due to fire events (Fagundes et al., 2015). Even when an effect is detected, it may be temporary, with a quick recovery of the ant community after some time (Costa et al., 2018). Moreover, an experimental approach is still pretty rare in the literature of fire disturbances for tropical arboreal ants (e.g. Fagundes et al. 2015).

Fire can have a marked effect on vegetation structure (Ratchford et al., 2005; Andersen et al., 2006), and this can constrain the availability of nesting sites for arboreal ants (Frizzo et al., 2012; Maravalhas and Vasconcelos, 2014). Indeed, the effects observed in our study may be due to a deleterious effect of the fires on the existing nesting resources available for the arboreal ant community. Therefore, the negative impact of fire on resource availability may have been more important for the observed cavity occupation patterns than ta direct effect of fire on the ants. Thus, the higher species richness in the high-intensity fire could likely be due to the fact that the experimental cavities were one of the few good quality resources available right after the fire. The fact that we observed high colonization rates after fire events can be an indication of a smaller availability of nesting sites within the burned area, which forced some colonies to use the few cavities available after the fire. The smaller availability of nesting sites would be especially true for the high intensity fire regime. Thus, the higher ant species number and number of trees colonized in the high-intensity fire could be indicating nest relocations within the colony. Confirming this, we observed more ant individuals using the natural nests when fire was of low intensity or in the absence of fire. In this case, the experimental cavities were less attractive to the ants, due to the higher availability and heterogeneity of natural nests. Thus, the ants using the experimental cavities were presumably those species with specific nesting requirements, that were mirrored on the experimental range of entrance sizes. Nesting sites for arboreal ants in the Cerrado can be quite diverse (Priest et al. *unpublished data*), and there can be variation in the quality of these resources (Camarota et al., 2016). Some nests are located on thick live wood, which means that they are very resistant to fire and that the colony inside is safer. Other nests are located on terminal tips of stems and branches, which are much more fragile and prone to disturbance (Camarota et al., 2016). Thus, it is possible that those species with larger colonies did not go locally extinct, maintaining the core nest of the colony while losing smaller satellite nests.

Different ant species often have distinct responses to fire events, and some species can decrease drastically in abundance, or even vanish from burned areas altogether (Andersen, 1991; Farji-Brener et al., 2002). However, some species of ants may benefit from fire events, like savanna-adapted species that increase their range after fire events in Australian tropical forests (Andersen et al., 2006). We found that three ant species (*Cephalotes betoi*, *Camponotus crassus*, and *Crematogaster* sp.1) had a strong relationship with a given fire regime, including the fire absent regime. These three species are numerically dominant in the study area (Arruda et al. *unpublished data*), and their significant presence on different fire intensities may be related to their colony nesting strategies. Numerically dominant arboreal ant species usually have large and polydomous colonies, with satellite nests spread all over the tree that the colony inhabits (Debout et al., 2007). This is the case for *Crematogaster* sp. 1, which has extremely populous colonies and occupies a large area of their host tree (Camarota et al., 2016). While

Cephalotes betoi does not have colonies as large as *Crematogaster* sp. 1, it still has a relatively large number of individuals on a single colony, with satellite nests spread all over the tree. On one hand, it is possible that fire has partially destroyed the colonies of *Crematogaster* sp. 1, and that their higher colonization of experimental cavities is a consequence of their search for suitable nesting sites. On the other hand, a higher intensity fire would lead to the local extinction for *C. betoi*, which have much smaller colonies and usually nest on lower quality cavities available on the trees. The finding that *C. crassus* was found more in an intermediate fire regime could be related to the fact that *C. crassus* do also nest on the litter, especially in twigs, which may have been depleted in a moderate intensity fire (Vasconcelos et al., 2009). In the low-intensity fire, their natural nesting resources (i.e. twigs) were still relatively abundant, while in the high-intensity fires they would be completely extirpated.

In our study, we have shown that there are differential effects of distinct fire regimes on arboreal ant colonization of experimental cavities. This work it is not the first showing the impact of fire on cavity colonization (e.g. Fagundes et al., 2015; Morais and Benson, 1988), but is the first assessing the differential effects of fire intensity on colonization patterns. We hope that our data helps to provide insight into the indirect effect of disturbances on the ant resource usage. These insights would help in fostering better policies concerning fire management and a new view on such important and ancient disturbance patterns.

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CAPÍTULO 3

FIRE AND FLOOD: HOW THE PANTANAL ANT COMMUNITIES RESPOND TO MULTIPLE DISTURBANCES

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Abstract

Environmental disturbances are key events in ecological systems and can cause impacts at different temporal and spatial scales. Many areas are affected by different disturbances and the interaction between them can have null, dominant, multiplicative, additive, synergistic and antagonistic effects. In this study, we evaluated the effect of different disturbances (fire and flood) on the richness and composition of ant species at different temporal scales (short-, mid- and long-term). Samplings were performed in the floodplain of Cuiabá River, in the Pantanal area of Poconé, Mato Grosso, Brazil, ten days (short-term), one year (mid-term) and four years (long-term) after the fire event. Twenty-four sampling points were distributed in areas with and without fires and at different elevations, associating different levels of flood influence. Results showed a short-term fire effect on species richness and composition, however, these effects tended to decrease in the medium term and disappear in the long term. Elevation not influenced ant communities, indicating a dominant effect of fire on ant communities in flooded areas.

Keywords: Disturbance interactions; flood periods; wetlands; ant richness; ant composition.

1. Introduction

Natural or anthropogenic environmental disturbances are key events of terrestrial and aquatic ecological systems and influence the structuring of populations, communities and ecosystems (Mouillot *et al.* 2013). Their effects on communities can be found at different temporal and spatial scales (Whites & Picketta 1985; Turner 2010). The type, frequency, and intensity of disturbances determine the extent to which communities are affected and their ecological resilience (Gentry 1992; Tanentzap *et al.* 2014; Radchuk *et al.* 2019). The resistance and resilience of communities to disturbances also vary among taxonomic groups, reinforcing the context-dependency of biological responses to disturbances (Donohue *et al.* 2016; Garnier *et al.* 2017). Despite the importance of disturbances for community organization and the variety of biological responses, most studies are limited to immediate temporal effects and focus on determining the effects of disturbances in isolation, neglecting their interactive effects (Kéfi *et al.* 2019).

The effects of different disturbances on biological communities can be classified as dominant, multiplicative and additive when evaluated independently or as synergistic or antagonistic when considered interactively (Côté *et al.* 2016). Synergistic disturbances when combined have a greater impact than isolated disturbances and antagonistic disturbances produce smaller effects than in isolation (Folt *et al.* 1999; Côté *et al.* 2016).

We assume that the majority of disturbances with potential for changing the biological patterns do not occur in isolation(Crain *et al.* 2008; Graham *et al.* 2011). Among the disturbances often studied in isolation are the floods (Lake 2000; Oliveira *et al.* 2014; Poff *et al.* 2018) and fires (Verkaik *et al.* 2015; St. Clair *et al.* 2016; Karavani *et al.* 2018). These disturbances are oftentimes associated with the expansion in human activity, the increase in the number of anthropogenic fires and the climate change and thus, studies evaluating the response of communities to the combination of these disturbance are necessary (Oliveira *et al.* 2014; Paolucci *et al.* 2016; Power *et al.* 2016; Heim *et al.* 2019).

Floodplains are riverbank ecosystems that are subject to periodic flooding during the rainy season. They have high productivity and rich biodiversity that support indispensable ecosystem services locally, regionally and globally (Tomas *et al.* 2019). Previous studies have shown that the period these areas are flooded, which may indicate the disturbance intensity, directly impacts terrestrial communities (Tanentzap *et al.* 2014; Poff *et al.* 2018; Röhl *et al.* 2018; Duong *et al.* 2019). Rainfall has an important effect on floodplain communities, yet there is growing evidence in the literature that other disturbances, such as fire, also have significant effects on these ecosystems (Kleindl *et al.* 2015). Fires have become frequent over time, mainly those of anthropic origin (Oliveira *et al.* 2014; Arruda *et al.* 2018). For example, in the Pantanal biome, which is one of the largest continuous freshwater floodplains in the world (Harris *et al.* 2005), fires are conducted by cattle breeders as a strategy of pasture management (Seidl *et al.* 2001; Junk *et al.* 2006). Unlike floods, the occurrence of fires is unpredictable temporally and can vary widely in space. Thus, the terrestrial organisms of these floodplains are subject to both disturbances, in which the consequences for the organization of their communities are still poorly understood. In this paper, we evaluate the effects of interactions between these disturbances at different temporal scales, using the ant communities as a model.

Ants are widely used to evaluate the effect of environmental disturbances (Majer 1983; Andersen 1999; Andersen & Majer 2004; Underwood & Fisher 2006) and their responses to different impacts can vary at different temporal and spatial scales (Andersen 1991, 1999; York 2000; Parr *et al.* 2004; Maravalhas & Vasconcelos 2014). For example, studies have shown that the fire changes the structure of ant communities in the long term (Parr *et al.* 2004; Maravalhas & Vasconcelos 2014). However, fast community recovery has been observed in other studies in savannas and Australian semiarid regions (Parr & Andersen 2006; Andersen *et al.* 2014; Farnsworth *et al.* 2014). In floodplains such as the Brazilian Pantanal, ants of flood zones are constantly subjected to flood disturbances (Ribas & Schoereder 2007; Dambros *et al.* 2018). Depending on the elevation of a given location, the flood period may vary from days to months but are predictable occurring seasonally (Junk *et al.* 2006). In this sense, we expect the fire effect to be punctual and to disappear over time, while the flood effect to be constant, thus: 1) the effects of both (flood and fire time) will act synergistically in the short term post-fire, positivamente affecting the number of local species and changing the ant community composition; 2) in the medium term post-fire, we still expect a synergistic effect, but with less fire effect on the community richness and composition; 3) in the long term post-fire, the community will stabilize, without observing the fire effects, only the flood effect in determining community richness and composition (Figure 1).

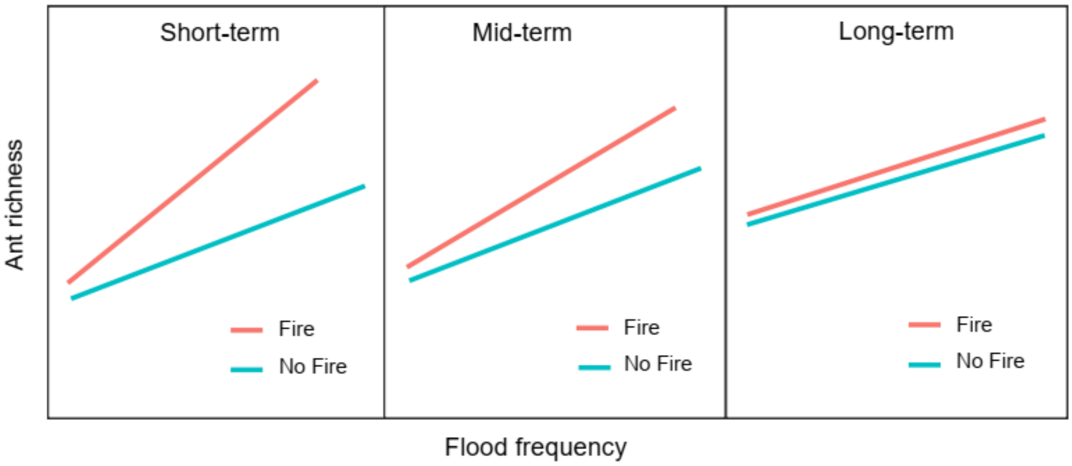

Figure 1: Conceptual diagram showing predictions about the relationship between species richness and multiple disturbances (flood and fire) at different time scales: a) in the short term, we predict that the disturbances will have synergistic effects; b) in the medium term, will also be synergistic with low fire effect; c) in the long term, the flood effect will be dominant.

2. Materials and Methods

2.1. Study area

Samplings were carried out in the São Sebastião do Borba farm (16°40'15.92"S, 56°28'24.44"W), located in the municipality of Poconé, State of Mato Grosso, Brazil. The farm is located in the floodplain of the Corumbá River, in the Pantanal area of Poconé (Figure 2). The Pantanal has a distinct seasonality and a slightly variable topography (Hasenack et al., 2003). In the study area, the highest flooding level occurs between January and February, having the full flood with a water depth of approximately 90 cm (Nunes da Cunha & Junk 2001, 2004). The difference between areas that remain flooded for a few days or months is determined by a few inches in the relief (Junk *et al.* 2006).

The vegetation consists of several mixed forest habitats and a seasonally flooded mosaic. Native fields are dominated by species of the genus *Combretum* (Nunes da Cunha & Junk 2001; Junk *et al.* 2006). These shrubs impose difficulties on cattle breeding and often the management of these shrubs and pasture formation is conducted using fire, even though this practice is illegal (Junk & Nunes da Cunha 2012). Fire often spreads reaching other adjacent areas, resulting in fires in native vegetation areas (Layme *et al.* 2012).

We evaluated the effects of flood and fire through the comparison of areas with different fire histories (short-, mid- and long-term), throughout an altitudinal gradient of the ground, which can be interpreted as the period the ground was flooded, where low areas remained flood for more time than the highest areas. We also tested different datasets to test the effects of short-, mid- and long-term fires. The fire history in this region has been known for the last eight years due to long-term projects being carried out in the study area (Layme *et al.* 2012; Candelária *et al.* 2016). In this period, specifically in the dry seasons of 2010, 2011 and 2015, illegal fires reached the study area and provided data collection for this study.

We performed three samplings of ant communities, of which two were in October 2015, with the first before a fire in the region (2015 pre-fire) (n=24) and the second 10 days after the fire (2015 post-fire) (n=10). The decrease in the number of samples was due to logistical constraints. The third sampling was performed in October 2016 (2016 post-fire) (n=24), a year after the 2015 fire. These points are distributed within an area of approximately 1500 ha, with an average distance of 450 m between adjacent points (Max: 625 m; Min: 130 m). At each point, we installed 10 pitfall traps at least 20 meters apart, within a 60 x 80 m plot. These pitfall traps were plastic containers of 500 ml (15 cm in diameter) containing about 50 ml of water and mild detergent. The traps remained active in the field for 48 hours. For each sampling point, we measured the terrain altitude above sea level using the Garmin GPS model GPSMAP 64. The measurements were posteriorly double-checked using satellite images (Landsat 8) analyzed by the QGIS Development Team, 2019. The sampling points had altitudes ranging from 118 to 123 m, which represents a considerable variation within the range predicted for local studies in the Pantanal (Junk *et al.* 2006). The elevation of sampling points was used as a proxy to infer the flood period, assuming that higher areas are less subject to flooding. Importantly, we sampled 13 areas at lower altitudes (118, 119, and 120 m) and 11 areas at higher altitudes (121 and 122 m), thus, our areas are well distributed regarding their altitudes. Besides, it is important to highlight that all sampled areas flood every or almost every year. All ants collected were identified at the genus level using a Brazilian ant genus key (Baccaro *et al*. 2015), then assigned a sequential morphospecies code or valid species name whenever possible. The specimens were deposited in the Zoological Collection of the Universidade Federal de Mato Grosso, Cuiabá, Brazil.

Short-term effect: We used the data of 2015 post-fire sampling to test the short-term effect after the fire. We selected 10 points located in areas burned 10 days before (n

= 5) and in unburned areas (n = 5). The points composed of both groups do not differ on the history of fire incidents since 2010, where none of the points burned twice in 2010 and 2011 or has been burned since 2012.

Mid-term effect: We used the 2016 post-fire data, a year after the last fire in the area. For this, we compared the community patterns among the points burned a year before (n = 14) and unburned points (n = 10)

Long-term effect: To evaluate the long-term effect, we used the data obtained in 2015 before the fire (2015 pre-fire) and compared the ant community patterns among points located in burned areas (n = 14) and unburned areas (n = 10) by the fires of 2010/2011.

2.2. Data analysis

We performed three Analysis of Covariance (ANCOVA) corresponding to each temporal scale independently, to evaluate the variation in the number of species in relation to the terrain elevation (continuous variable) and fire occurrence (categorical variable). Since we have 10 pitfall traps (subsamples) in each sample, the frequency of occurrence of each species in subsamples varies from 0 to 10 and was used as a covariable. The frequency of local occurrence has been incorporated into the analysis to allow exploring the mechanisms underlying the variation in species richness, since increased species richness may be an artifact of increased ant displacement, increasing their capturability. With the vegetation burning, there is a clear structural simplification (or roughness reduction) of the environment after the fire, which would facilitate to forage (Fewell 1988; Parr *et al.* 2007).

We used a Permutational Multivariate Analysis of Variance (PERMANOVA) using 999 permutations to test whether there is an effect of fire (with and without fires as levels) and flood (elevations of points as levels) on the species composition for each of the temporal scale individually. The PERMANOVA was performed using dissimilarity matrices (Bray Curtis coefficient) of the composition and abundance of species obtained from the abundance matrix after Hellinger transformation as response variables. To visualize the results, we use the ordination biplot produced by the Non-Metric Multidimensional Scaling (NMDS). All analyses were performed in the R software (R Core Team 2016).

3. Results

3.1. Richness

We found a total of 64 ant species distributed into 26 genera and seven subfamilies (see Table S1, Supplementary Material). In the short term, the richness was influenced by the fire ($F_{1,4}$= 14.994, p= 0.0180) and by the local frequency of occurrence ($F_{1,4}$= 19.130, p= 0.0107), but not by the terrain elevations ($F_{1,4}$= 3.850, p= 0.1212) (Figure 3). The richness was greater in points subjected to fire and with higher frequency of occurrence that in unburned points with lower frequency of occurrence, regardless of elevations. In the medium and long term, only the frequency of occurrence has influence on species richness ($F_{1,18}$= 78.649, p< 0.01; $F_{1,18}$= 112.729, p< 0.001, respectively), without effect of fire ($F_{1,18}$= 0.073, p< 0.791; $F_{1,18}$= 0.938, =0.3457, respectively) or flood ($F_{1,18}$= 2.247, p=0.151; $F_{1,18}$= 3.294, p=0.0862, respectively) (Figure 2).

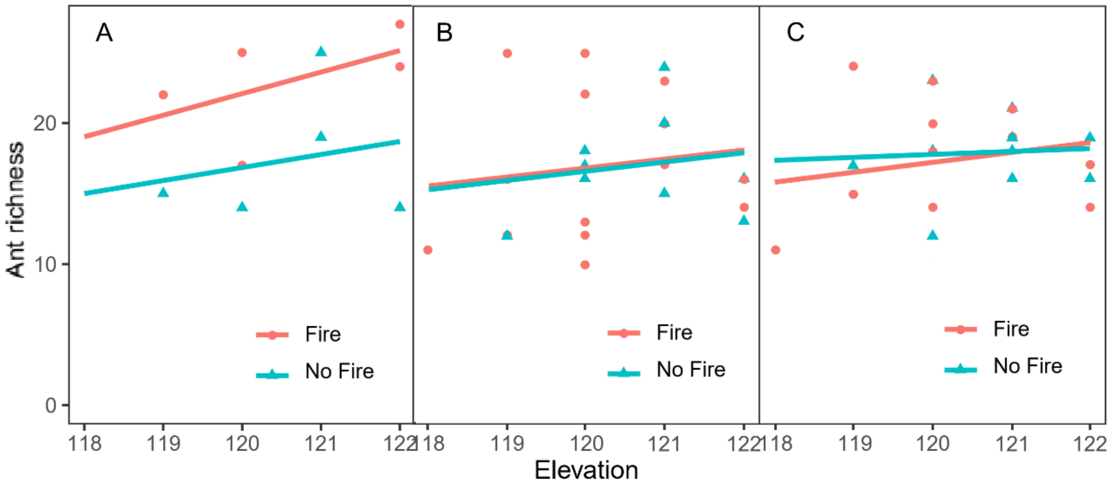

Figure 3: Relationship between species richness and flood disturbances (elevation as proxy) and fire: in short term (a), dominant effect of fire on species richness; in medium (b) and long term (c), none of the predictor variables influenced species richness.

3.2. Composition

Species composition was influenced by short- and mid-term fire (R^2 0.181, p= 0.019; R^2 0.09, p= 0.007, respectively), but not the long-term (R^2 0.090, p= 0.007) (Figure 4). The flood, inferred by the elevation, did not influence the species composition at the three spatial scales (short-, mid- and long-term) (R^2 0.125, p= 0.234; R^2 0.034, 0.557; R^2 0.055, p= 0.185, respectively) (Figure 3, see Table S2, Supplementary Material).

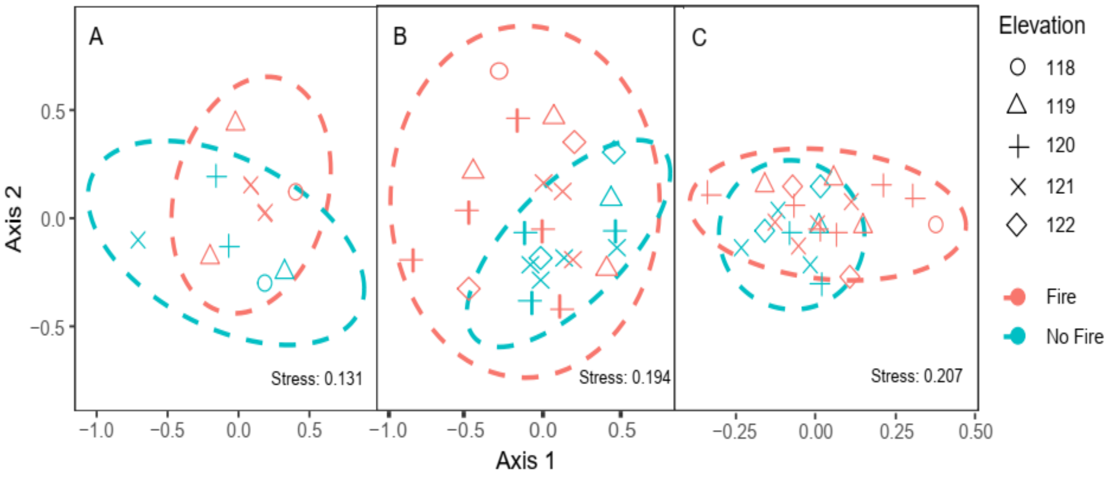

Figure 4: Ordination biplot obtained by the Non-Metric Multidimensional Scaling (NMDS) evidencing the sampled points regarding the fire and flood inferred by elevation, in short (a), medium (b) and long (c) term.

4. Discussion

In this study, we have unprecedentedly evaluated the relationship between the fire and flood disturbances in ant communities. Unlike what we expected, we found no synergistic effect between fire and flood. Ten days after the fire, we observed a dominant effect of fire, with an increase in the number of ant species in burned areas. However, the effect of fire is captured only by the mid-term species composition and tends to disappear completely after one year. Our results indicate that fire is a major disturbance in floodplains, but its effects are temporary. This suggests that fire events, at the frequency observed in this study, do not cause changes at local scale extinction and colonization rates, but serve as barriers modifier, increasing ant displacement or capturability and momentarily increasing the community richness of burned sites.

The short-term fire effect was characterized as dominant, i.e., the effect of fire did not show any positive or negative interactions with the flood (Côté *et al.* 2016). Rather, the effect of fire associated with the flood was equal to the fire effect (dominant factor) measured in isolation (Folt *et al.* 1999). Some previous studies have described the effects of dominant disturbances. These studies show results regarding bioactive metals traces on ocean productivity (Bruland *et al.* 1991), the relationship between nutrients and productivity of deciduous forests (Vadeboncoeur 2010), and the relationship between dominant disturbances and invasive species (Tanentzap *et al.* 2014). However, our results demonstrate the dominant effect of occasional anthropogenic disturbance (fires) over natural and predictable disturbance (floods), showing resilience over time towards stability when the effect of fire becomes neutral.

Increasing species richness in short-term burned areas may be misinterpreted as beneficial to ant communities. However, fire causes several indirect impacts (Morais & Benson 1988; Parr & Andersen 2008; Andersen 2018), affecting habitat structuring and the availability of resources used by ants (Andersen *et al.* 2012; Frizzo *et al.* 2012; Fagundes *et al.* 2015; Vasconcelos *et al.* 2017; Andersen 2018). The increase in ant richness in the burned areas may be related to the structural simplification of the habitat and the change in surface roughness due to burning the aerial parts of plants and the litter, exposing the soil where the pitfall traps were placed. Simplification increases the capacity and the need to forage the soil ants and vegetation (Fewell 1988; Parr *et al.* 2007). Due to decreasing obstacles and diminishing resources, ants concentrate their activities on the ground, resulting in greater capturability. In fact, the greater ant richness was correlated with the frequency of occurrence, which in turn is higher in short-term burned areas. Thus, the increased displacement in the burned areas may have contributed to the higher number of ants in the burned areas. This mechanism may be observed in other terrestrial organisms that move primarily on the ground and secondarily on low vegetation.

In contrast to fire, we did not detect any effect of flood period on species richness and composition at any time scale. We expected that the lower areas that remain longer flooded would have lower species richness because they had a shorter emergent period available for ant colonization (Tanentzap *et al.* 2014). However, our results suggest that ant communities rapidly colonize post-flood areas. Probably, species found in flooded areas are a random subgroup of common species in adjacent non-flooded Cerrado areas. However, further studies comparing flooded and non-flooded communities need to be undertaken to answer this question (e.g. Ribas & Schoereder 2007; Meurer *et al.* 2015), since the present study was limited to flooded areas at different periods.

Ant species resilience to floods can be interpreted as a result of adaptations of the community species to a natural and cyclical disturbance (Orians 1975). However, the communities showed low resistance to less predictable anthropogenic disturbances such as fires. Despite the low resistance, the results show that the communities returned to their original state after one year, indicating resilience to fires. These results have implications for biomonitoring: ant communities are able to capture the signal of fires regardless of flood exposure, but only in the short and medium term. For sampling purposes in fire-free areas, the interval of one four after the fire disturbance would be sufficient.

Although many studies conclude that disturbances are important for community structuring, few have evaluated how natural and anthropogenic disturbances can interact in structuring them at multiple time scales. This gap can be explained by the complexity of experiments with this approach (Kéfi *et al.* 2019). Our results show that fire (anthropogenic effect) tends to have a dominant effect on the structuring of communities in the short and medium term. Flooded areas have low fire resistance and high flood resistance. However, the effect of fire tends to disappear indicating that wetland ant communities are resilient to fire. The wetland ant communities in the Pantanal seemingly consist of ants with high habitat colonization capacity that become seasonally available.

Unpredictable anthropogenic disturbances (fires) have a dominant effect on this community at the studied spatial scale.

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Supplementary Material

Tabela S1: Records of occurrences of the 64 species collected at 24 sampling sites at three different time scales related to burns (short term, medium term and long term) in Poconé, Mato Grosso do Sul, Brazil.

Formicidae	Short term		Medium term		Long term	
	No Fire	Fire	No Fire	Fire	No Fire	Fire
Dolichoderinae						
Tribe Dolichoderini						
Azteca sp. 2	0	0	0	0	0	1
Dolichoderus bispinosus (Olivier, 1792)	3	6	4	0	2	6
Dolichoderus lujae Santschi, 1923	0	0	0	0	0	2
Dolichoderus diversus Emery, 1894	0	0	0	0	0	1
Linepithema sp. 1	4	0	4	18	5	8
Tribe Ecitonini						
Eciton vagans (Olivier, 1792)	1	1	0	0	0	0
Neivamyrmex gibbatus Borgmeier, 1953	4	4	1	6	8	6
Neivamyrmex sp. 2	0	0	1	1	0	0
Neivamyrmex pilosus (Smith, 1858)	0	0	1	3	0	0
Tribo Tapinomini						
Tapinoma melanocephalum (Fabricius, 1793)	0	0	3	0	1	3
Ectatomminae						
Tribe Ectatommini						
Ectatomma brunneum Smith, 1858	32	29	27	47	37	57
Ectatomma sp. 2	0	0	0	0	1	1
Gnamptogenys moelleri (Forel, 1912)	0	11	7	10	2	13
Gnamptogenys sulcata (Smith, 1858)	0	1	0	0	0	0
Formicinae						
Tribe Camponotini						
Camponotus leydigi Forel, 1886	1	9	9	20	8	6
Camponotus crassus Mayr, 1862	6	16	20	19	18	22
Camponotus sp. 2	0	2	6	7	4	5
Camponotus melanoticus Emery, 1894	10	9	34	36	22	15
Camponotus rufipes (Fabricius, 1775)	9	24	17	28	30	27
Camponotus sexguttatus (Fabricius, 1793)	3	6	10	6	9	6
Camponotus sp. 3	0	0	8	5	1	4
Tribo Myrmelachistini						
Myrmelachista sp. 1	0	0	0	1	1	2
Tribe Plagiolepidini						
Brachymyrmex sp. 1	0	5	5	22	6	15
Nylanderia sp. 1	9	22	8	14	6	25
Nylanderia sp. 2	0	0	0	0	1	0
Nylanderia sp. 3	1	1	2	1	0	0

Nylanderia fulva (Mayr, 1862)	5	8	20	41	11	30
Mymicinae						
Tribe Attini						
Acromyrmex sp. 1	2	21	0	11	3	8
Acromyrmex sp. 2	0	0	0	0	1	0
Cyphomyrmex sp. 1	0	0	0	0	9	8
Cyphomyrmex sp. 2	3	6	3	8	0	0
Cyphomyrmex (gr.rimosus) sp. 3	0	0	0	0	0	1
Trachymyrmex sp. 1	0	0	0	2	0	0
Trachymyrmex sp. 2	0	0	0	0	1	0
Tribe Blepharidattin						
Blepharidatta brasiliensis Wheeler, 1915	0	0	0	0	1	0
Wasmannia auropunctata (Roger, 1863)	20	13	20	30	27	33
Tribe Cephalotini						
Cephalotes pusillus (Klug, 1824)	6	11	20	21	21	36
Cephalotes atratus (Linnaeus, 1758)	1	1	0	1	0	0
Cephalotes minutus (Fabricius, 1804)	0	2	1	0	0	0
Procryptocerus sp. 1	0	0	0	1	0	0
Tribe Crematogastrini						
Crematogaster distans Mayr, 1870	4	9	22	35	12	13
Crematogaster obscurata Emery, 1895	6	5	5	6	4	5
Crematogaster sp. 3	0	0	0	0	0	3
Crematogaster sp. 4	4	0	0	2	2	0
Tribe Pheidolini						
Pheidole sp. 1	8	2	7	8	3	8
Pheidole transversostriata Mayr, 1887	6	7	12	15	32	32
Pheidole sp. 3	4	10	0	0	0	0
Pheidole sp. 4	0	0	2	21	1	7
Pheidole fimbriata Roger, 1863	0	0	0	1	0	1
Pheidole (complex radoszkowskii) sp. 5	10	23	41	52	38	75
Tribe Solenopsidini						
Solenopsis sp. 1	3	5	0	20	3	5
Solenopsis sp. 2	22	15	34	60	41	53
Solenopsis sp. 3	0	1	0	1	0	0
Ponerinae						
Tribe Ponerini						
Hypoponera sp. 1	1	4	0	4	0	0
Hypoponera sp. 2	0	0	0	8	0	0
Leptogenys sp. 1	0	2	1	1	1	1
Odontomachus sp. 1	14	9	36	15	34	35
Odontomachus sp. 2	0	0	0	0	2	0
Odontomachus sp. 3	0	0	0	0	0	1
Pachycondyla harpax (Fabricius, 1804)	0	2	26	2	5	4
Pseudomymecinae						

Pseudomyrmex termitarius (Smith, 1855)	9	8	41	22	28	9
Pseudomyrmex aff. *Flavidulus* (Smith, 1858)	0	1	0	2	1	2
Pseudomyrmex gracilis (Fabricius, 1804)	1	1	3	3	0	2
Pseudomyrmex pallidus (Smith, 1855)	0	0	0	1	0	0

Tabela S2: Summary of PERMANOVA. Variation of ant species composition in habitats with different levels of disturbance (fire and flood) at different time scales related to burning (short term, medium term and long term).

Short term			
	F.Model	R2	Pr(>F)
factor(elevation)	1.3364	0.12568	0.234
factor(fire)	1.9283	0.18135	0.019*
factor(elevation):factor(fire)	1.3687	0.12871	0.204
Residuals		0.56426	
Meduim term			
	F.Model	R2	Pr(>F)
factor(elevation)	0.88521	0.03496	0.557
factor(fire_2015)	2.29732	0.09073	0.007 *
factor(elevation):factor(fire_2015)	1.13659	0.04489	0.333
Residuals		1	
Long-term			
	F.Model	R2	Pr(>F)
factor(elevation)	1.31593	0.05536	0.1858
factor(fire_history)	0.95492	0.04017	0.5035
factor(elevation):factor(fire-history)	1.49971	0.06309	0.1049
Residuals		0.84138	

CONSIDERAÇÕES FINAIS

Nessa tese, realizada em dois Biomas savânicos Brasileiros: o Cerrado e o Pantanal, direcionamos o foco para o uso do fogo no manejo de áreas naturais. Ambos os biomas são influenciados sazonalmente pelo fogo, mas que recentemente experimentaram queimas extensivas de sua área. Especificamente para o Cerrado, por ser mais estudado nessa temática, buscamos compreender o atual estado da arte dos estudos com fogo e preencher algumas lacunas apontadas pelos sequentes trabalhos empíricos realizados para essa tese.

Nós observamos que existem estudos relacionados as queimadas no bioma Cerrado e que existe uma tendência de aumento no número de publicações ao longo dos anos. Porém, como a imensa maioria (75%) dos estudos estão relacionados a plantas, o efeito das queimadas nos diferentes táxons de animais e microrganismos do Cerrado e, principalmente, interações biológicas, vem sendo negligenciados. Também, a distribuição dos estudos e da realização das queimadas não é coincidente. O número de queimadas é maior na região do Arco do desmatamento, a nova fronteira agrícola do Brasil que corresponde à fronteira da Amazônia e o Cerrado. Entretanto os maiores números de estudos com fogo no Cerrado estão concentrados em regiões próximas aos grandes centros urbanos e nos estados mais ricos, ou seja, com os maiores produtos bruto (PIB). Devido à grande extensão do Cerrado e sua biodiversidade a concentração de estudo pode se restringir a padrões locais e que não poderão ser utilizados para inferências regionais. Concluímos aqui que para o entendimento do efeito do fogo sobre a biodiversidade em escala de Bioma, são necessários estudos em diferentes regiões, com maiores escalas espaciais e que os estudos devem abranger um maior número de táxons.

A partir da demonstração de que uma das grandes lacunas dos estudos são os efeitos das queimadas em interações biológicas entre diferentes táxons realizamos estudos realizamos um experimento para determinar os impactos das queimadas em formigas que nidificam em plantas. Também determinamos que técnicas de queimadas utilizadas descritas por técnicos que manejam o fogo proporcionam impactos diferentes na biodiversidade. Demonstramos que as queimadas com diferentes técnicas possuem diferentes intensidades de fogo e calor e, consequentemente, impactam de formas diferentes as formigas que ocuparam ninhos artificiais instalados nas árvores. Concluímos que quanto maior a intensidade das queimadas menores serão as taxas efetivas de colonizações dos ninhos e menor a sobrevivência efetiva de colônias dessas plantas, que são importantes para a distribuição da biodiversidade e para a própria proteção da planta hospedeira. Por fim, para fins práticos, demonstramos que a seleção da técnica de queima é uma importante etapa no manejo com fogo no Cerrado, sendo que entre as técnicas testadas, as queimadas circulares apresentaram maiores intensidades e as queimadas contra o vento apresentam as intensidades mais baixas.

Uma vez que a distribuição geográfica sobre estudos com fogo é extremamente desigual, estabelecemos um estudo no Pantanal, uma área de vegetação savânicas, inundável sazonalmente, sujeita a incêndios (geralmente de origem antrópica) e que tem pouquíssimos estudos com os efeitos das queimadas, a ponto de não ser incluída em nossa cienciometria. Aqui nós demonstramos que os distúrbios antrópicos imprevisíveis (queimadas de origem antrópica) têm efeito dominante sobre essa comunidade na escala espacial estudada. Para fins de monitoramento, os resultados sugerem que as comunidades de formigas são influenciadas por queimadas independentemente da exposição à inundação, mas somente em curto e médio prazo. Para fins de amostragens em condições livres do efeito do fogo, o intervalo de quatro anos após o distúrbio seria suficiente.

Uma particularidade é que, durante todas as etapas de estudo ficamos em contato com técnicos de manejo de fogo do IBAMA, cuja missão é realizar queimadas programadas impedindo fogo em grandes extensões. Esperamos então que nossos resultados, além de gerar subsídios para a conservação de formigas e outros organismos, possa gerar informação que subsidie tomada de decisão por estes técnicos. Porém, é preciso investir em pesquisas que auxiliem no aprimoramento do manejo com fogo, assim como investir na qualificação da mão de obra utilizada para tal. Pois as queimadas podem ser utilizadas de formas benéficas desde que sejam utilizadas de forma responsável e com o conhecimento teórico e prático apropriado.

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