Fire footprint in the Pantanal: evaluation of the impact in forest areas at the Ramsar Site, Taiamã Ecological Station

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Keywords: Floristics; conservation unit; vegetative regeneration.

ABSTRACT – Fires are important factors in the disturbance of forest ecosystems, with a strong impact on the biotic and abiotic conditions of the environment. In recent decades, there has been a substantial increase in the occurrence of these events worldwide, resulting in an imbalance in ecosystem recovery. In this sense, the present work aimed to evaluate the impact of wildfires on polyspecific forest plots located at the Taiamã Ecological Station, which is a federal conservation unit located in the Pantanal biome. To this end, the circumference at breast and total height ≥ 3 m of each individual were measured, in two permanent plots of 1 hectare each, with the identification of all arboreal individuals by scientific names. The first sampling was carried out in 2019, with one of the plots (A) being affected by a fire in 2011 and the other (B) not. The second sampling took place two months after a fire that affected both plots in 2020. The findings unambiguously demonstrate that the occurrence of wildfire in the sampling sites significantly diminished their abundance and diversity, resulting in a shift in the

composition of the plots. Total richness in 2019 was more than double that obtained after the 2020 fire, and there was a loss of almost 80% of trees in this period, which indicates that wildfires have a profound impact on the vegetation at the Station region. Obtaining data on the impacts of large fires in forest environments is essential for effective management of fires in the Pantanal biome.

Pegada do fogo no Pantanal: avaliação do impacto em áreas florestais no Sítio Ramsar, Estação Ecológica de Taiamã

Palavras-chave: Florística; unidade de conservação; regeneração vegetativa.

RESUMO – Os incêndios são fatores importantes de perturbação aos ecossistemas florestais, com forte impacto sobre as condições bióticas e abióticas do ambiente. Nas últimas décadas houve um aumento substancial nas ocorrências desses eventos em todo o mundo, resultando em um desequilíbrio em relação à recuperação dos ecossistemas. Nesse sentido, o presente trabalho teve como objetivo avaliar o impacto de incêndios florestais em parcelas de floresta poliespecífica localizadas na Estação Ecológica de Taiamã, uma unidade de conservação federal localizada no bioma Pantanal. Para tal, foram aferidas a circunferência na altura do peito (CAP) e altura total ≥ 3 m de cada indivíduo, em duas parcelas permanentes de 1 hectare cada, com a identificação de todos os indivíduos arbóreos. A primeira amostragem ocorreu em 2019, sendo que umas das parcelas (A) foi atingida por um incêndio em 2011, e a outra (B) não. A segunda amostragem ocorreu em 2020, após um incêndio que afetou as duas parcelas neste mesmo ano. Os resultados indicam claramente que a passagem do fogo nos sítios de amostragem diminuiu substancialmente sua abundância e a diversidade, e que houve alteração na composição das parcelas. A obtenção de dados dos impactos dos grandes incêndios em ambientes florestais é essencial para uma gestão eficaz dos incêndios no bioma Pantanal.

Huella del fuego en el Pantanal: evaluación del impacto en las áreas forestales del Sítio Ramsar, Estação Ecológica de Taiamã

Palabras clave: Florística; unidad de conservación; regeneración vegetativa.

RESUMEN – Los incendios son factores importantes en la perturbación de los ecosistemas forestales, con un fuerte impacto en las condiciones bióticas y abióticas del medio ambiente. En las últimas décadas ha habido un aumento sustancial en la ocurrencia de estos eventos en todo el mundo, resultando en un desequilibrio en relación a la recuperación de los ecosistemas. En este sentido, el presente trabajo tuvo como objetivo evaluar el impacto de los incendios forestales en parcelas de bosque poliespecífico ubicadas en la Estação Ecológica de Taiamã, una unidad de conservación federal ubicada en el bioma del Pantanal. Para ello se midió la circunferencia a la altura del pecho y la altura total ≥ 3 m de cada individuo, en dos parcelas permanentes de 1 hectárea cada una, con la identificación de todos los individuos arbóreos. El primer muestreo se realizó en 2019, estando una de las parcelas (A) afectada por un incendio en 2011 y la otra (B) no. El segundo muestreo se realizó en 2020, tras un incendio que afectó a ambas parcelas ese mismo año. Los resultados indican claramente que el paso del fuego en los sitios de muestreo redujo sustancialmente su abundancia y diversidad, y que hubo un cambio en la composición de las parcelas. La obtención de datos sobre los impactos de los grandes incendios en ambientes forestales es fundamental para una gestión eficaz de Incendios en el bioma Pantanal.

Introduction

Fires play a crucial role as disturbance agents in forest ecosystems and can cause significant impacts on both biotic and abiotic components. As a natural disturbance element, fire is an essential component for the functioning of many ecosystems. However, over the past few decades, there has been a substantial increase in fire occurrences worldwide, resulting in an imbalance between fire events and ecosystem recovery. This imbalance leads to landscape fragmentation and degradation[1].

Furthermore, the occurrence of fires poses a continuous threat to the objectives of Conservation Units (CU), which are specially protected areas primarily designated for maintaining biodiversity in remaining natural habitats[2][3].

The environmental impacts resulting from forest fires in conservation areas vary in magnitude according to the environmental and climatic conditions present in the ecosystem. These conditions determine the extent of significant losses in biodiversity and natural resource quality, landscape alteration, CO_2 emissions, disruption of biological processes, and other effects[4][5].

Given the importance of conservation units in protecting, conserving, and preserving ecosystems and their biodiversity, it is crucial to systematically and holistically identify the environmental impacts caused by fire across different contexts[6]. Therefore, continued research is essential to assist in the development of regional public policies.

The Taiamã Ecological Station (TES) is a federal conservation unit and a Ramsar site located in the Pantanal biome, where the primary threat to arboreal vegetation cover is wildfire[7]. Consequently, an annual wildfire prevention and combat brigade is hired during the second semester (dry season). In instances of severe wildfires, many trees in the TES burn and die. The replacement of these trees is slow due to the characteristic water stress in the region. This stress affects the area in such a way that only regions with higher altimetric data support arboreal vegetation. However, even these regions become flooded during the peak of the Paraguay River's flood[7].

This fact is concerning and deserves attention because wildfires during the dry season result in more significant changes in the structure and floristic composition of vegetation than those occurring during the rainy season[8].

In the second half of the year 2020, the area burned by fires in the Pantanal was significantly larger than in previous years. Since 2019, the Pantanal has faced a prolonged drought, worsened in 2020. Annual precipitation in the Brazilian Pantanal hit a record low, 26% below the 1982-2020 average. This dry environment, combined with available combustible material, has increased the risk of fires[9]. Specifically, the Mato Grosso state portion of this biome experienced 42% of its area being affected by fire[9]. Additionally, 34% of the TES was directly impacted by these fires (Figure 2). Studying the impacts caused by forest fires in conservation areas is crucial for assessing the potential for forest regeneration and, more importantly, quantifying the effects on biodiversity and its ecological functions[10].

In this sense, the data obtained in this study can be useful to compose analyzes of wildfire occurrence in the Pantanal, as well as assist in the development of future integrated fire management plans in the TES region. Therefore, the present study aimed to assess the impacts of wildfires that occurred in 2011 and 2020 at the TES, exploring the hypothesis of the changes caused by fires on the tree structure of the community, as well as its diversity and species composition.

Material and Methods

Sampling area

The TES is a federal protected area (16°48'S-16°58'S, 57°24'W-57°40'W) between the Paraguay and Bracinho rivers and is in the northern Pantanal, Cáceres municipality, Mato Grosso state of Brazil, and comprehends 115.55 km^2. The Pantanal is one of the largest freshwater wetlands in the world[11][12][13], harbouring a great diversity of aquatic environments influenced by the the flooding pulse[14][15]. This protected area is mainly composed of floodplains, and its interior contains a great variety of aquatic environments, such as permanent, temporary lagoons, meander lagoons and 'corixos' (natural connections between rivers and lagoons that have great importance to water bodies in the Pantanal) (Figure 1). The TES has high levels of biodiversity, high rates of fishing productivity and the occurrence of populations of vulnerable or endangered species[16].

It is classified as an Alluvial Semideciduous Seasonal Forest, located in the Pantanal depression with macrohabitats consisting of floating swamps

(batume) that occupies 48% of the island, flooded fields with 24%, monospecific forest with 16%, polyspecific forests with 8% of the area and lakes with an occupancy of 4% [17]. The Station was declared a Ramsar site in 2018. To the southeast of TES, is located the Sararé Island, which is part of a proposal for the creation of a new protected area[18].

In the 1980s and 1990s, the area of water bodies within the TES was greater than 2000 hectares, which is much larger than recent values of 774 ha in 2011 and 677 ha in 2020 [19].

Between 1985 and 2022, only two fires occurred within the TES. The first in 2011, with the burning of approx. 2000 ha, and another in 2020, which affected approx. 2600 ha [19].

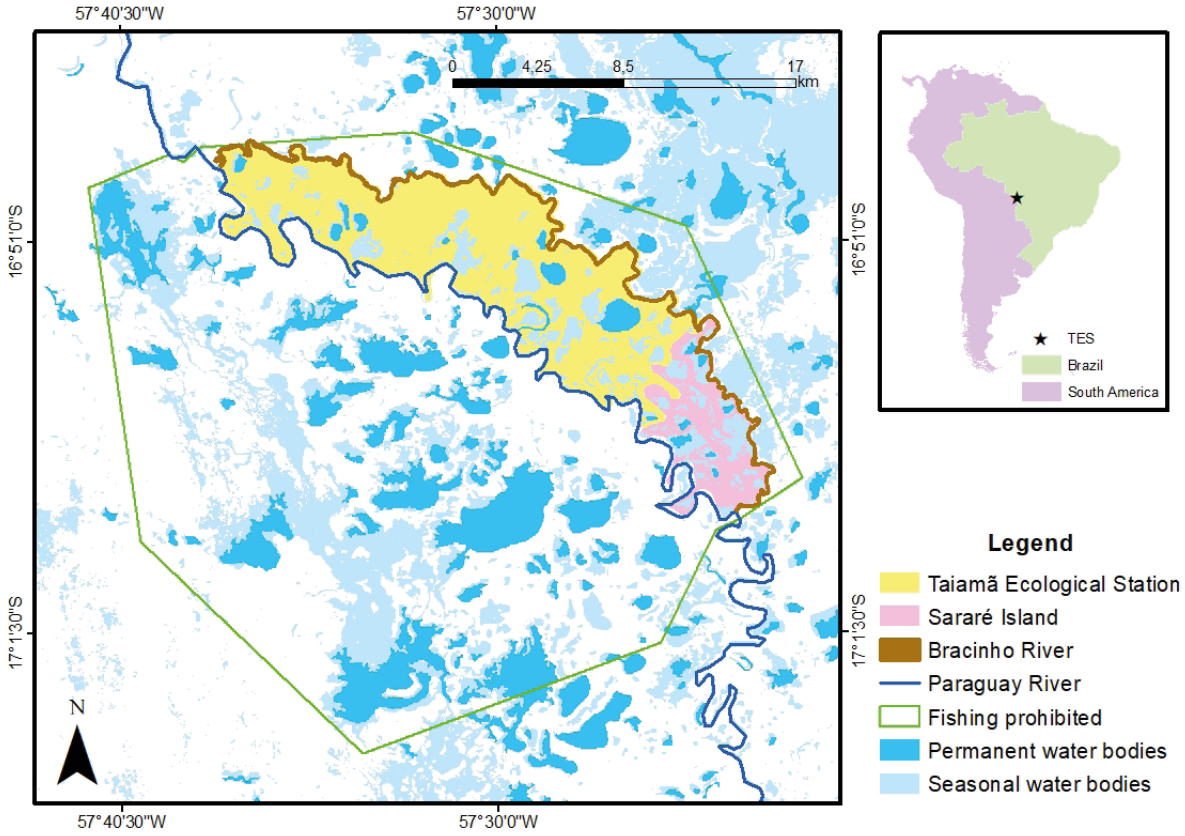

Figure 1 – Region of the Taiamã Ecological Station (TES), delimited by the Paraguai River and one of its branches; note that the region is an area with many water bodies.

Data set

In 2019, two plots of one hectare each were defined in the polyspecific forest macrohabitat, one of which was burned during 2011 and the other was not (Figure 2). All individuals in each plot were numbered, georeferenced, identified and height and circumference measured at chest height (1.30 meters from the ground). In December 2020, new surveys were carried out on the same plots with the aim of identifying the effect of the fires (2011 and 2020) on the structure and composition of the tree community. The two sampling areas are in similar topologies and are characterized as riparian forest[17].

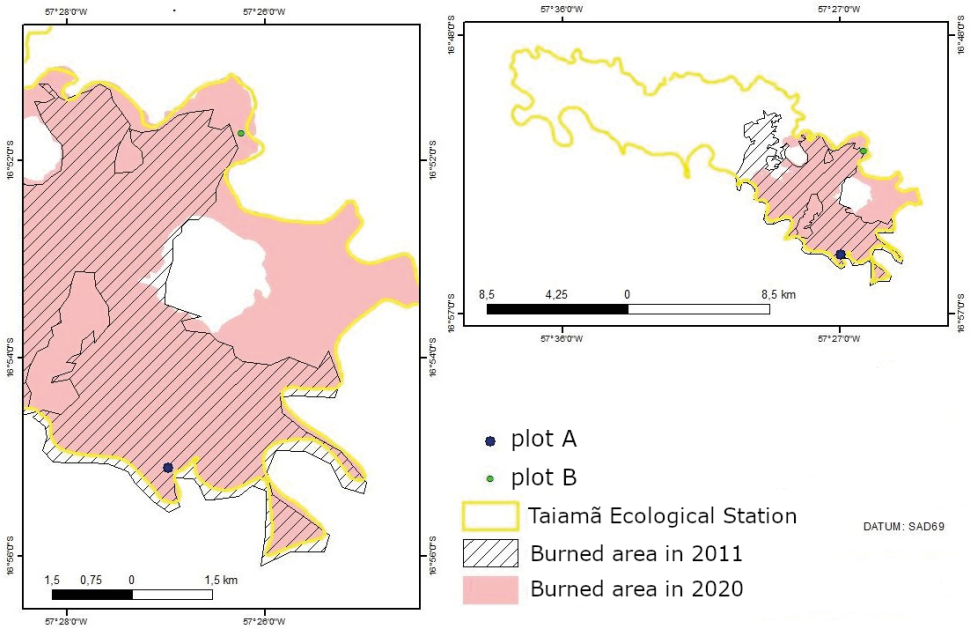

Figure 2 – Map of the Taiamã Ecological Station with sampling sites A and B, which burned, respectively, in 2011 and 2020 and only in 2011.

The installed plots followed the methodology used by the DARP-Pantanal project[20], which is adapted to the PPBio (Biodiversity Research Program) style RAPELD (Rapid Assessments and Long-Term Research) [21], containing a 250 m x 40 m plot, subdivided into 5 plots of 50 m x 40 m, installed perpendicularly along the river, with circumference measurement when > 10 cm and total height ≥ 3 m. The measurements were made using a measure tape and the height was estimated visually.

Data analysis

Phytosociology data were assessed using the following parameters: absolute density, relative density, absolute frequency, relative frequency, absolute dominance, relative dominance, and importance value index (IVI). The last is an indicator of the ecological relevance of species to the environment. Species with higher IVI values can be seen as those that have been more successful in exploiting natural resources in the environment[22]. Floristic diversity analysis was evaluated using species richness, Fisher alpha index[23] and the Chao 1 non-metric estimator method[24]. To understand changes in composition between 2019 plots we performed a non-metric multidimensional scaling (NMDS) analysis based on the "zero-adjusted" Bray-Curtis measure[25]. To compare species similarity between communities from 2020, we performed similarity analyzes (ANOSIM) [26]. All analyzes were performed in the R interface, using the Vegan and ggplot2 packages.

To facilitate understanding when reading the text, plots A and B are described with the state of burning or not burning and the year of sampling. Example: burnedA19 means: plot A was burned in 2011 fire and sampling was in 2019.

Results

The diversity of tree communities obtained by the non-metric Chao 1 estimator method in the burnedA19 and non-burnedB19 plots were 26,75 and 38,00 species, with a total of 672 and 1083 individuals, respectively. The total richness obtained by the same method in the burnedA20 plot was 16 species, in a total of 170 individuals. The burnedB20 plot has 192 specimens, and the total richness observed was 19 (Figures 3 and 4).

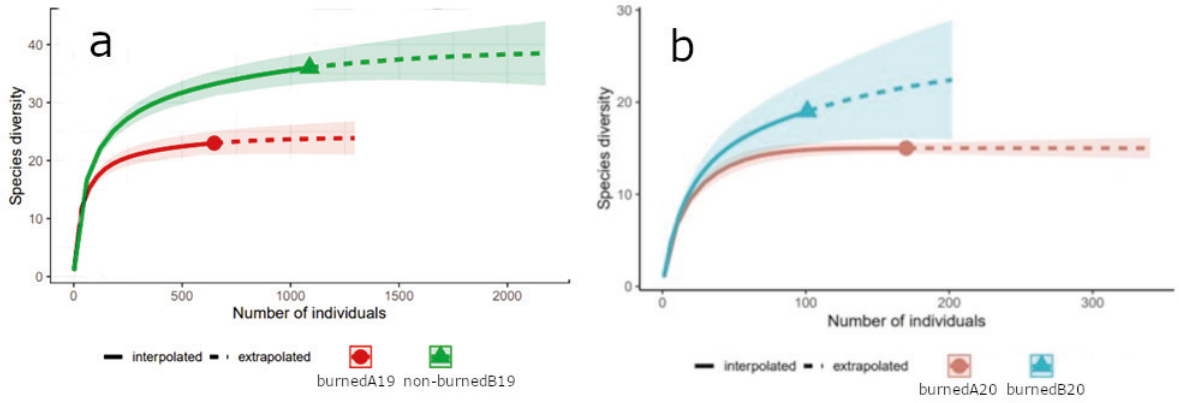

Figure 3 – Rarefaction curve of species from sample plots A (a) and B (b) at the Taiamã Ecological Station, in the years 2019 (a) and 2020 (b).

The diversity values obtained by Fisher's method for plot A were 5.38 (2019) and 4.33 (2020). In plot B, the values were 7.16 (2019) and 5.24 (2020). And the results for portion A + B were 9.35 (2019) and 6.75 (2020). In all cases there was a drop in values.

Figure 4 – Species diversity indices (Chao 1 and Fisher) in forest plots at the Taiamã Ecological Station, in the years 2019 and 2020.

Sampling in 2019 for the two plots led to the identification of 49 species of tree plants, distributed in 48 genera and 25 botanical families, highlighting the considerable number of species for the families Fabaceae, Salicaceae, Rubiaceae, Lauraceae, Myrtaceae, Nyctaginaceae and Malpighiaceae. The December 2020 sampling provided records of 27 species, distributed into 24 genera and 12 botanical families for the same plots analyzed in 2019, with emphasis on the number of representatives of the Fabaceae, Salicaceae, Rubiaceae, Lauraceae and Myrtaceae families. This sampling occurred after the fire that occurred in September/October 2020 at TES.

The most representative families in 2019 for the burnedA19 (Figure 5a), the Fabaceae families, followed by Rubiaceae, Salicaceae, Lauraceae,

Myrtaceae and Clusiaceae were the most abundant (Fig. 5a and Fig. 5b). In the non-burnedB19 (Fig. 5b) were Fabaceae, Salicaceae and Meliaceae. The burnedA20 plot (Fig. 5c), which experienced the impact of fires in both 2011 and 2020, exhibited a prevalence of Fabaceae, Rubiaceae, Lauraceae and Solcicaceae. In the burnedB20 plot (Fig. 5d) the Fabaceae family has the largest number of specimens.

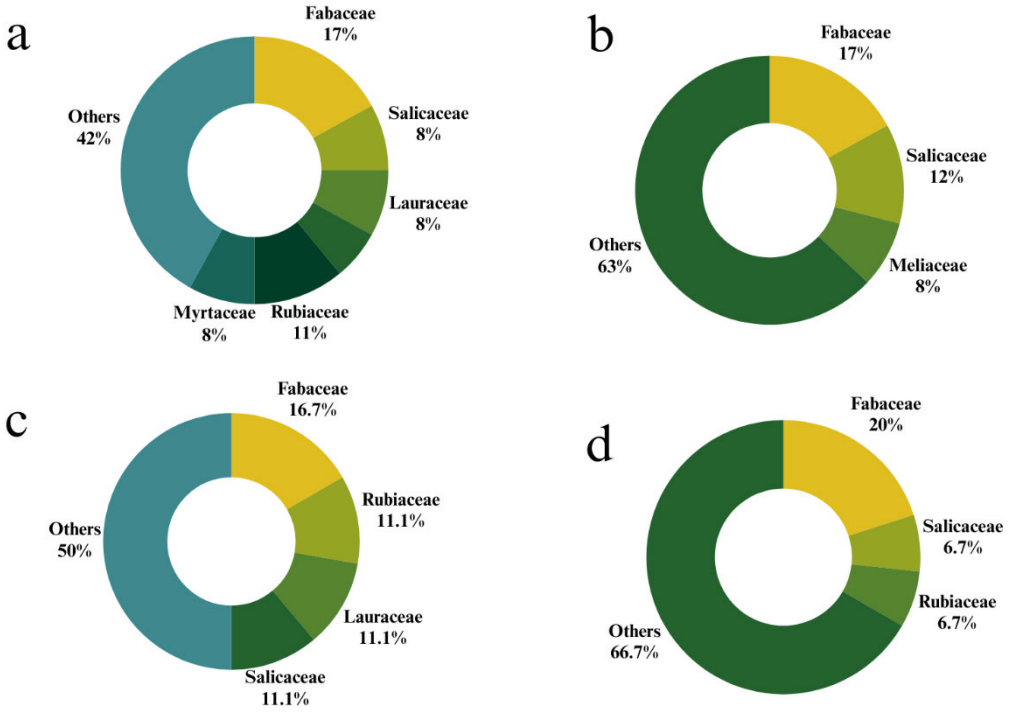

Figure 5 – Most representative botanical families in plots A (a – burnedA19; c – burnedA20) and B (b – non-burnedB19; d – burnedB20) during the years 2019 and 2020, at the Taiamã Ecological Station.

The total richness value (site A + B) in 2019 was almost double that obtained after the 2020 fire, indicating that high severity wildfires like those in 2020 have a profound impact on the vegetation in the TES region, with a 44.9% decrease in this variable. When analyzing the total abundance values (from sites A and B), a decrease of 79.4% in the number of specimens sampled was observed after the occurrence of the fire. When comparing the sites individually, there was also a reduction in richness values (A – 38.5%; B – 47.2%). Furthermore, sampling site B, which had not been burned for a long time and had 1083 individuals in 2019, had a drastic reduction (82.3%) to 192 specimens. At site A there was also a significant reduction (74.7%) in abundance between the different sampling years. Even when we compare plots A and B in 2019, where the fire occurred eight years before sampling, but only in A, we noticed differences of 27.7% in richness and 40.0% in abundance (Figure 6).

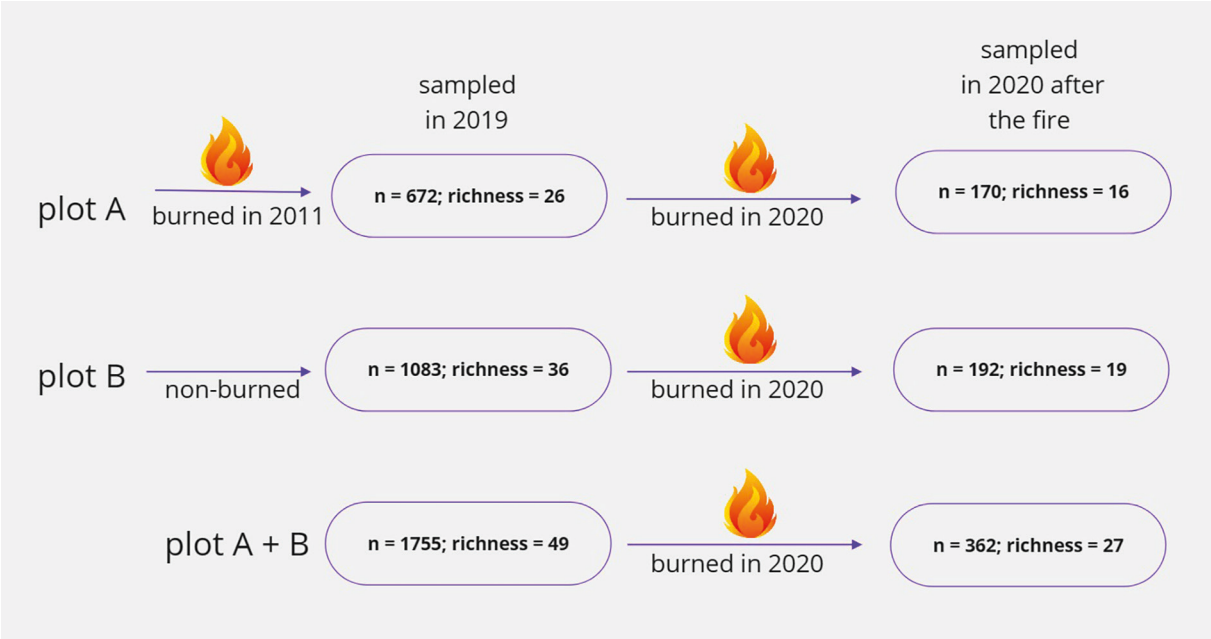

Figure 6 – Visual abstract of the richness e and abundance (n) from the plots sampled at the Taiamã Ecological station. n = abundance.

The most abundant species for the non-burnedB19 plot are: *Trichilia catiga* A.Juss, *Zygia inaequalis* (Willd.) Pittier, *Inga vera* Willd, *Duroia duckel* Huber, *Casearia decandra* Jacq, *Crataeva tapia* L, *Cassia grandis* L.f, *Cecropia pachystachya* Trécul, *Byrsonima spicata* (Cav.) DC, *Triplaris americana* L, *Sloanea cf. terniflora* (DC.) Standl, *Pterocarpus santalinoides* L'Hér. ex DC. The following species were the most abundant in burnedA19 plot: *T. americana* L., *Zygia cauliflora* (Willd.) Killip., *Garcinia brasiliensis* Mart., *Genipa americana* L., *C. grandis*. Some species were found in both areas (Figures 7A and 7B). The most abundant species for the burnedA20 plot were: *Trichilia catigua* A.Juss, *Zygia inaequalis* (Willd.) Pittier, *Inga vera* Willd, *Crataeva tapia* L and *Sloanea* cf. *terniflora* (DC. In the burnedB20 plot, the species with the highest occurrence were *Zygia cauliflora* (Willd.) Killip., *Garcinia brasiliensis* Mart., *Genipa americana* L., *C. grandis* and *T. americana* (Figure 7).

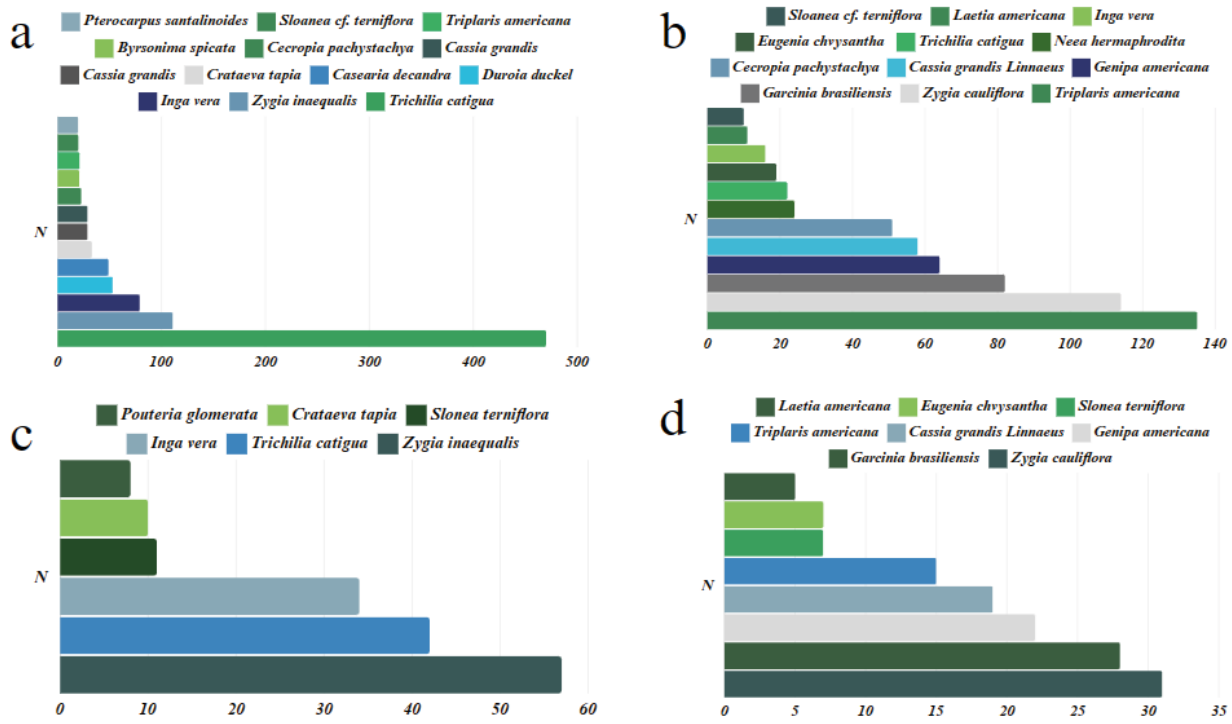

Figure 7 – Number of individuals of the main tree species sampled in plots A (a and c) and B (b and d) at the Taiamã Ecological Station, years 2019 (a – burnedA19; b – non-burnedB19) and 2020 (c – burnedA20; d – burnedB20). n = abundance.

The species with the highest IVI for the non-burnedB19 plot were: *T. catigua*, *C. grandis*, *Z. inaequalis*, *I. vera*, *Spondias mombin* L, *S. terniflora* (DC.) Standl, D.duckel, *C. decandra*, *Albizia polycephala* (Benth.) Killip ex Record, *Crataeva tapia*, *P. santalinoides*, *Ficus* cf. *trigona*, *T. catigua*, representing 71% of the total IVI value among the species present in the plot. For the plot burnedA19 they were respectively: *C. grandis*, *Z. cauliflora*, *G. americana*, *T. Americana.*, *S. cf. terniflora*, *G. brasiliensis*, *C. pachystachya*, C, *E. chvysantha*, *Neea hermaphrodita*, *S. mombin*, *T. catigua*, representing 76% of the total IVI value among the species present in the plot. The species with the highest IVI for burnedA20 were *Z. inaequalis*, *T. catigua*, *I. vera*, *S. terniflora* (DC.) Standl, and *Crataeva tapia*, accounting for 77% of the total IVI among the species present in the plot. For burnedB20, the species *Z. cauliflora*, *G. brasiliensis*, *G. americana*, *C. grandis*, and *T. americana* represented 71% of the total IVI among the species in the plot (Figure 8)

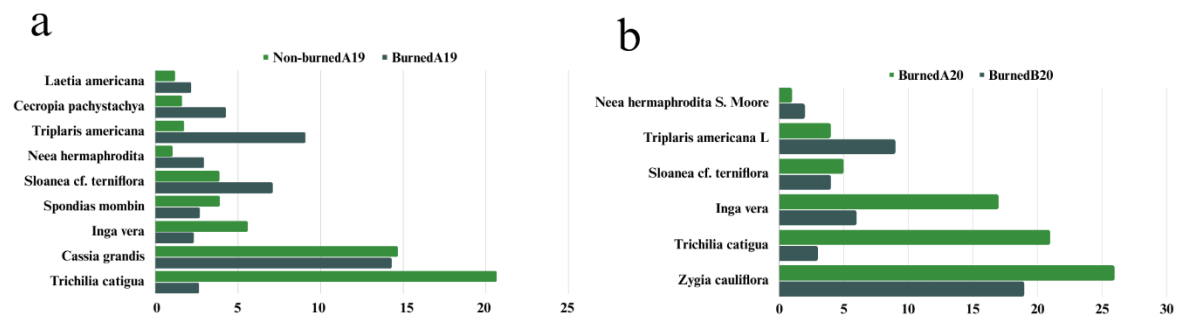

Figure 8 – Importance value index (IVI) for species recorded in two plots A and B of the Taiamã Ecological Station, in the years 2019 (a) and 2020 (b).

The comparison between the subplots from de 2019 samples with non-metric multidimensional scale analysis resulted in the formation of two clusters, which correspond to the non-burnedB19 and burnedA19 plots, with the similarities residing in structural aspects of the communities between subplots of the same group (Figure 9).

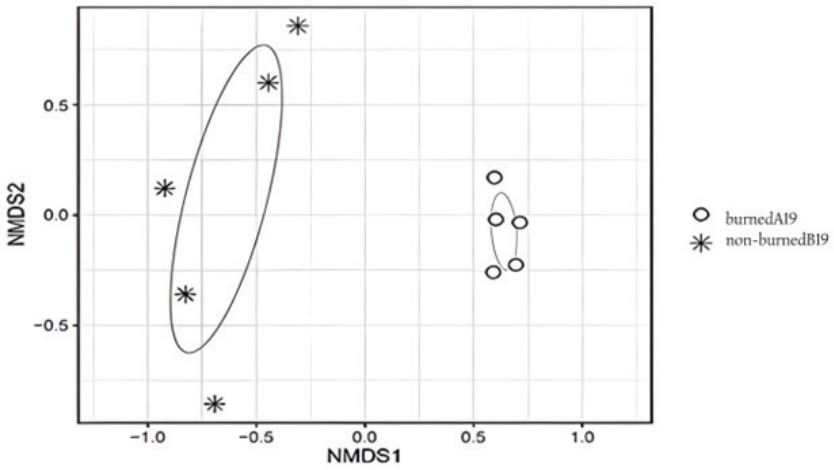

Figure 9 – NMDS (Nonmetric Multidimensional Scaling) analysis of the subplots of sites A and B at the Taiamã Ecological Station in 2019.

No significant differences in cluster analysis were observed when comparing subplots sampled in 2020, with eight subplots forming cluster one, and the other two forming two other clusters (Figure 10).

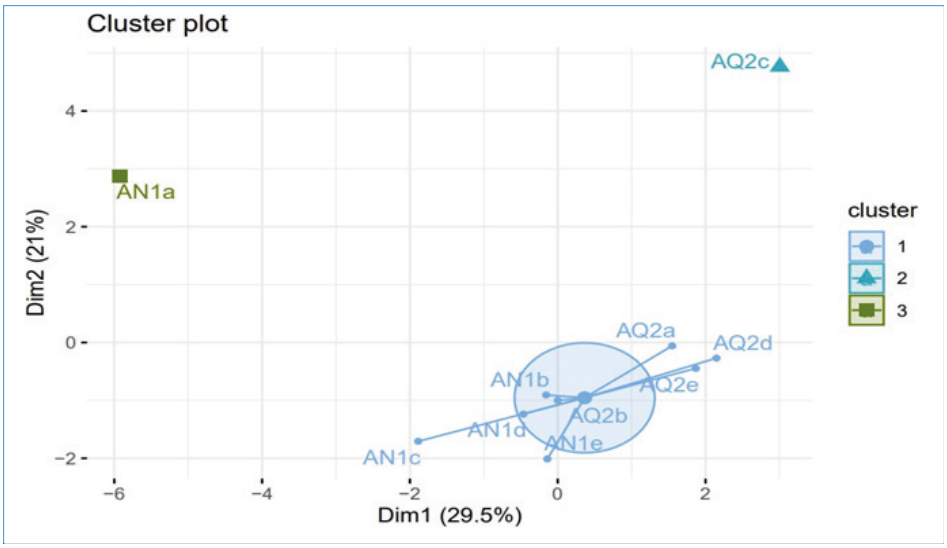

Figure 10 – Analysis of clusters between the subplots of sites A (AQ) and B (AN) at the Taiamã Ecological Station, after the 2020 wildfire.

Discussion

The study area exhibits a flat topography and is characterized by the overflow of waters from the Paraguay River. Throughout most of the year, the region remains flooded[27]. During the wet season, specific soil portions, locally referred to as "cordilheiras" remain elevated. These "cordilheiras" either take longer to flood or remain unflooded altogether, depending on annual variations in water flow within the hydrographic basin. The origin of these "cordilheiras" is linked to both old and recent marginal river dikes, which are covered by arboreal vegetation (28). These elevated areas serve as crucial refuges for wild animals during the flood season and have arboreal vegetation[29]. Normally, fields with non-arboreal vegetation occur around the "cordilheiras". However, the presence of fire in these forested regions, which already face challenges due to cyclical flooding, poses a significant threat to conservation efforts in the Taiamã Ecological Station (TES) region[7]. Therefore, collecting data on the impacts of large fires in forest environments is essential for effective fire management in this area.

The total of 35 species in the tree communities of the non-burned plotB19 is similar to previous studies (30), which was also carried out at TES, and which evaluated the effect of flooding in a polyspecific forest and recorded 34 species in an area of 1.6 ha. Furthermore, stabilization in the rarefaction curves was observed, indicating that the area covered in one hectare per study plot was sufficient to capture the richness and diversity of the studied communities.

The differences in data on abundance, richness and diversity of tree communities and species composition between sampling sites are probably due to the effect of wildfires that occurred at the TES. Total richness data in 2019 was more than double that obtained after the 2020 fire, indicating that wildfires have a profound impact on the vegetation in the Station region. Furthermore, there was a drastic drop in the number of individuals sampled in the two plots after the 2020 fire, indicating that the event was very severe. In an analysis carried out in the Pantanal biome with several environmental variables, such as CO_2 flow and others, several places where wildfires occurred in 2020 were identified and classified as high severity in 2020, with TES being one of these places[31]. The worst recorded fire episode in the history of the Pantanal occurred in 2020 [32] and, consequently, severe ecosystem destruction and biodiversity loss were linked to this unique event[33]. The estimated burned area in Pantanal during the megafire of 2020 surpassed 4.5 million hectares[9], resulting in the death of 17 million vertebrates, and negative impacts on at least 65 million animals due to *habitat* loss and resource scarcity (food, water, shelter) caused by environmental change[34].

The data obtained in 2019, about 8 years after the 2011 wildfires, with plot A containing much lower richness, diversity and abundance values than plot B, indicate the possibility of a slow pace in the succession process and little resilience of the forest in relation to the environmental stress suffered. Furthermore, annual flooding can hinder forest regeneration after fires. Flooding has been considered the primary factor driving the composition and distribution of plant species in wetlands (35, 36), with species diversity and abundance varying within and between the different *habitats* along the topographic flood gradient[14][37].

When comparing the species with the highest importance index in the two plots sampled in 2019, there was an inversion of the index for *Cecropia pachistaquia* and *Triplaris americana*, with an increase in importance for these species that have a high reproduction rate and can colonize environments of faster way[38]. It can also be seen that after the 2020 fire, the *T. americana* species had its index increase even further, possibly due to the reoccurrence of the fire. In areas impacted by wildfires of medium and high severity, where many trees die, it is expected that pioneer species will be the first to colonize.

A study carried out in the Corumbá Pantanal compared burned sites with different topography (39) and identified that the lowest altitudes contain the lowest diversity of tree species. However, the diversity of unburned areas did not vary much with altitude and was greater than in low-burned areas and lower than in high-burned areas. In this proposed model, and considering the long periods of annual flooding, it is possible that the TES region fits this pattern where lowlands are impacted by fire, given that in the 2019 sample the burned area (A) has less diversity than the unburned area (B). Both plots are classified as riparian forests and are in very similar topographies[17], so it is expected that if there had been no wildfire in 2011, the two areas could have had more similar diversities than those observed in 2019. Furthermore, diversity decreased even further when both plots were burned in 2020. According to the proposed model, it is plausible to assume that fires could increase diversity if the TES region was located at a higher topography. However, it must be analyzed whether the intensity of forest fires could interfere with this pattern.

Similarity analysis using the NMDS method between the subplots of the two plots sampled in 2019 identified two clusters that correspond to plot A and plot B. This indicates that the two sites have distinct floristic composition, and fire is possibly responsible for most of the differences, as there was no fire in plot B in 2011. Conversely, the cluster analysis for the year 2020 did not identify clusters between the subplots, which indicates that a homogenization process occurred due, possibly, to the high severity of the fire from 2020 that occurred at TES.

In a study carried out with satellite images that analyzed the impact of fire on the vegetation of the Pantanal Matogrossense National Park (PMNP), high severity was identified in the 2020 fire, in addition to the detection of serious deterioration of the vegetation[40]. PMNP and TES are the only two federal conservation units in the Pantanal biome, and both fires left footprints in the vegetation. In this context, management strategies such as prescribed fire become crucial to prevent and reduce the negative impacts of future forest fires in conservation units. This technique proves to be beneficial for fire-prone ecosystems, promoting biodiversity, nutrient cycling and reducing the risk of catastrophic events[41]. It is important to highlight that these practices play a fundamental role in mitigating the negative repercussions of large fires on wild species and create a mosaic of habitats. This approach recognizes the intricate balance between natural fire regimes and human efforts to safeguard ecosystems and the diversity of species that inhabit them.

Due to the heterogeneity of riparian forests like the regions sampled in this study and their elevated levels of diversity, which are higher than other types of forest formations in the region, these forests are important for the multiplication of plant species due to the formation of migration corridors[42]. In this way, they help protect water courses, create habitats for various components of wildlife, reduce water temperature, support aquatic life, provide food, among other functions. The loss or severe alteration of these tree communities can cause an inestimable imbalance in the environment, affecting an entire ecosystem[43].

Conclusion

The empirical findings from this study unequivocally demonstrate that high-severity wildfires in 2020 left visible marks on the diversity, richness, abundance, and composition of tree species in the polyspecific forest of the Taiamã Ecological Station. Studies like this are essential to understand the impacts of wildfires in the forests of the Pantanal biome and thus assist in planning integrated fire management. Other studies in regions that suffered the same type of impact can help to better understand the impacts of fire on the Pantanal, to create a broad view of the Pantanal biome and the impacts of wildfires. On the other hand, planned use of fire are vital for preventing and mitigating the detrimental effects of future wildfires. There are no records in the scientific literature of prescribed fire in the Pantanal biome, nor is this activity common in this region. This is possibly due to the fear of losing control of the fire in a region that normally accumulates a lot of organic matter in the soil and thus causing severe damage to biodiversity. However, as we observed in the results of our study, wildfires can be very damaging to forest areas and therefore it is time for new research with the aim of better understanding prescribed fire in flooded areas.

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