FIRE REGIME AND THE IMPACT ON BIOMASS STOCKS OF WOODED AND FORESTED SAVANNAS IN MARANHAO STATE

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RESUMEN. Comprender los límites entre el fuego como componente ecológico y la degradación de la vegetación es crucial para la gestión de las áreas naturales. Este estudio propone un análisis espacial para identificar patrones entre la recurrencia del fuego y los intervalos sin fuego, evaluando el cambio en el stock de biomasa en dos tipos de sabana en Maranhão: boscosa y arbolada. En primer lugar, se consideraron las áreas no perturbadas: áreas sin quemas, cambio de clase, a 300 m de los bordes de las áreas deforestadas. En segundo lugar, áreas con las mismas condiciones, pero con degradación por fuego en configuraciones variables de recurrencia e intervalo sin fuego. Los resultados mostraron que las áreas prístinas tenían una biomasa media de

119 Mg.ha-1 en la vegetación boscosa y de 74 Mg.ha-1 en la vegetación arbolada. En la sabana arbolada, la recurrencia del fuego durante tres eventos mostró existencias con menos del 50 % de la biomasa no perturbada, cayendo a menos del 40 % después de seis eventos de quema. La sabana arbolada, por su parte, mostró una mayor resistencia, con existencias de biomasa que aumentaban a medida que aumentaba la recurrencia de incendios, pero que disminuían hasta el 20-10 % tras siete eventos de quema. Los puntos de inflexión en las curvas de biomasa pueden indicar umbrales de conversión de un estado resistente al fuego a un nuevo estado con menos biomasa remanente. Este conjunto de información es importante para la aplicación del PNMIF, donde es necesario comprender la dinámica de los incendios y estructurar una planificación adecuada de su gestión.
Palabras-clave: Cerrado; Intervalo sin fogo;Recurrencia; Vegetación autóctona.

RESUMO. Compreender os limites entre o fogo como componente ecológico e a degradação da vegetação é crucial para a gestão das áreas naturais. Este estudo propõe uma análise espacial para identificar padrões entre a recorrência do fogo e intervalos sem fogo, avaliando a mudança no estoque de biomassa em dois tipos de savana no Maranhão: florestada e arborizada. Primeiramente foram consideradas as áreas não perturbadas: areas sem queimadas, mudança de classe, a 300m de bordas em areas desmatadas. Em segundo, áreas com as mesmas condições, mas com degradação por fogo em variadas configurações de recorrência e intervalo sem queima. Os resultados indicaram que áreas pristinas apresentaram média de biomassa na vegetação florestada de 119 Mg.ha^{-1} e arborizada com 74 Mg.ha^{-1}. Na savana florestada, a recorrência do fogo acima de três eventos apresentou estoques com menos de 50% da biomassa sem distúrbio, caindo para menos de 40% após seis eventos de queima. Já a savana arborizada mostrou maior resiliência, com aumento dos estoques de biomassa conforme a recorrência do fogo crescia, mas caindo para 20-10% após sete eventos de queima. Os pontos de inflexão nas curvas de biomassa podem indicar limites para a conversão do estado resiliente ao fogo para um novo estado com menor biomassa remanescente. Esse conjunto de informações são importantes para implementar o PNMIF, onde é necessário compreender a dinâmica do fogo e estruturar um planejamento adequado de gestão de queimadas.
Palavras-chave: Cerrado; Intervalo sem fogo; Recorrência; Vegetação nativa.

ABSTRACT. Understanding the limits between fire as an ecologic component and vegetation degradation is crucial for the management of natural areas. This study proposes a spatial analysis to identify patterns between fire recurrence and non-fire intervals, evaluating the change in biomass stock in two types of savannah in Maranhão: forested and wooded. Firstly, undisturbed areas were considered: areas without burning, change in class, 300m from the edges of deforested areas. Secondly, areas with the same conditions, but with degradation by fire in varying configurations of recurrence and non-fire interval. The results showed that pristine areas had an average biomass of 119 Mg.ha^{-1} in the forested vegetation and 74 Mg.ha^{-1} in the wooded vegetation. In the forested savannah, the recurrence of fire over three events showed stocks with less than 50 % of the undisturbed biomass, falling to less than 40 % after six burning events. The wooded savannah, on the other hand, showed greater resilience, with biomass stocks increasing as fire recurrence increased, but decreasing to 20-10% after seven burning events. The inflection points in the biomass curves may indicate thresholds for conversion from a fire-resilient state to a new state with less remaining biomass. This set of information is important for implementing the PNMIF, where it is necessary to understand fire dynamics and structure-appropriate fire management planning.
Keywords: Cerrado; Non-fire Interval; Recurrence; Native vegetation.

1. INTRODUCTION

The Cerrado Biome (Savanna) has a biodiversity and ecosystems historically influenced by natural fire regimes. This regime shapes the structure and composition of the vegetation, as well as maintaining the ecosystem's health (Pivello, 2011) However, changes in fire regime patterns are transforming the natural landscape, altering the spatial distribution of fires and increasing their severity. These changes have compromised the preservation of several types of vegetation in the biome and increased atmospheric emissions from fire (Lapola et. al. 2023; Alvarado *et al*., 2017).

Maranhão state has 64% of its territory covered by the Cerrado biome and is under pressure from an increase in burned areas and the frequency of fires (IPAM, 2023). This process emphasizes the urgency of protecting cerrado vegetation in the region, given the threat to socio-biodiversity as only 8% of the cerrado is protected by conservation units, a rate three times lower than in the Amazon (IPAM, 2017). The comprehension of the boundaries between the extent of fire is an ecological component and the degree of degradation of these different types of vegetation is crucial for drawing up policies on fire management and conservation.

A proposed law for the National Integrated Fire Management Policy (PNMIF-PL 1818/2022) is currently being discussed in the Federal Senate. The PNMIF-PL aims to promote inter-institutional coordination on integrated fire management, reducing the incidence of and damage caused by forest fires in the national territory, recognizing the ecological role of fire in ecosystems and respecting traditional fire use knowledge and practices. To implement the PNMIF, we still have limited knowledge of its impacts in at least three areas: on the stocks, on biodiversity, and on the communities that use and depend on the natural resources of the Cerrado (IBAMA, 2010)

In light of these challenges, remote sensing techniques are effective tools for mapping burned areas (Giglio et al., 2018; Chuvieco et al., 2019; Alencar et al. 2022), land use and land cover change (Souza et al., 2020), mapping deforested areas (INPE, 2024) and combining the synergies between all these data to understand the ecological processes and their impacts, in addition to providing useful knowledge to support environmental management planning. Therefore, this study proposed a heterogeneous spatial analysis approach to identify uniform patterns combined between fire recurrence and non-fire intervals, to better comprehend and establish degradation limits. For this, the analysis was based on Above-Ground Biomass (AGB) stock changes in two different types of savannas: forested and wooded. This study aims to contribute to a better understanding of the implications of fire and its recurrence for the stocks in these two types of savannas.

2. MATERIAL AND METHODS

2.1. Study area

Maranhão's Cerrado is home to different types of vegetation (**Figura 1**), ranging from forest to savannah (**Figure 2**). There are four types of savannahs present in the state: Forested (Sd); Wooded (Sa); Park; and Grassy-woodland. **Figure 1** shows the spatial distribution of each physiognomy.

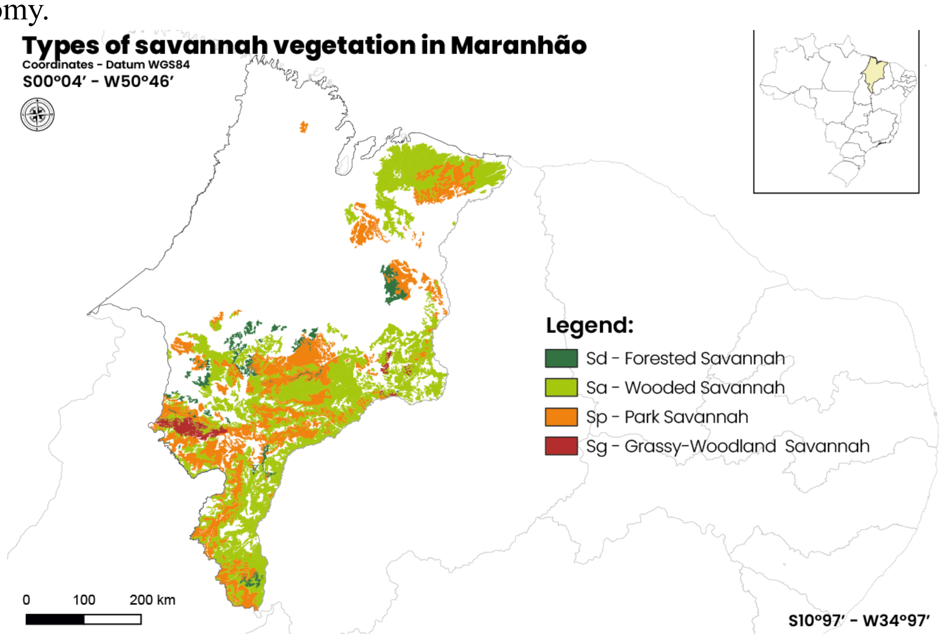

Figure 1: Distribution map of savannah vegetation in Maranhão.

The Forested Savannah occurs in sandy areas with deep soils in seasonally dry tropical climates and is characterized by small woody vegetation and underground reserve organs, reaching heights of six to eight meters. The Wooded Savannah, subject to annual fire, varies from open areas to dense shrubs, sharing a similar floristic composition to the Forested Savannah. The Park Savannah is dominated by spaced grasses where the bush and wooded levels are interspersed among the abundant herbaceous layer. Finally, the Grassy-woodland Savannah is characterized by grasses interspersed with stunted woody vegetation, adapted to management by fire or grazing, with geophytes resistant to trampling and fire gradually replacing the dominant hemicryptophytes (IBGE 2012).

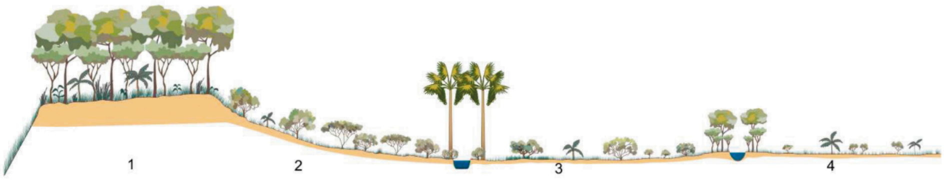

Figure 2: Schematic profile of the Savannah (Cerrado): 1 - Forested; 2 - Wooded; 3 - Park; 4 - Grassy-woodland. Veloso, Rangel Filho e Lima (1991).

For this study, two of the four savannah vegetation types were selected: Forested and Wooded. This choice was made to deepen our knowledge of the differences between the Cerrado types in forest and wooded vegetation.

2.2. Input data

To perform the proposed method, the Google Earth Engine platform (Gorelick et al., 2017) was used, where the process was organized into three stages: data input, filtering areas of interest, and extraction of statistical biomass metrics. The workflow is illustrated in **Figure 3**.

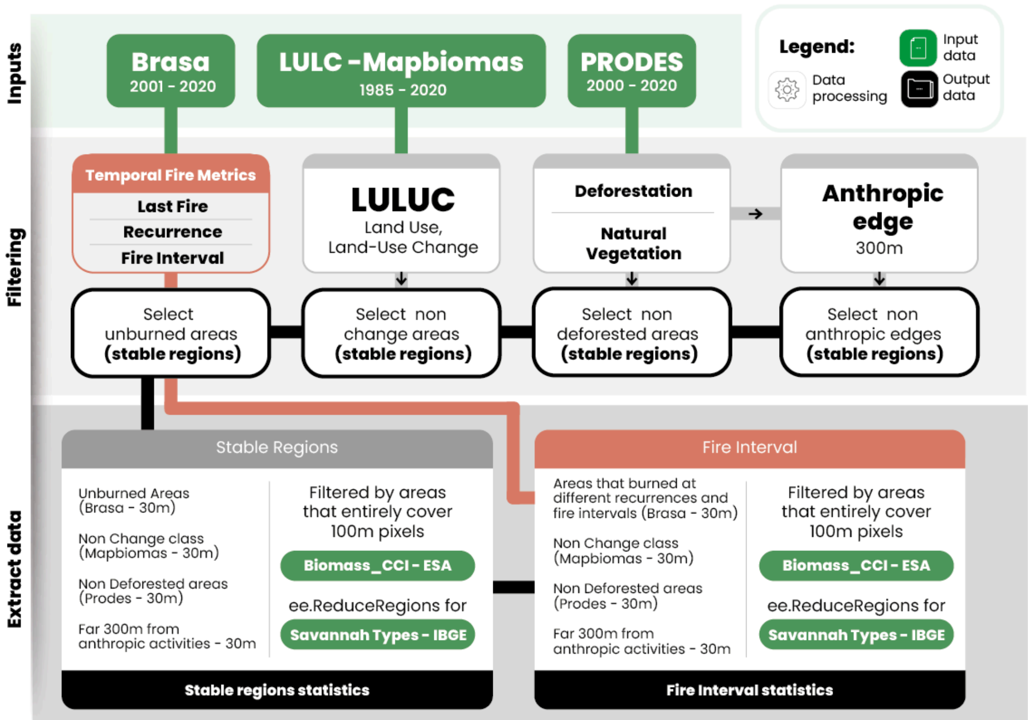

Figure 3: Flow diagram of the proposed method.

We used as input data the ESA's above-ground biomass map (Santoro & Cartus, 2023) for 2020, which provides biomass estimates based on C-band radar data (Sentinel 1A and B), L-band (ALOS-2 PALSAR-2), and LiDAR sensors from the Global Ecosystem Dynamics Investigation (GEDI) mission and has a spatial resolution of 100m. Information on savannah types was obtained from Instituto Brasileiro de Geográfia e Estatística data (IBGE, 2023), which initially came from the RADAM Brazil project and was later updated by IBGE for 2021. Based on the reference AGB values (areas unaffected by fire and without edge effect) for each savannah type, the remaining biomass was estimated for the areas affected by different fire intervals and recurrence. Thus, the AGB was worked out in terms of the percentage remaining concerning the reference biomass.

To identify burned areas, we used the BRASA product (Leão et al., 2023a) analyzing the period from 2001 to 2020, which presents a proposal for mapping the largest extent of burned area from the fusion of 3 products, with a spatial resolution of 30m. In addition, we used the time series of Land Use and Land Cover from Mapbiomas (Collection 8 - Souza et. al., 2020) from 1985 to 2020, with 30m spatial resolution, and the deforestation and natural vegetation data from the Prodes project for the interval from 2000 to 2020 with 30m spatial resolution (INPE, 2024).

2.3. Filtering

From the BRASA time series, the *Temporal Fire Metrics* function (Leão et al., 2023b) was applied to identify the first and last year of fires, the recurrence, and the non-fire interval between years. The first fire indicates the year when the first fire was identified in the time series, from 2001 to 2020. The last fire indicates the year when the last fire was identified in the same period. Recurrence of fire identifies the number of times that area has burned during the time series. The non-fire interval identifies the years in which there was no fire between the first and last fire. All analyses were performed at pixel level (30 m).

Based on the Mapbiomas land use and land cover product time series, we identified the areas that remained in the same natural vegetation class throughout the years. Using PRODES data, we obtained the vegetation mask and the areas of deforestation from 2000 to 2020. PRODES' vegetation mask shows all the natural areas that have not been deforested since the start of the program's monitoring (1988). From the PRODES deforestation information, we defined a 300m buffer (Silva-Junior, 2020) as an area of edge influence by human activity, and filtered these areas to reduce potential interference from the edge effect on the biomass data.

2.3. Data extraction.

The first extraction of selected pixels for the analysis considered undisturbed areas based on the data analyzed, i.e. defined as those that were not burned, had no change in class, are located at least 300 meters from edge areas, and are located in the mask of PRODES old-growth forest.

The second pixels selection extraction was conducted in two stages. In the first stage, areas with a fire recurrence ranging from 2 to 20 years were selected, with non-fire intervals ranging from 1 to 18 years, with the most recent fire occurred in 2019, the year preceding the biomass assessment by the biomass product. This procedure was conducted considering all pixels where a fire was identified as the only disturbance, based on the first extraction stage, i.e. no deforestation, no class change, within the PRODES old-growth forest mask and 300 meters from the anthropogenic edge. The measurements show the response of the remaining biomass in the different configurations of recurrence and non-fire intervals.

Afterward, only biomass pixels overlaid 100% by the layers of natural vegetation (PRODES), land use land cover, and the areas for which the fire metrics were calculated were considered. To characterize the metrics, the "median" descriptive statistic was used and calculated on the biomass pixel. Thus, for each vegetation polygon, median values of biomass affected by different fire regimes and unaffected biomass were calculated. Subsequently, the burned values are weighted in proportion to the median value of the unburned biomass to identify possible growth rates and losses of fire resilience in vegetation as fire recurs.

2.4. Model Logistic Equation

From the biomass data obtained for the configurations between non-fire intervals and fire recurrence variation, we used the decreasing logistic equation, which describes the point of change in biomass resilience in the face of fire recurrence, creating a sigmoid curve representation of this inflection point (Mendes & Vega, 2011). The following adjusted model was used:

$$P(t) = \frac{K}{1 + e^{r*(t-a)}} + b \quad (1)$$

where **t** is the independent variable with fire recurrence values; **K** is the amplitude parameter that represents the initial stable stage of the remaining biomass; **r** is the angular coefficient where the slope of the sigmoid curve and the magnitude of **r** control the accentuation of the curve; **a** is the displacement on the x-axis, which represents the change in the stable state and the loss of resilience of the biomass in the face of recurrent burning; and finally, **b** is the parameter that defines the new equilibrium state of the curve.

3. RESULTADOS E DISCUSSÃO

The results from the first filtering, which establish the AGB reference values for unburned and undisturbed areas detected by the products used, are shown in **Figure 4a**. The representative median AGB value obtained from the forested vegetation (Sd) samples (**Figure 4a**) corresponded to 119 $Mg.ha^{-1}$, which is 38% higher than the wooded vegetation (Sa), with a median of 74 $Mg.ha^{-1}$. This is expected given that forested vegetation has the highest density of trees.

Based on the AGB reference values (**Figure 4a**), the remaining biomass percentage was calculated considering different non-fire intervals and fire recurrence **(Figure 4b** and **c**). According to **Figure 4b**, the Sd vegetation type showed values on biomass percentage remaining below 30 % on the median (yellow, orange, and red in the heatmap), regardless of the non-fire interval and recurrence. This response could indicate a higher sensitivity and lower resilience of this vegetation to fire events, confirming the results found by Pivello (2011). After three recurrences, the percentage of AGB remains below 50 %, and above six recurrences the values decrease to 40 % or less.

Regarding the Sa vegetation (**Figure 4c**), a different response can be observed, with remaining AGB values above 40% on the median (yellow and green in the heatmap) mostly between seven recurrences and five non-fire intervals. It is possible to infer that this type of vegetation is less sensitive and more resilient to fire events, with an increase in remaining AGB of between 40% and 90% up to approximately 11 fire recurrences, after which the biomass values reduce to 20% and 10%. The observations discussed here can be better visualized in the logistic curves in **Figure 5**, which show the relationship between biomass and recurrence over five non-fire intervals.

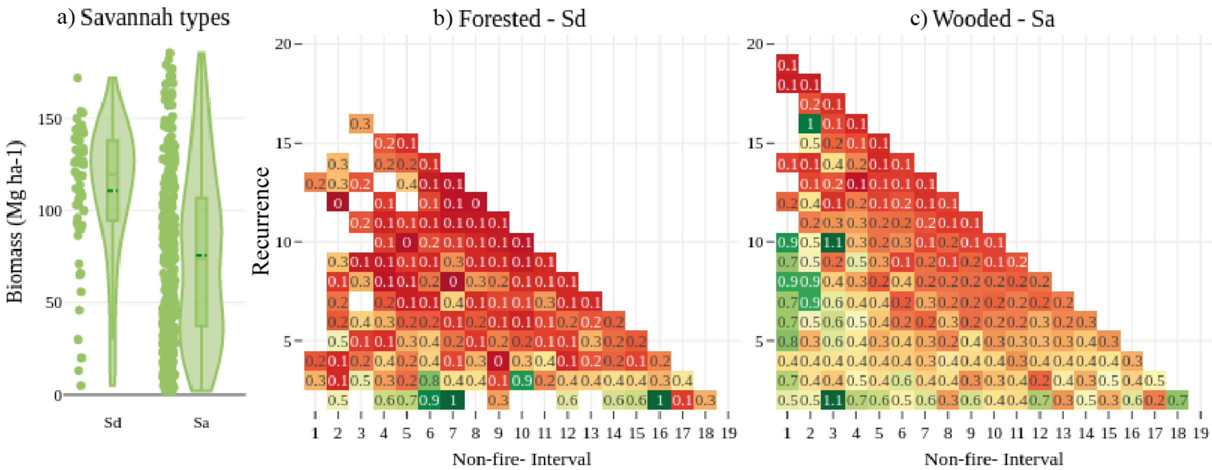

Figure 4: a) Distribution and boxplot of sample medians. b and c) Heatmap graphs, representing the medians of all polygons for the two vegetation types, with fire recurrence / non-fire interval configurations, with the last burn in 2019. On the x-axis we have the burning interval starting with 1 and ending with 18 intervals to the right, and on the y-axis we have the burning recurrence gradually increasing from 2 to 20 burns.

On **Figure 5** it is possible to observe when the intersection of the recurrence and non-interval occurs, where the change in the remaining AGB response takes place, or the most expressive decrease in AGB. This inflection point, described by the parameter 'a' in the logistic model, marks the transition from a stable state resilient to fire to a new state with lower remaining biomass. This phenomenon occurs first in forested vegetation, where the change begins after approximately three fire recurrences, while in wooded vegetation this transition occurs after seven recurrences. The proportion of biomass remaining in five non-fire interval configurations for Sd (**Figure 5a)**, biomass tends to remain below 50%, and after the inflection point, values stabilize between 20% and 10% of AGB. In the case of Sa (**Figure 5b)**, the initial remnants are generally above 50% and decrease to between 20% and 10% after the inflection point.

The Sd model curves exhibit an atypical response, with remnants oscillating between 30% and 50% after three recurrences of burning. However, this variation can be attributed to the scarcity of burned area data, since fire is not a common event in this ecosystem. This prevents obtaining sufficient samples to establish representative averages and a clear understanding of trends. The model's limitation is clear when trying to interpolate in regions where no data is available, which can lead to an overestimation of the analysis due to the null sample space.

A crucial point in understanding the outliers is the nature of our research: we evaluated heterogeneous areas with similar burning characteristics to analyze the response of the two vegetation types under the influence of fire. We concentrated our studies on Maranhão's savannah vegetation in these initial analyses. However, to obtain a more comprehensive and accurate understanding, we intend to include additional areas from other states with the same type of vegetation in the future, thus increasing the number of samples available for analysis.

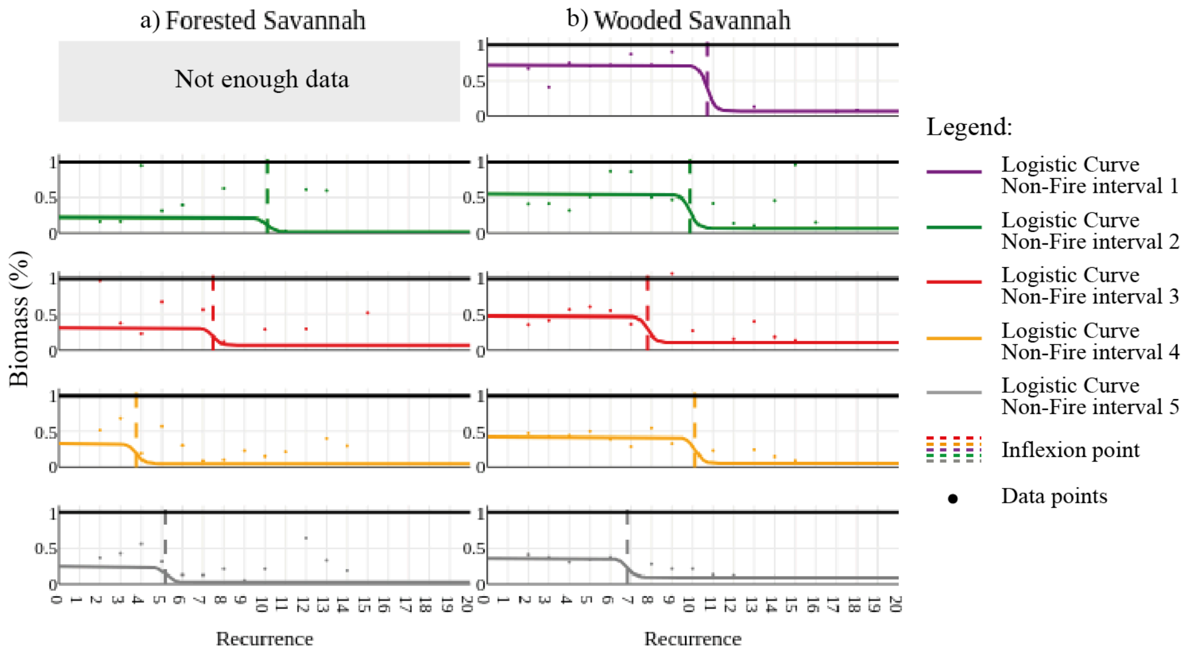

Figure 5: Logistic curve projecting the biomass pattern of the two savannas (a) Forested and b) Wooded) studied, in recurrence configurations between 2 and 20 burns and non-fire intervals from 1 to 5 years.

We obtained information that reflects the response of above-ground biomass to these events. However, previous studies (Pivello, 2011) emphasize that this is only one aspect to consider, especially in savannas, where above-ground biomass represents only a fraction of the total in this system. Around 40 % of the biomass is located below ground, playing a crucial role in vegetation recovery and regrowth.

This variation in residual biomass in response to the frequency of burning is a crucial aspect that requires further investigation to understand the quality and diversity of the species that survive. Preliminary observations suggest that an increase in the recurrence of burning can lead to a reduction in species diversity and, consequently, a decrease in the potential biomass stock in these ecosystems (Fidelis et al., 2011). However, for a comprehensive analysis, detailed studies on vegetation composition and richness are needed to fully understand how these changes affect both the biomass and resilience of these systems.

CONCLUSIONS

This study provides a methodological test for assessing the fundamental basis of understanding the complex interaction between fire, biomass, and vegetation in the savannas of Maranhão. The results provided important insights into the influence of fire on the resilience of savannah ecosystem biomass. After three fire recurrences in forest savannas and seven recurrences in wooded savannas, only 10-20% of biomass remained in the different configurations. This emphasizes that each vegetation type has its tolerance limits to the frequency of burning.

This information is essential not only for quantifying greenhouse gas emissions and assessing the recovery potential of areas degraded by fire but also for implementing the PNMIF and guiding effective Cerrado management and conservation strategies. The study presents preliminary results on biomass dynamics about recurrence and non-fire intervals, however, a full understanding of these dynamics requires more detailed studies of vegetation composition and richness, as well as further testing of models predicting vegetation response in interaction with fire.

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