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Assessing the Dynamics of Woody Vegetation in the Abobral region, southern Pantanal wetland (Brazil): Contributions of Functional Indices Derived from Satellite Image Time Series

Avaliação das Dinâmicas da Vegetação Lenhosa no Pantanal do Abobral: Contribuições de Índices Funcionais Derivados de Séries Temporais de Imagens de Satélite

Uelison Mateus Ribeiro[*], Mauro Henrique Soares da Silva[**], Samuel Corgne[***], Damien Arvor[****]

[*] CNRS, Univ Rennes, Univ Brest, Nantes Université, LETG, UMR 6554, uelison.ribeiro@univ-rennes2.fr
[**] Universidade Federal de Mato Grosso do Sul, Campus Três Lagoas - UFMS/CPTL, mauro.soares@ufms.br
[***] CNRS, Univ Rennes, Univ Brest, Nantes Université, LETG, UMR 6554, samuel.corgne@univ-rennes2.fr
[****] CNRS, Univ Rennes, Univ Brest, Nantes Université, LETG, UMR 6554, damien.arvor@univ-rennes2.fr

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Abstract

The Pantanal biome is a heterogeneous and dynamic ecosystem in central South America, exhibiting complex relationships with climatic and geomorphological factors. This study investigates the spatiotemporal variability of woody vegetation dynamics in the *Pantanal do Abobral*, a subregion of the Pantanal. We analyzed: (1) Land cover changes (2015–2023) using annual maps from the Brazilian Annual Land Use and Land Cover Mapping Project (MAPBIOMAS); Normalized Difference Vegetation Index (NDVI) from the Harmonized Landsat Sentinel-2 (HLS) product and precipitation from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) to identify spatial patterns in vegetation-precipitation relationships via Pearson correlation; and Functional indices derived from NDVI time series. Although woody cover remained stable (~16.75% from 2015–2023), we observed a 19.85% loss in savanna areas relative to 2015, compensated by a 21.81% transition from non-woody to savanna areas. Even within the same land cover class, distinct vegetation types showed differential responses to local precipitation regimes. Functional indices corroborated this heterogeneity, revealing spatial patterns in plant functional groups. Our findings underscore the importance of vegetation functional trait mapping for climate change mitigation and adaptation planning in this ecosystem.

Keywords:
Tropical wetlands, Functional attributes, Satellite image time series, NDVI.

Resumo

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O bioma Pantanal é um ecossistema heterogêneo e dinâmico localizado no centro da América do Sul que possui relações complexas com fatores climáticos e geomórficos. Aqui, investigamos a variabilidade espaço-temporal nas dinâmicas das formações lenhosas no Pantanal do Abobral (2015-2023), uma das sub-regiões do Pantanal. A evolução dessas formações foram analisadas a partir dos mapas do Projeto de Mapeamento Anual do Uso e Cobertura da Terra no Brasil (MAPBIOMAS). Séries temporais do Índice de Vegetação por Diferença Normalizada (NDVI) do produto Harmonized Landsat Sentinel-2 (HLS) e de precipitação do Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) foram utilizados para identificar padrões espaciais nas relações entre a fenologia dessas formações e a precipitação. As relações foram avaliadas por meio da correlação de Pearson. Adicionalmente, foram mapeadas variações espaciais em índices funcionais derivados das séries temporais de NDVI. Embora a proporção de cobertura lenhosa tenha se mantido estável entre 2015-2023 (~16,75%), foram observadas 19,85% de perda nas áreas savânicas em relação à 2015, compensada pela transição de 21,81% de áreas não-lenhosas para savânicas. Adicionalmente, tipologias distintas, mesmo dentro de uma mesma classe de cobertura da terra, respondem diferentemente aos regimes locais de precipitação. Essa heterogeneidade das formações lenhosas foi evidenciada pelos índices funcionais, que também identificaram padrões de distribuição de grupos funcionais. Este estudo ressalta ainda a importância de mapeamentos que descrevem atributos funcionais da vegetação para o planejamento de estratégias de mitigação e adaptação às mudanças climáticas.
Palavras-chave:
Áreas úmidas tropicais, Atributos funcionais, Séries temporais de imagens de satélite, NDVI.

I. INTRODUCTION

The Pantanal is one of the largest seasonally inundated wetlands in the world. This ecosystem comprises an area of approximately 150,000 km² (Bergier et al., 2018) in a region of geological subsidence in central South America (Bergier, 2013) and extends across Brazil (78%), Bolivia (18%) and Paraguay (4%) (Tomas et al., 2019). Surrounded by *Cerrado*, Amazon, Atlantic Forest, *Chaco* and Chiquitano dry forest of Bolivia (Bergier et al., 2018), it has unique landscapes and a great diversity of vegetation types, favored by these neighboring ecosystems (Pott et al., 2011; Alho; Silva, 2012). Given its importance for the biodiversity conservation and its value for humanity, this region was declared a National Heritage Site by the Brazilian Constitution, has four Regional Sites on the List of Wetlands of International Importance (Ramsar List) and a complex of continuous protected areas declared as a Biosphere Reserve and Natural World Heritage Site by UNESCO.

This ecosystem is subject to a predictable monomodal flood pulse (Junk; Cunha, 2005). The flooding is synchronized with the austral summer rain in its northern part and spreads slowly from North to South, reaching the southern Pantanal several months after the rainfall peak (Ivory et al., 2019). This flooding regime plays an

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important role in the heterogeneity of the Pantanal habitats and, consequently, in the diversity of flora and fauna (Alho, 2008).

However, this region has been directly influenced by climate change in recent years. Future scenarios for the Brazilian territory due to global climate change have already indicated a trend towards an increase of dry periods with higher concentration and less intense rainfall in the Pantanal (Marengo, 2006). Such extreme events occurred in recent years and are affecting the hydrological regime of the Pantanal (Marengo, 2021), which suffered severe droughts and catastrophic forest fires (Thielen et al., 2021). Furthermore, there is a loss of biodiversity associated with the occupation and land use in the Pantanal territory, characterized by a structure of large farms and estates (Silva et al., 2017).

The *Pantanal do Abobral*, one of the sub-regions of the Pantanal do Mato Grosso do Sul (Silva; Abdon, 1998), illustrates this scenario. According to Andrade et al. (2020), since 1995 the *Pantanal do Abobral* has been losing areas with a predominance of forest formations, which are being replaced by pasture. Additionally, an increase in areas composed of monodominant formations was identified.

In this sense, the detailed mapping and monitoring are essential to understand the processes and dynamics of formation and evolution of landscape units that constitute complex environmental mosaics such as the *Pantanal do Abobral*. Although valuable global or regional mapping initiatives exist (e.g., the MAPBIOMAS Project; Souza Jr et al., 2020), wetlands present unique characterization challenges. These includes the narrow threshold between its different land cover types (Rapinel et al., 2019) and reliance on static vegetation classes (broad categories such as, for example, 'forest formation') (Arvor et al., 2021). Current approaches fails to capture seasonal dynamics (i.e., an area may be called "herbaceous vegetation", for example, but the same area may be "water" at certain times of the year) and are subject to exclusion between classes (if a pixel is "forest", it means that it cannot be "savanna", while in the Pantanal a pixel may be "tree", "herbaceous" and "water" at the same time or at different times of the year). In other words, there is still a gap in the description and spatialization of functional attributes of vegetation based on remote sensing data.

Several vegetation indices have been developed for remote sensing studies of biophysical parameters; the Normalized Difference Vegetation Index (NDVI; Rouse Jr et al., 1974) is the most widely used (Miranda et al., 2017). Remote sensing-based NDVI time series, for example, have been frequently used to assess phenological patterns (Miranda et al., 2017). However, the revisit rate must be sufficient to capture the patterns of the signal under investigation (Inglada et al., 2016). On the other hand, satellite imagery time series (SITS) are often hampered by high cloud cover in regions such as the Pantanal. Therefore, high temporal resolution data

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are essential in this type of ecosystem. The Harmonized Landsat Sentinel-2 (HLS) products provide observations with a 2- to 3-day revisit cycle at 30 m spatial resolution, thanks to the combined measurements derived from data of the Landsat-8/9 Operational Land Imager (OLI) and the Sentinel-2A/B Multi-Spectral Instrument (MSI). The HLS project is a NASA initiative that produces continuous surface reflectance data from the OLI and MSI sensors based on a collection of algorithms (for details, see Claverie et al., 2018).

In the context of climate change, to understand how different vegetation physiognomies respond to ongoing hydroclimatic regimes is an essential information to plan mitigation and adaptation strategies at the landscape level. Extreme events, especially droughts and fires, are becoming more recurrent and, when associated with anthropogenic impacts, may change the Pantanal as it is today. These events impoverish the floristic composition and degrade ecological functions of different vegetation typologies. Therefore, the application of a functional assessment approach to wetlands would improve the efficiency of environmental management (Rapinel et al., 2015), as well as guide forest restoration strategies in the landscape. Rapinel et al. (2019), showed that analyses of temporal changes in functional indicators highlighted the effects of climate and hydrological management practices on wetland functions.

In this study, the objective was to investigate the spatio-temporal variability at the dynamics of woody vegetation in the *Pantanal do Abobral*, Mato Grosso do Sul State. The specific objectives were: (1) analysis of the evolution from these formations between 2015 and 2023; (2) identification of the spatial distribution patterns for the relationships between phenology and precipitation; and (3) mapping the spatial heterogeneity of ecosystem functional attributes derived from NDVI time series.

II. Materials and Methods

Study area

The *Abobral Pantanal* is one of the sub-regions of the Pantanal biome, according to the delimitation proposed by Abdon; Silva (1998) (Figure 1). It comprises an area of 2,833 km^2 located in the Pantanal territory of *Mato Grosso do Sul* (S 19°18'31'' and WGr 57°03'15''), this sub-region constitutes a floodplain common to the rivers *Abobral*, *Miranda* and *Negro* (Andrade et al., 2022), which flow in an E-W direction towards to the Paraguay River. It is also noteworthy that the *Abobral* River originates in the fluvial plain and does not have an own basin, receiving overflow water from the other two rivers.

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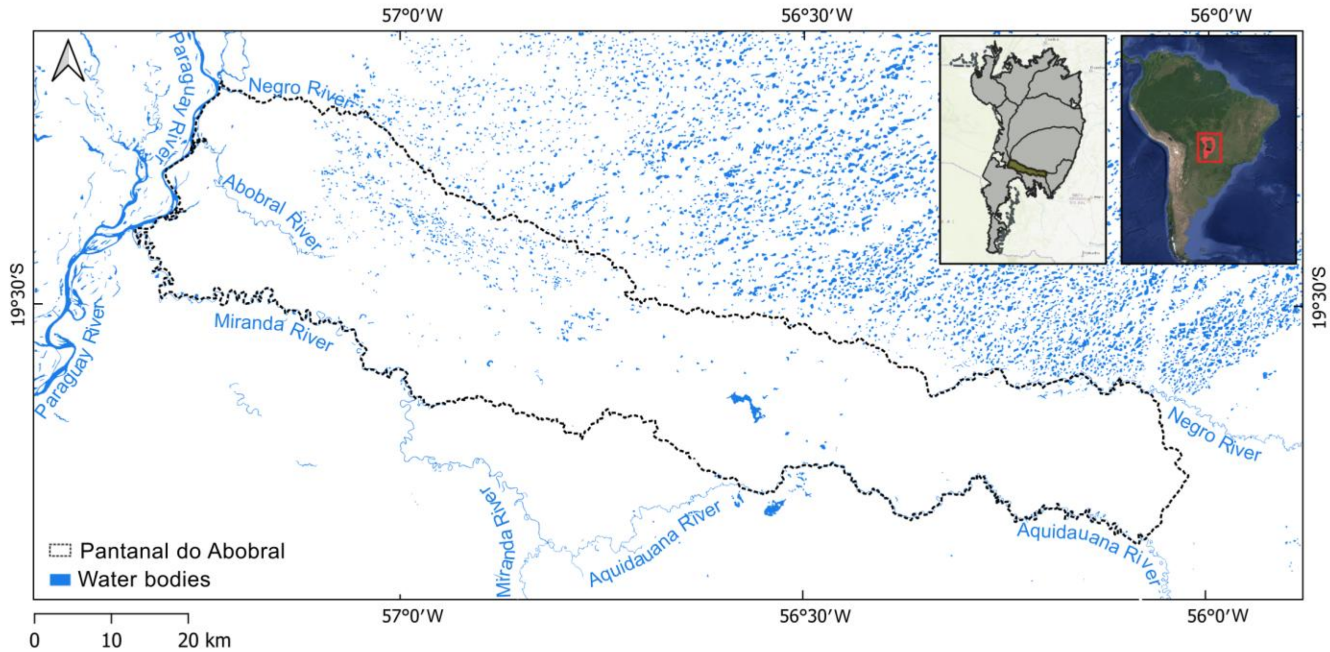

Figure 1 – Localization of *Pantanal do Abobral.*

According to the RADAMBRASIL Project (1982), the region's phyto-physiognomies are characterized as park savanna, a strictly rural physiognomy found in the floodplains; grassy-woody savanna, formed by graminoid substrate, stunted woody plants and small palm trees; and steppe savanna, with steppe tree cover, such as low and thorny woody plants.

Andrade et al. (2022) presents the details of the phyto-physiognomy from the landscape units called *capões* and *cordilheiras*. These are forest formations constituting tree islands occupying with elevations up to three meters in relation to the floodplain, which are not reached by water during the flood period. These tree islands differ in shape, while the *cordilheiras* form elongated cords, and the *capões* have a circular or elliptical shape. Additionally, the vegetation is generally characterized by deciduous species in the center and riparian species on the edges (Pott; Silva, 2015).

In this sense, Boni et al. (2022) point out that these forest formations are ecologically important in this region due to their function as shelters for fauna, especially during flood periods. Silva et al. (2017) also point out the microclimatic function of these landscape units in the region, attributing more importance to these areas. However, both authors agree that these are vulnerable areas, which are consequently used by farmers as refuge for livestock and under pressure due to land use changes in the surroundings.

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Land cover

The land cover evolution was assessed for both the forest and savanna formation classes using maps from Collection 9 of the Brazilian Annual Land Use and Land Cover Mapping Project (MAPBIOMAS; Souza et al., 2020) and freely available at https://code.earthengine.google.com/?accept_repo=users/mapbiomas/user-toolkit. Land cover variation between 2015 and 2023 was obtained using map algebra.

Phenology of arboreal vegetation

Vegetation phenological patterns were assessed using monthly mean NDVI based on HLS image time series. HLS data (T21KVU and T21KWU tiles) with cloud cover less than 80% were acquired free of charge for the period 2015–2023 from NASA's Land Processes Distributed Active Archive Center (LP DAAC) Cumulus Cloud Archive (Masek et al., 2021). For each band, the NDVI was calculated considering all observations (Equation 1).

$$NDVI = (NIR - R) / (NIR + R) \quad (1)$$

where, NIR is the surface reflectance in the near infrared and R the surface reflectance in the red band.

The quality assessment band (Fmask) was used to remove pixels classified as clouds or cloud shadows. Erroneously highly positive [negative] pixels were also masked by removing values above 1 [less than -1]. The monthly mean NDVI was calculated as the mean value of all observations for each month from 2015 to 2023, generating a raster data cube with 108 layers (12 layers per year).

Woody vegetation was obtained from the MAPBIOMAS Project. Only areas always classified as forest formation and always classified as savanna formation from the 2015 to 2023 classifications were used to minimize variability unrelated to phenology. Time series of monthly mean NDVI were then extracted only for pixels from these two formations.

Monthly rainfall

Precipitation regimes at the study sites were monitored using daily precipitation data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; Funk et al., 2015). The 2014–2023 precipitation dataset with 0.05° spatial resolution is freely available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily. The dataset was clipped to the study area, and monthly precipitation obtained by summing the daily values for each month from 2014 to 2023 (2014 was included due to lagged correlations).

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Pointwise correlation

The relationships between phenology and hydrological patterns were assessed using Pearson's correlation (R). Pointwise correlation (correlation between the time series of each NDVI pixel with the time series of the corresponding precipitation pixel) was performed at the HLS spatial resolution (i.e., 30 m). Therefore, the CHIRPS monthly precipitation time series were resampled to the HLS resolution using the nearest neighbor method. Correlation was performed between the monthly mean NDVI (i.e., series with the mean NDVI for each of the 108 months between 2015 and 2023) and the monthly accumulated precipitation.

In addition to the conventional correlation where, for each point (i.e., for the location of each pixel), the values of both time series (NDVI and rainfall) are aligned in pairs of the same date, lagged correlations were also performed. These correlations were performed so that, for a correlation with a one-month delay, the pair of a given NDVI on date i would be the corresponding rainfall value on date i – 1. These correlations were performed with a delay of one to six months. Correlations with p-value < 0.001 were considered significant. From the seven correlation maps, with a delay of 0 to 6 months, the following was obtained: i) the maximized correlation map where, for each pixel, that one with the highest absolute value is selected among the seven correlation values; and ii) the map with the lag time associated with the maximum correlation of each pixel.

Functional indices

The monthly mean NDVI series derived from HLS products were used to assess variations in functional processes of forest and savanna formations. The functional indices derived from the annual NDVI curve were: (1) the annual NDVI integral (NDVI-I), as an indicator of net primary production and (2) the intra-annual relative range (RREL), to describe the seasonality of carbon fluxes (Rapinel et al., 2019; Alcaraz et al., 2006). Negative values in the pixels were replaced by zeros to avoid flood-related trends (Rapinel et al., 2019). Due to the high cloud cover, which would directly affect the NDVI-I (because there would be a tendency to underestimate the NDVI-I due to the lack of data) and, consequently, the RREL, the mean annual cycle was calculated from the mean monthly NDVI for the period 2015-2023. Finally, the NDVI-I was obtained from the sum of the NDVIs of the mean annual cycle, and the RREL from the subtraction between the maximum and the minimum NDVI of the mean annual cycle, divided by the NDVI-I.

All processing and analysis steps were performed using the R v.4.2.3 software.

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III. Results and Discussion

Evolution of the forest and savanna formations

The area occupied by forest and savanna formations in the Pantanal do Abobral remained practically unchanged between 2015 and 2023, based on the classification of the MAPBIOMAS Project (Collection 9) (Figure 2). These classes represent approximately 16.74% of the land cover in 2015, with 9.39% forest and 7.38% savanna, and occupied 16.77% in 2023, when there was a small reduction in the area of forest (9.21%) and an increase in savanna formations (7.52%).

Although there was no significant change in woody vegetation cover during this period, there were transitions between woody and non-woody formations (see the Sankey diagram in the lower left corner of Figure 2). For example, from approximately 209 km² classified as savanna formation in 2015, 19.85% changed to other non-woody land covers by 2023. However, this loss of savanna formation was offset by transitions in the opposite direction (pixels from the non-woody classes to the savanna class), which represented an area equivalent to 21.81% of the savanna formation area in 2015.

Additionally, the landscape of the *Pantanal do Abobral*, saturated with *capões*, favors the occurrence of a high number of mixed pixels between forest and grassland formations on the edges of these tree islands, leading to omission and commission errors in the classification maps (Figure 3). However, Collection 9 products showed notable improvement over previous versions for this study area. In a preliminary study (Ribeiro et al., 2024), MAPBIOMAS Project's Collection 8 data showed that forest formation covered 10.2% and savanna 10.0% of the *Pantanal do Abobral* in 2015. This represents a 3.36% higher woody vegetation coverage compared to Collection 9 estimates for the same year. This difference may indicate an overestimation of woody vegetation in 2015 at Collection 8, since some of the main overlap errors present in this collection were resolved in Collection 9 (Figure 4).

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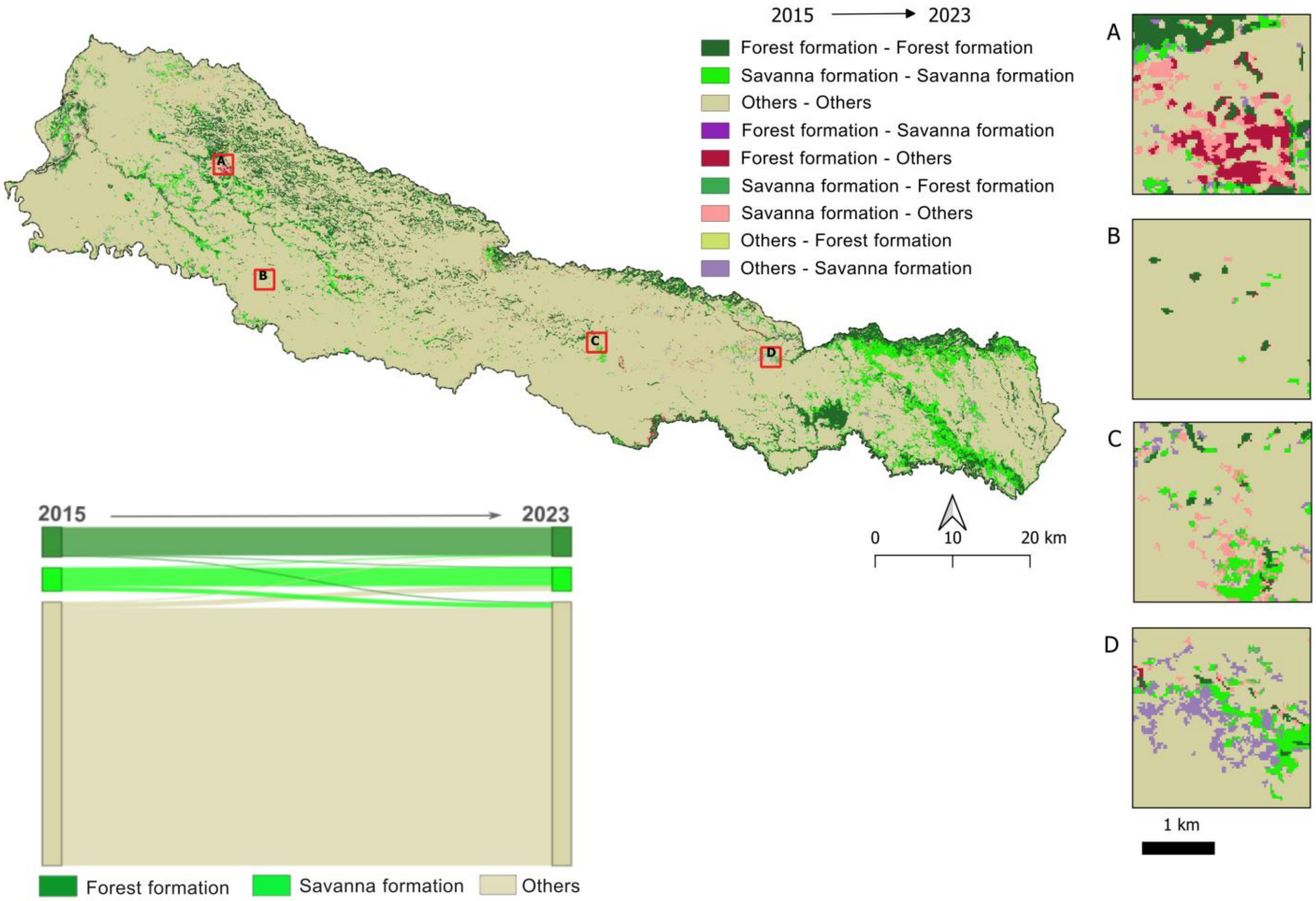

Figure 2 – Evolution of forest and savanna formations in the Pantanal do Abobral Pantanal between 2015 and 2023 based on the land cover/land use classification of MAPBIOMAS Project. 'Others' includes the following classes (MAPBIOMAS): grassland formation, pasture, flooded field and marshy area, and water bodies.

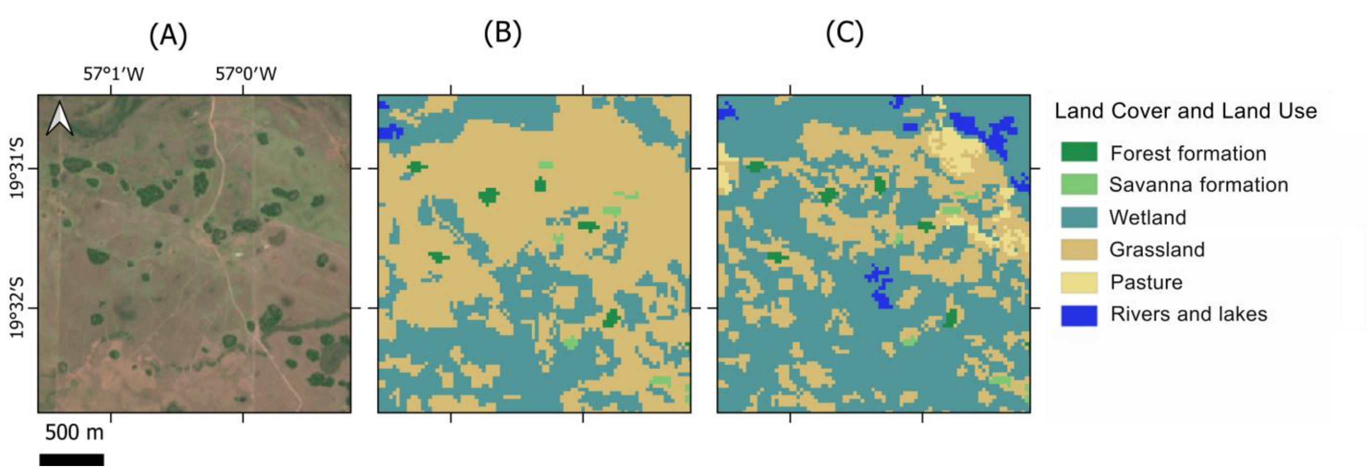

Figure 3 – Land cover in an area of *Pantanal do Abobral* characterized by the presence of *capões*. A) Satellite image: Sentinel-2 (02/03/2023); B) MAPBIOMAS Project Classification for 2015; and C) MAPBIOMAS Project Classification for 2023. Location indicated in Figure 2 (B).

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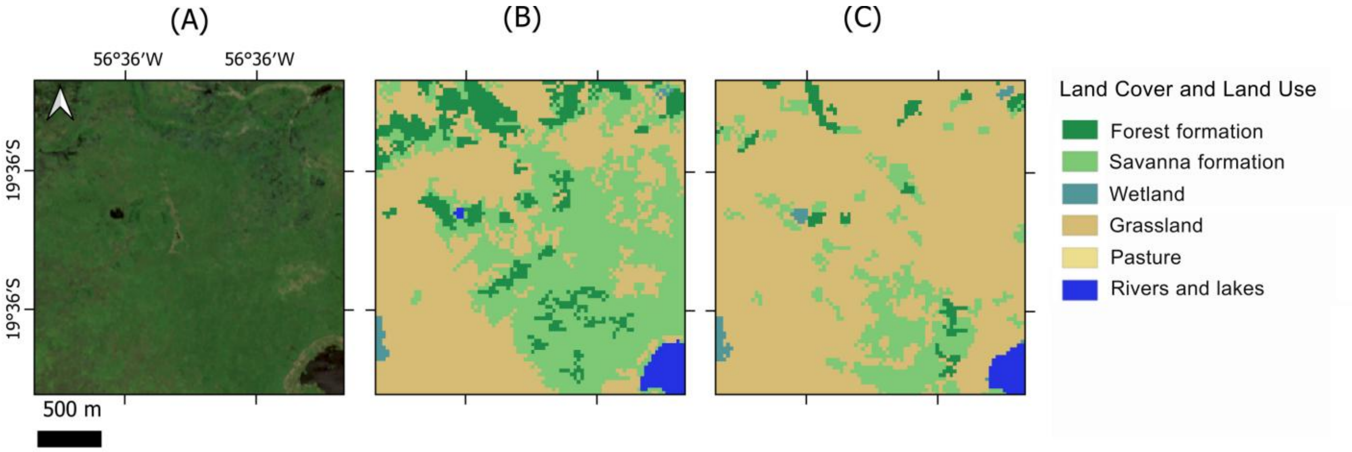

Figure 4 – Comparison between land cover classifications from collections 8 and 9 of the MAPBIOMAS Project for the same area of the *Pantanal do Abobral* in 2015. A) Satellite image: Sentinel-2 (03/13/2016); B) Collection 8; and C) Collection 9. Location indicated in Figure 2 (C).

Dynamics between phenology and rainfall

In general, arboreal tree vegetation responds to rainfall with a delay of one to two months (Figure 5). The correlation was higher with a delay of one month in 43.3% of the pixels and a delay of two months in 42.2%. There was no significant correlation (p-value > 0.001) in 7.4% of the area and R was maximized with a delay of three months in another 4.9%. In the remaining area, R is maximized with delays of 6, 0 (zero-month lag or conventional R), 4, and 5 months (respectively, 1.1%, 0.8%, 0.2% and 0.02% of the pixels). This spatiotemporal dynamic highlight the wide variety of vegetation typologies in this ecosystem. Among the woody formations of the Pantanal, for example, Pott et al. (2011) mention semi-deciduous forests, mesotrophic and dystrophic cerrado, gallery forest and riparian forests (flood-prone). These authors also refer to communities dominated by a single species, generally pioneers, where ecological succession is impeded due to the occurrence of regular floods.

Despite being part of the same land cover class, distinct typologies respond differently to local precipitation regimes (Figure 6 and Figure 7). Areas that replied to precipitation with a one-month lag, for example, presented significant intra-annual amplitudes in their NDVI series (e.g., Figure 6-C, G and Figure 7-C, G). In these areas, typical formations of Lowland Deciduous Forest are expected, where more than 60% of the trees are deciduous (Pott et al., 2011). On the other hand, riparian formations are characterized as Alluvial Semideciduous Forest, where 20 to 50% of the trees lose their leaves (Pott et al., 2011). Since evergreen trees tend to predominate in these areas, the contribution of deciduous species to the annual variation of NDVI is minimized and the values of this index remain high throughout the year (Figure 7-E). In such sectors, flood dynamics also play an important role in the variability of vegetation (Ivory et al., 2019), which is less susceptible to water stress.

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The droughts in recent years favored the spread of fires in the Pantanal (Marengo et al., 2021). These forest fires, in turn, affected the composition and structure of woody formations in several areas of the *Pantanal do Abobral*. In the affected areas (areas burned during 2019, 2020, and 2021 can be identified in Figures S1, S2, S3), the impact of these events on woody vegetation is evident in the NDVI time series, which show an abrupt drop in values after the fires, followed by a change in intra-annual dynamics (Figure 7-A, B, F, H). The area indicated in Figure 6-F, for example, suffered a large reduction of tree species richness after the 2021 fires and became a fragment dominated by *Acuri* palms (*Attalea phalerata*) (Figure S4), which occupied the understory. Additionally, prolonged periods of drought also favor the colonization of seasonally flooded fields by woody species (Alho et al., 2019), as it probably occurred in the area indicated at Figure 6-D, which shows a downward trend in the annual amplitude of NDVI over the last few years (Figure 7-D).

However, the correlations maximized with long lags (5–6 months), which represented ~1.1% of the area, are possibly associated with limitations inherent to the time-lag analysis method. A lag of six months, for example, causes the NDVI of August (dry season) to be compared with the precipitation of February (rainy season), providing an inverse relationship that does not reflect a real ecological response, but rather an artificial temporal disconnection between variables that follow opposite seasonal cycles. Intermediate lags (3–4 months in ~1.0% of the area) may reflect ecological processes, such as adaptive responses of specific vegetation formations to particular water regimes and cumulative effects resulting from prolonged water stress. However, these maximized correlations with long lags may also reflect the influence of surface water on open-canopy floodplains. In these cases, reductions in NDVI throughout the year would be associated with water interference in partially vegetated pixels, and not necessarily with a decline in photosynthetic activity resulting from water stress (de Almeida et al., 2018).

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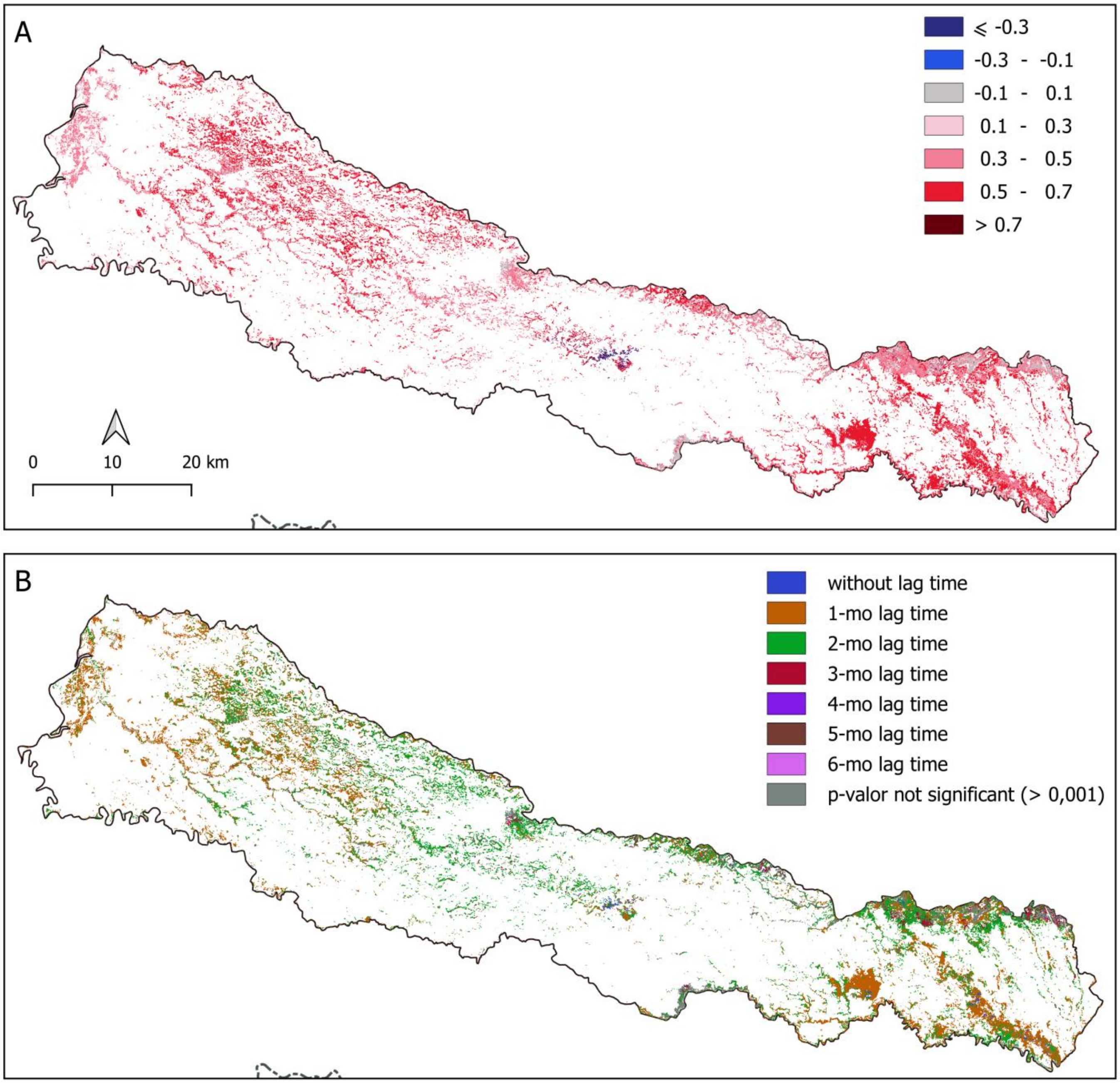

Figure 5 – Spatial distribution of the maximized Pearson correlation between monthly time series of NDVI from woody vegetation and precipitation for the *Pantanal do Abobral*, (A) and the lag time in months required to maximize the correlation (B).

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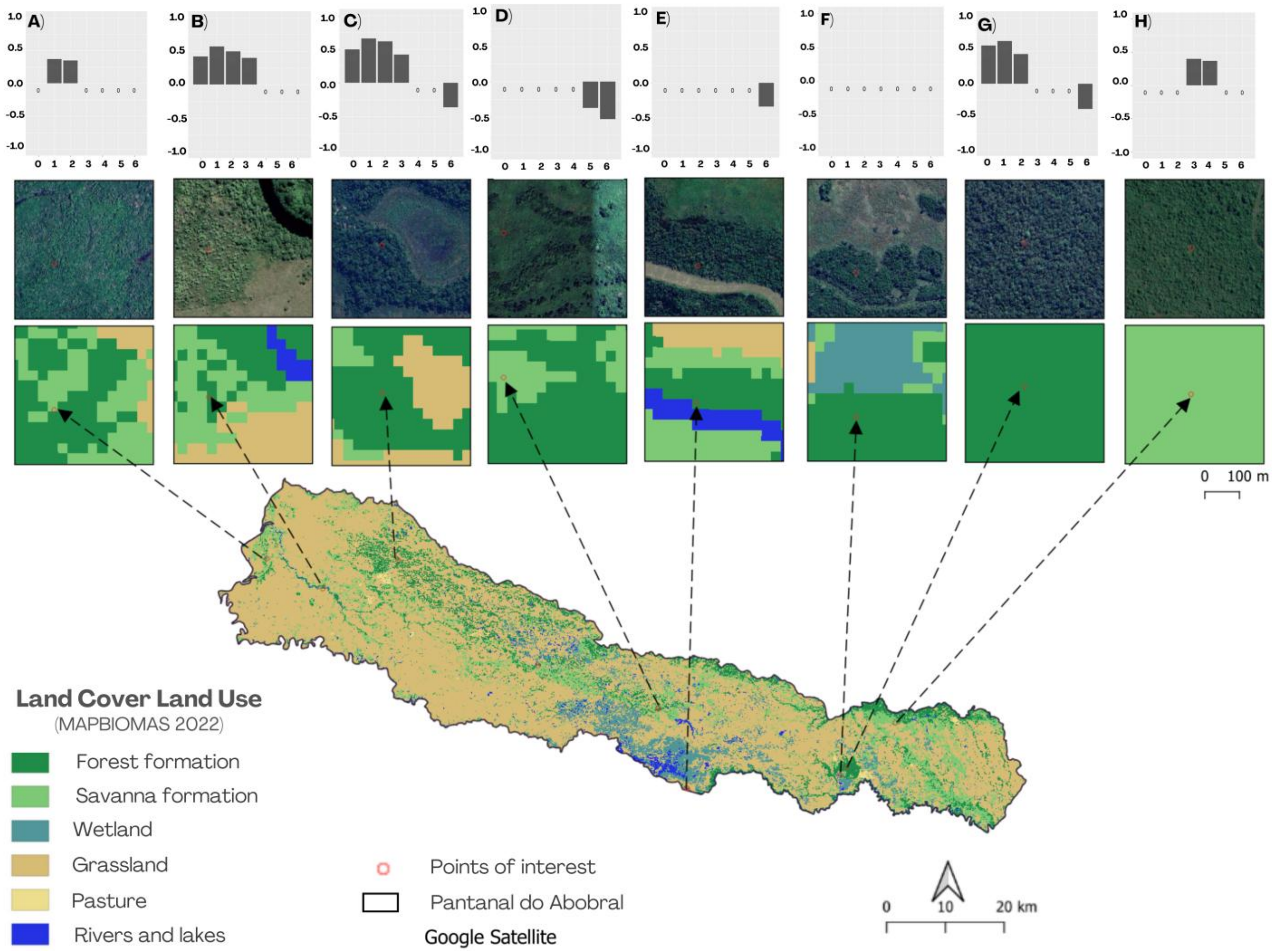

Figure 6 – Land cover and use in the *Pantanal do Abobral* in 2022 (MAPBIOMAS Project). Highlight points A-H with graphical representations of Pearson correlations with 0 (conventional correlation) to 6 months lag time.

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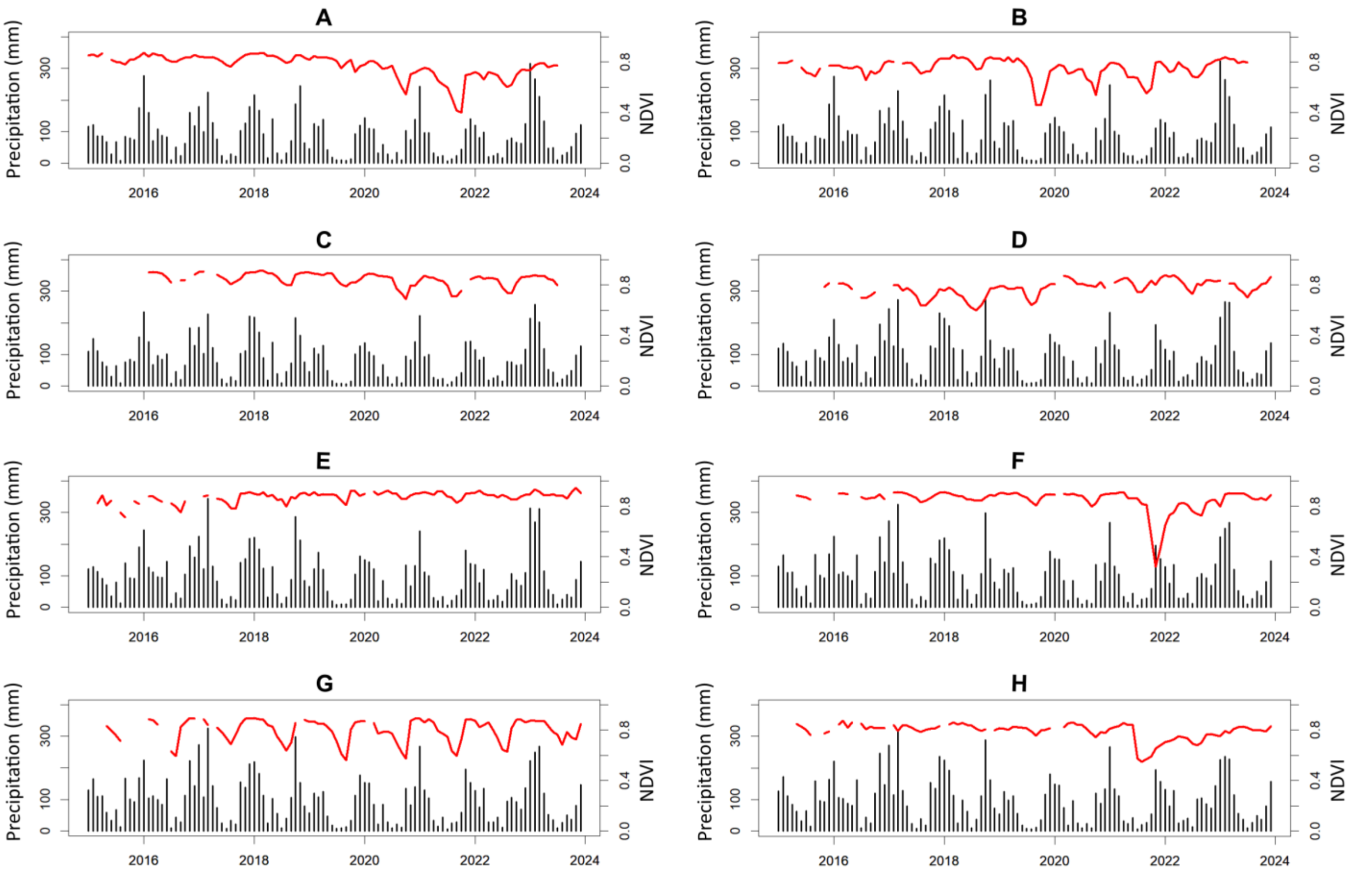

Figure 7 – Average monthly NDVI of points A to H indicated in Figure 6, *Pantanal do Abobral*.

Spatial variations in functional indices

The spatial variability of functional processes within forest and savanna formations was mapped using the annual NDVI integral (NDVI-I) and the intra-annual relative range (RREL) (Figure 8), as indicators of net primary production and seasonality of carbon fluxes (Rapinel et al., 2019). The mean NDVI-I was 9.78 (±0.48) for the forest formation and 9.27 (±0.51) for the savanna formation, and these means being significantly different (t = 352.56, df = 455643, p-value < 2.2e-16). Furthermore, NDVI-I tends to be higher in riparian forests and lower in the Paraguay River floodplain, in the western part of the *Pantanal do Abobral*.

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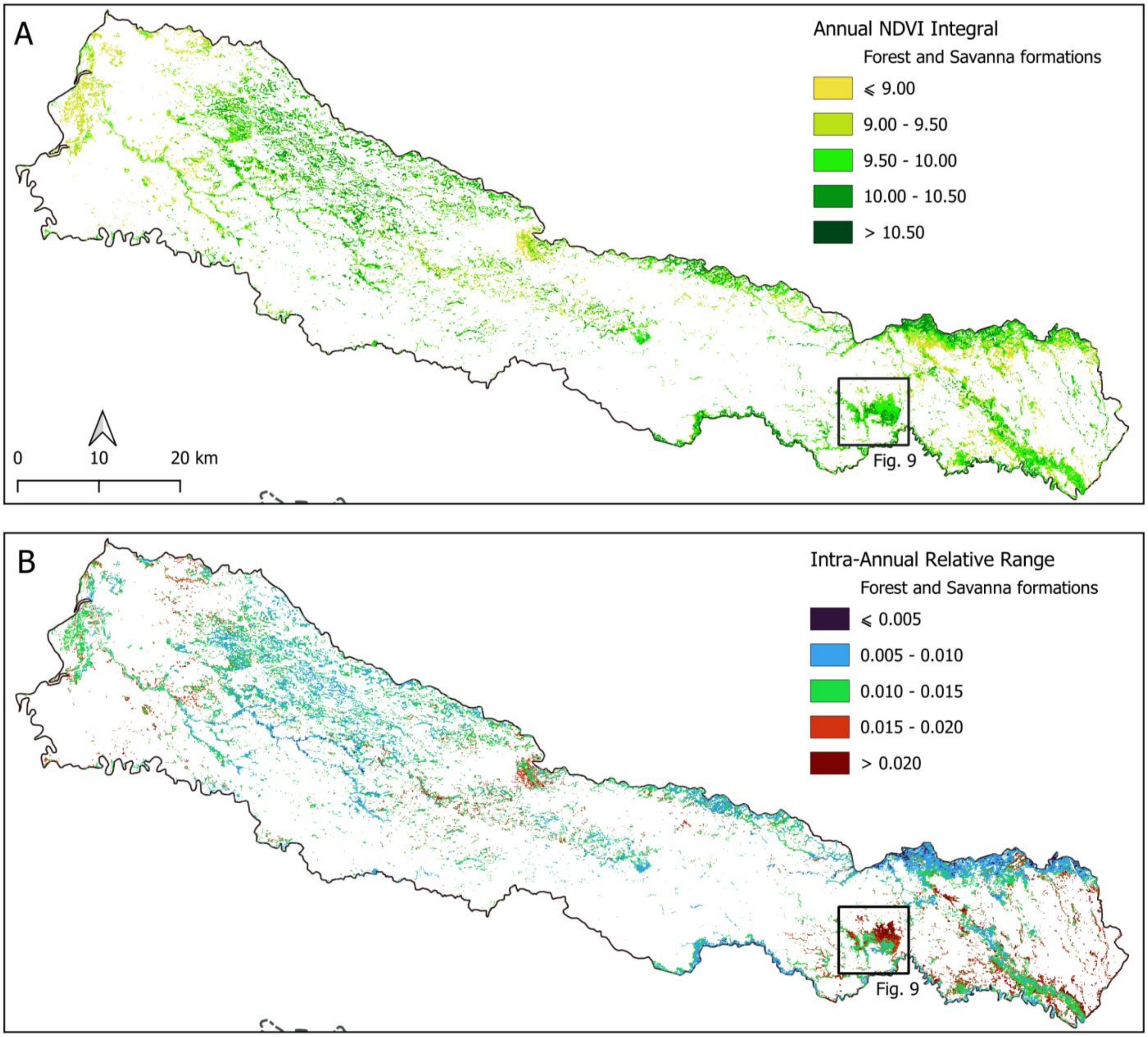

Figure 8 – Annual NDVI integral (A) and intra-annual relative range (B) of forest and savanna formations derived from the average annual NDVI cycle (2015-2023), Pantanal do Abobral, MS.

The intra-annual relative range, in turn, shows that the NDVI seasonality is significantly lower in the forest formation (0.011 ± 0.0042) compared to the savanna (0.013 ± 0.0047) ($t = -134.03$, $df = 442870$, $p\text{-value} < 2.2e-16$). Complementing the NDVI-I, this functional index indicates that the NDVI amplitude is lower mainly in riparian forests. Additionally, Figure 9 highlights the heterogeneity of a forest fragment in this region. In this fragment, both functional indices show a N-S increase gradient in annual primary production and decrease in the seasonality of carbon fluxes. Considering that severe droughts are recurrent events in the Pantanal, an advance of communities with more marked seasonal patterns is expected.

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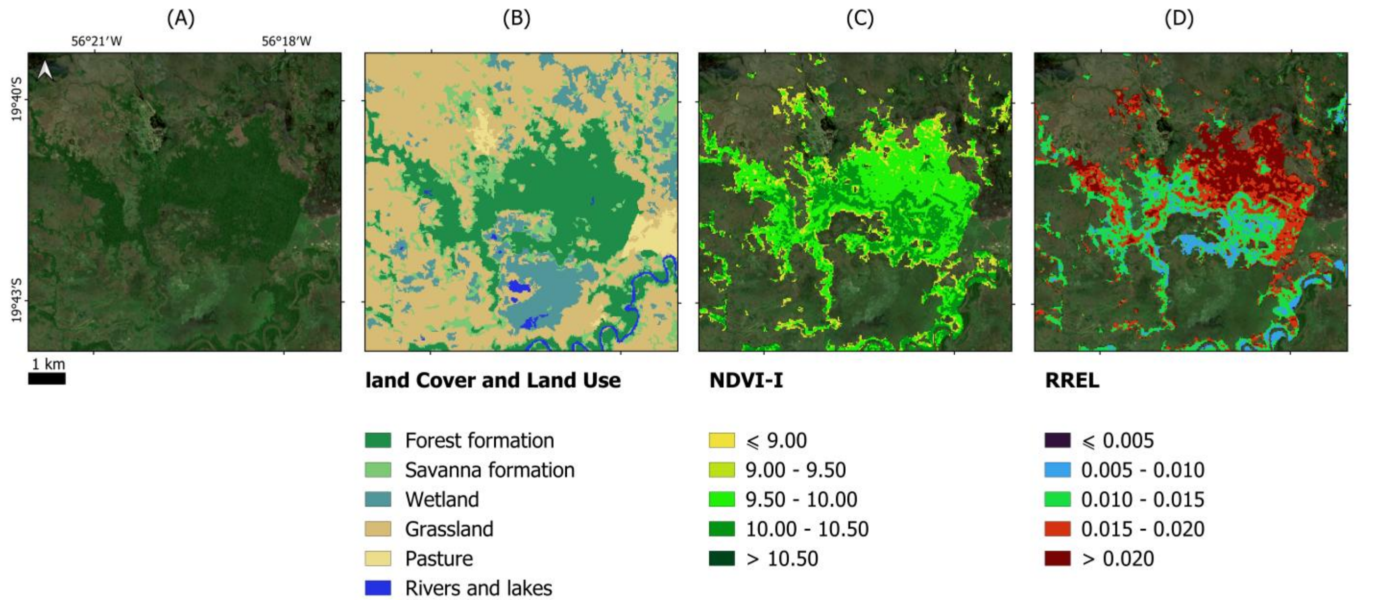

Figure 9 – Characteristics of a forest fragment in the Pantanal do Abobral, A) Satellite image: Sentinel-2 (02/03/2023); B) annual classification of land cover and use (MAPBIOMAS, 2022); C) annual NDVI integral (NDVI-I); and D) intra-annual relative range of NDVI (RREL). NDVI-I and RREL were derived from the mean annual cycle of NDVI for the period 2015-2023. Location indicated in Figure 8.

The functioning of the Pantanal ecosystem will be severely impacted by changes in inter- and intra-annual flood dynamics caused by the climate change (Thielen et al., 2020). Among these impacts, signs of habitat loss have been observed. Alho et al. (2019), for example, observed that homogeneous formations of woody plants have colonized seasonally flooded fields in the Pantanal during drought years. Important expansion dynamics of pioneer formations in the *Pantanal do Abobral* between 1995 and 2015 were also identified by Andrade et al. (2020). Although fire is part of the Pantanal natural dynamics (Marengo et al., 2021), the increase in the frequency and intensity of forest fires may favor a transition from forest to savanna formations, thus characterizing a process of 'cerradization' associated with fire, when species with cork rhytidomes are favored to the detriment of sensitive species (Pott; Pott, 2004).

Several land cover maps at global or regional scales are currently available and are essential for many applications, particularly detecting abrupt land cover changes (e.g., deforestation). However, classification schemes and methodological approaches still have important limitations, especially for monitoring vague and ambiguous geographic concepts (Arvor et al., 2021), such as vegetation gradients in complex areas like the Pantanal. Although the boundaries between macro-classes are generally well defined (e.g., between forest and grassland formations), the transitions between typologies are difficult to observe and may hide interannual changes in the composition and structure of these classes. In this sense, mapping approaches to describe the functional attributes of vegetation can better explain transitions and trends within landscape units. This

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information, in turn, contributes to improve understanding and monitoring of the influence from management practices and climate on wetland functions (Rapinel et al., 2019). Furthermore, future management of fire-vegetation dynamics in seasonally dry tropical forests requires knowledge of its natural variability on short and long-time scales, as well as reflections on how these processes link climate change to impacts on the diversity of such plant communities (Power et al., 2016).

IV. CONCLUSIONS

This study highlights the complex dynamics between apparent stability and subtle changes in the vegetation of the *Pantanal do Abobral*. Although the woody cover (forest + savanna) maintained a similar proportion between 2015-2023 (~16.75%), a compensatory process was observed: the losses of savanna areas were balanced by the transition of non-woody sectors to this class. The phenological response of woody vegetation occurred predominantly one to two months after the precipitation. However, the variation in response time reflects the heterogeneity of vegetation typologies. This diversity includes deciduous seasonal forests to semi-deciduous riparian formations, cerrado (mesotrophic and dystrophic) and monodominant formations, each with particular ecophysiological strategies.

While extreme events increasingly threaten these sensitive ecosystems, monitoring their dynamic landscape changes, though critically important, continues to present significant challenges. Since vegetation typologies typically occur along continuous gradients rather than discrete boundaries, traditional approaches are unlikely to capture changes in the distribution of plant communities and, consequently, in the functional attributes of the ecosystem. In this context, methods based on functional attributes emerge as essential tools to: (1) discriminate patterns within vegetation macro-classes; (2) monitor subtle transitions; and (3) support climate adaptation strategies at the landscape level.

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