Cuadernos de Investigación Geográfica *Geographical Research Letters*	2025	Nº 51 (2)	pp. 109-120	EISSN 1697-9540

http://doi.org/10.18172/cig.6801

SPECTRAL-TEMPORAL ANALYSIS OF WETLAND FIRES IN THE PANTANAL-BRAZIL SUPPORTED BY UAV MULTISPECTRAL IMAGERY

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ABSTRACT. The Wetlands of the Pantanal in Brazil are highly sensitive to environmental changes, and events such as wildfires pose a significant threat to biodiversity. In 2020, approximately 80% of its area was affected by high-intensity fires. Therefore, this study aimed to analyze, both spectrally and temporally over a three-year period (2019, 2020, and 2021), the behavior of four macrohabitats located within two study areas of the Private Reserve of Natural Heritage SESC Pantanal (RPPN SESC Pantanal), situated in the state of Mato Grosso, Brazil. For the analysis conducted over the three-year period in the study areas, the Micasense Altum multispectral camera was employed, along with processing methods involving spectral and temporal analysis. The results revealed a drastic decrease in reflectance within the red-edge and near-infrared (NIR) spectral bands in 2020, following the fire event, in both mapped areas. A subsequent recovery was observed in 2021, although reflectance levels remained below those recorded in 2019 (pre-fire conditions). The Acurizal and Tabocal macrohabitats exhibited the highest reflectance amplitudes and the greatest variability over the years, particularly in longer wavelengths (NIR). The Campina macrohabitat showed the lowest reflectance values, due to its vegetation being composed predominantly of shrub and herbaceous species. The Dry Forest (Mata Seca) displayed the highest spectral stability and demonstrated a continuous downward trend in average reflectance, indicating a loss of species diversity following the fire event. The findings contribute to the enhancement of conservation measures in wetland ecosystems, the management of protected areas, and the effectiveness of public policies, highlighting the potential of high-resolution multispectral data for spectral monitoring as a tool for detecting environmental changes.

Análisis espectral y temporal de incendios en humedales del Pantanal-Brasil apoyado en datos multiespectrales obtenidos con UAV

RESUMEN. Las zonas húmedas del Pantanal en Brasil son altamente sensibles a los cambios ambientales, y eventos como los incendios representan una amenaza para la biodiversidad. En el año 2020, aproximadamente el 80% de su superficie fue afectada por incendios de alta intensidad. En este contexto, el presente trabajo tuvo como objetivo analizar, de manera espectral y temporal a lo largo de tres años (2019, 2020 y 2021), el comportamiento de cuatro macrohábitats presentes en dos áreas de estudio ubicadas en la Reserva Privada del Patrimonio Natural SESC Pantanal (RPPN SESC Pantanal), situada en el estado de Mato Grosso, Brasil. Para los análisis realizados durante los tres años en las áreas de estudio, se utilizó la cámara multiespectral Micasense Altum, junto con métodos de procesamiento que incluyeron análisis espectral y temporal. En el análisis efectuado, se observó que en ambas áreas mapeadas ocurrió una drástica pérdida de reflectancia en las bandas del red-edge y del infrarrojo cercano (NIR) en el año 2020, posterior al evento de incendio, seguida de una recuperación en 2021, aunque todavía por debajo de los niveles registrados en 2019 (antes del incendio). Los macrohábitats de Acurizal y Tabocal presentaron las mayores amplitudes de reflectancia y mayor variabilidad a lo largo de los años, especialmente en longitudes de onda más altas (NIR). El macrohábitat de Campina fue el que presentó los valores más bajos de reflectancia, debido a que su vegetación está compuesta por especies arbustivas y herbáceas. La Mata Seca mostró la mayor estabilidad espectral y presentó una tendencia continua de disminución en la reflectancia media, lo que indica una pérdida de diversidad de especies tras el evento de fuego.

Los resultados obtenidos contribuyen a mejorar las medidas de conservación en zonas húmedas, la gestión de Unidades de Conservación, así como la efectividad de las políticas públicas, evidenciando el potencial de los datos multiespectrales de alta resolución como herramienta para el monitoreo espectral y la detección de cambios ambientales.

Keywords: Conservation Unit, Spectral Analysis, High Resolution, Sensors, Remotely Piloted Aircraft.

Palabras clave: Unidad de conservación, análisis espectral, alta resolución, sensores, aeronaves pilotadas remotamente.

Received: 14 May 2025

Accepted: 30 October 2025

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1. Introduction

The Pantanal is a floodplain covering approximately 140,000 km² of Brazilian territory. It is characterized as one of the largest floodplains and one of the most extensive continuous wetlands on the planet. The biome is part of the Upper Paraguay River Basin, which drains an area of about 500,000 km² (Zarista and Zeilhofer, 2015; Ministério do Meio Ambiente, 2007). Located in the Central-West region of Brazil, the Pantanal spans the states of Mato Grosso (35%) and Mato Grosso do Sul (65%) (Fernandes, Signor and Penha, 2010), situated in the Upper Paraguay Depression and bounded by the Andes Mountain Range to the west and the Brazilian Central Plateau to the east (Ferreira, Carvalho and Rabelo, 2019).

The Pantanal floodplain is characterized by a predictable flood pulse, alternating between an aquatic phase and a terrestrial phase of low amplitude and long duration (Peixoto, Luz and Brito, 2016). The annual flood cycle varies in intensity from year to year, with some years experiencing heavy rainfall and others, drought. The interplay between hydrological regimes, topographical variation, and soil characteristics creates a complex and heterogeneous landscape composed of diverse wetland types. These environmental factors jointly determine both the frequency and duration of inundation events, giving rise to a dynamic mosaic of wetlands that may remain dry most of the year, experience seasonal flooding, or stay permanently inundated. This spatial and temporal heterogeneity promotes high ecological diversity and supports a wide range of habitats and ecosystem processes, contributing to the overall complexity and resilience of wetland systems (Fernandes, Signor and Penha, 2010).

In 2020, wildfires of catastrophic proportions affected 29.7% of the Pantanal and 91% of the total area of the SESC Pantanal Private Natural Heritage Reserve (RPPN), prompting urgent mobilization of resources and efforts to control the fires. Despite the unprecedented devastation, fire suppression measures helped mitigate impacts on biodiversity and human populations.

The RPPN SESC Pantanal, the focus of this study, comprises a network of distinct landscape elements referred to as “macrohabitats” (Nunes da Cunha and Junk, 2014), which contribute to local biodiversity. Macrohabitats are landscape units subject to similar hydrological conditions and characterized by distinct vegetation. They can be considered operational units for scientific research and activities related to sustainable management, protection, and restoration (Nunes da Cunha and Junk, 2014; Junk *et al.*, 2018). This scale of analysis enables a synthesis of the structural and functional components of these complex landscapes, thereby contributing to the scientific foundation needed for ecosystem service valuation.

Among the abiotic variables, the flood pulse governs the Pantanal, with its extremes of inundation and drought, followed by fire as a key driver affecting both flora and fauna. Fires can occur naturally (typically at the onset of the rainy season), but most are caused by human activity. The dynamics of these extremes control vegetation patterns, promoting either retraction or expansion. Many woody species tolerate flooding but are rarely resistant to fire (Nunes da Cunha and Junk, 2004).

The advancement of remote sensing and geoprocessing techniques, combined with the evolution of computational image processing, opens new possibilities for the identification of macrohabitats through periodic data collection from otherwise inaccessible areas. In wetland mapping and classification, remote sensing demonstrates robust and repeatable performance in workflows utilizing optical, SAR, LiDAR, and multi-source sensors, enabling accurate inventories at local, global, and temporal scales, as evidenced by comprehensive reviews and recent large-scale products. Recent products and workflows combine orbital systems such as Landsat, Sentinel-1 SAR, and ancillary data to map wetlands at 30 m resolution, with mapping accuracy validated through field data and cross-validation procedures (Boon and Tesfamichael, 2017; Mahdavi *et al.*, 2017; Zhang *et al.*, 2023).

A recent and increasingly accepted technology in vegetation research is the use of RPAs (Remotely Piloted Aircrafts) (Doughty and Cavanaugh, 2019; Samiappan *et al.*, 2016), due to the improvement in the spatial resolution of images captured with multispectral sensors.

This study aimed to analyze two areas within the RPPN SESC Pantanal by characterizing the spectral and temporal patterns of macrohabitats before and after the wildfires, thereby supporting the development of improved landscape restoration protocols.

2. Materials and Methods

This study was conducted in a Federal Sustainable Use Conservation Unit, RPPN SESC Pantanal, which encompasses a total area of 106,308.85 hectares. The RPPN is located in the state of Mato Grosso, 140 km from the state capital, Cuiabá, between the geographical coordinates 16º 28'31" South and 56º 30'5" West. The area is considered very flat, with elevations ranging from 101 to 117 meters above sea level (RAMSAR, 2003).

The delineation and selection of the study areas for mapping were based on species composition, ecological heterogeneity, and the diversity of existing habitat types, taking into account prior field campaign analyses and previous studies developed for RPPN monitoring. Figure 1 shows the locations of the two selected study areas within the RPPN. These areas are dominated by the macrohabitats of Acurizal, Campina, Dry Forest (Mata Seca), and Tabocal, which are distributed in varying proportions throughout the RPPN and the analyzed sites, considering annual flooding variations and topography. These macrohabitats constitute the focus of temporal and spectral analysis.

The Acurizal macrohabitat is characterized by the presence of palms found in areas with dark, fertile soils, and an intermediate canopy dominated by *Scheelea phalerata* (syn. *Attalea phalerata*), commonly known as Acuri. This macrohabitat was described by Dubs (1992) as “semi-deciduous forest facies-Attalea.” Following the Acuri palm, the most frequent tree species include *Combretum leprosum*, *Tabebuia roseoalba*, and *Casearia gossypiosperma*.

Campinas are open areas with little presence of tree species and a predominance of herbaceous-grass vegetation. Grass species in these areas can reach heights of up to two meters. They occur in slightly lower topographic gradients and are seasonally flooded, typically circular in shape and bordered by dry forests (Mata Seca) located in higher, usually non-flooded areas covered by forest vegetation.

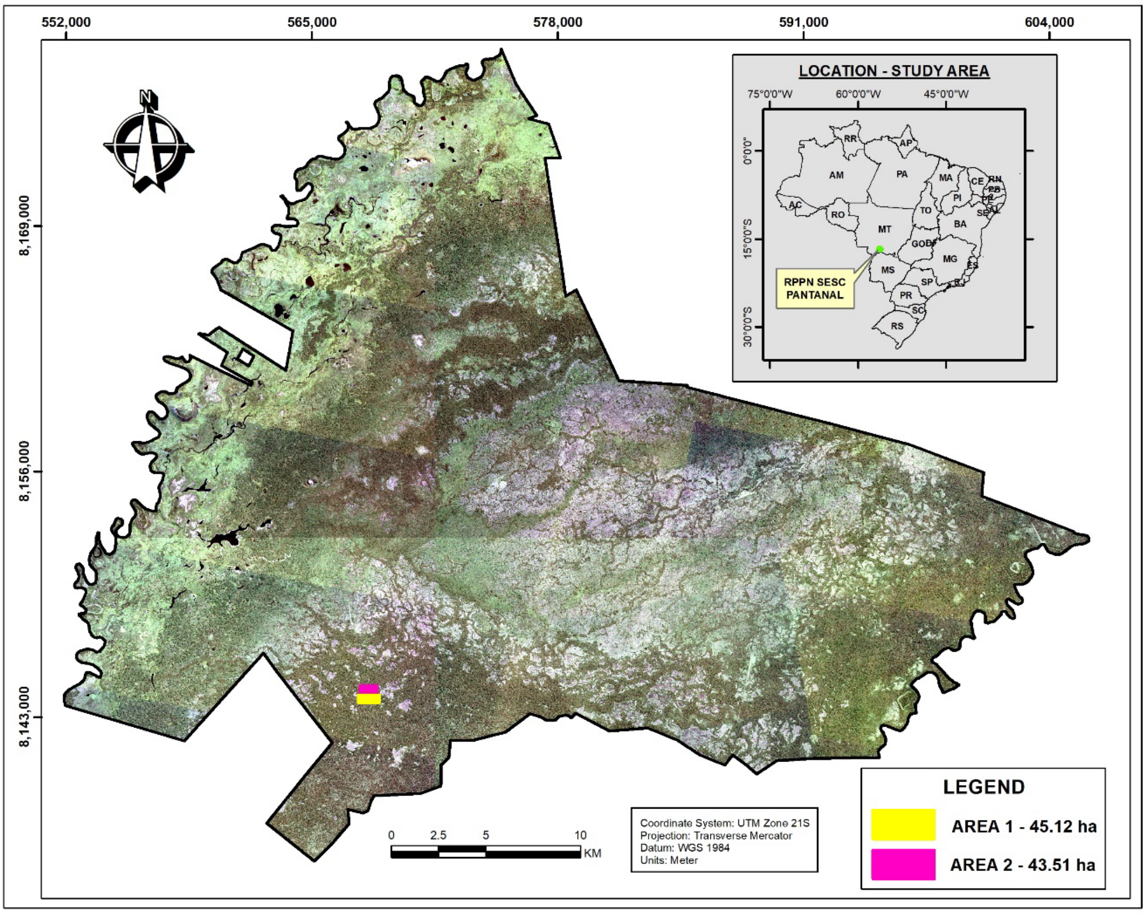

Figure 1. Location of the analyzed areas within the SESC Pantanal Private Natural Heritage Reserve.

Mata Seca is physiognomically similar in tree species composition and is characterized by a higher density of mature trees with minimal spacing between individuals, resulting in canopies that touch during the wet season.

The Tabocal macrohabitat includes tree species that form a canopy ranging from 25 to 30 meters in height, with a mid-canopy densely populated by bamboo. These bamboo-dominated forests are characterized by large populations of *Bambusa* sp. (Poaceae) in the intermediate layer, along with multi-stemmed species such as *Coccoloba* sp. (Ratter *et al.*, 1988).

2.1. Data Acquisition and Processing

The UAV DJI Matrice 100 equipped with the Micasense Altum multispectral camera was used for image acquisition. This camera features five high-resolution narrow bands in the blue (475 nm), green (560 nm), red (668 nm), red edge (717 nm), near infrared (840 nm), as well as a thermal channel (11 µm), producing both multispectral and thermal images of the programmed flight areas. The system also includes a calibrated reflectance panel (CRP) to collect information on ambient conditions and solar illumination before and after each flight mission, enabling spectral calibration for each band.

Aerial images were captured through pre-planned flight missions using the Litchi app and the Altum camera integrated with the UAV DJI Matrice 100. These missions were conducted on November 21, 2019 (pre-fire), November 3, 2020 (post-fire), and June 1, 2021 (during regeneration). Flight parameters included 75% longitudinal and lateral overlap and a flight altitude of 170 meters.

For image preprocessing, Agisoft Metashape software was used. Initially, image alignment was performed using SIFT (Scale Invariant Feature Transform) algorithms (Lowe, 1999; 2004) and SfM (Structure from Motion) techniques (Szeliski, 2010) to identify similarities between photos by selecting key points, homologous zones, and calibrating focal parameters. As a result, calibrated multispectral orthomosaics with a Ground Sampling Distance (GSD) of 9 cm were generated for the five spectral bands for each analyzed area.

2.2. Spectral Analysis of Macrohabitats Before and After Fire

Spectral analysis was performed through field sampling and visual interpretation for each macrohabitat, generating spectral signatures. For this, both analyzed areas—each with orthomosaics from 2019 (pre-fire), 2020 (post-fire), and 2021 (regeneration)—were sampled using 1000-pixel samples per macrohabitat, including Acurizal, Tabocal, Campina, and Mata Seca.

Subsequently, the results were expressed as reflectance percentages based on the average spectral response of the classes for each study date.

3. Results and Discussion

3.1. Spectral Analysis of Vegetation Before and After Fire - Area 1

The variation in area in hectares for each of the existing macrohabitats was respectively 28.77 ha for Dry Forest (Mata Seca), 8.67 ha for Campina, 5.8 ha for Tabocal, and 1.88 ha for Acurizal. After data processing steps, multispectral orthomosaics were generated for the three analyzed periods, with the results for Area 1 shown in Figure 2.

The spectral sampling of macrohabitats comprising Area 1 enabled the creation of spectral response curves for each macrohabitat, as shown in Figure 3 below.

The spectral curves show how each macrohabitat responded spectrally over the analyzed period. Notably, all four sampled macrohabitats exhibited lower reflectance values in 2020, which corresponds to one month after the fire event. In 2021—approximately eight months after the fire—the spectral response for all macrohabitats indicated an increase in reflectance, especially in the near-infrared spectral region, which is typically associated with vegetation health. This trend reflects the beginning of natural regeneration and increased vegetative cover, although still far from the original spectral signatures observed in 2019 (pre-fire).

The observed pattern of lower reflectance in the blue and red spectral bands, alongside higher reflectance in the green band, indicates the presence of chlorophyll and other pigments. This behavior contrasts with 2020, when the reduced pigment presence led to higher reflectance and lower absorption in the visible spectrum.

For the Campina macrohabitat, the spectral curve in 2021 closely resembled that of 2019, demonstrating rapid recovery of low-stature herbaceous-grassy vegetation from 2020 to 2021. There was an overall decline in mean reflectance from 2019 to 2021, particularly in the Acurizal and Tabocal macrohabitats, which experienced more pronounced decreases and indicating growing spectral heterogeneity in these areas. The spectral variability (represented by variance) was significantly higher in 2019 across all macrohabitats, suggesting more heterogeneous environmental conditions or more intense seasonal/vegetative transitions during that year. In 2020, all macrohabitats showed reduced variance, implying greater spectral homogeneity, likely due to the immediate post-fire landscape, characterized by reduced vegetation cover and biomass. By 2021, although the mean reflectance remained lower in most macrohabitats, the variance increased again.

It is important to highlight the high severity of fire damage in areas with monodominant stands of Tabocal, which is typically composed of dense, intertwined bamboo. Post-fire classification indicated that this macrohabitat was heavily impacted due to the abundance of combustible material.

Figure 4 shows the spatial relationship of the four distinct macrohabitats before and immediately after the fires.

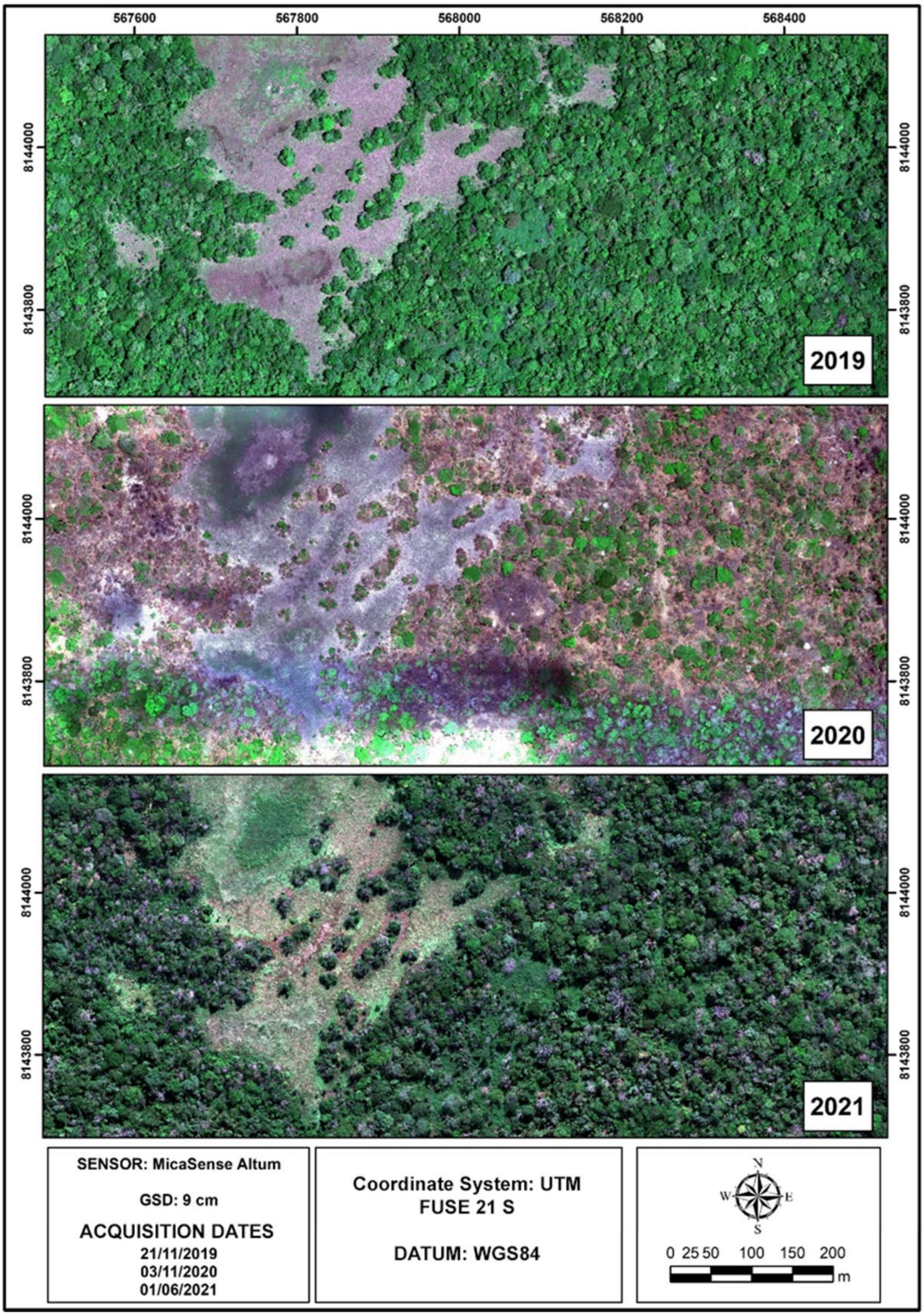

Figure 2. Orthomosaics obtained in 2019/2020/2021 for Area 1.

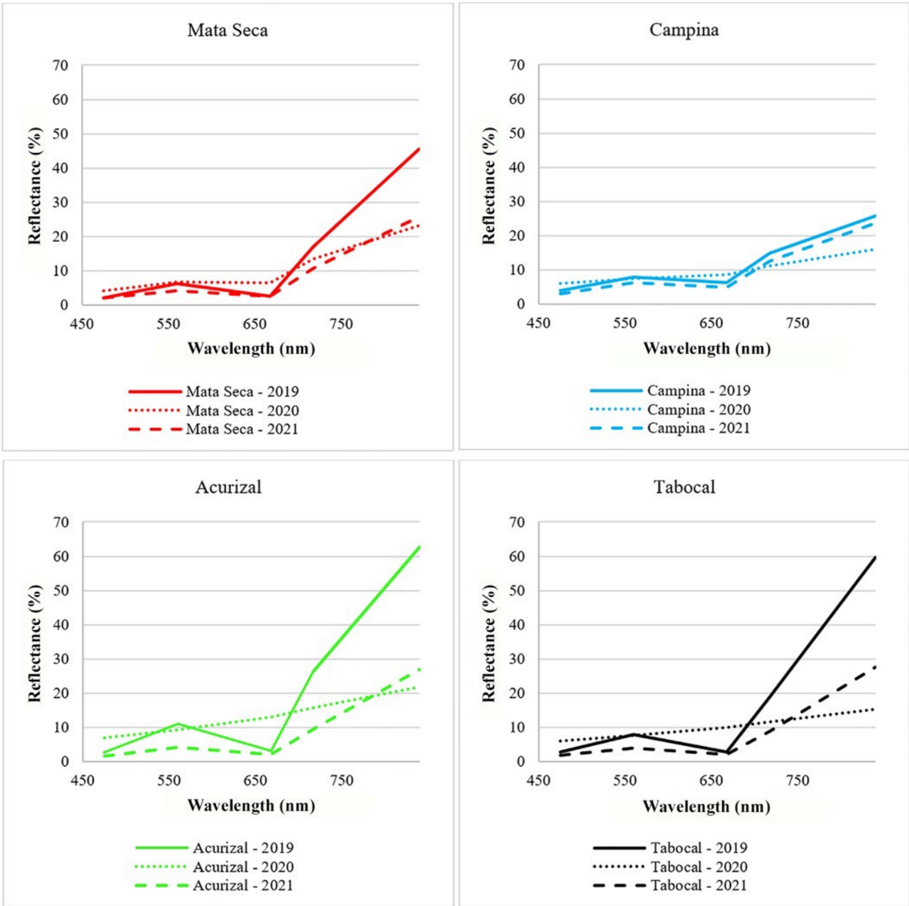

Figure 3. Individual spectral responses of the macrohabitats Mata Seca, Campina, Acurizal, and Tabocal.

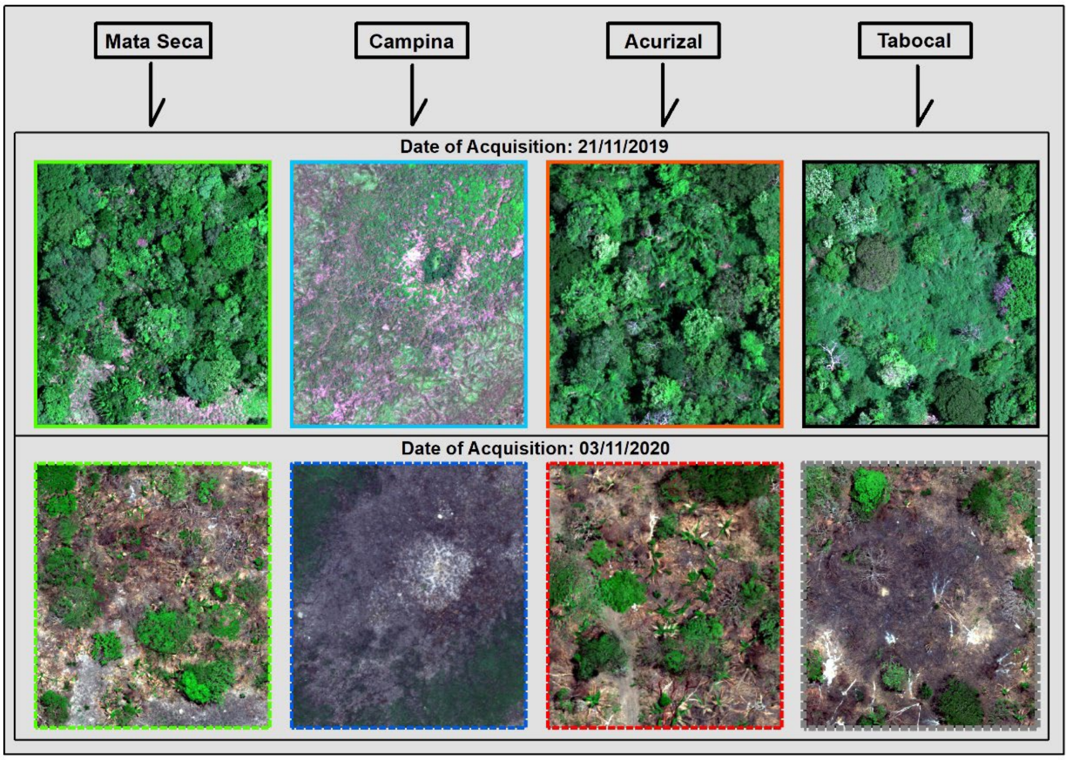

Figure 4. Spatial comparison of macrohabitats in Area 1 before and shortly after the fires.

3.2. Spectral Analysis of Vegetation Before and After Fire – Area 2

The variation in area in hectares for each of the existing macrohabitats was respectively 29.46 ha for Dry Forest (Mata Seca), 7.78 ha for Acurizal, 4.11 ha for Campina and 2.16 ha for Tabocal. After the data processing steps, multispectral orthomosaics were generated for the three analyzed periods, with the results for Area 2 presented in Figure 5.

The spectral responses of the studied classes demonstrate that, morphologically, the vegetation in both areas tends to return to its pre-fire state. This trend can be observed across the four evaluated macrohabitats, as shown in Figure 6.

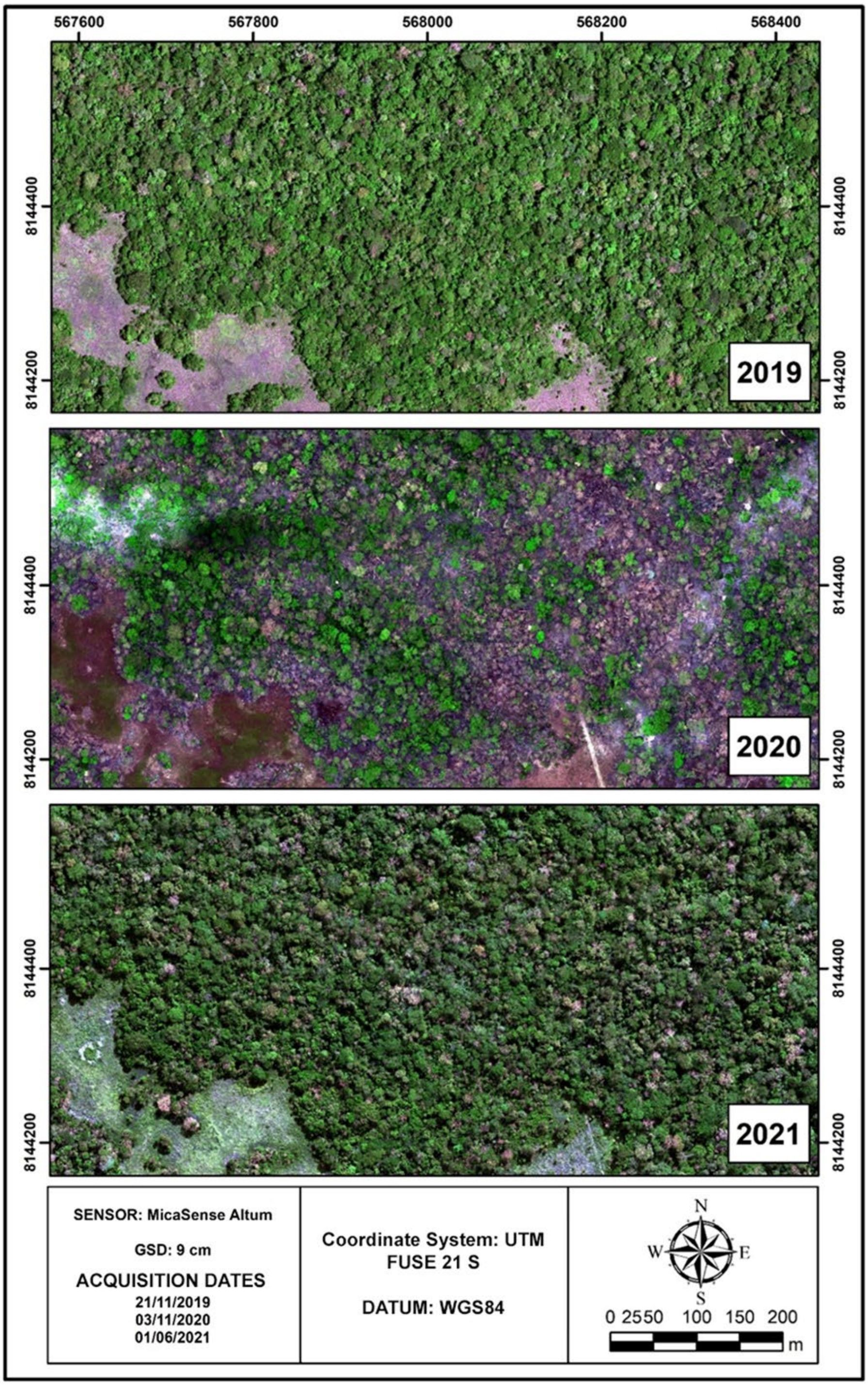

Figure 5. Orthomosaics obtained in 2019/2020/2021 for Area 2.

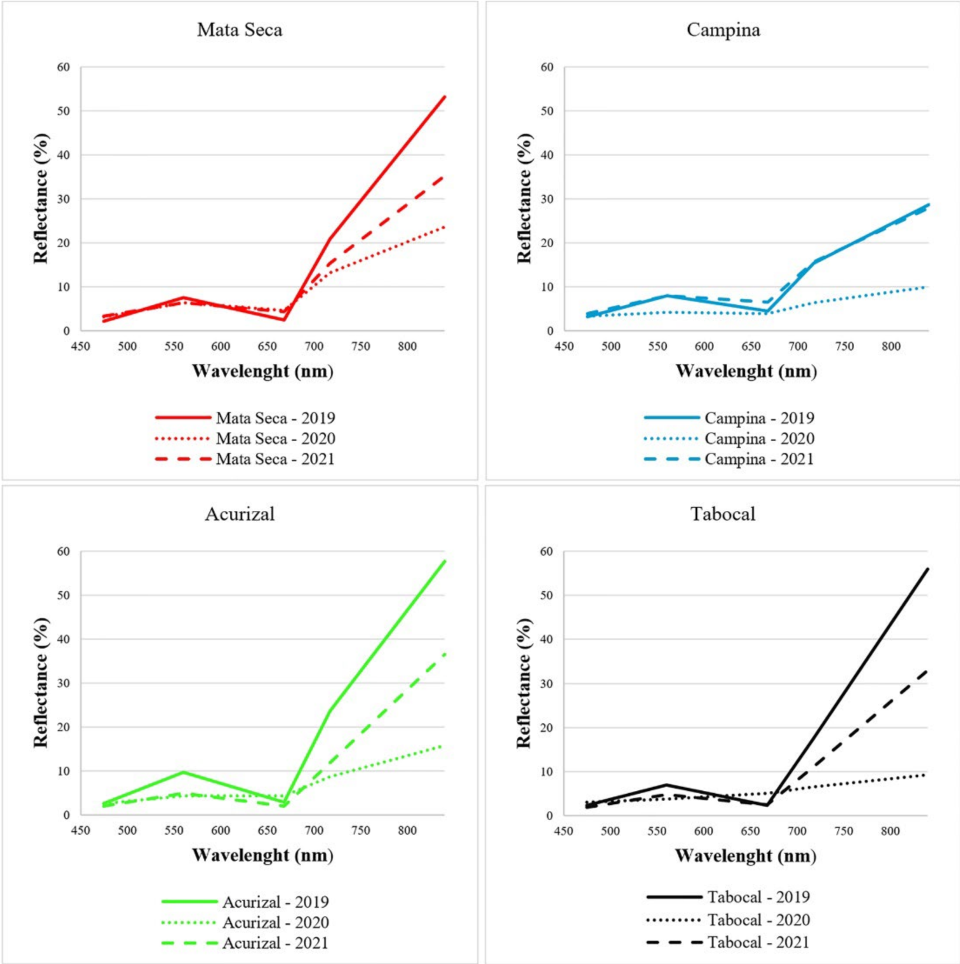

Figure 6. Spectral responses of the macrohabitats Mata Seca, Campina, Acurizal, and Tabocal in Area 2.

Similar to Area 1, the spectral signatures of the four macrohabitats showed a decline in the red-edge and near-infrared wavelengths in the two post-fire periods (2020 and 2021).

In 2019, the Tabocal and Acurizal macrohabitats showed the highest reflectance values at 840 nm (NIR), both exceeding 55% reflectance. Additionally, although Campina had the lowest reflectance values compared to the other macrohabitats—mainly due to its composition of native grassland and shrub/herbaceous vegetation—its individual spectral curve revealed the best recovery in terms of photosynthetic activity. Its 2021 spectral curve most closely resembled the pre-fire 2019 curve.

In 2020, there was a general decline in reflectance across nearly all habitats and bands, likely associated with environmental changes caused by the fire.

By 2021, partial recovery was observed in all habitats due to the regeneration of different vegetation types and species. The Campina and Mata Seca macrohabitats showed the most stable values across the years, with Campina in particular demonstrating a spectral curve similar to the pre-fire period, indicating effective environmental recovery.

3.3. General Analysis of Spectral Behavior of Macrohabitats – Areas 1 and 2

The general trend observed in both areas was a sharp loss of reflectance in the red-edge and near-infrared regions in 2020, followed by the beginning of recovery in 2021—although still below 2019 levels. Therefore, the spectral bands at 717 and 840 nm proved to be the most useful for distinguishing between macrohabitats.

In both areas, the Acurizal and Tabocal macrohabitats exhibited the greatest reflectance amplitudes and variability over the years, especially at higher wavelengths (NIR). Campina consistently showed the lowest reflectance, as expected due to its shrub/herbaceous composition. Mata Seca displayed the most stable spectral pattern, with a continuous decline in average reflectance, which may be associated with vegetation phenology changes and the degradation caused by fire.

Furthermore, in 2021, despite eight months after the fire, although vegetation regeneration was evident, some spectral responses remained lower than those recorded in 2020. This may indicate a loss in species diversity and could also be influenced by the onset of the dry season, which begins around June.

Ngo (2024), when analyzing mangrove ecosystems in wetland areas of Vietnam, employed UAV-based multispectral imagery and machine learning, emphasizing that the characterization of different habitats enables the identification of specific protection strategies for each environmental condition. One of the experiments conducted involved mapping plant taxonomy in the study area based solely on a spectral reflectance value chart across five individual spectral bands, along with normalized difference vegetation index (NDVI) values, which allowed determining the spatial distribution of each mangrove species present.

Despite its advantages, the use of UAV multispectral sensors in wetland environments poses specific challenges due to climatic and meteorological factors that were not addressed in this study. In general, the environmental conditions of the Pantanal, after the fire period that occurred in 2020, with the return of the flood and rain cycle and the decrease in temperature, favored the regeneration of vegetation. Salim *et al.* (2024) investigated the impact of environmental conditions (such as solar reflections, wind-generated waves, and cloud shading) on reflectance values obtained from UAS-based multispectral imaging of inland waters. Their findings showed that solar reflection significantly increases reflectance variability when the solar elevation angle exceeds 54°, leading the authors to recommend flight operations under solar elevation angles between 25° and 47°.

Considering the context of the Brazilian Pantanal, the largest floodplain on Earth, the region exhibits unique characteristics that make UAV monitoring particularly relevant. Its predictable hydrological regime, alternating between aquatic and terrestrial phases of low amplitude and long duration, combined with topographic variation and soil properties, creates a complex and heterogeneous landscape composed of multiple wetland types.

The results obtained in this study contribute to improving conservation measures for wetland ecosystems, the management of protected areas, and the effectiveness of public policies. The ability to detect distinct regeneration patterns among macrohabitats and assess species diversity losses provides an essential scientific basis for landscape restoration protocols.

A study by Wu *et al.* (2023) demonstrated that an enhanced understanding of wetland vegetation dynamics and ecohydrology, achieved through monthly UAV-based classification, allows establishing bidirectional relationships between the spatiotemporal distribution of minimum soil moisture and NDVI peaks in the local community, as well as explaining grass distribution patterns based on both topography and low-moisture conditions. These relationships indicate that, beyond strengthening the evidence base for wetland management, UAV-based vegetation mapping and characterization through multiple flight campaigns can offer fundamental insights into wetland ecohydrology.

4. Conclusions

The analyses demonstrated that the regeneration and establishment of pioneer species associated with the macrohabitats of the burned areas contributed positively to the natural restoration of the landscape and, consequently, to ecological balance.

Both Acurizal and Tabocal are found as monodominant clumps in the understory and tend to be more opportunistic, developing rapidly in deforested areas. In particular, Tabocal forms a tangled mass of branches, stems, and leaves that easily swelled to fire and subsequently rapidly regenerated naturally, as corroborated by analysis of post-fire spectral data.

It is important to highlight that due to the impact of high-intensity fires, there was significant mortality among large tree individuals, resulting in a loss of species diversity—especially in the Mata Seca and Acurizal macrohabitats. During the vegetation succession process, many fast-growing, smaller, and more opportunistic species emerged.

The use of multispectral sensors integrated into UAVs offers several advantages over orbital sensors, including flexible on-demand acquisition and greater possibilities for radiometric/geometric quality control. They also enable detailed analysis of spectral variations in vegetation cover. The use of UAV data for monitoring and validation is recommended, and can be combined in a hybrid mode with temporal data obtained from satellites.

The annual variation in spectral behavior clearly demonstrates the potential of spectral monitoring as a tool for detecting environmental changes. Its use is recommended in forest and environmental restoration programs.

Acknowledgements

The authors thank the logistical and financial support of the project "Recovery of Riparian Forests in the Pantanal: benefiting water, soil, fish, and surrounding communities of the RPPN SESC Pantanal". The project was developed through an institutional arrangement between *Mulheres em Ação no Pantanal (Mupan)*, *Wetlands International Brazil*, *Pantanal Research Center (CPP)*, *National Institute of Science and Technology for Wetlands (INAU)*, and *SESC Pantanal*, in accordance with Brazilian legislation and the guidelines of the GEF Terrestrial Project.

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