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ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 116 – 135, 8/2025
https://doi.org/10.5380/raega.v63i2.99552

Fire Hot Spot Characterization and Detection in the Pantanal using satellite images

Detecção e caracterização de focos de incêndio no Pantanal com o uso de imagens de satélite

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https://doi.org/10.5380/raega.v63i2.99552

Abstract

The Pantanal, the world's largest floodplain, is area prone to fire, presenting major impacts on the distribution and survival of fauna and flora species. The recent drought in the Pantanal has been more intense, increasing the occurrence of seasonal fires in the Biome. The objective of this paper is to detect possible fire foci and evaluate the burned areas considering the radiative power of fire in June-July 2020 and in June-July 2024, using images from the GOES-16 meteorological satellite. For the detection and monitoring fire hot spots in real time, the Fire Detection and Characterization (FCDC) product was used, considering the visible and infrared spectral bands. The values of the radiative power of the fire and the burned area of the fire hot spot were extracted to assess the intensity of the fire in the years 2020 and 2024. The selected fire hot spots were only those which presented a high chance of fire. In 2020 the total burned area was 582,664 m^2 with an average radiative power of 43.41 MW and in 2024 a total burned area of 636,724 m^2 and an average radiative power of 56.17 MW. Data from the GOES-16 satellite can monitor the progression and spread of vegetation fires. It helps to guide the decision-making for the implementation of warning systems, providing high-quality information, such as the exact location of the outbreaks and the intensity of a fire.

Keywords:
Burned area, Radiative power, Monitoring, GOES-16 satellite.

Resumo

O Pantanal, a maior planície alagada do mundo, possui uma grande parte de sua área propensa ao fogo, apresentando grandes impactos na distribuição e sobrevivência das espécies da fauna e da flora. Nos últimos anos a seca no Pantanal tem sido mais intensa aumentando a ocorrência dos incêndios sazonais no Bioma. O objetivo desse trabalho foi detectar possíveis focos de incêndio e avaliar as áreas de queimadas no Pantanal por meio do poder radiativo do fogo, em junho e julho de 2020 e em junho e julho de 2024, utilizando imagens de satélite meteorológico GOES-16. Para a

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detecção e monitoramento dos focos de incêndio em tempo real, utilizou-se o produto de caracterização de focos de incêndio (FCDC) por meio de bandas espectrais do visível e do infravermelho. Foram extraídos os valores do poder radiativo do fogo e área queimada dos focos de incêndios para avaliar a intensidade do incêndio nos anos de 2020 e 2024. Os focos de incêndio selecionados foram apenas os que apresentavam alta probabilidade para fogo, os quais apresentaram em 2020 a área total queimada de 582.664m^2 com o poder radiativo médio de 43,41MW, e em 2024 a área total queimada de 636.724m^2 com o poder radiativo médio de 56,17MW. Os dados do satélite GOES-16 permitem monitorar a progressão e a propagação do incêndio da vegetação, auxiliando orientar as tomadas de decisões para a implantação de sistemas de alertas, fornecendo informações de alta qualidade como a localização exata dos focos e a intensidade de um incêndio.

Palavras-chave:
Área queimada, Poder radiativo, Monitoramento, Satélite GOES-16.

I. INTRODUCTION

Although natural processes can occasionally cause fires, the current prevalence of fire in the Pantanal in recent years is strongly linked to human activities, which are responsible for modifying climate regimes and land use/land cover, and to environmental conditions that exacerbate its' occurrence and intensity (Marques et al., 2021). Historically, fire has been used as a tool to remove pests and diseases, regenerate land and remove unwanted vegetation accumulation (Pelissari et al., 2023; Bayne et al., 2019). However, inappropriate practices and adverse weather conditions can transform these controlled burnings into large-scale fires, causing significant damage to the ecosystem (Libonati et al., 2020). In 2020, the Pantanal suffered its worst fire season recorded, with approximately 30% of the biome burned. These fires drew worldwide attention for its impact and environmental degradation, with millions of wildlife killed and a vast area affected. Approximately four million hectares of forest and savannah were burned (Libonati et al., 2020; Tomas, 2021; Da Silva Junior et al., 2020). In 2024, the area burned in the first half of the year increased by 529% compared to the average of previous years. The month June of that year concentrated 79% of burning in this area, the largest one ever observed in the biome during this period (MAPBIOMAS, 2024).

Researchers have linked the intensification of these events to recent climate changes, such as the combination of human actions with severe droughts, high temperatures, and loss of soil and vegetation moisture. According to Lovejoy and Nobre (2018), deforestation and the widespread use of fire in the Amazon are altering the hydrological cycle and reducing rainfall in parts of the La Plata basin, thus affecting the entire Pantanal. According to Marengo et al. (2021), the reduced transport of hot and humid summer air from the Amazon since 2019 resulted in a prolonged and severe drought in the Pantanal, consequently favoring an

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extensive occurrence of fires in this region. Libonati et al. (2022) showed that land-atmosphere interactions, characterized by strong atmospheric warming and high evaporation, have raised the average temperature above normal conditions and increased the risk of fire.

Wildfires can destroy vast tracts of land, releasing tons of aerosols and gases into the atmosphere. Smoke can increase the risk of respiratory diseases, affecting rural, indigenous and local traditional populations. In 2020, these fires may have affected at least 65 million native vertebrates and 4 billion invertebrates, based on known species densities (Berlinck et al., 2022).

Fire monitoring is necessary for fire planning and management, and it is essential to develop public policies that can at least minimize the causes, effects, and consequences of major fires such as those which occurred recently. According to Pelissari et al. (2023), it is possible to mitigate fires in the Pantanal and changes in the biome's landscape. Combined with climate change, these actions require greater attention and sensitivity from Brazilian governments, as well as new approaches to fighting fires to ensure the biome's environmental safety. Recording and monitoring fire from ground-based observations is a laborious and expensive process. Fire detection using satellite images is an essential low cost practice for environmental monitoring, allowing a rapid identification of hotspots and assessment of the affected areas, even when fires represent a small fraction of the satellite pixel.

Research with remote sensing data on active fire dynamics has contributed to understand wildfires, despite applying generally low spatial resolution data. Higa et al. (2022) proposed an approach based on object detection methods to map active fires in the Pantanal using images from the CBERS 4 satellite. Shimabukuro et al. (2023) mapped the extent of the burned area during this tragedy in the Brazilian portion of the Pantanal biome using Sentinel-2 MSI images**.** Li et al. (2020) showed that the probability of fire detection and characterization using images from the GOES-16 meteorological satellite is related to the size of the fire and the temporal period. GOES-16 provides information on the location, duration, size, temperature and radiative power of fires. This information can be used to track fires in real time, providing data for air quality modeling and to help separate the impact of fires from other sources of pollution (Schmidt et al., 2020).

Data from the GOES-16 satellite, such as products from the visible and infrared spectral bands, allow the location and recovery of fire characteristics. These products can be used to monitor forest fires and, more importantly, rapid changes in individual fires. Additionally they are used as part of an arsenal of forecasting tools designed to aid firefighting efforts. In this context, the objective of this study was to detect possible fire

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outbreaks and assess the areas of burning in the Pantanal, through the radiative power of fire, in June and July 2020 and in June and July 2024, using images from the GOES-16 meteorological satellite.

II. Materials and Methods

The study area of the work was the Pantanal Biome (Figure 1), the worlds' largest tropical wetland, located in the central portion of South America, with more than 84% of its territory currently preserved (Libonati et al., 2020). To monitor the burned areas, the years 2020 and 2024 were selected, when the most large-scale fires occurred in this Biome. According to INPE's Burning Program, there were 22,116 fire outbreaks in 2020 and 14,498 ones in 2024. The months of June and July 2020 and June and July 2024 were selected because they presented large numbers of fire outbreaks at the beginning of the fire season in the Pantanal.

The images used in this work were from the GOES-16 meteorological satellite, available in the database of the Center for Meteorological and Climate Research Applied to Agriculture (Cepagri) at Unicamp. The Advanced Baseline Imager (ABI) sensor, on board the GOES-16, measures energy at different wavelengths, reflected (visible to near infrared, from 0.47µm to 2.25µm) or emitted (infrared, from 3.9µm to 13.3µm) from the Earth's surface, and is composed of 16 different spectral bands, including two visible, four near infrared and ten infrared channels. These different channels (wavelengths) are used by models and tools to indicate various elements on the Earth's surface or in the atmosphere, such as water, clouds, humidity, smoke, among others. The spatial resolution ranges from 0.5 km for the visible channel to 1 km and 2 km for the near infrared and infrared (>2µm) channels, respectively.

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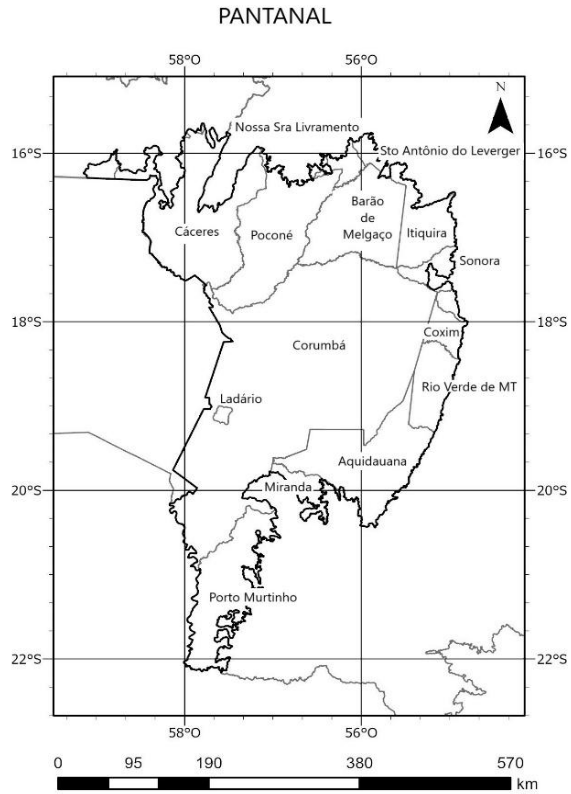

Figure 1 – Study area: Pantanal. Elaboration: the authors (2025).

The GOES-16 satellite provides a fire characterization product, using visible and infrared spectral bands to locate fires and retrieve its characteristics. This product is the Fire Detection and Characterization (FDCF), which provides hourly information on the location of fires, the area of fire (m^2) and the radiative power of fire (megawatts - MW), with a spatial resolution of 2 km for the composition of bands 2, 7, 13, 14 and 15. It can detect heat signatures with improved temporal and spatial resolution, including smaller fires, compared to the previous GOES imager. Fire properties can be measured in three ways: by its size (burned area), temperature and radiative power.

The FDCF is an already processed product available at NOAA (National Oceanic and Atmospheric Administration). It is obtained by an algorithm, described by Schmidt et al. (2020): a dynamic, multispectral, threshold contextual method that uses the 0.64 µm shortwave (ABI Channel 2, when available during daytime) and the 3.9 µm and 11.2 µm bands (ABI Channels 7 and 14) to locate fires and retrieve sub-pixel fire features. Channel 13 (10.3 µm) is used together with Channel 14 when the ABI focal plane temperature exceeds a defined threshold. Channel 15 (12.3 µm) is used along with the previously mentioned bands to help identify opaque clouds, but it is not required for the algorithm to run. Only channels 7 and 14 are required for the algorithm for fires under normal conditions. The code uses a two-step approach to identify and characterize

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sub-pixel fires. The first step loops through all pixels and identifies potential fire pixels, as well as blocking zones due to solar reflection and selects surface types. This initial pass also characterizes potential fire pixels when they meet certain criteria. For each hot pixel, the algorithm incorporates ancillary data to track false alarms, correct for water vapor attenuation, surface emissivity, solar reflectivity, and semi-transparent clouds. The performance of the FDCF product is better and complementary to Landsat, for example, as it detects more fire pixels with low false alarm rates (Hall et al., 2023).

The fire properties calculated by the algorithm (Schmidt et al., 2020) are coupled to each other, and it is not possible to calculate the instantaneous size of the fire without estimating the temperature and radiative power of the fire, which are a function of the size and temperature. The fires in the FDCF product are divided into six categories: saturated, processed, cloudy, high probability, medium probability and low probability. For monitoring the fire outbreaks in this work, only the "processed" and "high probability" categories were selected. The other categories presented very high rates of false alarms for fire detection (Hall et al., 2023). The algorithm uses the Dozier technique to calculate sub-pixel estimates of instantaneous fire size and temperature (Dozier, 1981; Matson; Dozier, 1981). Fires are treated as a single sub-pixel entity of a given size, temperature, and radiative power, an approximation that must be made given the fundamental limitations of retrieving sub-pixel properties. The second step loops over all possible fire pixels identified in the first step. Additional thresholds are applied and previous fire detections are used to filter out false alarms, trading early detection for greater confidence that a fire was detected.

From the FDCF product, the area (in m^2) and radiative power (in MW) values were extracted for each point with a fire focus, in the "processed" and "high probability" categories. The data obtained were analyzed using basic statistical methods, including measures of central tendency (mean and median), dispersion (standard deviation), in addition to the construction of histograms and graphs to better understand the distribution and variability of the data.

III. Results and discussion

The results obtained from GOES-16 satellite images highlighted the severity of the fires that hit the Pantanal in 2020 and 2024. The spatial and temporal analysis of the hotspots, the radiative power of the fire, and the burned area allowed not only to quantify the extent of the impacts, but also to identify worrying trends that have been intensifying over the last decade. Figure 2 shows the fire hotspots obtained by the GOES-16 FDCF product, with the selection of the processed and high probability categories. These two

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categories present a higher probability of fire (Hall et al., 2023). Visible and infrared (IR) spectral bands were used to locate, detect the fire hotspots, and recover fire characteristics. Fires produce a stronger signal in mid-wave infrared bands (around 4 µm) than in long wave infrared bands (such as 11 µm). Band 7 (3.9 µm) was particularly useful for fire detection. Its shorter wavelength is sensitive to the hottest part of a fire pixel.

Figure 2 shows the accumulated fire outbreaks across the Pantanal Biome for the months June (Figure 2A) and July (Figure 2B) 2020 and June (Figure 2C) and July (Figure 2D) 2024. In June and July 2020, 1,277 fire outbreaks were detected, while in June and July 2024, this amount was 995. Figures 2A, 2B, 2C and 2D show this difference in the number of accumulated fire outbreaks between 2020 and 2024, years in which large burned areas were recorded, including in forest formations, compromising the recovery of ecosystems and leaving them more vulnerable to new fire events (MAPBIOMAS, 2024).

These fire outbreaks illustrated in Figure 2 are extremely important for guiding appropriate fire management in the Biome and predicting future fire activity. According to Correa et al. (2022), monitoring fire outbreaks is a first step towards unraveling the role of anthropogenic factors, i.e., changes in land use and occupation areas, shaping the fire regime in the Pantanal. Fires in the Pantanal over the past two decades tended to occur more frequently in pastures than in other types of vegetation cover, but the 2020 fires burned preferentially forest regions. Large patches of fire are more frequent in forests and pastures; in contrast, agricultural lands have small patches.

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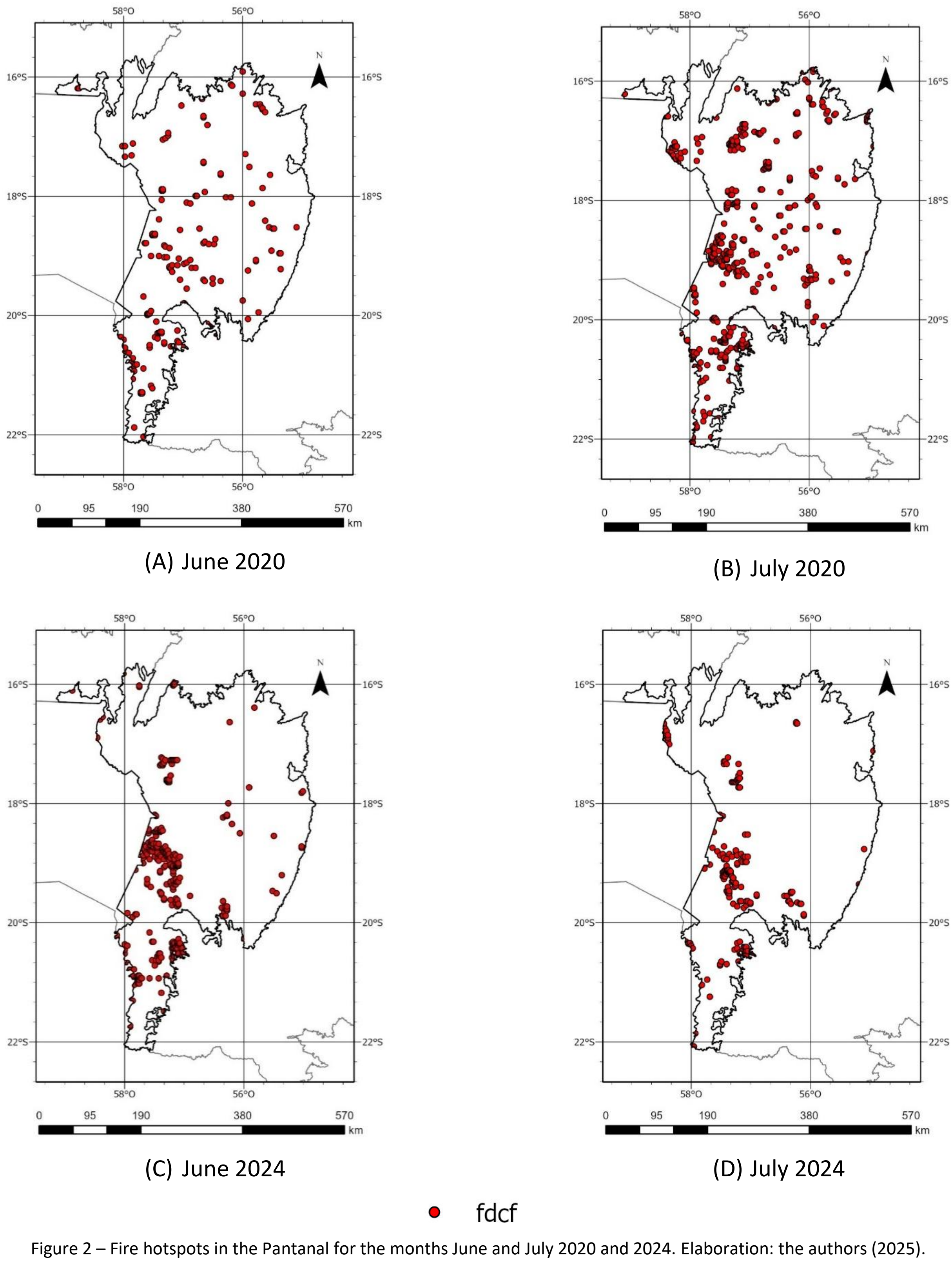

Figure 2 – Fire hotspots in the Pantanal for the months June and July 2020 and 2024. Elaboration: the authors (2025).

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Pelissari et al. (2023) analyzed the vegetation recovery using the differentiated normalized burning ratio in the Brazilian Pantanal between 2001 and 2022. They identified priority areas, where the highest intensities of fire outbreaks occurred, to guide public policies in Brazil to maintain local conservation. The large fire in 2020 is correlated with the low rainfall in 2019 and the most vulnerable areas to severe fires were the municipalities of Cáceres, Poconé and Corumbá. At Figure 2 one identifies a large number of fire outbreaks in these municipalities. Figure 3 illustrates the radiative power (in megawatts - MW) of fire outbreaks obtained by the GOES-16 FDCF product in the entire Pantanal Biome for the months June (Figure 3A) and July (Figure 3B) 2020 and June (Figure 3C) July (Figure 3D) 2024. The radiative power of the fire is a measure of the thermal energy emitted by the fire in the form of electromagnetic radiation, especially in the infrared range captured by the satellite. It represents the instantaneous rate of energy release by fire. This data provided by the satellite allows the calculation of the total energy released, and assess the environmental impact of the fires. This approach is essential for modeling and mitigating fires, providing accurate information on its intensity and spread.

The use and analysis of this radiative power data is extremely important for fire monitoring, as it is possible to obtain an estimate of emissions. In this case, the radiative power is used to calculate the amount of biomass burned and the emissions of gases and particles emitted to the atmosphere, such as carbon dioxide (CO_2) and carbon monoxide (CO). Pelissari et al. (2023) evaluated the relationship between fire outbreaks and carbon absorption; precipitation and carbon dioxide (CO2) flux; Nobrega and Correia (2025) analyzed particle and gas emissions from forest fires in the Southern Amazon, from 2020 to 2022, based on fire radiative energy recoveries from GOES-16. The results obtained increased the understanding of forest fires in the Amazon, its emission fluxes and environmental implications, contributing with valuable insights to the complex ecosystem of the Amazon Basin.

According to Monteiro dos Santos et al. (2024), the unprecedented 2020 fire season in the Pantanal resulted in well-reported local impacts on the ecosystem, economy, and health. This study reported the cascading risks of hazards associated with fire events linking smoke transport, worsening of air quality, and health impacts in the State of São Paulo, the SE region of Brazil, and the largest megacity in South Africa located more than 1,500 km distant from the Pantanal. Integrating models, observational, and satellite-based data, it was possible to identify that episodes of smoke-induced air pollution coincided with widespread heat waves, amplifying health risks.

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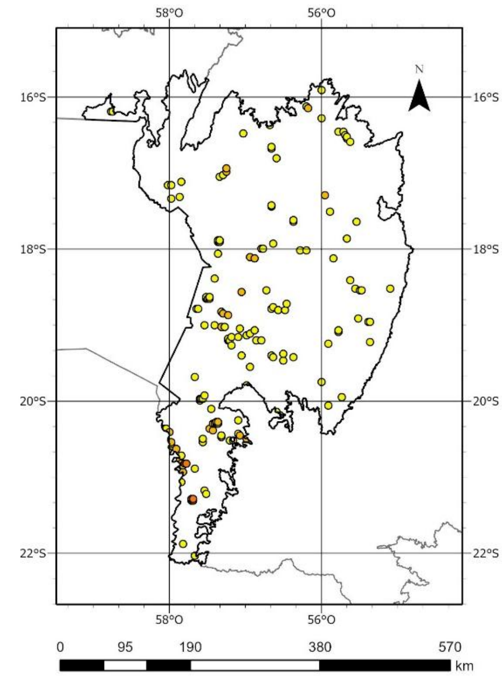
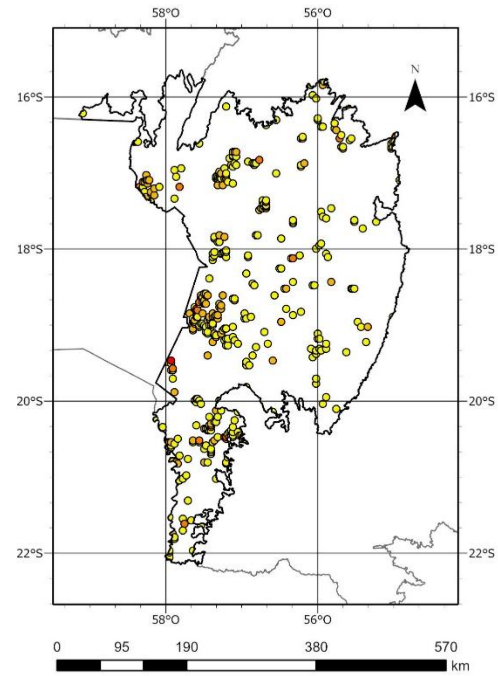
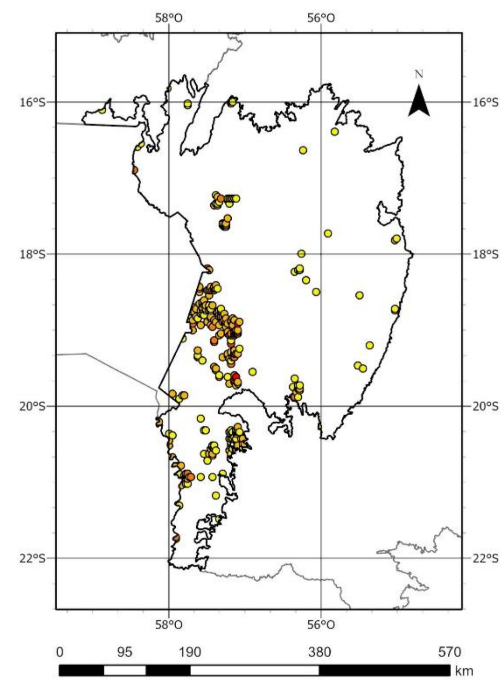


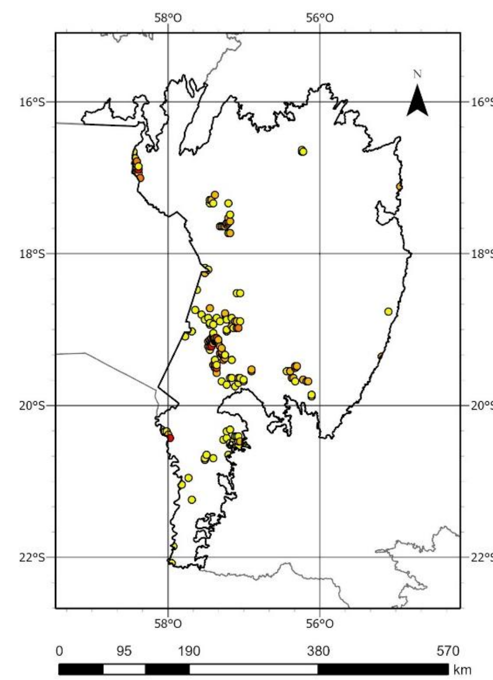
(A) Radiative power – June 2020



(B) Radiative power – July 2020



(C) Radiative power – June 2024



(D) Radiative power – July 2024

17.00 - 50,00 | 50,00 - 100,00 | 100,00- 150,00 | 150,00 - 200,00 | 200,00 - 650,00

Figure 3 – Radiative power (MW) of fire in the Pantanal for the months June and July 2020 and 2024. Elaboration: the authors (2025).

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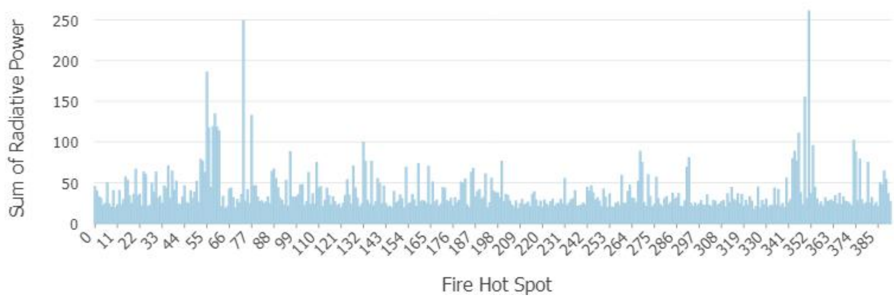
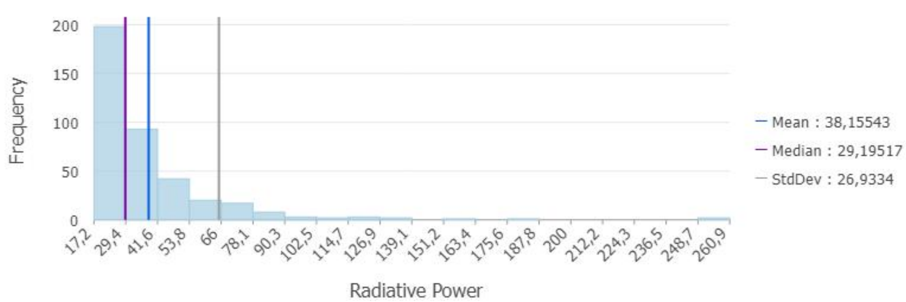
Pereira et al. (2010) used the radiative energy of fire from both MODIS and GOES sensors to estimate emissions of carbon monoxide (CO) and particulate matter with a diameter smaller than 2.5μm for the 2002 burning period in South America. This estimate of greenhouse gas emissions from biomass burning is necessary for annual inventories and its estimation from data derived from environmental satellites is of fundamental importance for weather and climate modeling.

Figure 4 shows the distribution of values and histograms of radiative power of fire in the Pantanal for the months June (Figure 4A and B) and July (Figure 4C and D) 2020 and June (Figure 4E and F) and July (Figure 4G and H) 2024. The results showed an average radiative power per fire focus of 38.15 MW in June 2020, 48.67 MW in July 2020, 57.57 MW in June 2024 and 54.77 MW in July 2024. The results indicate a maximum radiative power per fire focus of 260.90 MW in June 2020, 648.40 MW in July 2020, 561.90 MW in June 2024 and 395.60 MW in July 2024. The classification of Fire Intensity is essential to understand the severity of fires. Fires with high radiative power values indicate more severe and rapidly spreading events. Table 1 shows the radiative power of fire for the most affected municipalities by fire in the months June and July 2020 and 2024.



(A) Radiative power - June 2020



(B) Radiative power histogram - June 2020

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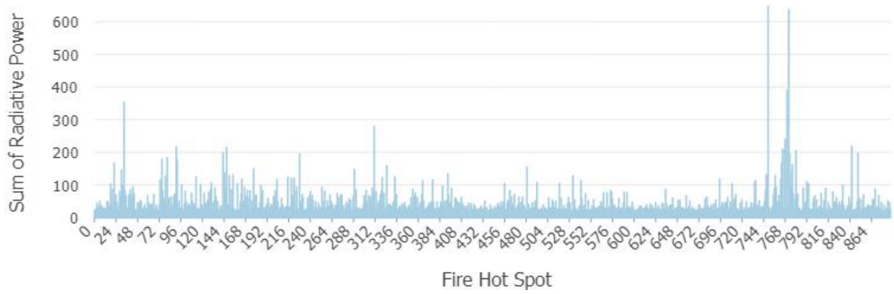
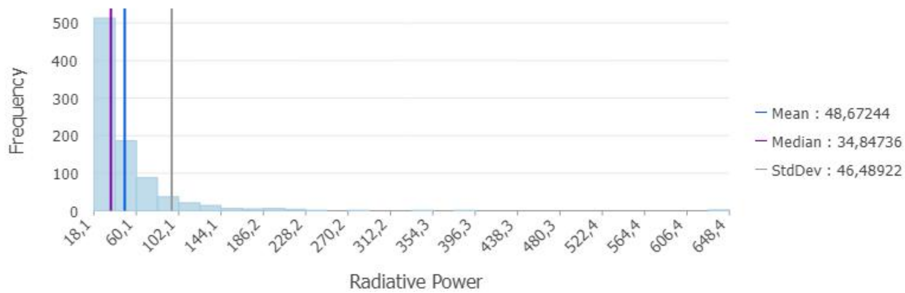
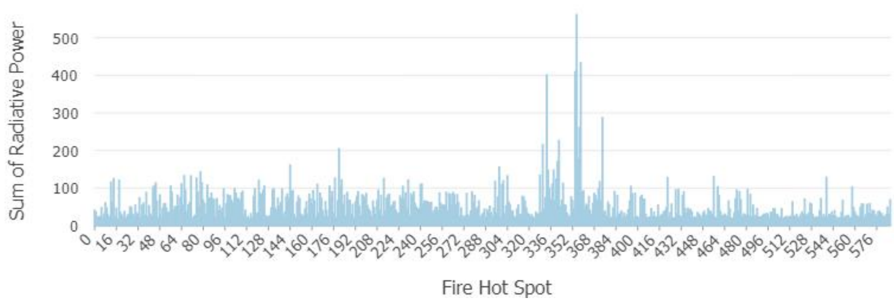


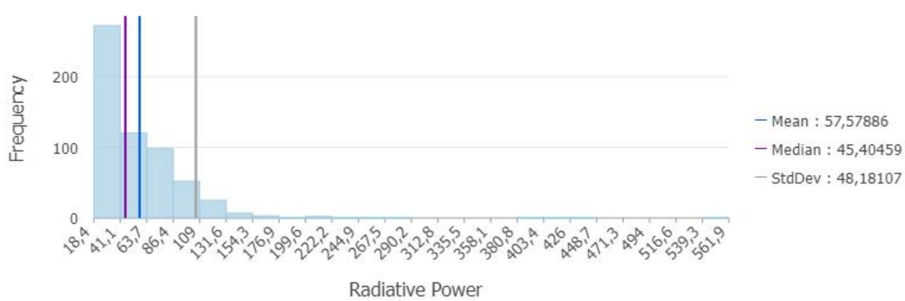
(C) Radiative power - July 2020



(D) Radiative power histogram - July 2020



(E) Radiative power - June 2024



(E) Radiative power histogram - June 2024

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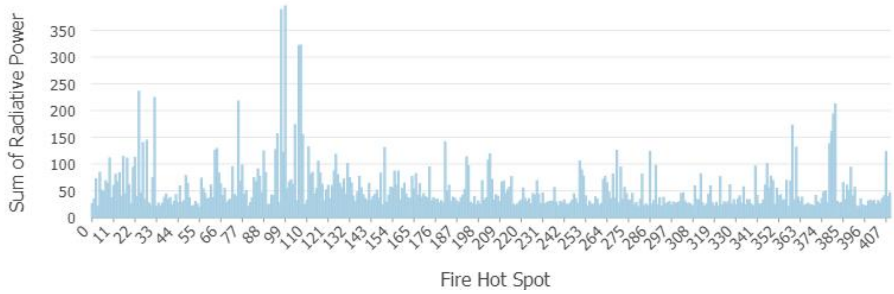
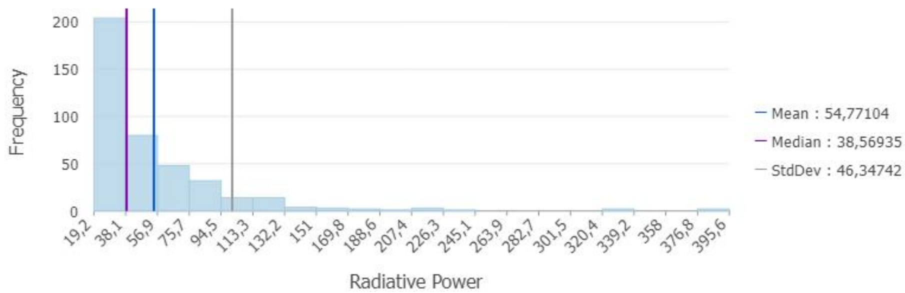


(G) Radiative power - July 2024



(H) Radiative power histogram - July 2024

Figure 4 – Distribution of values and histograms of the radiative power (MW) of fire in the Pantanal for the months of June and July 2020 and 2024. Elaboration: the authors (2025).

Table 1 – Radiative Power (MW) of fire from municipalities

Municipality	Radiative Power June/20	Radiative Power July/20	Radiative Power June/24	Radiative Power July/24
Cáceres	27,05	68,76	44,82	70,41
Corumbá	38,56	48,75	79,93	75,90
Poconé	36,37	51,75	51,58	62,07
Porto Murtinho	56,11	44,60	52,58	36,70

Figure 5 shows the area (in m^2) of fire outbreaks obtained by a GOES-16 FDCF product across the Pantanal Biome for the months June (Figure 5A) and July (Figure 5B) 2020 and June (Figure 5C) and July (Figure 5D) 2024. Wildfires typically burn very intensely and can last from several days to months, and so it is important to map and quantify the total burned area. GOES-16 data performs very well to quantify the area affected by fires and provides critical information on fires for suppression and evacuation of active fires globally, detecting operationally fires on all continents of the Americas with unprecedented spatiotemporal resolution (Li et al., 2020).

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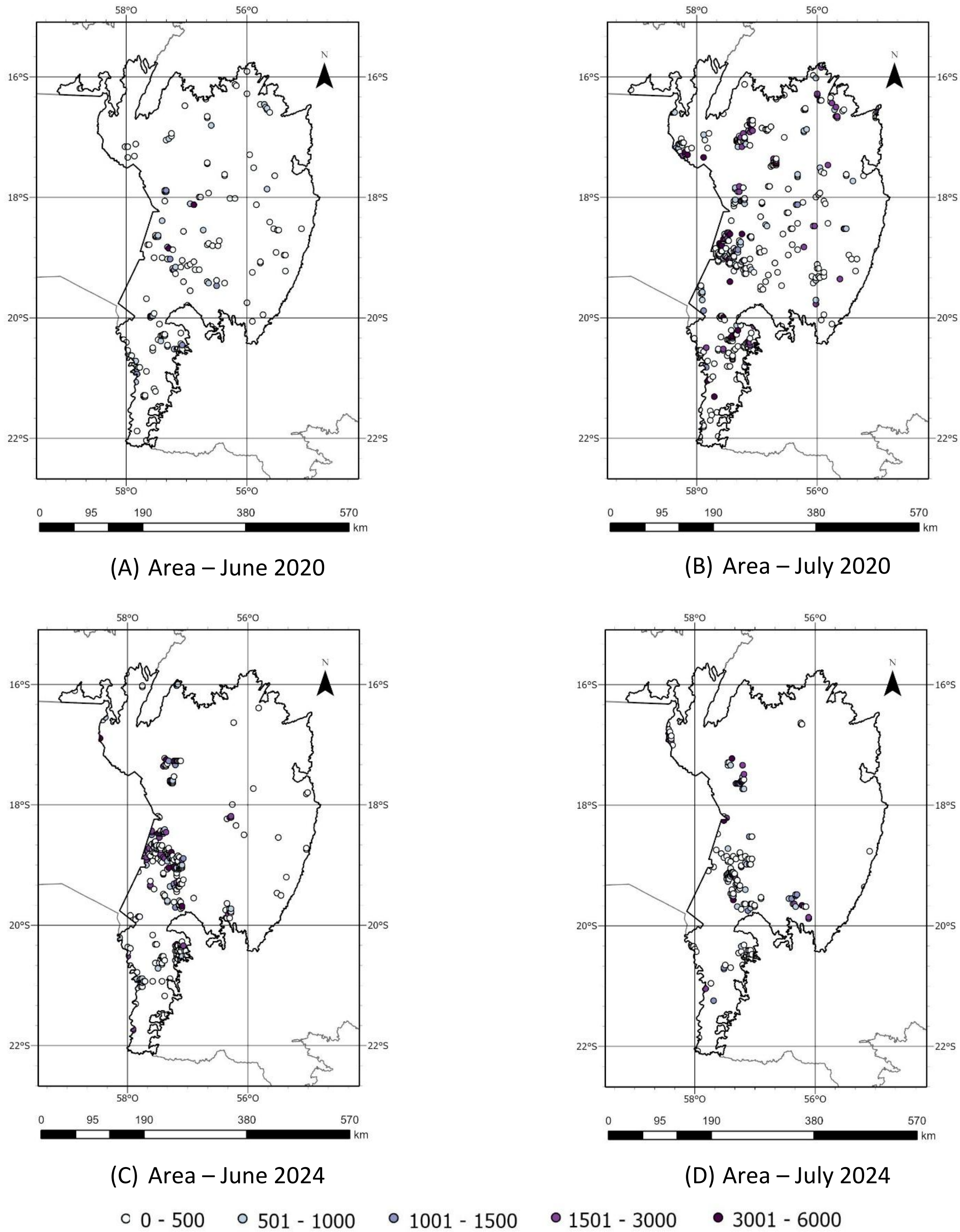

Figure 5 – Area (m²) of fire in the Pantanal for the months June, July 2020 and 2024. Elaboration: the authors (2025).

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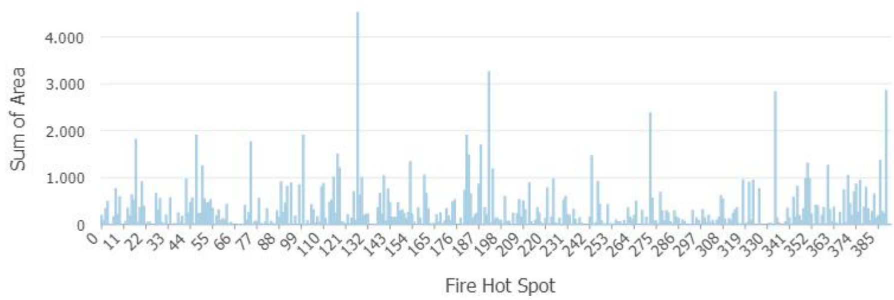
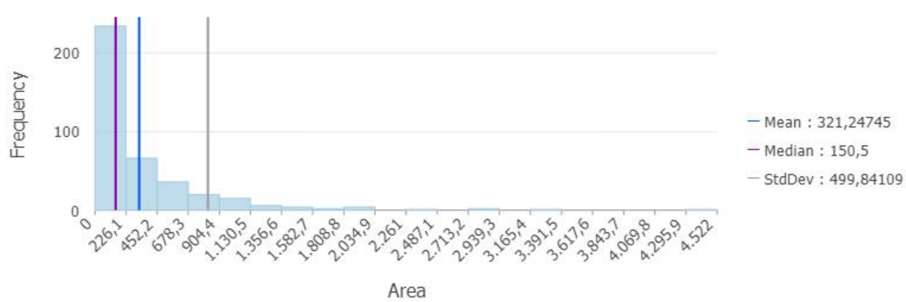
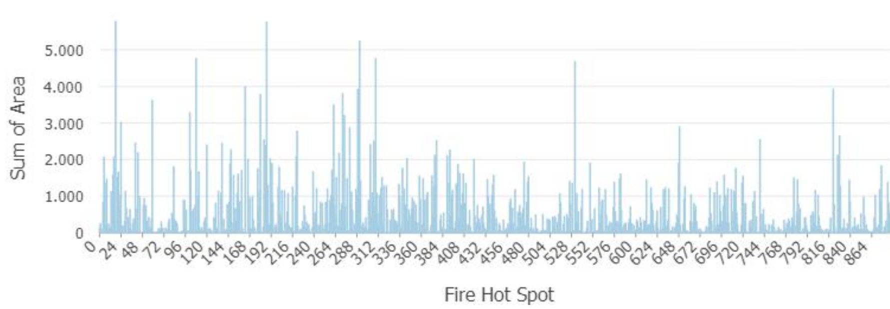
Figure 6 shows the distribution of fire values and histograms in the Pantanal for the months June (Figure 6A and B) and July (Figure 6C and D) 2020 and June (Figure 6E and F) and July (Figure 6G and H) 2024. The results present an average area per fire focus of 231.24 m^2 in June 2020, 515.50 m^2 in July 2020, 622.92 m^2 in June 2024 and 661.14 m^2 in July 2024. These are the maximum area values per fire focus of 4,522 m^2 in June 2020, 5,777 m^2 in July 2020, 5,363 m^2 in June 2024 and 6,060 m^2 in July 2024. The total burned area was 125,929 m^2 in June 2020, 456,735 m^2 in July 2020, 365,654 m^2 in June 2024 and 271,070 m^2 in July 2024. Table 2 shows the burned areas for the most municipalities affected by fire for the months June and July 2020 and 2024.



(A) Area - June 2020



(B) Area histogram - June 2020



(C) Area - July 2020

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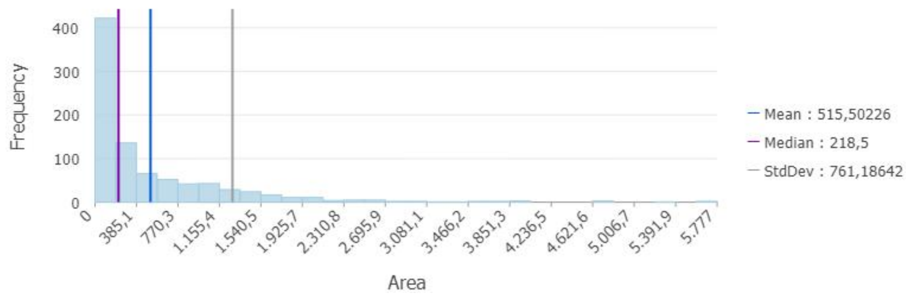
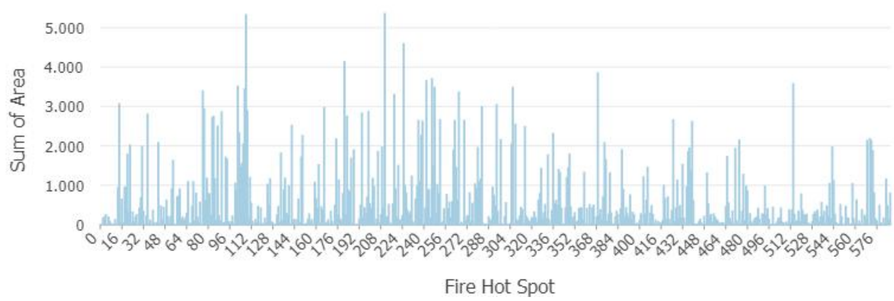
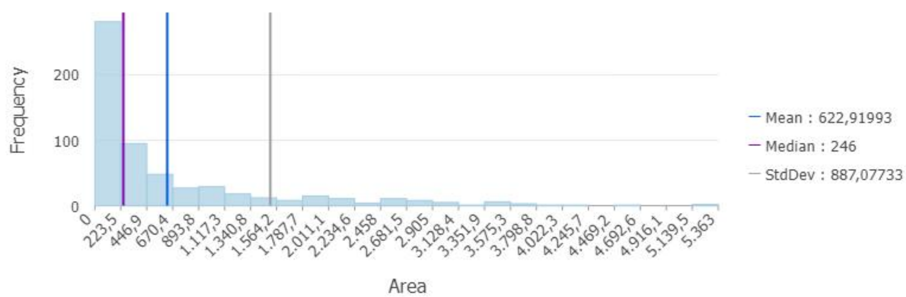


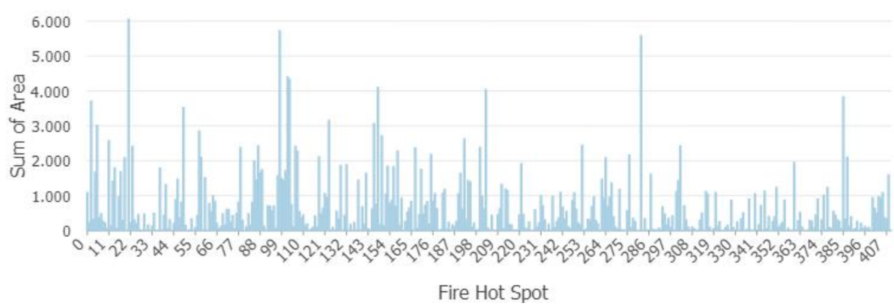
(D) Area histogram - July 2020



(E) Area - June 2024



(F) Area histogram - June 2024



(G) Area - July 2024

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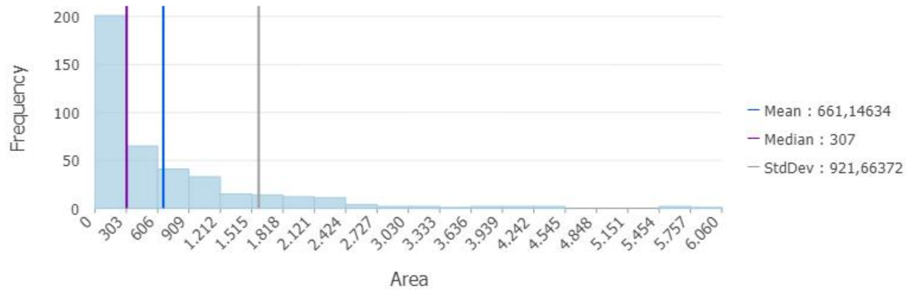

(H) Area histogram - July 2024

Figure 6 – Distribution of fire area values (m²) in the Pantanal for the months June and July 2020 and 2024. Elaboration: the authors (2025).

Table 2 – Burned area (m²) of municipalities

Municipality	Area June/20	Area July/20	Area June/24	Area July/24
Cáceres	1.758	29.981	31.080	29.773
Corumbá	43.186	180.139	191.794	92.247
Poconé	4.386	53.939	31.527	32.785
Porto Murtinho	11.157	36.821	37.766	33.634

According to Feron et al. (2024), South America is suffering severe impacts from climate change, although the warming of the subcontinent follows closely the global trajectory, rising temperatures, drought and high fire risk have been more pronounced in some regions, including the northern Amazon and part of the Pantanal. The surface temperature of the tropical Pacific Ocean modulates the inter-annual variability of dry regions in South America. While El Niño increases fire risk in the northern Amazon, extreme dry in the Pantanal appear to be more responsive to La Niña. Thielen et al. (2020) and Thielen et al. (2021) also showed that severe and prolonged drought events are becoming more frequent in the Pantanal and neighboring areas, such as the *Cerrado* and the Amazon, leading to intensified fire risk and the extension of fire-prone areas from the Pantanal into historically flooded areas.

Severe droughts in the Pantanal have been occurring since 2018, and it was the biome that dried most throughout the MapBiomas Água historical series (2024), which covers the period between 1985 and 2023. The annual water surface (at least 6 months with water) in 2023 was 382 thousand hectares – 61% below the historical average. Only 2.6% of the biome was covered by water and it was 50% drier than 2018, which was the last major flood in the biome. This explains the greater intensity of fire in the Pantanal in 2024 with a total burned area of 636,724m^2 and an average radiative power of 56.17MW against a total area of 582,664m^2 with an average radiative power of 43.41MW in 2020. The Corumbá municipality was the most affected in 2024, in June it had 191,794m^2 of its area burned with a radiative power of 79.93MW.

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IV. Conclusions

The results from this study demonstrate the effectiveness on the use of the GOES-16 meteorological satellite to monitor and characterize fires in the Pantanal Biome. The analysis of months June and July 2020 and 2024 showed not only the exact location of the hotspots, but allowed also the measurement of the radiative power of fire and the burned area with a high degree of precision and detail. In 2024, a considerable increase in the severity of fires was observed. It reflected both the average radiative power (56.17 MW compared to 43.41 MW in 2020) and the total burned area (636,724 m² compared to 582,664 m² in 2020).

These data demonstrate that the 2024 fires were more intense and potentially more destructive, resulting from a combination of factors such as persistent drought, climate change, and inadequate human practices to fire management. The use of the FDCF product derived from GOES-16 proved to be essential for early detection, real-time monitoring and detailed analysis of fire dynamics, supporting response actions and the formulation of public policies aimed to mitigate environmental and social impacts.

This reinforces the importance of warning systems based on remote sensing as a strategic tool for risk management and conservation of the Pantanal, especially considering worsening of climate change and the biome's increasing vulnerability to extreme fire events.

Acknowledgements

For the support provided throughout this work, we would like to thank the Brazilian Institute of Data Science (BI0S).

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