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EFFECTS OF BIOMASS BURNING ON ISOPRENE EMISSION RATIOS

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ABSTRACT

Biogenic volatile organic compounds play a key role in ecological functions and influence atmospheric chemistry and regional climate. This study investigated how specific environmental conditions in the Pantanal, such as seasonal hydrological patterns and fires, influence isoprene emissions compared to the Amazon. Campaigns conducted in 2016 and 2017 during the dry season correlated isoprene emissions with meteorological factors, such as temperature and solar radiation, and assessed the impact of fires. It was observed that in 2017, isoprene emissions in the Pantanal were lower than in 2016, due to lower temperatures, lower solar radiation and higher oxidative capacity of the atmosphere caused by fires. In contrast, in the Amazon, emissions were consistently higher in 2016, reflecting favorable environmental conditions and greater density and diversity of vegetation in the biome. These results confirm that isoprene emissions in the Pantanal are strongly modulated by its specific environmental conditions, highlighting the influence of fires on the atmospheric chemistry of isoprene. The conclusions highlight the need for policies that address environmental degradation and promote the conservation of Pantanal ecosystems, ensuring their resilience and the continuity of essential ecosystem services, both for local communities and for mitigating global climate change.

Keywords: Atmospheric Chemistry. Fire. Biogenic Emissions. Wetland.

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INTRODUCTION

Biogenic volatile organic compounds (BVOCs) are chemicals that influence atmospheric chemistry and ecological interactions, playing a central role in atmosphere-ecosystem dynamics (Šimpraga *et al.*, 2019). In forest ecosystems, especially those with high biodiversity, emissions of BVOCs, such as isoprene (C_5H_8), have a significant impact on aerosol formation and the regulation of atmospheric chemistry, affecting cloud formation and the scattering of solar radiation (Guenther *et al.*, 2012). According to Arneth *et al.* (2010), these processes can alter the Earth's radiative balance, with potential effects on the global climate.

BVOCs are emitted by vegetation, bacteria, algae, fungi, and animals, with their emission rates influenced by biotic and abiotic factors (Laothawornkitkul *et al.*, 2009). Vegetation, especially tropical trees, is the main source of these compounds, accounting for about 80% of global terpenoid emissions and 50% of other BVOCs (Harley *et al.*, 2004; Guenther *et al.*, 2012). Among them, isoprene stands out for its impact on the oxidative capacity of the atmosphere and for being a precursor of tropospheric ozone (Karl *et al.*, 2010; Bela *et al.*, 2015). Isoprene also contributes to the formation of secondary organic aerosols (SOA) via photo-oxidation, affecting human health (Wells *et al.*, 2020), and due to its relevance in the biosphere, isoprene emissions and its oxidative processes has been widely studied worldwide (Langford *et al.*, 2022).

Due to their significant impact on air quality and climate, biogenic isoprene emissions are now commonly integrated into coupled climate and chemistry models, including regional and global air quality and earth system models (Jiang *et al.*, 2018). Despite advancements in estimating biogenic isoprene emissions through numerical modeling, substantial uncertainties persist regarding the magnitude and variability of these emissions, both in field measurements and model estimates (Arneth *et al.*, 2010; Guenther *et al.*, 2012; Wells *et al.*, 2020).

In Brazil, the Amazon, home to half of the world's tropical forests, plays a vital role in the energy, water, and carbon cycles, storing 50% of tropical forest carbon and harboring the greatest biodiversity on the planet (Ter Steege *et al.*, 2013; Andreae *et al.*, 2015; Yáñez-Serrano *et al.*, 2020). This ecosystem emits significant amounts of isoprene, with effects extending within and above the Amazon rainforest canopy. It is estimated that Amazon vegetation can emit about 150 mg m-2 day-1 of isoprene (Guenther *et al.*, 2012). Furthermore, due to its sensitivity to climate change and land use, recent human activities

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are altering conditions in the Amazon, making understanding isoprene in the region more complex (Shrivastava *et al.*, 2019). However, it is important to note that the estimate of annual global isoprene emissions still presents uncertainties, and its dynamics in other Brazilian biomes remain little studied.

The Pantanal, the smallest biome in Brazil, covers approximately 150,355 km², representing about 1.7% of the country's total area (Correa *et al.* 2022). Unlike the Amazon, the Pantanal is characterized by its unique vegetation and climate, being a vast wetland with complex hydrological dynamics, marked by seasonal precipitation, annual flood pulses and deciduous vegetation during the dry season. Over the decades, the natural environment of this biome has undergone significant transformations due to deforestation, burning and the expansion of extensive livestock farming, which has led to the conversion of natural areas into pastures and agricultural lands (Wantzen *et al.*, 2024).

There is currently a paucity of research on isoprene emissions in the Pantanal, a biome of great importance for biodiversity, with unique ecosystems that are vulnerable to climate change and human activities (Silva *et al.*, 2024). Isoprene measurements can reveal how the Pantanal is responding to these changes and how these emissions influence atmospheric chemistry and local and regional climate dynamics. This investigation is particularly relevant in the context of the UN 2030 Agenda, especially Sustainable Development Goals (SDGs) 13 and 15, which emphasize the protection of vulnerable ecosystems and the mitigation of climate impacts. As a biome sensitive to these changes, the Pantanal plays an essential role in climate regulation and the maintenance of ecosystem services, and the analysis of these emissions can significantly contribute to global conservation and climate action goals (UN, 2024).

In this context, the question arises: "How do specific environmental conditions in the Pantanal, such as seasonal hydrological patterns and fire occurrence, influence isoprene emissions compared to the Amazon?" Investigating this question will allow an understanding of the chemical and ecological dynamics of the Pantanal related to BVOCs and will provide essential comparative data for the formulation of conservation and mitigation strategies in both ecosystems. In this context, investigating how specific environmental conditions of the Pantanal, such as seasonal hydrological patterns and fire occurrence, influence isoprene emissions compared to the Amazon will allow a better understanding of the chemical and ecological dynamics of the Pantanal and will provide

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essential comparative data for the formulation of conservation and mitigation strategies in both ecosystems.

With the aim of quantifying isoprene emissions and assessing their correlations with environmental factors, this study presents the first measurements of isoprene mixing ratios in the Pantanal biome. By assessing the diurnal cycle of emissions at the Pantanal Study Base in Miranda, Mato Grosso do Sul, and at the Cuieiras Biological Reserve, in Central Amazonia, a comparative analysis was performed to determine the magnitude and differences in isoprene mixing ratios between these regions. The analysis of these correlations will contribute to a better understanding of isoprene chemistry in the region, with implications for improving climate models and supporting conservation strategies and mitigating the impacts of climate change.

MATERIAL AND METHOD

SITE DESCRIPTION

pantanal

The measurements were carried out at the PTN flux tower, located at the Pantanal Research Base of the Federal University of Mato Grosso do Sul (BEP-UFMS) (19º 34' S, 57º 01' W, 90 m), near the Miranda River in the Paraguay watershed, which represents a typical Pantanal landscape (Oliveira *et al.*, 2006). The terrain in this area consists of floodplains with horizontal surfaces and slopes ranging from 0 to 3% (Theodorovisck, 2010), which favors the prevalence of hydromorphic soils (Fernandes *et al.*, 2007). The vegetation consists of riparian forests and a layer of herbaceous shrubs, with trees reaching a height of up to 10 meters, with a predominance of Tabebuia aurea, (De Paula *et al.*, 1995; Mota *et al.*, 2011). The climate is humid tropical, characterized by distinct rainy and dry seasons, with average monthly precipitation varying between 1,000 mm during the rainy season (October to March) and less than 100 mm during the dry season (April to September) (De Paula *et al.*, 1995). The average summer temperature is 25°C and in winter it reaches 10°C. Only two campaigns were carried out due to difficulties in accessing the Pantanal region, logistical constraints and the need for extensive fieldwork.

amazon

The measurements were performed at the K34 flux tower, located in the Cuieiras Biological Reserve (2° 36' S, 60° 12' W, 130 m), managed by the Brazilian National Institute

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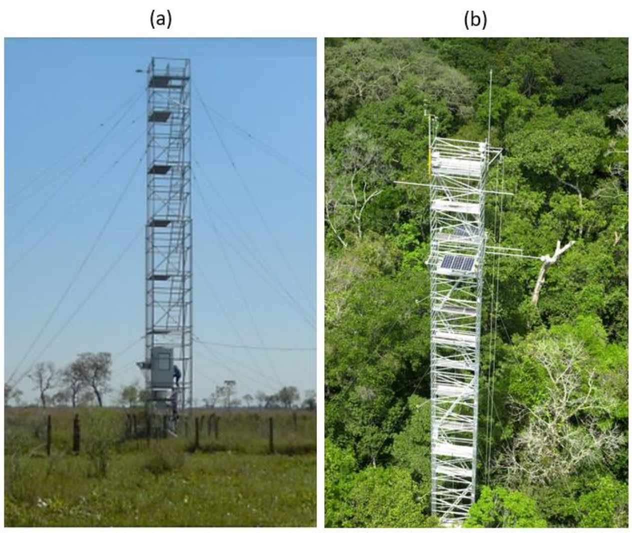
for Amazonian Research (INPA). This reserve represents a plateau area characterized by predominantly clayey and highly porous soils (Zanchi *et al.*, 2012). The vegetation consists of a dense tropical rainforest mosaic of terra firme, with canopy heights ranging from 35 to 45 meters, and lowland forests characterized by campinarana and riparian forests, whose presence is influenced by factors such as slope, soil type, nutrient content, and drainage conditions (Luizão *et al.*, 2007). The area experiences a humid tropical climate (Silva *et al.*, 2009), with an average annual rainfall of 2,286 mm. The rainy season extends from October to June, with monthly rainfall occasionally exceeding 300 mm, while the dry season occurs between July and September, with monthly rainfall falling below 100 mm. The average annual temperature is 26.7°C (Da Rocha *et al.*, 2009).

SAMPLING DESCRIPTION AND DATA ANALYSIS

Sampling was conducted during the dry season in both the Pantanal and the Amazon. The first campaign in the Pantanal occurred from August 30 to September 2, 2016, followed by a second campaign from September 13 to 15, 2017. In the Amazon, sampling took place from October 4 to 6, 2016. Isoprene mixing ratio measurements were taken at 15 meters above the canopy in the Pantanal (Figure 1a) and 36 meters above the canopy in the Amazon (Figure 1b). Measurements were conducted between 8 am and 5 pm in the Pantanal and between 8 am and 4 pm in the Amazon, both in local time, using a sequential autosampler (STS-25, Perkin Elmer), which was calibrated daily before fieldwork, with an average flow rate of 60 mL min^{-1} and a sampling duration of 90 minutes.

Figure 1. Measurement sites for isoprene mixing ratios in the Pantanal (1a) and the Amazon (1b).



Source: Authors.

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Air samples were collected in preconditioned stainless steel adsorption tubes (Perkin Elmer, Air Toxics) and chromatographic analysis was performed at the LAPBIO laboratory (National Space Research Institute, INPE). Samples were preconcentrated in a thermal desorber (Turbo Matrix ATD350, Perkin Elmer) at 0°C and desorbed at 280°C. Gas chromatography (GC-FID) (Clarus 580, Perkin Elmer) was used for the chemical separation of isoprene using a Rt-Alumina Bond-Na_2SO_4 capillary column (50 m x 0.32 mm) with a temperature ramp from 45°C to 290°C among 18 minutes and a carrier flow of 4 ml min^{-1}.

Compound quantification was performed using daily calibration curves generated by diluting a standard gas (300 ppb isoprene). Air Toxics adsorption tubes were used for the analysis of hydrocarbons from C_2 to C_6. The detection limit of the method, calculated by linear regression, corresponded to a minimum injection of 0.23 ppb (0.2 μg m^{-3}) of isoprene, with a relative precision of 4% over seven injections of the same standard mixture ratio.

The diurnal cycle of the isoprene mixture ratio was determined by calculating hourly averages. Isoprene concentrations were compared with temperature and incoming solar radiation to evaluate factors affecting isoprene emissions from vegetation (Bai, 2015). Each sample was analyzed individually, and all data are presented in local time.

Air temperature and global solar radiation data for the Pantanal were obtained from the Brazilian National Meteorological Institute (INMET) at the Miranda, Mato Grosso do Sul, automatic weather station. For Amazon, data were provided by the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA).

Statistical analyses were performed to assess differences in isoprene concentrations across sites and years. A one-way analysis of variance (ANOVA) was used to determine significant differences in mean isoprene levels, followed by a Tukey HSD post-hoc test to identify specific group differences. The analyses were conducted at a 0.05 significance level.

RESULTS AND DISCUSSION

In this section, we present the results of our study on isoprene emissions in the Pantanal and Amazon biomes, emphasizing the influence of environmental drivers such as temperature, solar radiation, and fire activity. The analysis draws on isoprene mixing ratios measured during field campaigns in 2016 and 2017, offering a detailed perspective on the emission patterns in these contrasting ecosystems.

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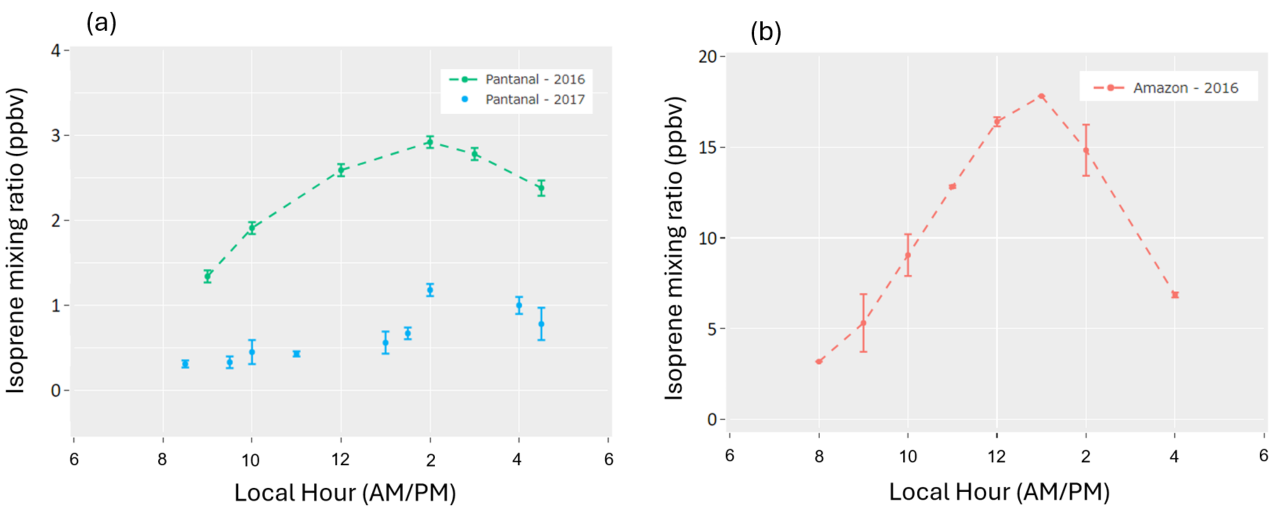
The results are organized into two main aspects. First, we provide a comparative analysis of isoprene mixing ratios between the two biomes, highlighting the distinct ecological and climatic conditions that shape these emissions. Second, we examine how seasonal dynamics and fire events contribute to variations in isoprene emissions, focusing on the differing responses of the Pantanal and Amazon to natural cycles and anthropogenic disturbances.

Finally, we discuss the broader atmospheric implications of these findings, considering how isoprene emissions from these biomes influence air quality and chemical processes at regional and global scales. By integrating data on seasonal trends and fire impacts, this study underscores the complex interactions between ecological systems and human activities, offering insights into the role of tropical biomes in atmospheric chemistry.

ISOPRENE MIXING RATIO FOR PANTANAL AND AMAZON

Figures 2a and 2b illustrate the diurnal cycles of the isoprene mixing ratio measured at the end of the dry season in the two biomes: Pantanal, in 2016 and 2017, and Amazon, in 2016. In both biomes, the dashed lines, in green and red, indicate the trend of these cycles under cloud-free sky conditions.

Figure 2. Diurnal cycles of isoprene mixing ratios measured during the dry season in both biomes: (a) Pantanal in 2016 and 2017, and (b) Amazon in 2016. The dashed lines represent the trend of the diurnal cycle in unclouded sky conditions.



Source: Authors.

Differences in average isoprene concentrations between the Pantanal and Amazonian biomes are evident from the results of the isoprene measurements. In 2016, the

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Pantanal presented an average isoprene concentration of 2.32 ± 0.57 ppbv, based on 12 measurements. In the same year, the Amazon exhibited an average isoprene concentration of 10.38 ± 5.17 ppbv, with a total of 18 measurements. The following year, in 2017, measurements in the Pantanal showed a reduction in the average isoprene compared to 2016, recording 0.65 ± 0.30 ppbv from 22 measurements.

The data obtained for the Pantanal in 2016 and 2017 are consistent with the values found by Donoso *et al.* (1996) and Holzinger *et al.* (2002) in savanna environments in Venezuela during the dry season. Holzinger *et al.* (2002) reported mean isoprene mixing ratio values of 0.8 ± 0.2 ppbv in a woodland savanna and 0.6 ± 0.1 ppbv in a grassy savanna, showing a similarity with the values obtained in the Pantanal. Similarly, the results of Yáñez-Serrano *et al.* (2015) in the Amazon indicated a median isoprene of 7.6 ± 6.1 ppbv, which is in the same magnitude range as the measurements carried out in this research for the Amazon in 2016, which presented an average of 10.38 ± 5.17 ppbv. This correspondence validates the consistency of the data obtained in this study and highlights the different emission rates between biomes.

The results of the ANOVA indicate that there are statistically significant differences in the means of isoprene concentrations between the analyzed groups (Pantanal 2016, Pantanal 2017 and Amazon 2016), with an F value of 53.43 and a p value of 4.88e-13, suggesting that at least one of the means differs statistically from the others. The Tukey test, performed as a post-hoc analysis, confirmed these differences: the comparison between Amazon 2016 and Pantanal 2016 revealed a mean difference of -8.06 ppbv ($p < 0.05$), while the comparison between Amazon 2016 and Pantanal 2017 showed an even greater mean difference of -9.73 ppbv ($p < 0.05$), both differences being statistically significant. On the other hand, the comparison between Pantanal 2016 and Pantanal 2017, although showing an average difference of -1.67 ppbv, was not statistically significant ($p = 0.2913$). These results indicate that isoprene emissions are substantially higher in the Amazon compared to the Pantanal and that, in the Pantanal, there was a reduction in isoprene mixing ratios from 2016 to 2017. In 2016, the average isoprene mixing ratio in the Pantanal was approximately 77.6% lower than in the Amazon, while in 2017 this difference increased to approximately 93.7%.

The lower isoprene concentrations observed in the Pantanal compared to the Amazon can be attributed to a combination of ecological and environmental factors. The Amazon biome, characterized by its greater diversity and density of vegetation, tends to

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support more intense isoprene emissions. In contrast, the Pantanal, with its seasonal vegetation, lower plant density, and the presence of deciduous species, along with its distinct environmental conditions, may result in reduced emissions.

From the figures (2a and 2b) depicting data from 2016, similar diurnal patterns are observed in both biomes. In the Pantanal, the highest isoprene mixing ratio occurs around 2:00 p.m., whereas in the Amazon, the peak is recorded around 1:00 p.m., both local times. The rapid increase in the mixing ratio during the morning, peaking in the early afternoon, is attributed to the influence of temperature and solar radiation on isoprene emissions (Sanadze, 1969), leading to pronounced diurnal variation.

IMPACT OF SEASONAL VARIATION AND FIRES ON ISOPRENE EMISSIONS

Figures 3a and 3b illustrate the seasonal variation in air temperature and global solar radiation at the end of the dry season in the Pantanal during 2016 and 2017. Figure 3a shows that temperatures were consistently higher in 2016 compared to 2017, reaching values within the ideal range for isoprene production and emission, between 30°C and 35°C, as suggested by Langford *et al.* (2022). Figure 3b reveals that incident solar radiation was also more intense in 2016, with a more pronounced peak throughout the day, reaching 820 W m^{-2} in 2016 and 680 W m^{-2} in 2017. According to Alves *et al.* (2018), under these conditions, plants tend to produce and emit isoprene more intensely, as the activity of the enzymes involved in isoprene biosynthesis is maximized, and cell membrane stability is maintained, facilitating the release of the compound into the atmosphere. Supporting this observation, during the 2016 campaign, the isoprene mixing ratio showed a stronger correlation with solar radiation (r = 0.91) than with temperature (r = 0.84), indicating that solar radiation was the primary driver of isoprene emissions that year. Conversely, in the 2017 campaign, the relationship was reversed: the correlation with temperature (r = 0.80) exceeded the correlation with solar radiation (r = 0.73), suggesting that temperature became the dominant factor in isoprene emissions under the conditions of that year.

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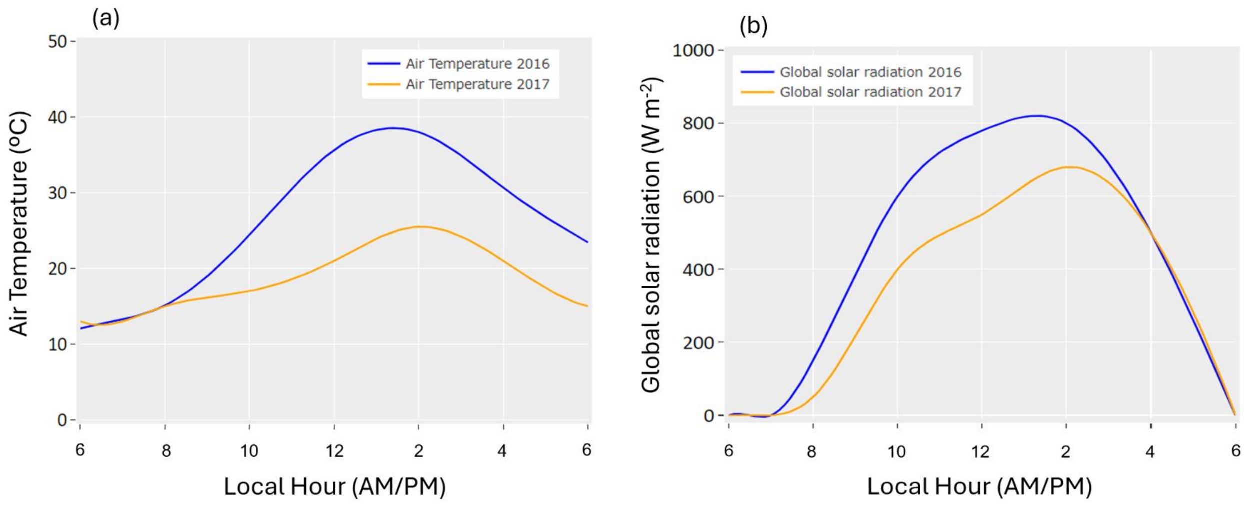
Figure 3. Air temperature (a) and global solar radiation (b) at the Pantanal site during the dry season sampling campaigns in 2016 and 2017.



Source: Authors.

As noted by Langford *et al.* (2022), seasonal variations in solar radiation and temperature directly impact isoprene emissions, which follow a seasonal cycle, with a higher mixing ratio during the dry season, in response to meteorological conditions, such as higher temperature and solar radiation. In this scenario, other environmental factors, such as soil moisture and precipitation, may also play a representative role in regulating isoprene emissions, especially in regions such as the Pantanal. Furthermore, according to these authors, the interference of anthropogenic pollutants, such as increased reactive nitrogen oxides (NOx) concentrations due to fires, may alter the atmospheric chemistry of isoprene, altering its oxidation pathways. This context suggests that environmental conditions in 2017, combined with possible anthropogenic influences, contributed to the significant reduction in isoprene concentrations in the Pantanal compared to 2016.

An analysis of fire activity during the sampling periods in the Pantanal revealed significant differences between 2016 and 2017. Satellite data from the National Institute for Space Research (INPE, 2024) showed that between August 28 and September 3, 2016, 474 fire spots were recorded. In contrast, from September 10 to 16, 2017, the number of fire spots surged to 8,384, a more than 15-fold increase compared to the previous year.

Figures 4a and 4b illustrate the spatial distribution of these fire spots, with red dots indicating fire locations and the yellow marker denoting the sampling site (Sobral, 2019). This substantial increase in fire activity in 2017 likely had a direct impact on the environmental conditions and the isoprene data collected during the sampling campaigns.

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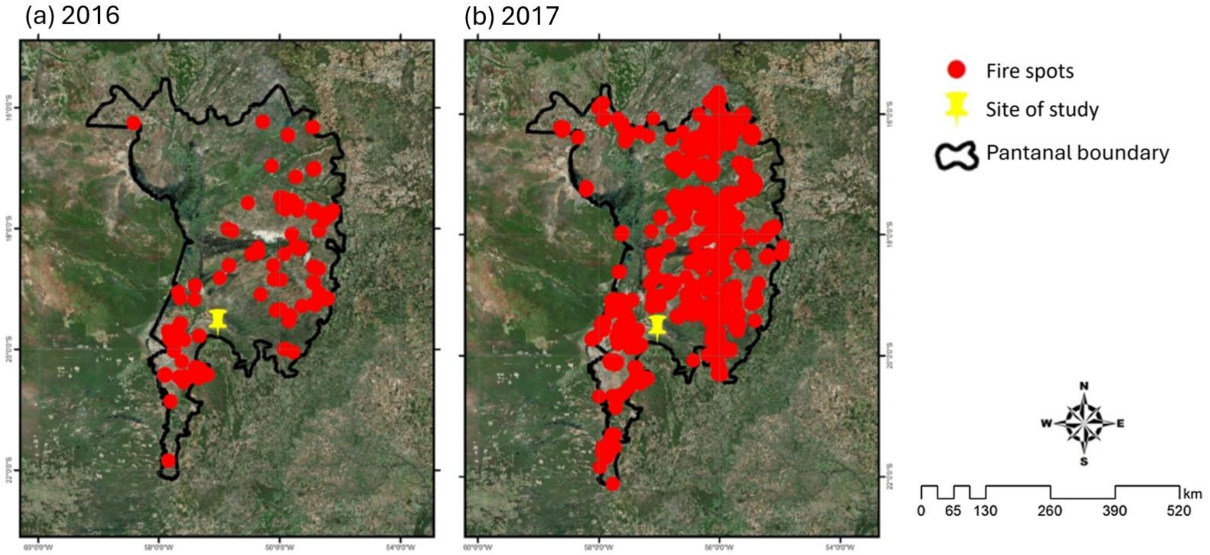
Figure 4. Satellite-registered fire spots within the Pantanal boundaries for 2016 (a) and 2017 (b). Red dots represent fire spots, and the yellow marker indicates the sampling location.



Source: Sobral (2019).

Seasonal changes in solar radiation and temperature are key drivers of isoprene emissions, with higher concentrations typically observed during the dry season (Langford *et al.*, 2022). But, additionally, environmental factors such as soil moisture and precipitation, along with anthropogenic influences like elevated NOx levels from fires, can significantly alter the atmospheric chemistry and emission pathways of isoprene, particularly in sensitive ecosystems like the Pantanal.

For comparison, Figures 5a and 5b present photos that characterize the region's landscape at the end of the dry season during the campaigns in the Pantanal in 2016 and 2017. In image (5a), from 2016, a predominantly sunny sky is observed, illustrating atmospheric conditions typical of the dry season. In contrast, image (5b), from 2017, shows the presence of fire plumes that obscure the sky, reflecting the influence of fires in the region during that year. This is also confirmed by back trajectories (not shown) constructed for the two periods, which demonstrate the influence of fire plumes in the sampling region in 2017.

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Figure 5. Photos obtained from the PTN flux tower at BEP-UFMS: (a) clear skies observed at the sampling site during the 2016 campaign, and (b) visible burning plumes at the sampling site during the 2017 campaign.

(a) (b)

Source: Sobral (2019).

The observed decrease in isoprene mixing ratios in 2017 can be largely attributed to the influence of anthropogenic factors, particularly the extensive fires in the region. This observation is consistent with findings by Lee *et al.* (2016) and Langford *et al.* (2022) in the Amazon, where pollution from regional fires, particularly during the dry season, significantly increases NOx concentrations. These elevated NOx levels can divert isoprene oxidation from its natural pathways, favoring the formation of alternative products that are less conducive to SOA formation. This suggests that while natural isoprene emissions are present, the introduction of anthropogenic pollutants can significantly alter the atmospheric chemistry of this compound.

Although direct measurements of ozone or NOx were not made in this study, the dramatic increase in fires in 2017 likely injected a significant amount of these reactive compounds into the atmosphere. The result was an increased oxidative capacity, leading to more extensive isoprene oxidation compared to 2016. This is consistent with the findings of Santos *et al.* (2018), who reported that biomass burning not only increases NOx and CO levels, but also facilitates the vertical transport of these pollutants, affecting oxidative processes at different altitudes.

In addition, the lower isoprene mixing ratios observed in 2017 may also be due to reduced solar radiation and temperature, both of which are critical drivers of isoprene emissions. However, the presence of fire plumes suggests that combustion by-products, particularly NOx, played an important role in altering the atmospheric behavior of isoprene. The interaction of these natural and anthropogenic factors likely resulted in the reduced isoprene levels compared to the clearer, less polluted conditions of 2016.

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To fully understand these dynamics, a comprehensive study that includes measurements of other volatile organic compounds, such as acetonitrile and acetaldehyde, in addition to isoprene would be beneficial. Such an approach, especially if conducted during the rainy season, would provide a deeper understanding of the oxidative processes at play in the Pantanal, given its unique environmental context compared to the Amazon. As highlighted by Santos *et al.* (2018), the ratio of isoprene to its oxidation products can serve as a valuable metric to assess the extent of isoprene oxidation and its impact on atmospheric chemistry.

Addressing the research question "How do specific environmental conditions in the Pantanal, such as seasonal hydrological patterns and fire occurrence, influence isoprene emissions compared to the Amazon?", the results suggest that the Pantanal's distinct environmental conditions lead to different responses to seasonal and anthropogenic forcing. The interplay of fire, temperature and radiation uniquely modulates isoprene emissions in this biome, underscoring its sensitivity to both natural and human-induced changes.

In the broader context of the UN 2030 Agenda, particularly SDGs 13 and 15, which emphasize climate action and the conservation of vulnerable ecosystems, these findings are critical. As a vital biome, the Pantanal contributes significantly to climate regulation and ecosystem services. Understanding the factors influencing isoprene emissions in this region can inform global conservation and climate action strategies, highlighting the importance of managing both natural and anthropogenic factors to preserve the Pantanal's role in global climate stability and ecosystem health.

CONCLUSIONS

The primary objective of this research was to quantify isoprene emissions in the Pantanal and compare them with those in the Amazon, assessing their correlations with environmental factors such as temperature, solar radiation, and fire occurrence. This study, which presents the first measurements of isoprene mixing ratios in the Pantanal biome, aimed to understand how these emissions are modulated by the unique environmental conditions in the region. The insights gained contribute to a better understanding of isoprene chemistry in tropical biomes, with significant implications for enhancing climate models, supporting conservation strategies, and mitigating the impacts of climate change.

The key finding of this study confirms that environmental factors, particularly the occurrence of fires and the associated increase in reactive nitrogen oxides (NOx),

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significantly alter the atmospheric chemistry of isoprene in the Pantanal. Specifically, the research demonstrated that isoprene mixing ratios were notably lower in 2017, a year characterized by reduced radiation and temperature, alongside an increased oxidative capacity of the atmosphere due to fire-related pollution. This finding substantiates the study's objective, demonstrating that the Pantanal's isoprene emissions are indeed modulated by its unique environmental conditions.

On a practical level, these findings can inform environmental management strategies in the Pantanal, particularly in mitigating the impact of fires and preserving the biome's critical role in climate regulation. In agreement with Ferreira *et al*. (2023a; 2023b), the research also carries social implications, emphasizing the need for policies that address environmental degradation caused by fires, which can have far-reaching effects on air quality and public health. Furthermore, understanding the role of isoprene emissions in climate dynamics can contribute to global efforts to combat climate change, aligning with the UN's Sustainable Development Goals (SDGs) 13 and 15.

A limitation of this research is the absence of direct measurements of other BVOCs and NOx, which could have provided a more comprehensive understanding of the atmospheric processes influencing isoprene emissions in the Pantanal. Additionally, the study was confined to the dry season, and the results may not fully capture the seasonal variability of isoprene emissions in this biome.

Future research should focus on expanding the scope of measurements to include a wider range of biogenic volatile organic compounds (BVOCs) and nitrogen oxides (NOx), which are essential for understanding the complex interactions between natural and anthropogenic factors influencing isoprene emissions. Such data would provide deeper insights into the chemical processes linking emissions to atmospheric dynamics in tropical regions. In addition, the inclusion of the rainy season in future studies would fill a critical gap and provide a complete perspective on the seasonal variations of isoprene emissions in the Pantanal. This would improve our understanding of how rainfall, vegetation activity, and other climatic factors shape emission patterns throughout the year.

Finally, it is essential to study the effects of land-use changes, such as deforestation and agricultural expansion, on isoprene emissions. These changes significantly alter ecosystem dynamics and emission patterns, making it important to assess their implications for the sustainability of the Pantanal under increasing environmental pressures. Such

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studies would support the development of conservation strategies and contribute to global efforts to mitigate climate and biodiversity challenges.

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