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The new microclimatic scenario of the Pantanal: a temporal analysis of thermo-pollutant dynamics

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Abstract

The Pantanal biome has been undergoing accelerated microclimatic transformations marked by progressive warming, aridification, and increased atmospheric pollution-factors that compromise ecosystem resilience and public health. In this context, this study aimed to quantify trends in air temperature, relative humidity, and fine particulate matter ($PM_{2.5}$) concentrations from 2000 to 2024 across three analytical scales: the Pantanal biome, the municipal area of Cáceres, and the urban perimeter of Cáceres, in Mato Grosso, Brazil. Air temperature and relative humidity were obtained from ERA5-Land reanalysis data, and particulate matter was derived from MODIS sensor products. The results indicate a 9.4% increase in mean annual temperature (from 25.52 to 27.96°C), whereas relative humidity declined by 16.7% (from 72.61% to 60.55%). Extreme $PM_{2.5}$ pollution episodes were identified in 2005, 2007, and 2020, with peaks exceeding 300 μg m^{-3}. These findings reveal a thermo-pollutant dynamic in which pronounced warming and elevated particulate concentrations act synergistically, intensifying thermal stress and degrading air quality. Over the 24-year period analysed, a growing trend of this interaction was observed, characterizing a new and critical environmental condition for the Pantanal and Cáceres, with serious implications for human health and ecological integrity.

Introduction

The Pantanal, one of the most important wetland ecosystems on the planet, is under acute threat from an accelerating climate crisis (Junk et al. 2014; Tomas et al. 2019). Extreme climatic events, such as the severe droughts and large-scale wildfires that occurred in 2020, have exposed the vulnerability of the biome, resulting in biodiversity loss and the degradation of ecosystem services (Tomas et al. 2021). Among the municipalities that make up the biome, Cáceres, Mato Grosso, located in the northern Pantanal, represents a strategic area both for natural ecological processes, being situated in an ecotone among the Pantanal, Cerrado, and Amazonia, and in the context of growing anthropogenic pressures such as pasture and soybean cultivation, unprecedented fires, and drainage (Galvanin et al. 2019; Schulz et al. 2019; Melo et al. 2025; Rosa Barros et al. 2025).

As in the Pantanal as a whole, the municipality of Cáceres faces a worrying situation marked by the interaction among progressive warming, loss of water mass, and intense fires (Thielen et al. 2020; Lázaro and Oliveira-Júnior et al. 2020; Barbosa et al. 2022). This scenario promotes atmospheric pollution and, when these factors are combined, they not only generate direct impacts on public health but also entail significant public costs (Santos et al. 2025; Sobreira et al. 2025). When these environmental stressors are considered together with declining precipitation and increasing evapotranspiration, the aridification process becomes increasingly imminent in these environments (IPCC 2021; Marengo et al. 2021).

Warming and aridification create conditions conducive to the occurrence and spread of wildfires, which release large amounts of fine particulate matter ($PM_{2.5}$) and other pollutants into the atmosphere (Da Silva et al. 2018). These pollutants may, in turn, alter the radiation balance and cloud-formation processes, potentially intensifying temperature anomalies and modifying precipitation regimes at local and regional scales (Artaxo et al. 2005). The interaction of these factors can result in a thermo-pollutant dynamic, characterized by synergy between elevated temperatures and air pollution, which amplifies the environmental and climatic impacts in the region.

There has been a significant increase in mean temperatures and in the frequency of heatwaves across central Brazil, with projections indicating the intensification of these events over the coming decades (Hansen et al. 2013; Marengo et al. 2016; Neto et al. 2026). Simultaneously, atmospheric pollution arising from biomass burning poses a serious risk to public health, being associated with an increase in respiratory and cardiovascular diseases in the local population (Wu et al. 2023). Thus, the Pantanal and the municipality of Cáceres have become hostage to these environmental changes, generating an inconsistency in the region's thermo-pollutant dynamic (Louzada et al. 2021). This also causes changes in the flood pulse, which becomes weaker and is marked by longer and more severe dry seasons, directly affecting the structure and functioning of the ecosystem (Alho 2008; Junk et al. 2014).

Between 2019 and 2020, the region faced the worst drought in the last 80 years, characterized by historically low river levels and record fire occurrence (Barbosa et al. 2022; Marques et al. 2021; Marengo et al. 2021; Silva et al. 2024). This extreme event highlights the vulnerability of the local hydrological system and foreshadows a worrying scenario, as climate models project an increase in the frequency and severity of droughts by the end of the century (Silva et al. 2024; Neto et al. 2026). Accordingly, there is a growing risk of recurrence of such events and of intensification of the aridification process (Thielen et al. 2020). The loss of vegetation cover and the expansion of agricultural frontiers act synergistically in this context, further aggravating environmental degradation, especially in areas less subject to flooding, which gradually lose their capacity for ecological resilience, while the same fire risk occurs in areas with biomass accumulation (Guerra et al. 2020; Marques et al. 2021; Martins et al. 2024).

In an integrated manner, all these factors interact with the microclimatic variation of the Pantanal and Cáceres, generating a feedback loop among warming, aridification, and atmospheric pollution that intensifies thermal extremes and reduces the region's environmental resilience (Marques and Rodriguez 2022). This interaction favours ecosystem imbalance, compromises urban thermal comfort, and increases risks to human health, underscoring the urgency of integrated strategies for climate monitoring and environmental management aimed at mitigating these impacts (Krüger et al. 2017; Antoniou et al. 2024).

Despite growing concern, the integrated quantification of microclimatic change and atmospheric pollution in the Pantanal and Cáceres remains incipient. The analysis of long time series, which makes it possible to identify trends and anomalies, is essential to support decision-making and the development of mitigation and adaptation strategies (Vachiano et al. 2024). In this context, the following scientific question arises: How does the interaction between thermal variation and atmospheric pollution affect the microclimate and air quality of the Pantanal biome and the urban perimeter of Cáceres, Mato Grosso? To address this question, this study aims to analyse the interaction between air temperature variation, bioclimatic indices (heat and thermal discomfort), and $PM_{2.5}$ concentrations, and how this interaction has affected the microclimate and air quality of the Pantanal biome and the urban perimeter of Cáceres between 2000 and 2024.

Materials and methods

Study area

The study was conducted at three analytical scales: the Pantanal biome, the municipal area, and the urban perimeter of Cáceres, Mato Grosso (Fig. 1). Cáceres is a strategic municipality whose territory occupies

approximately 10% of the entire Pantanal biome and that has historically suffered from the impacts of fires and climatic variation and, more recently, drainage at strategic sites (Silva and Abdon 1998; Rossetto and Girardi 2013; Rosa Barros et al. 2025).

Data acquisition

Time series from 1 January 2000 to 31 December 2024 were used for the variables air temperature (T, °C), relative humidity (RH, %), and fine particulate matter ($PM_{2.5}$, in μg m^{-3}). Temperature and RH data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) through the ERA5-Land reanalysis (Copernicus 2022). This dataset has a spatial resolution of 0.1° × 0.1° (Yan et al. 2021) and provides estimates at 2 m above the ground surface (Muñoz-Sabater et al. 2021). The temperature variable was originally expressed in Kelvin (K) and was subsequently converted to degrees Celsius (°C) according to Eq. 1:

$$T_{(^\circ C)} = T_{(K)} - 273.15$$

(1)

where *T*(K) is the air temperature in Kelvin and *T*(°C) is the temperature converted to degrees Celsius.

Atmospheric pollution data were derived from remote-sensing products. The Aerosol Optical Depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was used as a proxy for the column particulate-matter concentration, being particularly sensitive to fire emissions (Christopher and Gupta 2020). The AOD data were processed and correlated with surface measurements to estimate $PM_{2.5}$ concentrations by applying an empirical conversion factor (Eq. 2):

$$AOD = PM_{2.5}\, H\, f\,(RH)\, \frac{3\, Q_{ext,\,dry}}{4\, p\, r_{eff}} = PM_{2.5}\, H\, S$$

(2)

where f(RH) is the ratio between the extinction coefficients under ambient and dry conditions; ρ is the aerosol mass density (g m^{-3}); $Q_{ext,dry}$ is the Mie extinction efficiency under dry conditions; and r_{eff} is the effective particle radius. The term *S* denotes the specific extinction efficiency (m^2 g^{-1}) of the aerosol under ambient relative-humidity conditions.

Bioclimatic indices

After the T and RH data were collected, two well-established bioclimatic indices were calculated for the study areas: the heat index (HI) proposed by Steadman (1979) and the thermal discomfort index (TDI) proposed by Thom (1959), adjusted for tropical regions by Santos (2011). The formulas used were Eqs. 3 and 4:

$$HI = -8.7847 + 1.6114 \bullet T - 0.012308 \bullet T^2 + 2.3387 \bullet U - 0.01612 \bullet T \bullet U$$

(3)

where *HI* is the Heat Index, *T* is the air temperature in °C, and *U* is the relative humidity in %.

$$TDI = T - (0.55 - 0{,}0055 \bullet U) \bullet (T - 14.5)$$

(4)

where *TDI* is the Thermal Discomfort Index, *T* is the air temperature in °C, and *U* is the relative humidity in %. graphs.

Data processing and analysis

After collection, the data were organized in Microsoft Excel® spreadsheets. A manual check of the data was performed to identify and correct possible inconsistencies or technical errors. Descriptive statistical analysis was performed to determine the mean, maximum, and minimum values for the analyzed periods. The Python programming language was used for statistical analyses, with the Pandas library to organize the data into tabular structures and Seaborn to generate the graphs.

Results

Microclimatic variables and bioclimatic indices

The results obtained reveal an increase in mean air temperatures in the Pantanal biome over the last two decades. The mean annual temperature in the region rose from 25.52°C in 2000 to 27.96°C in 2024, corresponding to an increase of 9.4%. This warming trend is continuous and intensified from 2015 onward, when the highest mean values, above 27°C, began to be recorded. Consistently, the mean annual RH in the Pantanal decreased from 72.61% to 60.55% over the same interval, a decline of 16.7%.

In the municipal area of Cáceres, the mean annual temperature rose from 25.68°C (2000) to 27.88°C (2024), an increase of 8.6%. The mean RH fell from 73.77% to 63.03% over the same period, a reduction of approximately 14.5%. The combined impact of rising temperature and decreasing RH was reflected directly in the TDI and the HI. The mean annual TDI, which reflects the sensation of human thermal discomfort, rose from 24.09°C to 25.17°C, whereas the HI showed a more pronounced increase, rising from 27.56°C to 30.31°C, indicating a 10% increase. It is worth noting that, in 2023 and 2024, the maximum HI values reached 34°C, representing conditions of extreme discomfort and potential health risk.

When focusing on the urban perimeter of Cáceres, an increase from 25.71°C (2000) to 27.84°C (2024) was observed, representing an increase of 8.3%. The mean RH decreased from 73.71% to 63.35%, an estimated reduction of 14.1%. The mean TDI values rose from 24.10°C to 25.15°C, whereas the mean annual HI jumped from 27.46°C to 30.14°C, indicating a progressively hotter and drier environment, especially in the post-2015 period (Fig. 2).

Atmospheric pollution

The assessment of annual $PM_{2.5}$ concentrations between 2000 and 2023 in the three regions analysed, the Pantanal biome, the municipal area of Cáceres, and the urban perimeter of Cáceres, reveals recurrent episodes of air-quality deterioration, with marked pollution peaks especially associated with the region's dry season. In the Pantanal, although less direct anthropogenic influence is expected, the maximum $PM_{2.5}$ values occurred in 2007 (260 μg m^{-3}), followed by 2005 (254 μg m^{-3}) and 2020 (234 μg m^{-3}), demonstrating that the biome is not isolated from the regional effects of fires and the atmospheric transport of particles. At all three sites the years 2005, 2007, and 2020 recorded the highest mean annual $PM_{2.5}$ values, with concentrations exceeding 64 μg m^{-3}, values that are quite high when compared with the historical minima observed in 2009 and 2013.

In the urban perimeter of Cáceres, the highest annual mean was recorded in 2007 (80 μg m^{-3}), a value approximately three times higher than that observed in 2013 (29 μg m^{-3}), the year with the lowest mean of the historical series. With regard to maximum values, the peaks recorded in 2020 (328 μg m^{-3}) and 2005 (331 μg m^{-3}) stood out. In the municipal area of Cáceres, a pattern similar to the one described above was observed: in 2007, the annual mean reached 79 μg m^{-3}, representing an increase of 2.5 times higher than 2013 (31 μg m^{-3}), the year with the lowest mean of the series. High values were also recorded in 2005, with a mean of 65 μg m^{-3}, and in 2020, when the mean reached 70 μg m^{-3} (Fig. 3).

Discussion

The Pantanal and the municipality of Cáceres, Mato Grosso, show a continuous and pronounced process of microclimatic warming over the last two decades. Between 2000 and 2024, the mean air temperature increased by 9.4%, accompanied by a marked 16.7% reduction in RH. This combination of pronounced heat and low humidity represents a significant change in the region's thermal and water balance, indicating not only a reflection of the trends observed at the biome scale (Lázaro and Oliveira-Júnior 2020) but also a local intensification possibly associated with urban expansion, soil sealing, and changes in the use and cover of native vegetation, of which some species are fire-sensitive and others fire-adapted (Ghobadi et al. 2018; Lee 2024; Pivello et al. 2021).

The increase in mean temperature to values above 27°C raised the bioclimatic indices to critical levels. The HI exceeded 30°C in 2023 and 2024 across all areas analysed, which represents conditions of risk to human health, especially for more vulnerable groups such as the elderly, children, and workers exposed to the sun (Epstein and Moran 2006; Figueiredo et al. 2024). These results indicate that the population of Cáceres and the adjacent Pantanal areas already lives with potentially dangerous levels of thermal discomfort, capable of increasing the incidence of heat stress and aggravating cardiovascular and respiratory diseases (Oliveira et al. 2020; Réquia et al. 2024).

Added to this thermal reality is the worsening of air quality (Neto et al. 2024). $PM_{2.5}$ concentrations reached alarming values, especially in the dry years of 2005, 2007 and, most severely, 2020, when annual means exceeded 60 μg m^{-3} and daily peaks exceeded 200 μg m^{-3}. Annual $PM_{2.5}$ concentrations exceeded the World Health Organization (WHO, 2021) annual guideline value (5 μg m^{-3}) by a factor of twelve and are directly related to the intensification of fires in the Pantanal (Libonati et al. 2022). The year 2020, in particular, represented an extreme confluence of climatic and pollutant stressors, constituting a "perfect storm": record temperatures, HI

above 30°C, and critical $PM_{2.5}$ levels (> 300 μg m^{-3}). This co-exposure amplified the impacts on public health (Santos et al. 2025), reflected in the increase in hospitalizations for respiratory and cardiovascular diseases, as recent epidemiological studies for the region indicate (Caumo et al. 2022).

The main source of these emissions is associated with land-use and land-occupation practices; both in the biome and in the municipality, extensive cattle ranching is the predominant activity (Araujo et al. 2018; Marques et al. 2022), and fire is frequently used for pasture renewal (Schulz et al. 2019). When uncontrolled, these fires release large volumes of atmospheric pollutants that disperse into urban areas, further compromising air quality (Palácios et al. 2022; Souto-Oliveira et al. 2023; Neto et al. 2024). Our results indicate that even the less urbanized areas within the Pantanal plain showed the highest $PM_{2.5}$ peaks, demonstrating that atmospheric degradation transcends rural and urban boundaries, affecting the entire regional system.

In an integrated manner, the increase in temperature, the reduction in RH, and the deterioration of air quality configure a scenario of imminent concern for the Pantanal of Cáceres. This synergy of environmental stressors not only compromises the balance of local ecosystems but also endangers the well-being of the human population (García 2023). With the advance of climate change, extreme heat events and prolonged droughts are projected to become more frequent and severe (Marengo et al. 2021), broadening the impacts on the most socially and economically vulnerable groups.

Society's adaptive capacity in the face of the thermo-pollutant dynamic is influenced by various socioeconomic and contextual factors. Adaptation to high-intensity thermal events and air-pollution peaks is unequal among different social groups, with low-income populations and ethnic minorities generally more exposed to these stressors and with lower adaptive capacity (Zografos et al. 2016; Andrijevic et al. 2021; Slesinski et al. 2024). This reality highlights the discrepancy between the demands imposed by the climate crisis and the adaptation strategies currently implemented, which prove insufficient given the magnitude and speed of the phenomenon (Ellena et al. 2020).

Thus, the region faces a new microclimatic reality, a cycle of accelerated warming, low humidity, and recurrent atmospheric pollution that reinforces the socioenvironmental vulnerability of the biome and its inhabitants. In this context, it becomes urgent to develop integrated strategies for fire management, mitigation, and adaptation aimed at preserving ecological resilience and protecting public health (Vachiano et al. 2024; García 2023).

Conclusions

This study shows that the Pantanal is in transition toward a new and more dangerous environmental regime, characterized by the simultaneous intensification of thermal stress and critical episodes of atmospheric pollution. The analysis of 24 years of microclimatic data demonstrates an unequivocal trend of warming and aridification, conditions that favour the occurrence of more frequent and more intense fires. These events, in turn, amplify the levels of $PM_{2.5}$, configuring a feedback loop that threatens both the ecological integrity of the biome and the health of human populations.

Current public policies, which are predominantly reactive and aimed at responding to crises such as large fires or periods of extreme drought, prove insufficient given the chronic and progressive nature of the environmental degradation observed. The long-term results presented here demonstrate that extreme events (peaks of

temperature and atmospheric pollutants) are not exceptions but predictable consequences of a continuous process of climatic transformation and inappropriate, persistent land use. To persist with an emergency-based approach is to perpetuate the cycle of environmental destruction and social vulnerability.

Thus, attention to the Pantanal cannot be restricted to periods of calamity but must constitute a continuous policy of monitoring, management, and adaptation based on scientific evidence. The dissemination of microclimatic records, such as those presented in this study, is essential to give visibility to the ongoing degradation process and to support concrete mitigation and adaptation actions, such as the determination of safe outdoor-worker exposure times and of school schedules.

Declarations

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Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval Not applicable. This study used publicly available reanalysis and remote-sensing datasets and did not involve human participants or animals.

Consent to participate Not applicable.

Consent to publish Not applicable.

Data availability ERA5-Land reanalysis data are publicly available from the Copernicus Climate Change Service (https://doi.org/10.24381/cds.e2161bac). MODIS Aerosol Optical Depth products are publicly available through NASA's LAADS/Earthdata services. The processed datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Author contributions *C.R. Soaraes Viana, E.S. Oliveira Junior; Methodology and formal analysis: C.R. Soaraes Viana, M.C. dos Santos, D.F. Dias; Data curation and software: C.R. Soaraes Viana; Writing — original draft: C.R. Soaraes Viana; Writing — review and editing: M.C. dos Santos, D.F. Dias, A. Gioda, W.L. Lázaro, E.S. Oliveira Junior; Supervision: E.S. Oliveira Junior.*

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Figures

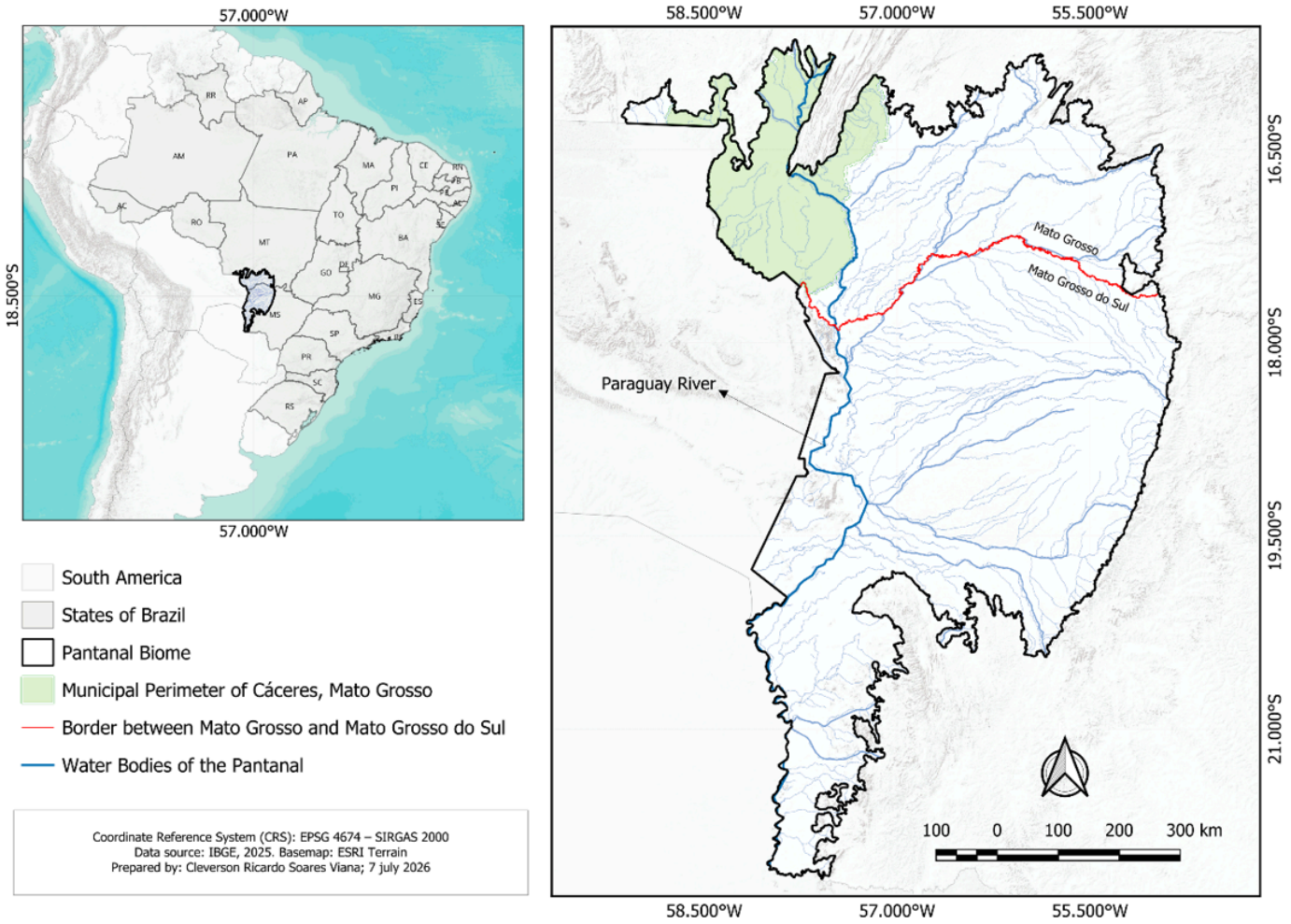


Figure 1

Representation of the Pantanal biome and its watercourses, highlighting the municipal boundary of Cáceres, Mato Grosso, located within the Pantanal biome. Source: Prepared by the authors.

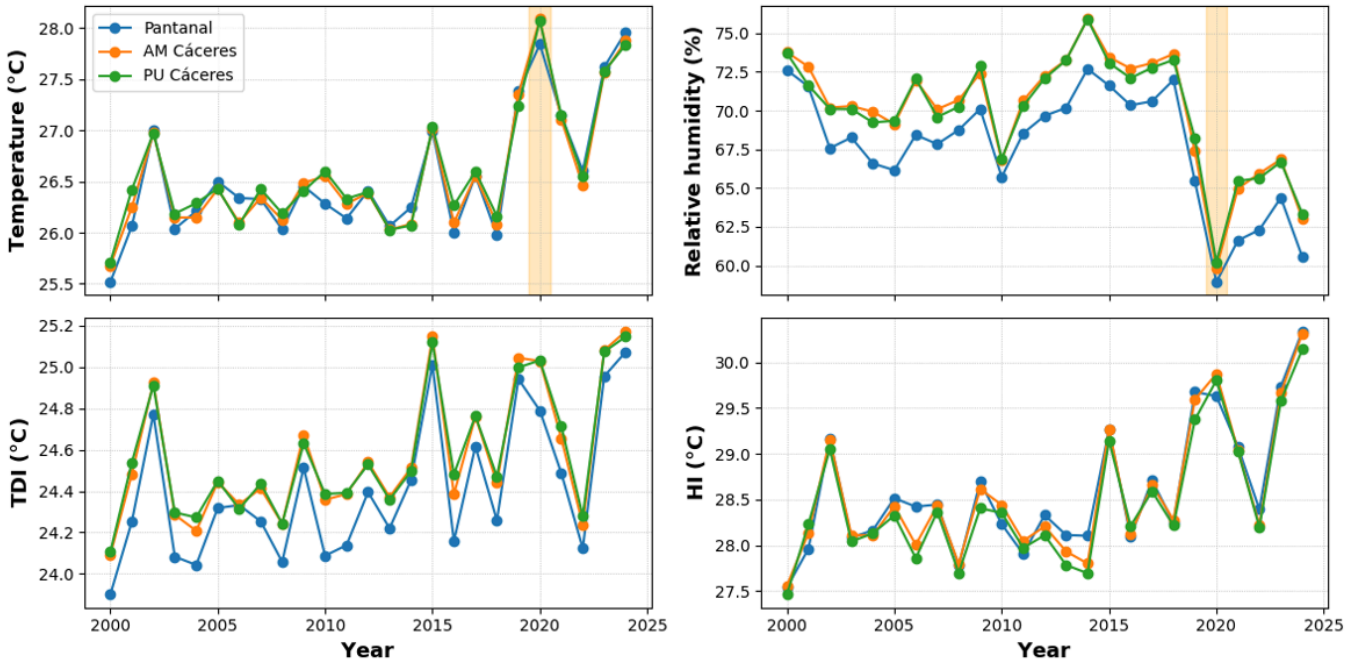


Figure 2

Annual variation of microclimatic parameters for the Pantanal biome, the municipal area of Cáceres (AM Cáceres), and the urban perimeter of Cáceres (PU Cáceres) from 2000 to 2024; the yellow band highlights the maximum-temperature and minimum-humidity peaks recorded in 2020. Source: prepared by the authors

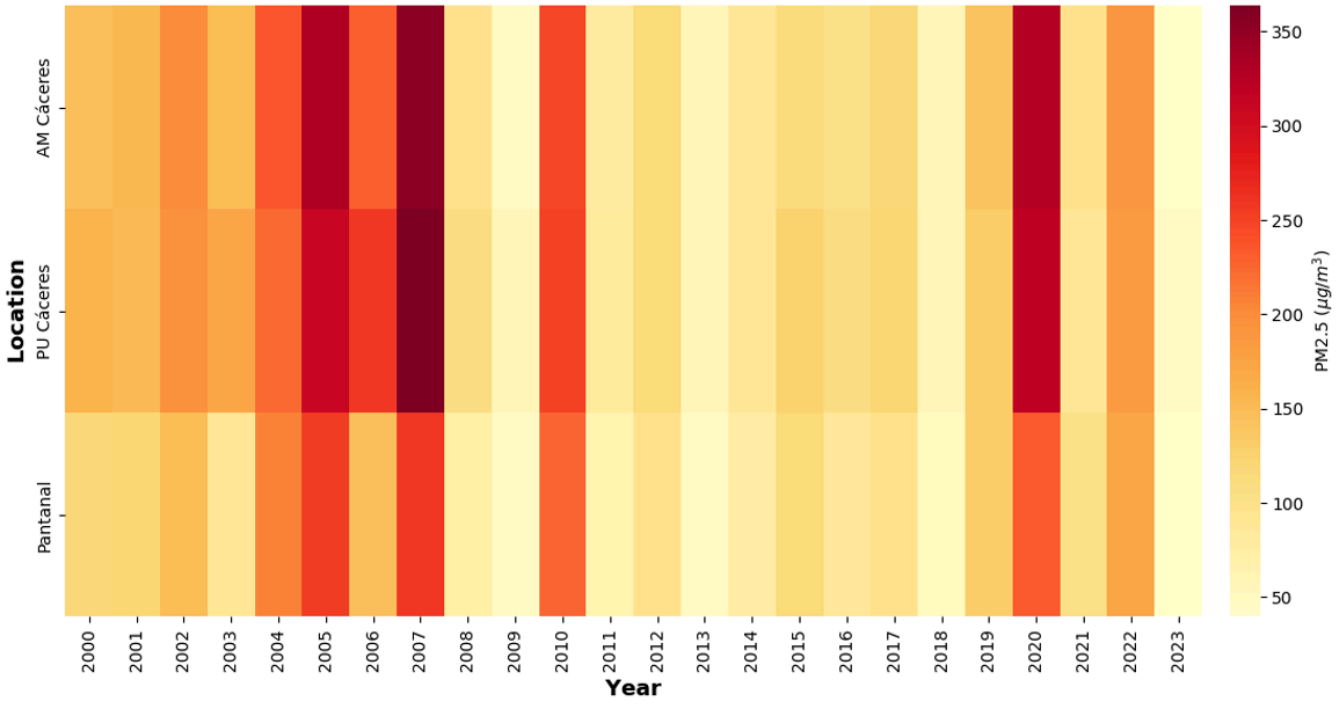


Figure 3

Annual concentration of fine particulate matter ($PM_{2.5}$, μg m^{-3}) at the Pantanal, the municipal area of Cáceres (AM Cáceres), and the urban perimeter of Cáceres (PU Cáceres) sites from 2000 to 2023. Source: prepared by the authors.