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From urban areas to conservation unities: assessing microplastic pollution across the Pantanal

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ABSTRACT

Microplastics are one of the most widespread problems that have drawn serious attention from researchers, policymakers and the public due to the potential ecological, environmental and human health implications. The objective was to verify the relationships between urbanization areas and microplastic contamination in selected freshwater locations. We estimate microplastic densities using a range of statistical analyses, including linear regression and distribution comparisons, considering two important factors: the distance from an urban center and the specific characteristics of the sites' (e.g., spring, intermediate, mouth) the urban and rural contexts. Our findings indicate a statistically significant positive relationship between the effects of proximity to urban centers to microplastic density in the freshwater environments. In other words, the density of microplastics tends to increase with decreasing distances to urban areas, showing higher concentrations compared to rural sites. The influence of some specific environmental characteristics (water quality and biodiversity in general) is based on the accumulation of microplastics suggesting a complex interaction of anthropogenic activities and natural features. This, therefore, calls for local mitigation measures and changes in the ways waste is handled, especially in urban areas, put in place systematically to mitigate the underlying causes of microplastic pollution. Finally, our research underscores the importance of urban areas in microplastic pollution studies and the necessity of interventions to reduce plastic consumption and improve waste management practices. As part of this research on the issue of microplastic pollution, a future policy that supports the reduction of contamination by these pollutants in freshwater ecosystems is essential.

Keywords: density of microplastics, urban water, wetland.

Das áreas urbanas às unidades de conservação: avaliando a poluição por microplásticos no Pantanal

RESUMO

Os microplásticos são um dos problemas mais difundidos que têm atraído a séria atenção de pesquisadores, formuladores de políticas públicas e do público devido às potenciais implicações ecológicas, ambientais e para a saúde humana. O objetivo foi verificar as relações entre áreas de urbanizadas e a contaminação por microplásticos em locais selecionados de água doce. Estimamos as densidades de microplásticos utilizando uma gama de análises estatísticas, incluindo regressão linear e comparações de distribuição, considerando dois fatores importantes: a distância do centro urbano e as características específicas dos locais (por exemplo, nascente, intermediário, foz) nos contextos urbanos e rural. Nossos achados indicam uma relação positiva estatisticamente significativa entre os efeitos da proximidade dos centros urbanos e a densidade de microplásticos nos ambientes de água doce. Em outras palavras, a densidade de microplásticos tende a aumentar com a diminuição das distâncias das áreas urbanas, apresentando concentrações mais altas em comparação com os locais rurais. A influência de algumas características ambientais específicas (qualidade da água e biodiversidade em geral) é estabelecida com base no acúmulo de microplásticos, sugerindo uma interação complexa entre as atividades antropogênicas e as características naturais. Isso, portanto, exige medidas locais de mitigação e mudanças na forma como o lixo é gerenciado, especialmente nas áreas urbanas, sendo implementadas sistematicamente para abordar as causas subjacentes da poluição por microplásticos. Por fim, nossa pesquisa destaca a importância das áreas urbanas nos estudos sobre poluição por microplásticos e a necessidade de intervenções para reduzir o consumo de plásticos e melhorar as práticas de gestão de resíduos. Como parte desta pesquisa sobre o problema da poluição por microplásticos, uma futura política que apoie a redução da contaminação por esses poluentes em ecossistemas de água doce é essencial.

Palavras-chave: água urbana, áreas úmidas, densidade de microplásticos.

1. INTRODUCTION

With the development of society, plastic production has grown substantially. The increasing demand for packaging in various commercial sectors has brought serious environmental consequences, specifically due to the poor management of these products in urban environments (Adeniran and Shakantu, 2022). The mechanical action of waves and currents in aquatic environments, as well as abrasion on land, contributes to the fragmentation of plastics into microplastics (Zhang *et al.*, 2021). Exposure to ultraviolet (UV) radiation from the sun causes chemical changes in plastics, such as the formation of new functional groups, which weaken the structure of the material and facilitate its fragmentation (Payel *et al.*, 2025). Additionally, certain types of plastic fiber may break down into microplastics more easily in water than on land (Chen *et al.*, 2021). Microplastics can be defined as plastic debris smaller than 5 mm and emanating from a wide range of sources, from the fragmentation of larger plastic items to cosmetic products and industrial processes (Thompson *et al.*, 2004). These particles are typically categorized into two main types: primary microplastics, which are intentionally manufactured at microscopic scales for use in products such as exfoliants, industrial abrasives, and medical applications; and secondary microplastics, which result from the degradation of larger plastic materials through processes like UV radiation, mechanical abrasion, or biodegradation over time (Andrady, 2011).

Microplastic pollution has recently emerged as one of the major environmental menaces of global importance, significantly threatening the world's aquatic ecosystems. Due to their small size and persistence in the environment, microplastics are ubiquitous in terrestrial and aquatic ecosystems, being found in oceans, rivers, soils, and even the atmosphere. Their high surface-area-to-volume ratio allows them to adsorb chemical pollutants such as heavy metals and persistent organic pollutants (POPs), enhancing their potential to act as vectors of contamination throughout the environment (Rochman *et al.*, 2013). Furthermore, their physical properties, such as density and polymer type, influence their transport and distribution across environmental compartments, making their monitoring and mitigation especially challenging. Microplastics have garnered increasing attention within the scientific community due to their environmental impacts and potential health risks to humans (Huang *et al.*, 2020). Once ingested, microplastics can cause physical damage, interfere with feeding behavior, and affect physiological processes such as reproduction and growth in aquatic species (Wright and Kelly, 2017). Moreover, emerging evidence suggests possible implications for human health, as microplastics have been detected in drinking water, food products, and even human tissues, underscoring the urgent need for further research on their long-term impacts. These pollutants are scavenged in the environment with a lot of difficulty and are exposed to that area for quite some time, which poses a threat to wildlife and human health (Wright and Kelly, 2017), the consequences of which are due to adsorption, which can subsequently cause lethal toxic effects to individuals (Caixeta *et al.*, 2018; Oliveira *et al.*, 2020).

Within aquatic ecosystems, microplastics can be ingested by organisms across various trophic levels, leading to intestinal blockages, metabolic disruptions, and, in severe cases, mortality (Foley *et al.*, 2018). In humans, exposure may occur through the consumption of contaminated food sources (Huang *et al.*, 2020), although fibers released in domestic environments may pose an even greater health hazard than ingestion alone (Catarino *et al.*, 2018). Notably, the presence of microplastics in aquatic systems often originates from land-based anthropogenic activities (Isaac and Kandasubramanian, 2021), illustrating a circular pathway: human activities → water contamination → accumulation in aquatic fauna → reintroduction to humans through the food chain.

It is on this premise that research in recent years focused much on the distribution of the particles and the density of the same in the freshwater ecosystem, more so as they relate to urbanization. Most likely, the inputs of microplastics received into most urban water bodies, originating from wastewater treatment plants or stormwater runoff, are through direct littering (Liu *et al.*, 2019). The latter, though, are probably not subject to plastic litter even in less developed and rural regions through agrarian runoff or atmospheric deposition (Haque and Fan, 2023).

This relationship between urban proximity and microplastic concentration highlights the urgent need for integrative urban planning and environmental governance. Studies have demonstrated that stormwater runoff, untreated sewage discharge, and inefficient solid waste collection in metropolitan regions serve as primary pathways through which microplastics enter aquatic ecosystems (Dris *et al.*, 2015). Moreover, informal settlements and areas lacking basic sanitation infrastructure tend to contribute disproportionately to microplastic pollution, especially in rapidly urbanizing regions of the Global South (Browne *et al.*, 2011).

In addition to aquatic systems, recent findings have revealed that urban microplastic emissions also contribute significantly to atmospheric contamination. Urban air samples have shown the presence of airborne microfibers and microplastic fragments, which can be transported over long distances and deposited in natural environments through atmospheric fallout (Allen *et al.*, 2019). This phenomenon suggests that even remote or seemingly pristine areas are not immune to the effects of urban-derived microplastic pollution, reinforcing the notion of environmental interconnectedness. Furthermore, the lack of harmonized monitoring methodologies and standardization of microplastic detection protocols hampers the comparability of data across regions and limits the formulation of effective transboundary environmental policies (Galgani *et al.*, 2015). To address this, researchers and policymakers have advocated for the implementation of unified monitoring frameworks and the integration of citizen science in urban and peri-urban environments. Such approaches can enhance surveillance efforts and facilitate evidence-based policy development to curb microplastic pollution at both local and global scales.

Recent work by Wang *et al.* (2017) showed that the number of microplastics could vary in relation to distance from urban centres and thus proved that waste flow and management in the cities contributed greatly to the dispersal of microplastics. It is notable that there is a gap in comprehensive public policies regarding waste management and plastic pollution in urban areas, which affects even the most remote areas of ecosystems (Souza *et al.,* 2023b).

Protected areas, such as Conservation Units (CUs), play a strategic role in environmental monitoring by serving as control sites with limited or no direct anthropogenic influence. These areas often exhibit significantly lower concentrations of microplastics compared to regions affected by urbanization, agriculture, or industrial activities, providing important baseline data for comparison. Their relative isolation allows researchers to distinguish between natural background levels and pollution resulting from human activity, which is essential for assessing the effectiveness of mitigation strategies and identifying pollution sources (Nunes *et al.,* 2025). Therefore, integrating CUs into microplastic monitoring frameworks strengthens the scientific basis for policy development and enhances the capacity to track environmental changes over time.

The widespread presence of microplastics has raised global concern not only due to their environmental persistence, but also because of their potential biological effects on organisms. However, the majority of studies are concentrated in the marine environment and in estuaries, as documented for example by Corrêa *et al.* (2021), and it is extremely important to expand research on these pollutants in rivers, streams and lakes. In these freshwater environments, microplastic pollution is influenced by urban concentration, hydrodynamics and riparian vegetation (Souza *et al.*, 2023b).

Sediment represents an important environmental compartment for the evaluation of microplastic pollution, as these particles often exhibit a tendency to settle and accumulate on the bottom of aquatic systems due to their size, density, and hydrophobic properties. Over time, sediments can act both as sinks and secondary sources of microplastics, depending on hydrodynamic conditions and bioturbation (Peng *et al.,* 2018). Consequently, assessing microplastic loads in sediments provides not only a snapshot of contamination levels but also valuable insight into the long-term persistence and potential remobilization of these pollutants within freshwater ecosystems. A study conducted on the Cuiabá River indicated higher average levels of microplastics compared to those found in sediments of other river basins worldwide (Camargo *et al.,* 2022). In Guanabara Bay, microplastics analyzed in sandy sediment samples on different beaches and in surface waters, in Niterói and Rio de Janeiro, presented serious pollution problems (Olivatto *et al.,* 2018). Studies have found high levels of microplastic pollution also in protected areas, including Canary Islands and hiking trails in Australian conservation areas (Baztan *et al.,* 2014; Forster *et al.,* 2023).

Furthermore, the spatial features of a river system have a strong influence on the distribution patterns of microplastics (Liu *et al.*, 2019). Variations in flow velocity, sediment composition, urban or industrial influence, and land use along these segments result in differing accumulation hotspots. This spatial heterogeneity complicates monitoring efforts and reinforces the need for location-specific sampling strategies. A deeper understanding of the environmental pathways and deposition zones of microplastics is therefore essential for the design of effective mitigation strategies, enabling interventions that are spatially and ecologically appropriate to reduce impacts on both terrestrial and aquatic ecosystems.

This study hypothesizes that microplastic concentrations are significantly higher in freshwater environments adjacent to urban areas compared to those located in rural settings. As a pioneering effort, this research represents the first systematic assessment of microplastic pollution within the hydrological basins of the Northern Pantanal. Sampling sites were categorized based on their proximity to urban centers and further classified according to distinct hydrological features in rural zones—such as headwaters, river mouths, lentic systems, river channels, and floodplains. The primary objective of this study is to identify spatial patterns in microplastic distribution and to evaluate the influence of land-use characteristics on pollution levels, thereby contributing critical baseline data for future monitoring and mitigation strategies in this globally significant wetland ecosystem.

2. MATERIAL AND METHODS

2.1. Study Area

The microplastics were sampled in eight flooded areas of the Northern Pantanal. In total, 42 sampling points were distributed across these areas (Figure 1), each with a different environment, in the dry season (from August to October). The selected locations belong to the Paraguay River Basin:

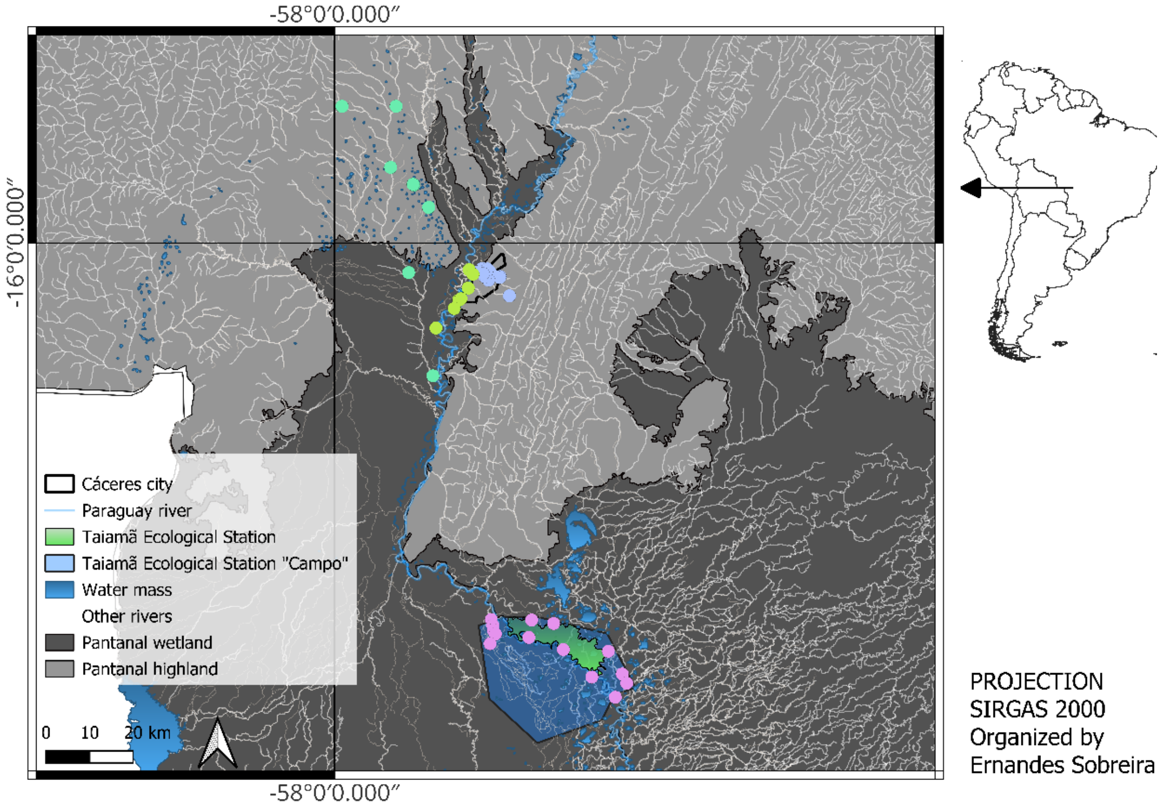

Figure 1. Study area pointing out each compartment analysed. Urban (lilac); Rural (light green); Transition Zone (green); Est - Taiamã Ecological Station (pink).

Four distinct environmental contexts were selected within the Pantanal region to assess variations in microplastic density according to land use and anthropogenic pressure:

1. Urban Area (Sangradouro and Fontes Streams): This area is located on the outskirts of the city of Cáceres, Mato Grosso, Brazil. It includes the Sangradouro and Fontes streams, which are urban water bodies receiving runoff from residential neighborhoods and roadways. The region is characterized by intense human activity, including domestic sewage discharge, waste disposal, and the presence of impermeable surfaces. These conditions make this area representative of high anthropogenic impact in an urban fluvial environment.

2. Rural Area (Caramujo Stream and Cattle Watering Lakes): Located near the rural district of Santo Antônio do Caramujo, also in the municipality of Cáceres, this area is predominantly surrounded by agricultural landscapes. It includes the Caramujo Stream, which flows through rural properties, and artificial lakes used for watering cattle. These water bodies are influenced by land management practices typical of rural areas, including livestock farming and potential runoff from pastures. The proximity to dirt roads and small-scale settlements adds

to the localized anthropogenic pressure. Additionally, the area is influenced by the BR-070 highway, where a former landfill site was repurposed to support road construction.

3. Transition Zone (Paraguay River): This zone encompasses sites along the Paraguay River between the urban area of Cáceres and the Taiamã Ecological Station. It represents a transitional gradient from moderate to reduced human activity. The river section analyzed here is subject to occasional navigation, fishing activity, and runoff from upstream human settlements. However, compared to urban and rural areas, direct land use impacts are less intense. The zone serves as an ecological corridor and buffer between human-dominated landscapes and the conserved region of Taiamã.

4. Ecological Station (Taiamã Ecological Station – EST): The Taiamã Ecological Station is a strictly protected conservation unit located within the Pantanal biome. It includes pristine areas along the Paraguay River, the Bracinho River, and seasonally flooded fields (locally known as “Campo”). The region is characterized by a flood-pulse dynamic and high biodiversity, with limited or no recent human occupation. Access is restricted for research and conservation purposes only, with no urban infrastructure, agriculture, or livestock. This area was selected as a reference site due to its minimal anthropogenic disturbance, as highlighted in Batista *et al.* (2022), and serves as a baseline for assessing microplastic contamination in natural environments.

To better understand the spatial distribution of microplastic contamination, the sampled sites were grouped into six categories based on their geomorphological and hydrological characteristics. The “Mouth” category includes sites located at the confluence of rivers or near the outlets where water bodies meet larger systems. “Intermediate” refers to sections situated between the spring and the mouth of a watercourse, generally influenced by mixed land use. “Spring” encompasses sites located near the natural emergence of water, often in less disturbed areas. “Standing water” includes artificial or natural bodies such as cattle watering lakes, characterized by stagnant or low-flow conditions. The “River” category includes flowing river sections not covered by other classifications, while “Marsh” represents flooded field areas or wetlands, often subject to seasonal inundation and located in more preserved zones. This classification was used to evaluate potential differences in microplastic density across distinct types of aquatic environments in the Pantanal.

2.2. Laboratory and Statistical Analysis

In a previous analysis, microplastics were recorded by chance along with aquatic macroinvertebrates when observing this community in samples. The samples were collected with a van Veen grab sampler (area of 0.048 m²) from the sediment of all water bodies. For the visualization of microplastics we conducted a screening with the aid of a stereoscopic magnifying glass. The classification of these structures was based on color, shape and size.

To generate continuous surface maps of microplastic concentration across the study area, the Inverse Distance Weighting (IDW) interpolation method was applied using QGIS software. IDW estimates values at unsampled locations based on the weighted average of nearby measured points, with closer points having greater influence than distant ones. The interpolation was performed using point data collected in the field, where each point was georeferenced and associated with its respective microplastic concentration. The power parameter was set to 2, which is commonly used to emphasize the influence of nearby points, and the number of neighboring points was optimized based on preliminary tests to ensure spatial accuracy. The resulting raster surface allowed for the visualization of spatial trends and identification of potential accumulation zones related to land use and proximity to urban areas.

To evaluate statistical differences in microplastic concentrations among different sampling environments, the non-parametric Kruskal-Wallis (KW) test was employed. This method was selected due to the non-normal distribution of the data, as confirmed by exploratory data analysis. The KW test was applied to compare four distinct types of rural freshwater environments – springs, mouths, river channels, floodplains/standing waters – in order to assess whether microplastic concentrations varied significantly based on hydrological characteristics. Additionally, a separate KW test was conducted to compare microplastic concentrations between urban and rural zones. This comparison aimed to test the hypothesis that proximity to urban areas results in significantly higher levels of microplastic pollution. All statistical analyses were performed using R software, with significance determined at a 95% confidence level ($p < 0.05$). Post-hoc pairwise comparisons (Dunn's test) were conducted when the KW test indicated significant differences among groups.

To investigate the relationship between the proximity to the urban center and microplastic contamination, two statistical approaches were applied. First, a binary logistic regression was performed to assess whether the distance to the city of Cáceres could predict the presence of microplastics (presence = 1, absence = 0). Distance values were normalized in kilometers, and the model's performance was evaluated using precision, recall, and accuracy metrics. The model was implemented using the Logit function from the statsmodels Python package. Odds ratios were calculated to interpret the effect size of the distance variable, and confidence intervals were estimated to evaluate statistical significance. Second, a Mann–Whitney U test was conducted to compare microplastic concentrations between two distance-based groups: sites located ≤ 50 km from Cáceres and those located > 50 km. This non-parametric test was chosen due to the non-normal distribution of the data and the high frequency of zero values in more remote areas. All analyses were conducted in Python using the scikit-learn, SciPy, and seaborn libraries.

3. RESULTS AND DISCUSSION

Based on the analysis of microplastics data across the different water bodies in the Pantanal, significant results have been revealed regarding the distribution and impact of these pollutants (microplastics). The average density of microplastics found was approximately 336 ± 975 microplastics.m^{-2}, indicating a wide variability in pollution levels across different places. This variability was highlighted by the highest density site, Sangradouro Stream, with a notable 5,604 microplastics.m^{-2}. In contrast, Caramujo Stream effectively did not present any microplastics detected in the researched area. The results of microplastic density showed that microplastics were found in all areas, even at the Ecological Station, however the urban area was characterized by a high concentration of this pollutant (Figure 2). The Ecological Station of Taiamã showed an average of 8.33 microplastics.m^{-2}, more than 220 times less than the urban streams, for instance.

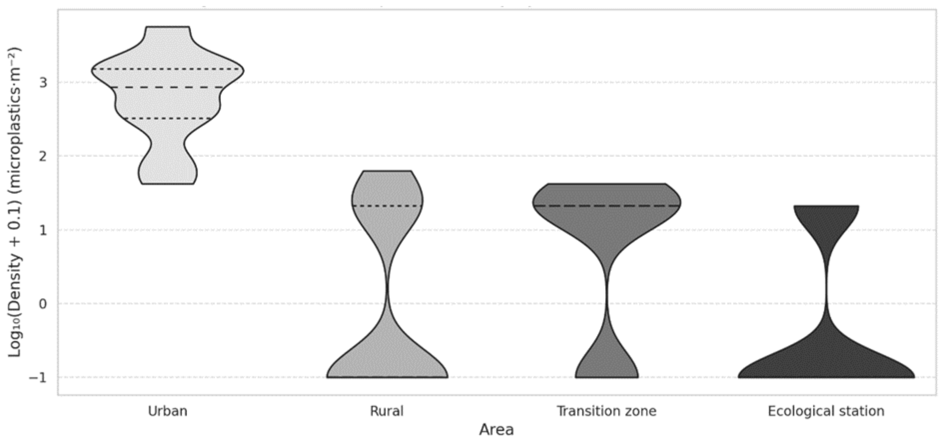

Figure 2. Distribution of microplastic density ($\log_{10}$ + 0.1) among urban, rural, transition, and protected areas (ecological station).

Regarding the analysis of microplastic density across four distinct environmental areas in the Pantanal, a clear gradient associated with the level of human interference was evident (Figure 2). The urban area, represented by Sangradouro and Fontes Streams near the city of Cáceres, exhibited the highest average microplastic density, with a mean of 144.10 microplastics.m^{-2} (±157.08 microplastics.m^{-2}). The rural area, which includes the Caramujo Stream and adjacent cattle watering lakes, showed a lower but still significant level of contamination, with an average of 49.24 microplastics.m^{-2} (±77.28 microplastics.m^{-2}). In the transition zone, covering sampling points along the Paraguay River between the city and the Taiamã Ecological Station, the mean density was 14.07 microplastics·m^{-2} (±18.97 microplastics.m^{-2}), indicating a moderate level of pollution. Finally, the ecological station – a protected area with minimal recent human activity – had the lowest density, with a mean of 2.59 microplastics.m^{-2} (±4.38 microplastics.m^{-2}). Statistically significant differences in microplastic density were observed between the environmental areas, with the urban group showing the highest contamination levels compared to all other groups (KW = 26.71; $p < 0.001$). The ecological station presented significantly lower microplastic concentrations than the rural, transition, and urban areas, confirming its role as a preserved reference site ($p < 0.05$).

On average, the density of microplastics was significantly higher in the mouth of the urban water body (Figure 3), reaching up to 2.395 ± 2.889 microplastics.m^{-2} (ANOVA; $p < 0.05$). It is important to note that microplastics were found even in the springs of the streams (41.66 ± 41.66 microplastics.m^{-2}).

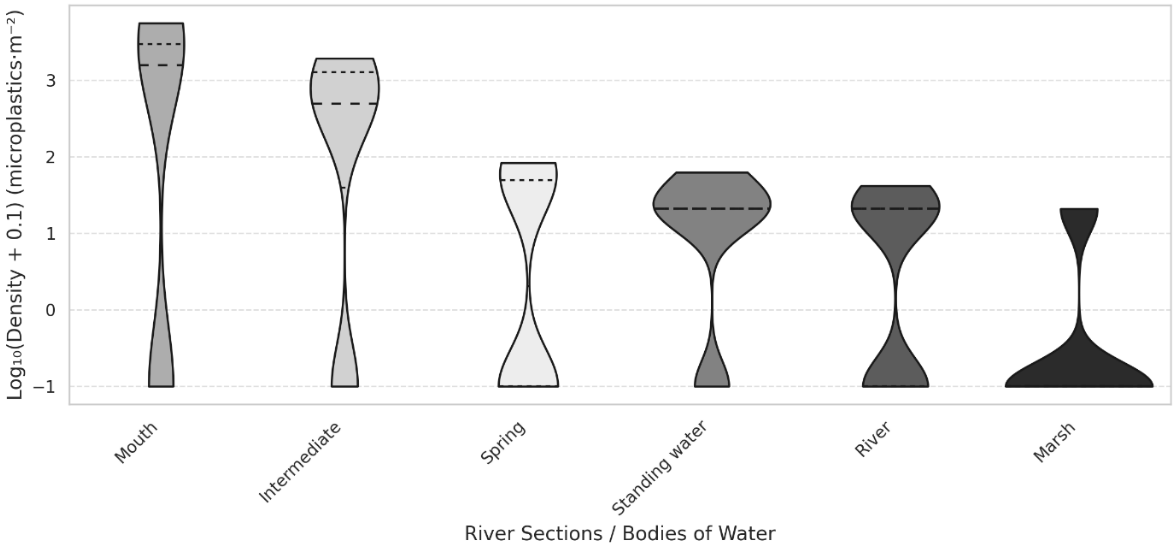

Figure 3. Log-transformed microplastic density across different types of water bodies in the Pantanal.

Plastics in urban areas are highly discarded compared to other areas and high environmental loads of microplastics, such as stormwater runoff and sewage systems (Haque and Fan, 2023; Huang *et al.*, 2020). In this sense, Souza *et al.* (2023a) found microplastics along the entire length of a river in the city of Manaus, except at the spring, in addition to a variety of chemical compounds in these materials. The analysis of microplastic density in different location characteristics (mouth, intermediate, spring, standing water, river and marsh) revealed a differentiated landscape of pollution distribution (Figure 4). This complexity suggests that microplastic accumulation is influenced by a combination of hydrological, geographic and anthropogenic factors, with certain locational characteristics acting as hotspots for microplastic deposition (Liu *et al.*, 2019), which generates a series of factors hostile to flora and fauna, especially organisms (Caixeta *et al.*, 2018).

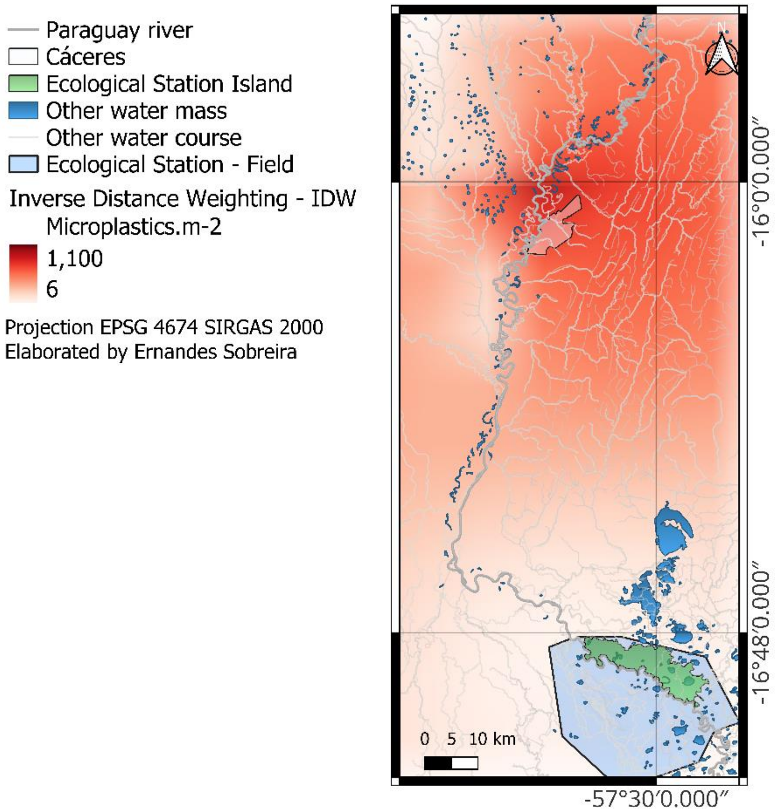

Figure 4. Density of microplastics based on the Inverse Distance Weighting in the study area. Red zones indicate higher density of microplastics.

A binary logistic regression was performed to assess whether the distance from the urban center of Cáceres predicts the presence of microplastics. The model achieved an overall accuracy of 73.8% and showed strong performance in identifying both presence and absence cases. Additionally, a Mann-Whitney U test revealed a statistically significant difference in microplastic concentrations between sites located ≤50 km and those >50 km from the city ($U = 332.0$, $p = 0.0007$). These results support the hypothesis that proximity to urban areas is a key factor influencing microplastic contamination in freshwater environments.

A binary logistic regression was conducted to model the probability of microplastic presence as a function of distance from the urban center of Cáceres (in kilometers). The model revealed a negative and statistically meaningful coefficient for distance ($\beta = -0.029$), suggesting that for every additional kilometer away from the city, the odds of detecting microplastics decrease by approximately 2.9% (Figure 5). The odds ratio for distance was 0.971, indicating that each kilometer increase in distance from the urban center reduces the likelihood of finding microplastics by about 3%, holding all else constant. The 95% confidence interval for the coefficient ranged from -0.048 to -0.011, reinforcing the robustness of this negative association.

The variability in microplastic density across different locations and location characteristics suggests a complex interplay of factors influencing microplastic distribution, such as proximity to urban areas, the nature of water flow and accumulation areas, and human activities. Locations with certain characteristics, potentially indicative of lower flow rates or higher human activity, may be more prone to accumulating microplastics (Farooq *et al.*, 2023; Wang *et al.*, 2019). Identifying these characteristics can help target cleanup efforts and preventive measures. Understanding the specific conditions that contribute to higher densities of microplastics is important for developing effective mitigation strategies (Talbot and Chang, 2021). Further research could explore the relationship between microplastic densities and additional environmental or anthropogenic factors. The identification and quantification of microplastics may require a determination of the degree of their manipulation in the environment, as they help to explain their toxicity, transport mechanisms, leaching capacity within rivers and lakes, their absorption of microplastics and, consequently, the level of contamination to which living beings are exposed (Montagner *et al.*, 2021).

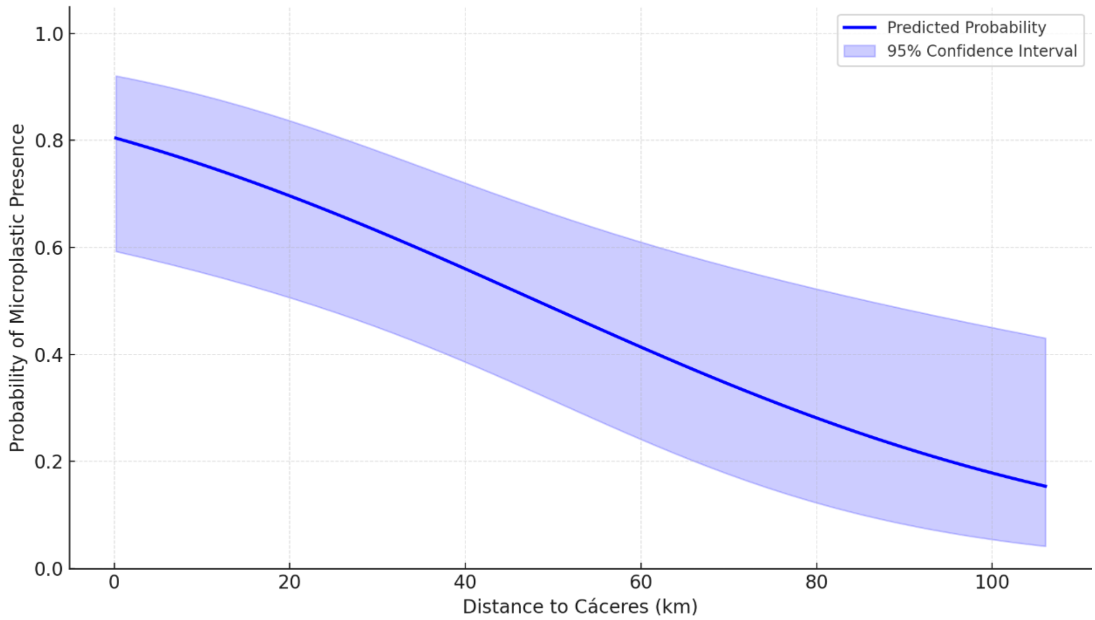

Figure 5. Predicted probability of microplastic presence as a function of distance from the urban center of Cáceres. The model shows a decreasing probability of detecting microplastics with increasing distance from the city, with a 95% confidence interval.

In aquatic environments, microplastics can directly affect biodiversity, as seen in cases of contamination in birds, fish, mussels, and other aquatic organisms, in addition to the water, sediments and sand contamination (Olivatto *et al.*, 2018; Nazário *et al.*, 2021). With this scenario, microplastics can bioaccumulate in different organisms and, depending on their distribution throughout the trophic level, contaminate fauna through the food chain and humans (Bugatti *et al.*, 2023; Silva *et al*, 2023). The effects caused by contamination are still the subject of studies by research groups around the world, whether due to the physical effect, they cause on the body, or the ability to become a vector for transporting other contaminants associated with them (Olivatto *et al*, 2018).

In a previous study conducted in the same region, Batista *et al.* (2022) identified the presence of microplastics within aquatic macroinvertebrate communities, while Viana *et al.* (2023) reported microplastic particles inside freshwater crabs. This information highlights the pressing need for urban planning and infrastructure development to include environmental protection measures. The dominance of urban environments in the production of microparticles requires effective waste management solutions with efficient public awareness to avoid any possible sources of pollution in the future.

Microplastics found in no-urban areas, such as conservation sites like the Taiamã Ecological Station, suggest a saturation in terms of the potential for contamination by these particles. In our study, urban streams flow into the Paraguay River, which runs through the ecological station approximately 100 km straight away from the urban center. The more neglected urban waters are, the greater the contamination in more distant places, even if they are protected areas. Considering that the Pantanal is an important region with rich biodiversity, the presence of microplastics, primarily from streams and rivers in urban areas, is concerning.

4. CONCLUSION

These findings highlight the importance of tailored monitoring and cleanup efforts that consider site-specific characteristics to effectively address microplastic pollution. While this study provided valuable information, future research should explore longitudinal trends in microplastic pollution and its ecological impacts in more detail. Furthermore, investigating the effectiveness of various mitigation strategies in real-world scenarios would provide practical guidance for policymakers and environmental managers. Other studies could also examine the role of atmospheric deposition in the distribution of microplastics, particularly in rural areas. This study can help the municipality of Cáceres, and other Pantanal cities, providing data to improve local solid waste management systems and, consequently, reduce the entry of these pollutants into the Paraguay River and its tributaries.

The clear linkage between urbanization and microplastic pollution identified in this study emphasizes the critical role of policy and regulatory frameworks in addressing this issue. Urban areas, in particular, require targeted interventions to reduce plastic consumption and improve waste management practices. Furthermore, the establishment of buffer zones around urban areas, enhanced street cleaning, and the installation of catchment devices in storm drains could significantly reduce microplastic pollution. Policies promoting plastic recycling and the development of biodegradable alternatives could also play a vital role in reducing microplastic sources.

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