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First assessment of microplastic and artificial microfiber contamination in surface waters of the Amazon Continental Shelf

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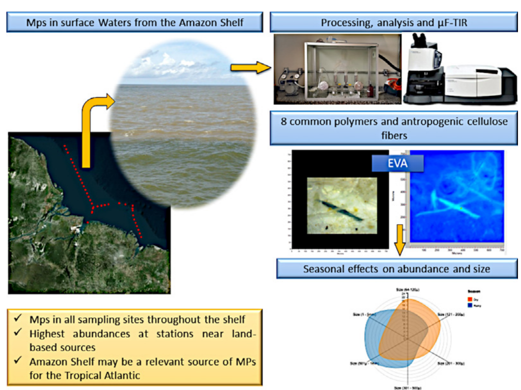
HIGHLIGHTS

- First evaluation of microplastics in Amazon Continental Shelf surface waters.
- Abundance was 4772 ± 2761 (rainy season) and 2672 ± 1167 items.m^{-3} (dry season).
- Highest abundances were recorded at stations near land-based sources.
- Cellulose fibers, polyamides, and polyurethane were the most frequent polymers.
- The Amazon Shelf may be a source of MPs for the Tropical Atlantic.

GRAPHICAL ABSTRACT



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ABSTRACT

The composition and distribution of microplastics (MPs) in the Brazilian Amazon Continental Shelf surface waters are described for the first time. The study was conducted during the 2018 rainy and dry seasons, using 57 water samples collected with aluminum buckets and filtered through a 64-μm mesh. The samples were vacuum-filtered in a still-air box, and the content of each filter was measured, counted, and classified. A total of 12,288 floating MPs were retrieved; particles were present at all 57 sampling points. The mean MP abundance was 3593 ± 2264 items·m^{-3}, with significantly higher values during the rainy season (1500 to 12,967; 4772 ± 2761 items·m^{-3}) than in the dry season (323 to 5733; 2672 ± 1167 items·m^{-3}). Polyamides (PA), polyurethane (PU), and acrylonitrile butadiene styrene (ABS) were the most common polymers identified through Fourier Transform Infrared Spectroscopy (FTIR) analysis. Cellulose-based textile fibers were also abundant (~40%). Our results indicate that the Amazon Continental Shelf is contaminated with moderate to high levels of MPs; the highest abundances were recorded at stations near land-based sources such as river mouths and large coastal cities.

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1. Introduction

Plastics are synthetic compounds with several advantages such as durability, flexibility, corrosion resistance, and low production cost, used in a myriad of products and applications (Hale et al., 2020; Shen et al., 2020). High plastics production coupled with inappropriate disposal have led to deposition and contamination of coastal areas (Cesar-Ribeiro et al., 2017) and even uninhabited environments such as areas of the Antarctic, Barents Sea, and the Siberian Arctic (Pakhomova et al., 2022), eventually resulting in widespread distribution of plastic particles (Hale et al., 2020).

Once discarded, plastics are slowly degraded and fragmented by physical, chemical, and biological processes (Barnes et al., 2009). The smaller particles, the microplastics (MPs, 1–5000 μm; GESAMP, 2019), which also includes particles produced in micrometric sizes such as nurdles, beads, and pellets, are already widely dispersed in the oceans (Jiang, 2018). Micro- and nanoplastics are transported over long distances by surface currents and winds, reaching the most remote marine ecosystems and the North and South poles (Pakhomova et al., 2022).

MPs are easily dispersed in the water column, where denser plastic polymers reach the bottom and may be accidentally assimilated or ingested by the benthic fauna (Courtene-Jones et al., 2017). Alternatively, low-density MPs in the water column may be ingested by zooplankton and nekton (Botterell et al., 2019). As a result, MPs have been found in many different compartments of the food chain (Cole et al., 2015; Setälä et al., 2016; Morais et al., 2020; Macieira et al., 2021). These organisms may be exposed to harmful chemical compounds associated with MPs, such as plastic additives, flame retardants, plasticizers, and dyes (Gallo et al., 2018; Pinheiro et al., 2020). Hence, MPs are recognized as potentially hazardous contaminants with global distribution, due to their wide dispersion and potential toxicity (UNEP, 2014).

Knowledge of plastic debris and MPs in the southern hemisphere is limited compared to the northern oceans (Cózar et al., 2014; Enders et al., 2015), and in-situ data for the South Atlantic and the western Tropical Atlantic are scarce (e.g., Ivar do Sul et al., 2014; Silvestrova and Stepanova, 2021; Zhao et al., 2022) or even absent for areas such as the Amazon shelf. In addition, a review of literature from 2010 to 2020 found that 85% of published studies on MPs for the South Atlantic are recent, released from 2015 to 2020, and only 16% (nearly 20 publications) investigated marine and estuarine waters (Campos da Rocha et al., 2021). Baseline data on debris abundances are thus necessary for modeling the risks associated with MPs, which are currently unknown for the Amazon shelf (Everaert et al., 2020), an important area for traditional coastal communities and for Brazilian artisanal and industrial fisheries (Isaac and Ferrari, 2017).

The Amazon Continental Shelf (ACS) is a highly dynamic environment, characterized by interchange among several physical forces, such as tidal currents, estuarine plumes, and the North Brazil Current (NBC), which produces unique oceanographic characteristics (Prestes et al., 2018). This region is distinctive in the entire South Atlantic due to the magnitude of river discharge from the Amazon basin, which functions as a dispersal system, releasing enormous volumes of water and sediments (Nittrouer et al., 2021), along with plastics, into the marine environment. The Amazon River basin is considered the seventh (Lebreton et al., 2017) or even the second (Giarrizzo et al., 2019) most polluted watershed in the world, regarding plastic emissions into the ocean. Knowledge of the composition, abundance, and distribution of MPs in the ACS and the Amazon River plume is thus urgent to determine the levels of contamination of this environment, which may act as a sink of MPs from the river basin, as well as a source for adjacent areas such as the wider Caribbean region.

Here, we investigated for the first time the presence, abundance, distribution, and composition of MPs in surface waters of the ACS. The variation of MPs among the sampling points was investigated; our hypothesis was that higher abundances would be detected at stations located near the coast and large urban centers. We also tested if seasonality was an important factor for variability, since freshwater discharge from the watersheds during the rainy season is much larger than during the dry season (Nittrouer et al., 2021) and would transport larger amounts of MPs.

2. Materials and methods

2.1. Sample collection

The samples were obtained during two oceanographic cruises: one in March (rainy season, at 25 points) and the other in October (dry season, at 32 points) of 2018, totaling 57 samples. The sampling points were distributed over the Brazilian ACS, from the states of Maranhão to Amapá (Fig. 1). The large river basins such as the Amazon and Tocantins-Araguaia as well as São Marcos Bay provide enormous inputs of fresh water and sediment to the shelf (Nittrouer et al., 2021). Half of the stations were located inside the Amazon River plume during the rainy season, with salinity levels below 34 (e.g., Molleri et al., 2010), while salinity was below 33 at only a single station during the dry season. Additional information on sampling station coordinates, sampling dates, and environmental variables (temperature, salinity, and total dissolved solids) is provided as supplementary material (Table S1).

Surface water samples were collected with the aid of a 20-L aluminum bucket. At each sampling point, 60 L of surface water was collected and filtered on board through a 64-μm mesh plankton net, which was washed between each sampling point. The retained material was immediately transferred to clean, labeled bottles with pre-filtered formaldehyde added in a 2% final concentration, and kept in a dark room until laboratory analysis.

2.2. Microplastic extraction and contamination control

The use of white cotton laboratory coats was standard, in addition to constant cleaning of materials and benches with reverse-osmosis water before and after use (Corcoran et al., 2020). Plastic materials in the laboratory were replaced by glass, aluminum, and paper whenever possible, to avoid contact with plastic fragments during manipulation of the samples.

To monitor possible contamination sources such as airborne fibers during laboratory procedures, the samples were prepared and filtered in a glass still-air box coupled to a vacuum pump. Blank controls were performed for the filtration steps, as well as for the sample bottles and the reverse-osmosis water (Provencher et al., 2020; Prata et al., 2021). The laboratory procedures and blank controls: i) glass bottle and reverse osmosis water, ii) still-air box (filtration steps), and iii) filtered formaldehyde included filtration of three replicates of 1 L of solution for each control treatment and converted to items.m^{-3}.

After filtration, the pre-calcinated GF/F filters (Whatman, 0.47 μm) were examined under a stereoscopic microscope (Olympus, model CX41). All potential plastic particles were classified, photographed, counted, and measured based on GESAMP (2019) and Shim et al. (2017). The potential MPs were selected by color (e.g., homogeneously colored fibers with colors not ascribable to natural compounds, such as blue, orange, yellow, red, or homogeneous black, or transparent, bright coloration), and shape (distinctive fiber shape with no irregular borders or mixed aggregates, fibers equally thick throughout their length, absence of cellular structures).

2.3. 2D imaging-Fourier transform infrared spectroscopy (FTIR)

Of the 57 filtered samples, 10 (five from each season) were randomly chosen and analyzed by 2D imaging FTIR, using a Cary 620–670 FTIR microscope equipped with an FPA (Focal Plane Array) 128 × 128 detector (Agilent Technologies) and a 15× Cassegrain objective. FPA detectors are widely accepted primary choices for the identification of MPs, as they allow spatial resolution in the micron range, allowing direct analysis of MPs on the filters without pre-treatments, even in the presence of mixed organic-inorganic matrices, such as deposits around the MPs or composite materials (Harrison et al., 2012; Mintenig et al., 2017; Andrades et al., 2018; Casini et al., 2021; Cincinelli et al., 2021). The analysis was carried out in reflectance mode, with an open aperture and a spectral resolution of 8 cm^{-1}, acquiring 128 scans for each spectrum. Each analysis run delivers a "tile", i.e., a map 700 × 700 μm^2 (128 × 128 pixels), where each

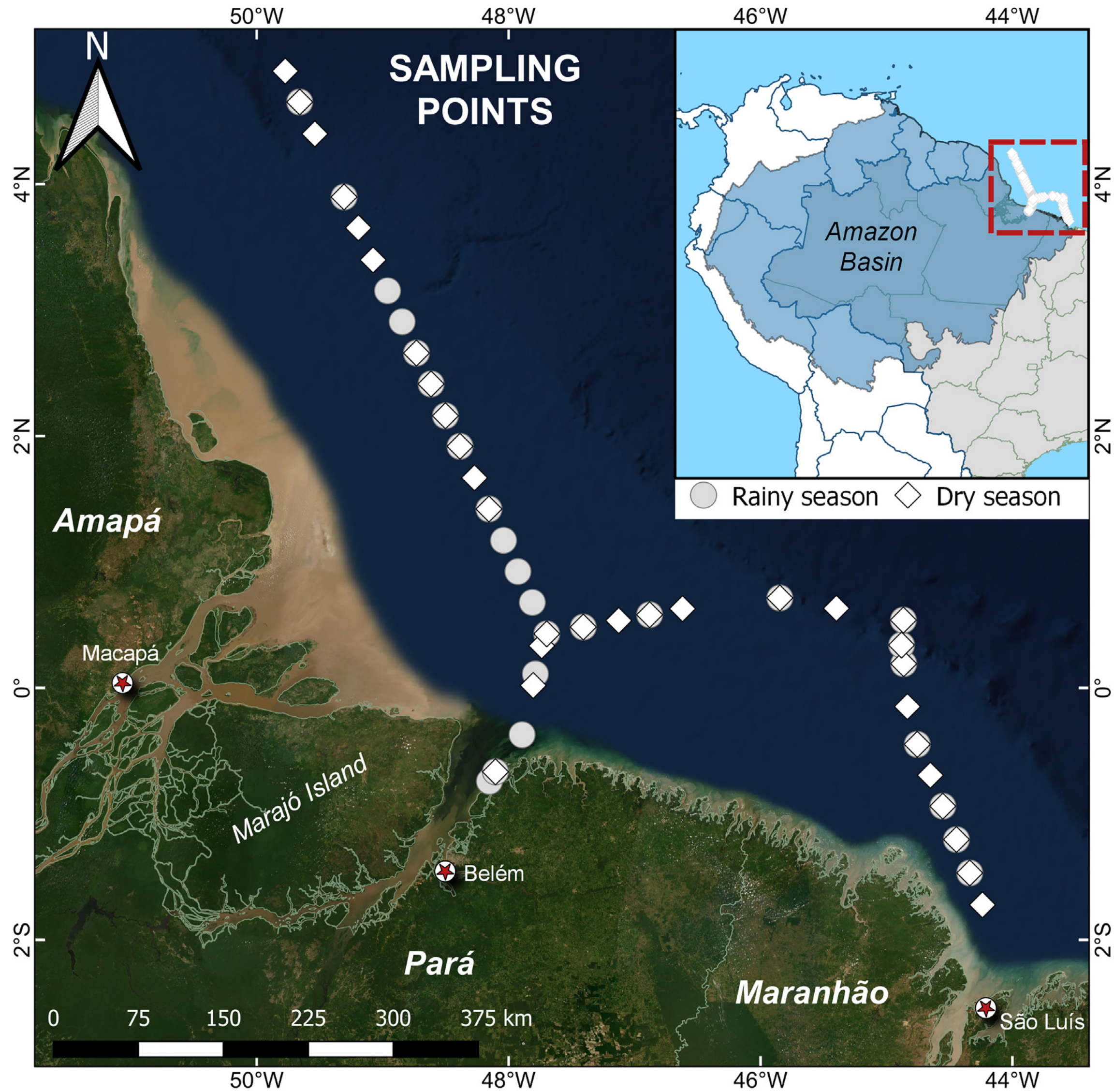

Fig. 1. Sampling points on the Brazilian Amazon Continental Shelf (ACS) during the rainy (March) and dry (October) seasons in 2018. Circles: rainy season; diamonds: dry season.

pixel has a size of 5.5 × 5.5 μm^2 and provides an independent spectrum. The detection limit of the FPA detector is ca. 0.02 pg.μm^{-2} (Mastrangelo et al., 2020). For each filter, ten tiles were acquired at different representative filter locations, analyzing micro-fragments and fibers. All the fragments/fibers were identified by comparison of their IR spectra with published standards for plastic and cellulose polymers (Garside and Wyeth, 2003; Jung et al., 2018).

Since all analyzed fibers were considered of anthropogenic origin (cellulose and mixed cellulose and *co*-polymers), they were included in the results, together with the MPs (Cincinelli et al., 2021).

2.4. Statistical analysis

The abundance of MPs and fibers at each sampling point was estimated by the number of particles recorded in each sample, divided by the volume of filtered water (60 L), converted to items.m^{-3}, and excluding the mean number of potential contaminants from the three replicas of each blank controls. The results from the control procedures showed limited contamination from laboratory steps since most blank control values were zero (Table S2 in supplementary material).

The data for each variable/parameter were tested for normality and equal variance by Shapiro-Wilk and Levene tests, respectively, to select the appropriate statistical tests (Zar, 1996). Due to the non-parametric nature of the variables, the Spearman's correlation analysis was chosen to test the relationship between environmental variables (temperature, salinity, and total dissolved solids) and the abundance of total MPs (plastics and cellulose fibers), synthetic MPs (excluding cellulose fibers), and cellulose fibers (Table S3).

To test possible differences in the abundance of the different types of MPs between the rainy and dry seasons, we opted for the Mann-Whitney test, since MP abundance was a non-parametric variable. The *p*-values were obtained for each variance test, considering the degrees of freedom and $\alpha = 0.05$ (Zar, 1996). Microsoft Office Excel and R software (R Core Team, 2021) were used to perform the statistical and spatial analyses.

3. Results and discussion

3.1. Microplastic abundance

A total of 57 surface-water samples, collected on two different research cruises (dry and rainy seasons), retrieved 12,288 MPs and cellulose fibers. A total of 7158 particles were identified during the rainy season, while 5130 were identified in the dry season. The particle abundance during the rainy season ranged from 1500 to 12,967 (4772 ± 2761) items.m^{-3}, and during the dry season the range was 1323 to 5733 (2672 ± 1167) items.m^{-3} (Fig. 2).

During the rainy season, MPs abundance was 1.8 times higher than the dry season, and the abundance and proportion of fibers (58%) was also higher, compared to the dry season (39%). Fragments were more common during the dry season; however, the abundances were similar between the seasons (Fig. 3).

The abundances of MPs estimated in this study are above those found on the shelf of northeastern Brazil (Lima et al., 2014, 2016; Garcia et al., 2020) and in adjacent areas such as the Gulf of Mexico (Di Mauro et al., 2017), the Gulf of Maine (Lindeque et al., 2020), or remote areas of the Atlantic (Silvestrova and Stepanova, 2021; Zhao et al., 2022) (Table 1). However, our values are moderate compared to levels reported in Shanghai estuaries, in the Pacific (27,840 ± 11,810 items.m^{-3}; Zhang et al., 2019); South Carolina estuaries, in the North Atlantic (30,800 ± 12,100 items.m^{-3}; Gray et al., 2018); Alexander Bay, eastern South Atlantic (19,500 ± 13,500 items.m^{-3}; Weideman et al., 2020); and Blanca Bay, Argentina (5900–782,000 items.m^{-3}; Fernández Severini et al., 2019).

Our relatively high values may be explained by the use of a 64-μm mesh, while most studies on MP sampling in marine waters still use mesh sizes above 120 μm. Here, almost half of the identified particles (47%) were smaller than 300 μm (the most common mesh size in marine MP studies), and large mesh sizes would underestimate the real abundances by nearly half our values. In an example of underestimation, the number of MPs

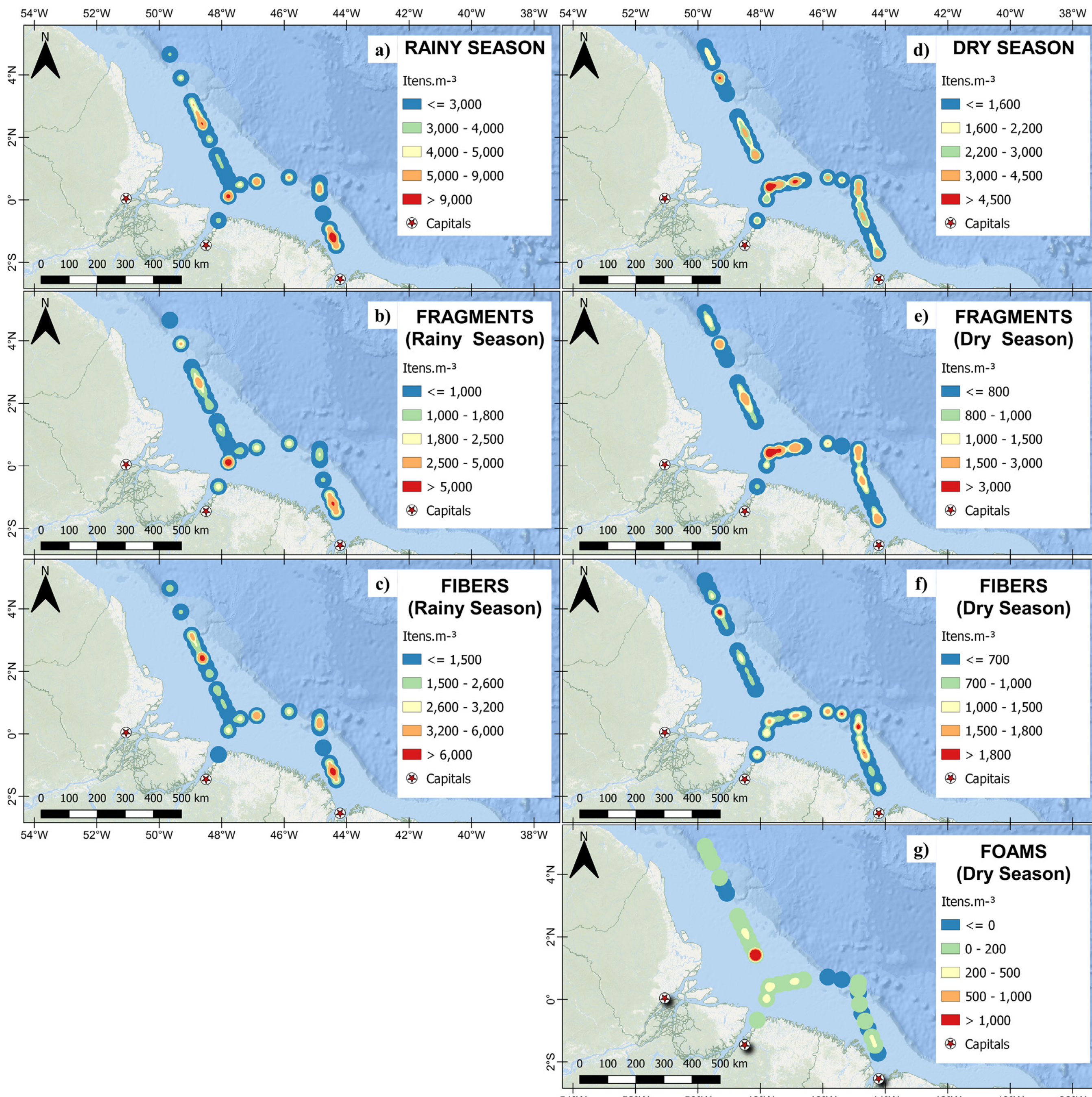

Fig. 2. Distribution of the abundance of total microparticles and categories of MPs (items.m^{-3}) on the Brazilian Amazon Continental Shelf (ACS) during the rainy (March) and dry (October) seasons in 2018. A: Total (rainy season); B: fragments (rainy season); C: fibers (rainy season); D: total (dry season); E: fragments (dry season); F: fiber (dry season); and G: foam (dry season).

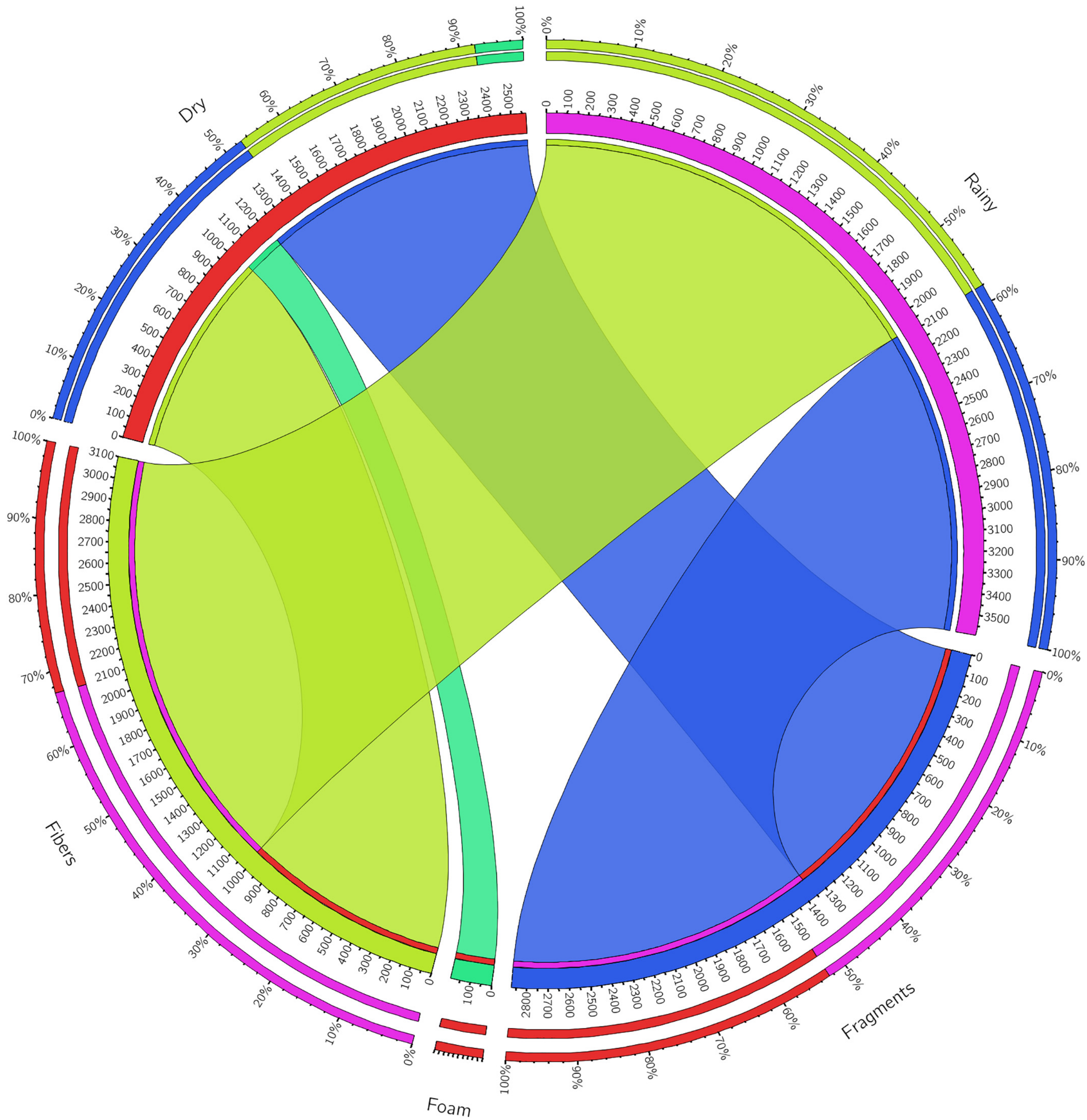

Fig. 3. Chord diagram showing the absolute and relative contributions of the different microplastic categories between the rainy and the dry season, from surface water samples collected at the Amazon Continental Shelf.

retained in a 120-μm mesh net was up to seven times the number obtained by larger nets, such as the 300-μm mesh (Garcia et al., 2020), further explaining our results.

3.2. Microplastic type, color, and size

Fibers and fragments were found in all samples, in different proportions in each season. Fibers were dominant during the rainy season (4138 units, 58% of the total), while fragments (2718 units, 53%) were dominant in the dry season. Foam particles were recorded in 75% of the dry-season samples, corresponding to 8% of the total MPs (388 units), and were absent during the rainy season.

Plastic fragments and fibers have been reported in the digestive tract of fish (Pegado et al., 2018, 2021) and sea anemones (Morais et al., 2020) from the Amazon coast, and in environmental samples from beach and river sediments (Martinelli Filho and Monteiro, 2019: Gerolin et al., 2020). These observations may be linked to the moderate to high amounts of MPs and fibers in the seawater found here, since the shelf water may be a source of particles for the adjacent coastal zone (Martinelli Filho and Monteiro, 2019).

Table 1
Abundance of microparticles collected in marine surface waters at different locations in the western Atlantic Ocean and coastal areas (temperate and equatorial areas), depicting the mesh size used, sampling method, and size range of the MPs in each study. *: estimated, modelled data, in units.km^{-2}.

Author	Region	Method	Mesh (μm)	Abundance (itens.m^{-3})	Size (μm)
Lima et al., 2014	Goiana River estuary (Brazil)	Net trawl	300	0.26 (mean)	2230 ± 1650
Castro et al., 2016	Jurujuba Cove (Brazil)	Net trawl	150	16.4 (mean)	1000–5000
Di Mauro et al., 2017	Gulf of Mexico (Mexico)	Net trawl	335	11.1 ± 2.8	350–5000
Figueiredo and Vianna, 2018	Guanabara Bay (Brazil)	Net trawl	64; 200	1.3; 4.8 (mean)	100–5000
Gray et al., 2018	Charleston Harbor and Winyah bay, South Carolina (USA)	Surface microlayer Apparatus	63; 150; 500	6600 ± 1300 (Charleston); 30,800 ± 12,100 (Winyah)	> 63
Olivatto et al., 2019	Guanabara Bay (Brazil)	Net trawl	300	7.1 ± 7.3	1000–5000
Fernández Severini et al., 2019	Blanca Bay (Argentina)	Water bottle; net trawl	60	42.6–113.6; 5900–782,000	170–5000
Garcia et al., 2020	Equatorial Atlantic	Net trawl	120; 300	0.14 ± 0.11; 0.02 ± 0.01	120–5000
Lindeque et al., 2020	Gulf of Maine (USA)	Net trawl	100; 333; 500	6.03 ± 1.03	> 50
Eriksen et al., 2014*	South Atlantic	Net trawl	330	66,400*	330–4750
Garcés-Ordóñez et al., 2021	Colombian Caribbean and Pacific	Net trawl	500	0.01–8.96	500–5000
Lima et al., 2016	Saint Peter/ Saint Paul Archipelago	Net trawl	300	~ 1.10^{-4}	300–5000
Silvestrova and Stepanova, 2021	Atlantic Ocean	Manta trawls; flow pump system	500; 200	0–0.12; 0–5.46	200–32,000
Zhao et al., 2022	South Atlantic Subtropical Gyre	WTS-LV Pumps; MultiNet; Manta net	2; 200; 500	0–244.3; 0–0.11; 0.4–3	2–5000
Our study	Brazilian Amazon inner shelf	Aluminum bucket	64	3593 ± 2264	64–5000

Visual inspection identified 12 distinct colors for MPs. The most common colors were blue (28%), transparent (25%), and yellow (16%). Blue stood out among the fragments, with 2445 of the identified particles (44%). Of the fibers, the transparent ones were dominant, with 2582 units (54%), while white was prevalent for the foams, with 320 (more than 80%) of the total (Fig. 4). Seasonal differences were observed: transparent and black fibers were more common during the rainy season, while blue and transparent fibers were dominant during the dry season.

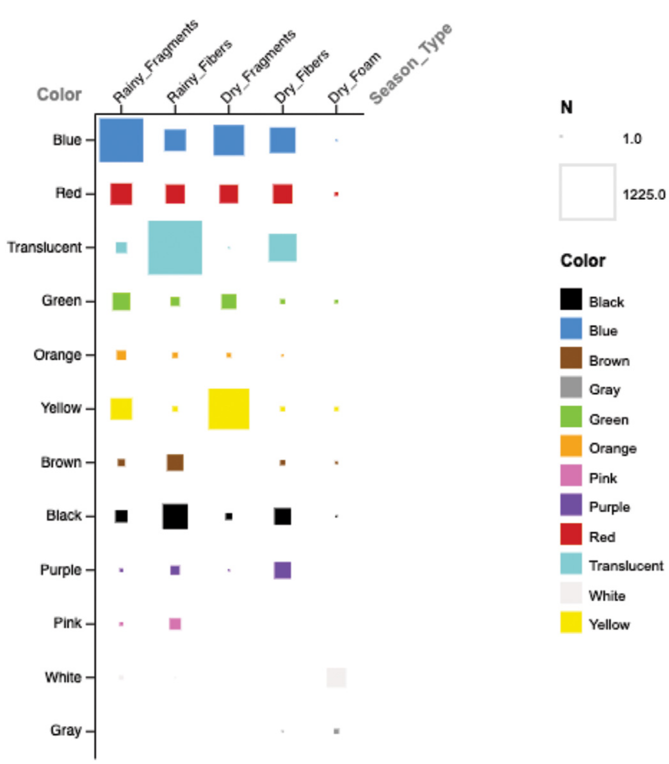

Fig. 4. Color classification for each type of microparticle during the dry and rainy seasons of 2018 on the Brazilian Amazon Continental Shelf. Size of squares corresponds to abundance of each category.

Blue fragments were the most abundant during the rainy season, while yellow ones were prevalent in the dry season.

The size-class distribution revealed that 61% of the particles were less than 500 μm long, 47% below 300 μm, and 19% less than 120 μm. A considerable proportion of the fragments (83 and 80% during the rainy and dry seasons, respectively), as well as the foams (86%) were shorter than 300 μm, while the reverse occurred in both periods for the fibers, with 88% and 91% being longer than 300 μm in the rainy and dry seasons, respectively (Fig.5).

Larger MPs (more than 300 μm long) were more abundant during the rainy season, while the proportion of shorter particles (64–300 μm) was higher in the dry season (Fig. 5). The higher abundance of MPs, together with their larger sizes during the rainy season, probably indicates a larger continental input through river basins. Larger particles should sink faster, and would sink even faster during the rainy season due to the lower salinity of surface waters of the ACS (Molleri et al., 2010). However, the input during the rainy season may be high enough to compensate for the sinking rates of the particles, allied to the highly turbulent environment on the inner ACS (Molinas et al., 2020), delaying vertical transport. This inference is supported by the absence of significant correlations between salinity values and MP abundances (Table S3).

3.3. Polymer composition

The spatial resolution of the FPA detector at the micron scale (pixel size 5.5 × 5.5 μm^2) allows collecting a large number of independent spectra from the micro-fragments and fibers, e.g., more than 150 independent spectra can usually be collected from a fiber 1 mm long and 10 μm thick, acquiring a single "tile" image (700 × 700 μm^2). The spectra shown in Fig. 6 are representative of all the independent spectra acquired for each type of polymer microfiber/fragment.

The most common polymeric compounds, retrieved through the FTIR analysis, were polyamides, PA (22%); polyurethane, PU (11%); and acrylonitrile butadiene styrene, ABS (8%). Other polymers included ethylene polyethylene, PET (7%); ethylene–vinyl acetate, EVA (6%); and polyethylene, PE (3%). Vinyl polychloride polymers (PVC) and polypropylene (PP) each comprised only 1% of the total MPs recorded. FTIR also revealed that approximately 40% of the particles (8580) initially identified as potential MPs were made of cellulose-based textile fibers.

The following diagnostic bands were used to identify the polymers from their FTIR spectra: PA, absorptions in the 3400–3300 cm^{-1} region (N—H

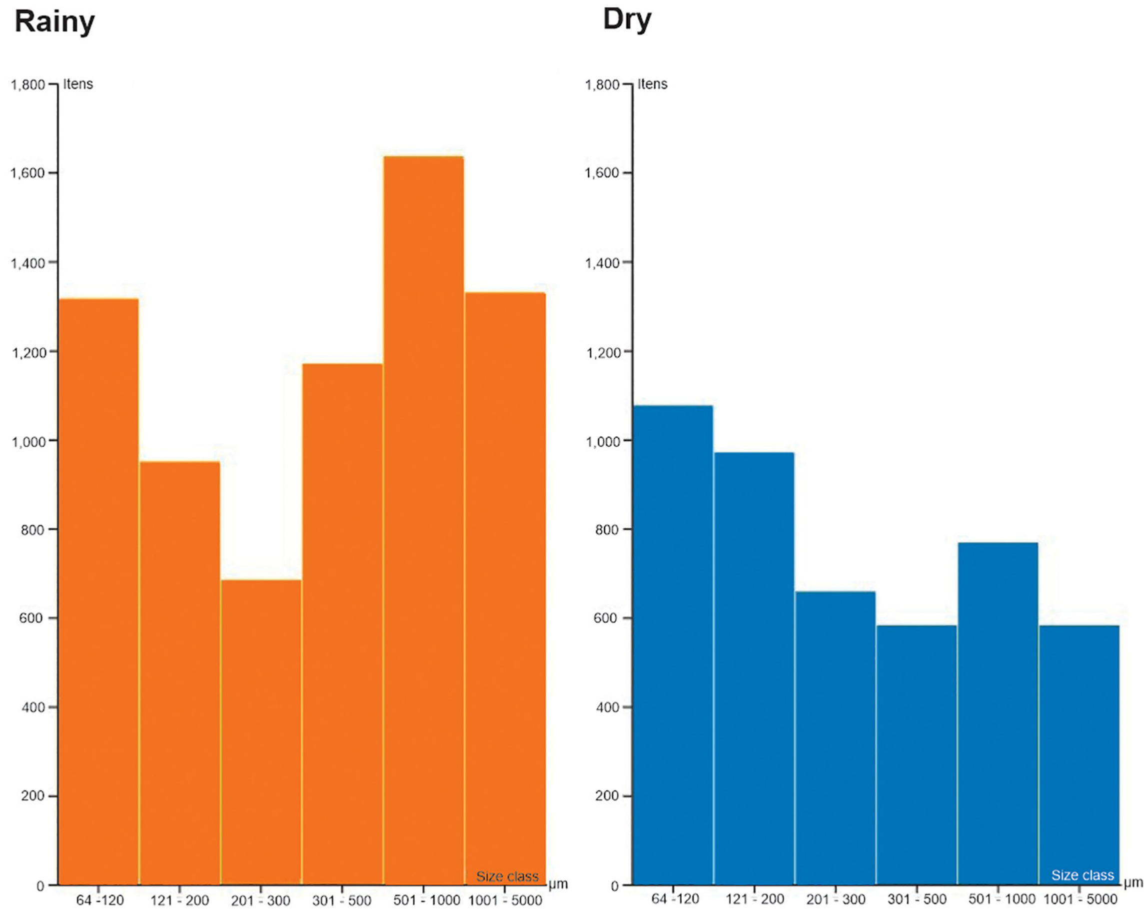

Fig. 5. Size-class distribution of microparticles in the dry and rainy seasons on the Brazilian Amazon Continental Shelf during 2018.

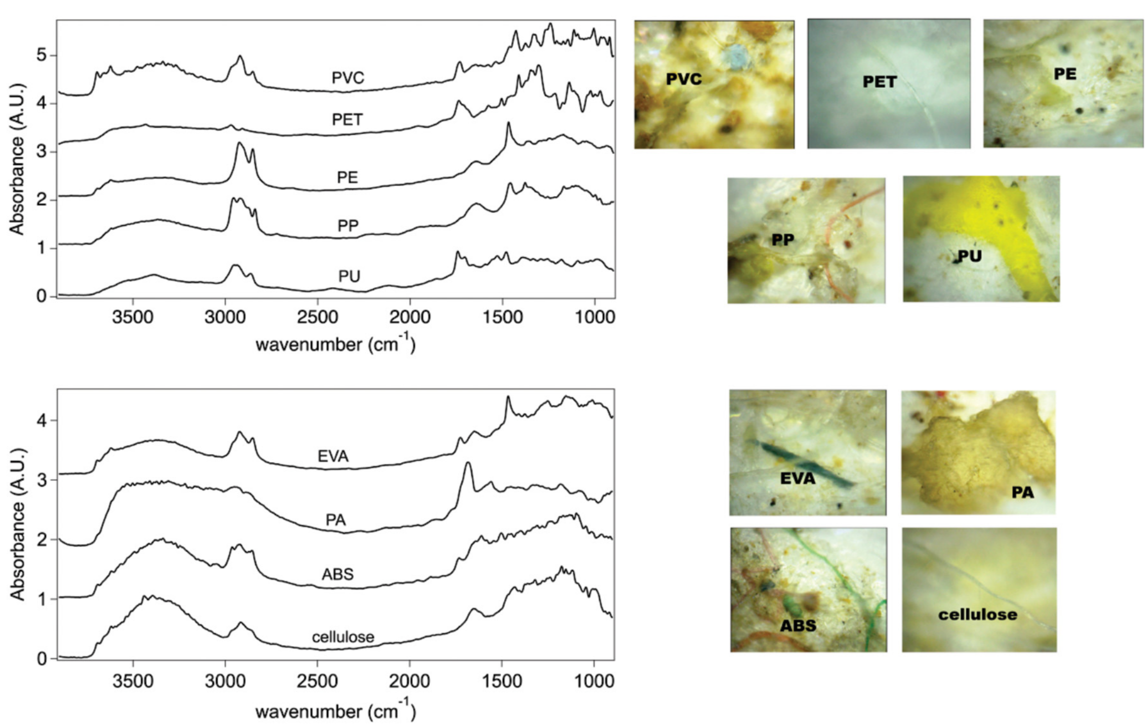

Fig. 6. FTIR Reflectance spectra (left panels) and visible-light images (right panels) of microfibers and fragments of plastics and cellulose polymers: PVC (transparent whitish fiber-fragment), PET (transparent fiber), PE (yellowish fragment), PP (central transparent fragment), PU (yellow fragment), EVA (blue fiber), PA (yellowish fragment), ABS (central green fragment), cellulose (transparent fiber). Spectra were assigned according to Garside and Wyeth (2003) and Jung et al. (2018).

stretch), 3000–2800 (C—H and CH_2 stretch), 1650 (amide I), 1570 (C(O)-N-H bend, C—N stretch), ~1450 cm^{-1} (CH_2 bend); PU, peaks at ~1730 (C═O stretch), 1530 (C—N stretch), 1450 (CH_2 bend) and 1225 cm^{-1} (C(=O)O); ABS, bands around 3000 and 3000–2900 (aromatic and aliphatic CH stretch), 1605 and 1490 (aromatic ring stretch), and 1450 cm^{-1}; PET, bands at 3000–2860 cm^{-1} (aromatic and aliphatic CH stretch region), 1730 cm^{-1} (C═O stretch), ~1577 and 1510 cm^{-1} (aromatic C═C stretch), 1410 (aromatic skeleton stretch) and ~ 1100 cm^{-1} (C—O stretch); EVA, bands at 2917 and 2948 (CH stretch), 1740 (C═O stretch), and 1469 cm^{-1} (CH_2 and CH_3 bend); PE, absorption peaks at 2920 and 2850 cm^{-1} (CH stretch region), and ~ 1465 (δ CH_2) cm^{-1}; PVC, bands at 1427 (CH_2 bend), 1330 (CH bend), 1255 (CH bend), and 1099 cm^{-1} (C—C stretch); PP, absorption peaks at 2950, 2915, and 2856 cm^{-1} (CH stretch region), at 1458 (CH_2 bend), 1373 (CH_3 bend), and 1161 cm^{-1} (CH bend, CH_3 rock, CC stretch); cellulose, intense bands at 3500–3100 (O—H stretch, hydroxyl groups of anhydroglucose unit), 3000–2900 (stretch of methyl and methylene C—H bonds), 1635 (OH bend of adsorbed water), and 1160–1060 cm^{-1} (C—O stretch). The full spectral profile of each polymer was compared to its published reference to confirm the assignment.

The Mann-Whitney test indicated significant differences in the polymer abundances, with higher levels observed during the rainy season for all the polymers, except only for PP and PVC, which occurred exclusively during the dry and rainy season, respectively (Table S4). PP relative density is 0.9–0.92, and PVC is 1.16–1.3, while the mean seawater density is 1.03. Considering the low salinities during the rainy season, the opposite pattern was expected, where higher-density polymers would be more frequent during the dry season, when seawater salinity is higher.

PET has an even higher relative density (1.34–1.39), and was the heaviest polymer identified in this study (Table S5). Since PET was more abundant during the rainy season, while the light PP was detected only during the dry period, the relative density alone cannot explain these differences in polymer distribution between the seasons.

The polymers PA and PE were also recorded in the other three studies in the Amazon region that performed FTIR analysis (Pegado et al., 2018; Morais et al., 2020; Pegado et al., 2021), all related to the ingestion of MPs by fish and a sea anemone. These authors attributed the presence of PA mainly to decomposition of fishing gear, since artisanal fishing is a main economic activity in the area, and we suggest that the high abundance of PA in surface seawater from our study is from the same source.

PE is one of the most common polymers found in coastal surface waters (Garcés-Ordóñez et al., 2021) and is widely used in packaging and storage containers (Geyer et al., 2017). The low relative density and possibly high environmental abundance may explain the recurrent records of PE on the Amazon coast and shelf (Pegado et al., 2018; Morais et al., 2020; Pegado et al., 2021). PET, PP, and ABS were also detected by Morais et al. (2020) and Pegado et al. (2021). Here, PET and ABS were also common polymers in surface seawater, enabling accidental ingestion by the local fauna.

While foams were absent from all 25 of the rainy season samples, they were present in 24 of 32 samples in the dry season. We believe the foam is distributed mainly by surface wind dynamics. The southerly winds during the dry season (Geyer et al., 1996) may transport these particles farther from the coast, reaching the sampling sites. In addition, foams always showed lower abundances than fragments or fibers, with a mean of 202 items.m^{-3} (Fig. 3).

Regarding cellulose fibers, possible sources include textiles (cotton and rayon) and cigarette filters (rayon). Even though, in principle, cellulose fibers decompose at a faster rate than MPs (Singh et al., 2020), they can still pose environmental risks, as these fibers can contain toxic additives (e.g., phthalates and dyes) whose release can affect the biota (Zambrano et al., 2021).

3.4. Distribution of microplastics

The largest numbers of MPs in the ACS were observed at sampling points located near the coast. Points near São Marcos and Marajó bays, with large riverine discharges, had the highest values (12,967 and 5733 items.m^{-3} respectively). Additionally, MP abundance gradually decreased with increasing distance from the coast (Fig. 2).

This result is probably due to the discharge of large continental rivers and the proximity of populous coastal metropolises such as Belém, with more than 1500,000 inhabitants, and São Luís, with nearly 1,115,000 inhabitants (IBGE - Instituto Brasileiro de Geografia e Estatística, 2021). Thus, the distribution of MPs in this region suggests that river basins are potential sources of MPs for the marine environment (Andrady, 2011; Lebreton et al., 2017; Castro et al., 2018). The lack of basic sanitation in 90% of the Brazilian Amazon cities is an important argument for this hypothesis (ANA – Agência Nacional de Águas e Saneamento Básico, 2012a), since discharge of untreated sewage is considered one of the most important sources of MPs for aquatic systems (Sun et al., 2019: Zhang and Chen, 2020: Bertoldi et al., 2021).

The Amazon River is the largest in the world, with a freshwater discharge volume of about 206,000 $m^3.s^{-1}$ (Callède et al., 2010), and a drainage area of approximately 7106 km^2 (Sioli, 1984). Added to other large basins such as the Pará and Tocantins-Araguaia rivers, the Amazon alters the coastal and oceanic system by releasing enormous volumes of water, together with plastics (Giarrizzo et al., 2019). Both Marajó and São Marcos bays, aside from the lack of basic sanitation in most cities, are also affected by inadequate soil management for agriculture, ranching, and industry, releasing contaminated effluents to the river basins. Inadequate disposal of solid waste that enters the channels through rain runoff (ANA – Agência Nacional de Águas e Saneamento Básico, 2012b) also makes the region a potential source of MPs. These huge drainage areas, undergoing intense changes in land use (Pelicice et al., 2021), may further explain the high abundance of MPs on the ACS.

The distribution of MPs over the shelf was probably similar to the behavior of other types of suspended particulate matter transported by the NBC (de Morais et al., 2006). Hence, the region may play a key role in the dispersal of plastic particles over the ACS and their transport to neighboring countries and adjacent areas such as the wider Caribbean region.

The same seasonal pattern was observed by Lima et al. (2014, 2015) in the Goiana River estuary, where the abundance was lower during the dry season (713 items.m^{-3}) and increased during the rainy season (1900 items.m^{-3}). For the same estuary, the variation between periods from 133 (dry season) to 1400 items.m^{-3} (rainy season) was attributed to increased freshwater discharge, which provided more MPs from continental sources (Barletta et al., 2019). The higher abundances during the rainy season for the Brazilian coast are thus linked to a possible higher flux of continental and riverine MPs to the oceans (Meijer et al., 2021).

Complex, regional-scale oceanographic processes may play an important role on MPs distribution patterns in the area. The Amazon River plume may reach more than a thousand kilometers from the river mouth, as detected by salinities between 32 and 35 (Hu et al., 2004). The plume is more restricted to the inner Amazon shelf during the rainy season, but, during the transition from the rainy to the dry season (April to July), the plume extends toward the western Tropical Atlantic, reaching the southern part of the wider Caribbean region. The plume may reach its largest extent during the dry season (August to December), to the central Equatorial Atlantic (Molleri et al., 2010). The Amazon plume dispersion and intensity may be linked to the higher MP abundance at sampling stations located mainly off Amapá state from March to June, but also off Pará and Maranhão from June to October (Molleri et al., 2010) (Figs. 1 and 2). However, a more appropriate sampling design is required to confirm the role of the Amazon River plume in the distribution of MPs.

All the polymers recorded here are widely used in urban areas. Since basic sanitation services are available for less than 8% of the population in the coastal states of the Brazilian Amazon, the lack of water-distribution systems, sewage-collection networks, solid-waste management, rainwater management, or sewage treatment (ANA – Agência Nacional de Águas e Saneamento Básico, 2020) make the urbanized coast a potential source of MPs from rivers to the ocean. Nevertheless, other important sources such as marine MPs should be investigated as additional sources of particles to the ACS.

4. Conclusions

This study is the first evaluation of contamination by MPs and anthropogenic cellulose fibers in surface waters on the Amazon continental shelf. The relatively high abundances of MPs and fibers were attributed to the proximity of large Amazonian coastal cities and to the discharge from the enormous continental river basins. The contribution of river basins as potential sources of MPs and fibers to the marine environment is highlighted. The study also emphasized the influence of seasonality on the abundance of MPs, as well as the importance of mesh size to estimate their abundance more precisely in aquatic environments.

CRediT authorship contribution statement

Arnaldo Queiroz: Methodology, Formal Analysis, Investigation, Data Curation, Writing – original draft, Visualization. **Amanda Saraiva**: Data Curation, Investigation, Visualization, Methodology, Formal Analysis. **Marcelo Rollnic**: Project administration, Funding acquisition, Resources. **David Chelazzi**: Data Curation, Methodology, Formal Analysis, Writing – review and editing. **Alessandra Cincinelli**: Resources, Writing – review and editing. **Tommaso Giarrizzo**: Conceptualization, Methodology, Writing – review and editing, Writing – original draft, Supervision. **José E. Martinelli Filho**: Project administration, Funding acquisition, Resources. Conceptualization, Methodology, Formal Analysis, Writing – review and editing, Writing – original draft, Resources, Visualization, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156259.

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