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PROGRAMA DE PÓS-GRADUAÇÃO EM BIODIVERSIDADE E CONSERVAÇÃO

Myckey Kenzy e Silva Gonçalves

RETENÇÃO DE RESÍDUOS SÓLIDOS EM ÁREAS INUNDADAS DA AMAZÔNIA

Orientador: Prof. Dr. Tommaso Giarrizzo

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Dissertação apresentada à Universidade Federal do Pará, como parte das exigências do Programa de Pós-Graduação em Biodiversidade e Conservação para obtenção do título de Mestre em Biodiversidade e Conservação.

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Dedico este estudo a todos os cientistas que nesse ano de adversidade doaram suas vidas em prol do avanço racional da humanidade, em busca de um bem maior, um bem comum, um bem real. Dedico a todos aqueles anônimos que trabalham diariamente para o avanço da ciência.

E quando você derrama venenos na terra e nos rios você enfraquece os espíritos, as plantas, os animais e a própria terra. Quando você enfraquece a terra assim, ela começa a morrer. Se a terra morrer, se nossa Terra morrer, nenhum de nós será capaz de viver, e todos nós também morreremos.

Cacique Raoni Metuktire, líder do povo Kayapó

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Sumário

Resumo

A poluição dos ecossistemas aquáticos por resíduos sólidos está se tornando rapidamente um dos maiores desafios ecológicos do mundo, causando diversas interações letais à habitats e espécies, além de prejuízos no que se refere a serviços ecossistêmicos e implicações para o bem-estar humano. Entretanto, a maioria das informações sobre esse tipo de poluição vem de pesquisas realizadas em praias e costas oceânicas, já ambientes de água doce e estuarinos permanecem menos estudados. No entanto, dados sugerem que esses sistemas funcionam como sumidouro para resíduos sólidos e são a principal forma veiculação desses para os oceanos. O plástico é o principal componente dos resíduos presente nos oceanos, devido sua alta produção e uso em produtos descartáveis, gerando danos como enredamento e ingestão de detritos plásticos que representam riscos a diversos táxons. Dada a sua posição intermediária entre os ambientes terrestre e marinho, os sistemas estuarinos são especialmente vulneráveis à poluição humana. Os estuários da região amazônica possuem uma série de características únicas, como uma paisagem heterogênea intercalando uma faixa de florestas alagadas pelas marés com bancos de areia e praias. No presente estudo, fornecemos os primeiros dados qualitativos e quantitativos sobre a retenção de resíduos solidos em um estuário amazônico, comparando áreas cobertas por vegetação com áreas de areia. Ao todo, foram coletados 12.003 itens, com densidade média ± DP de 1,69 ± 2,16 itens / m² e peso médio de 78,08 ± 93,11 g / m². O plástico foi o principal tipo de material (80,97% dos itens) encontrado nas amostras. O maior número de itens foi encontrado nas florestas inundadas pelas marés (73,11%), o que indica que essas áreas são as mais afetadas pela poluição do plástico. Os resultados do presente estudo fornecem informações importantes para o planejamento de pesquisas futuras e a implementação de políticas públicas eficazes para a conservação e gestão desses importantes ecossistemas.

Palavras chave: Brasil, Amazônia, Ecossistema Estuarino, Retenção de Resíduos, Poluição por Plástico.

Abstract

Pollution of aquatic ecosystems by solid waste is fast becoming one of the greatest ecological challenges in the world, causing several fatal interactions with habitats and species, in addition to losses in terms of ecosystem services and implications for human well-being. However, most of the information on this type of pollution comes from research conducted on beaches and ocean coasts, freshwater environments, compared to marine environments, remain less studied. However, data suggest that these systems work as a sink for solid waste and are the main form of transmission of these to the oceans. Plastic is the main component of waste present in the oceans, due to its high production and use in disposable products, generating damages such as entanglement and ingestion of plastic debris that represent risks to several taxa. Given their intermediate position between terrestrial and marine environments, estuarine systems are especially vulnerable to human pollution. The estuaries of the Amazon region have a number of unique characteristics, such as a heterogeneous landscape interspersing a strip of forests flooded by the tides with sandbanks and beaches. In the present study, we provide the first qualitative and quantitative data on litter retention in an Amazonian estuary, comparing areas covered by vegetation with areas of bare sand. Altogether, 12,003 items were recovered, with an average density ± SD of 1.69 ± 2.16 items / m² and an average weight of 78.08 ± 93.11 g / m². Plastic was the main type of material (80.97% of the items) found in the samples. The largest number of items was found in forests flooded by tides (73.11%), which indicates that these areas are the most affected by plastic pollution. The results of this study provide important information for planning future research and implementing effective public policies for the conservation and management of these important ecosystems.

Keywords: Brazil, Amazon, Estuarine Ecosystem, Waste Retention, Plastic Pollution.

Estrutura da dissertação

A dissertação intitulada **— Retenção de resíduos sólidos em áreas inundadas da Amazônia**, foi elaborada em formato de artigo, de acordo com a Instrução Normativa 01/2016 do Programa de Pós-Graduação em Biodiversidade e Conservação da Universidade Federal do Pará, sendo composta por uma introdução geral, objetivos e capítulo 1. O produto da dissertação é um artigo científico **"Are the tidal flooded forests sinks for litter in the Amazonian estuary?"** publicado na revista internacional Marine Pollution Bulletin, qualis A1, fator de impacto 4.049, volume 161, (Pt A): 111732, DOI: https://doi.org/10.1016/j.marpolbul.2020.111732

1. INTRODUÇÃO

1.1. Poluição de ecossistemas aquáticos

A poluição de ecossistemas aquáticos é uma das ameaças ecológicas mais desafiadoras da atualidade, contribuindo para a degradação da qualidade da água, além de causar diversas interações fatais com a biota marinha (Bergmann et al., 2015). Na cúpula do G7 de 2015, a proteção do ambiente marinho já estava no centro das discussões e foi reconhecido que os detritos marinhos representam uma ameaça global (Löhr et al., 2017). Detritos marinhos são resíduos de origem humana definidos como qualquer material sólido persistente, fabricado ou processado, descartado ou abandonado no ambiente marinho ou costeiro (Jeftic et al., 2009).

Entretanto, esses materiais não se limitam a ambientes marinhos, eles têm sido amplamente dispersos na natureza, ao ponto de se tornar onipresentes nas mais distintas áreas do planeta (Browne et al., 2011), podendo ser encontrados flutuando na superfície do mar ou submerso nos oceanos (Wright et al., 2013; Courtene-Jones et al., 2019), ao longo de linhas costeiras e isoladas (Andrades et al., 2018; Paler et al., 2019), em lagos e rios (Mani et al., 2015; Vincent e Hoellein, 2017), além de estuários (Gray et al., 2018).

A presença de resíduos sólidos em ambientes aquáticos não é novidade, posto que estudos de monitoramento estão sendo realizados desde a década de setenta (Carpenter et al., 1972; Carpenter e Smith, 1972; Gregory, 1977). Ainda assim, a maioria das informações vem de pesquisas realizadas em praias e costas oceânicas (Thiel et al., 2013; Jang et al., 2018; Rangel-Buitrago et al., 2018; Asensio-Montesinos et al., 2019).

Apesar de esforços amostrais terem sido realizados na última década, ambientes de água doce, comparados a ambientes marinhos, permanecem menos estudados (Wagner et al., 2014; Blettler et al., 2018; Windsor et al., 2019). No entanto, dados sugerem que esses sistemas funcionam como sumidouro para resíduos sólidos, principalmente aqueles localizados próximos a áreas urbanas (Lechner et al., 2014; Yan et al., 2019).

O papel dos grandes rios como principais forma de veiculação de detritos para os oceanos também foi evidenciado recentemente (Lebreton et al., 2017; Bruge et al., 2018; Crosti et al., 2018; Castro-Jiménez et al., 2019). Objetos de diversas origens, composição e finalidades são descartados nas bacias hidrográficas de rios próximos as cidades, principalmente na forma de esgotos, e por ação do fluxo da água são levados para os oceanos (Lahens et al., 2018).

Os danos causados pela presença de resíduos sólidos na natureza não se restringem a habitats e espécies (Gall e Thompson, 2015; Kershaw et al., 2019), também causam prejuízos em serviços ecossistêmicos e diversas implicações para o bem-estar humano (Thompson et al., 2009; Carbery et al., 2018; Kaza et al., 2018). Além dos prejuízos ecológicos, a poluição gera uma série de impactos negativos em diversos setores da economia, como no turismo, recreação, pesca, transporte e serviços de infraestrutura, para indivíduos, comunidades locais e empresas (Leggett et al., 2014; Watkins et al., 2015).

1.2. A era do plástico

O plástico é o principal item entre os resíduos sólidos encontrados na natureza (Tabela 1). Devido sua alta produção e uso em produtos descartáveis, esse material tem sido amplamente disperso e acumulado em habitats terrestres, de água doce e marinho (Erni-Cassola et al., 2019; Malizia and Monmany-garzia, 2019; Sarkar et al., 2019).

Tabela 1. Porcentagem de detritos plástico (P%) em diferentes regiões.

Local	Região	P%	Referência
Porto de Halifax	Canada	53.8	Ross et al., (1991)
Santa Lúcia	Caribe	51.3	Corbin e Singh, (1993)
Panamá	Caribe	56	Garrity e Levings, (1993)
Transquei	África do Sul	83.4	Madzena e Lasiak, (1997)
País de Gales	Reino Unido	82	Williams e Simmons, (1997)
N. Devon/Somerset	Reino Unido	58	Williams e Simmons, (1997)
Mar da Irlanda	Reino Unido	51	Williams e Simmons, (1997)
Nova Jersey	E.U.A	73.8	Ribic, (1998)
Ilhas Malvinas	Reino Unido	74	Otley e Ingham, (2003)
Sydney	Austrália	74.1	Cunningham e Wilson, (2003)
Golfo de Aqaba	Jordânia	44–56	Abu-Hilal e Al-Najjar, (2004)
Coqueiros	Brasil	69.8	Santos et al., (2005)
Ilhas Baleares	Espanha	54	Martinez-Ribes et al., (2007)
Bahia	Brasil	75	Santos et al., (2009)
Santos	Brasil	62.81	Cordeiro e Costa, (2010)
Ilhas Gotō	Japão	74	Nakashima et al., (2011)
Mar do Norte	Alemanha	61.8	Thiel et al., (2011)
Ilha Midway	E.U.A	91.1	Ribic et al., (2012)
Paranaguá	Brasil	92.4	Possatto et al., (2015)
Ilha de Corfu	Grécia	>90	Prevenios et al., (2018)
Buenaventura	Colômbia	65.33	Riascos et al., (2019)
Ciénaga	Colômbia	73-96	Garcés-Ordóñez et al., (2019)
Costa do Mediterrâneo	Espanha	82.6	Asensio-Montesinos et al., (2019)

1.2.1. Produção

A fabricação de produtos plásticos tem aumentado cerca de 4% ao ano desde 2000 (Geyer et al., 2017). Isso ocorre devido a diminuição do custo da matéria-prima utilizada na fabricação do plástico virgem, tornando assim, o plástico reciclável mais oneroso para a indústria. Com isso a produção ultrapassa o consumo, e como consequência, a maioria dos países não consegue reciclar ou tratar de forma adequada nem um terço do que produz (WWF, 2019).

Aproximadamente 80% de todo o plástico produzido acabam indo parar nos oceanos, e estima-se que já existam 5,25 trilhões de pedaços de detritos plástico nessas áreas e que sejam despejados de 4,8 a 12,7 milhões de toneladas métricas por ano (Van Sebille et al., 2015; Jambeck et al., 2015). Em 2017 a produção global de plástico atingiu 348 milhões de toneladas, e o volume deverá dobrar nas próximas duas décadas e quase quadruplicar até 2050 (WEF, 2016; Lyons et al., 2020).

1.2.2. Impactos ecológicos

O enredamento em detritos plásticos representa um dos principais riscos à biodiversidade aquática, afetando diversos táxons e podendo acarretar em lesões graves ou crônicas, com o potencial de causar mutilações e limitação de movimento (Duncan et al., 2017; Woods et al., 2019). A morte por asfixia também é amplamente registrada, sendo por estrangulamento ou por afogamento mantendo preso no fundo animas que precisam subir à superfície para captar oxigênio (Barreiros e Raykov, 2014; Franco-Trecu et al., 2017; Parton et al., 2019). Equipamentos de pesca perdidos ou abandonados são os principais responsáveis por esses danos à fauna aquática (Galgani et al., 2018).

Com o passar do tempo, objetos plásticos fragmentam-se em partículas menores em resposta à constante ação mecânico-química do movimento da água e da incidência de radiação UV oriunda dos raios solares, por consequência, acabam sendo ingeridos acidentalmente por diversas espécies (Murray e Cowie, 2011; Neves et al., 2015; Lusher et al., 2015; Nelms et al., 2019; Basto et al., 2019; Hermabessiere et al., 2019; Ke et al., 2019). Quando ingeridas, essas partículas liberam substâncias tóxicas que contaminam o animal e se propagam pela cadeia trófica (Farrell e Nelson, 2013), podendo representar um perigo inclusive para os seres humanos (Van Cauwenberghe e Janssen, 2014).

1.3. A poluição em ecossistemas estuarinos

Os estuários são ecossistemas importantes por fornecer uma ampla variedade de serviços ecológicos como sequestro de carbono, proteção costeira, fonte de abrigo e berçário para larvas e juvenis de diversas espécies (Barbier et al., 2011). Devido sua posição, sistemas estuarinos encontram-se fortemente ameaçada pela poluição humana, podendo receber cargas de resíduos sólidos tanto de correntes oceânicas quanto de fontes terrestres transportadas pelos rios (Vermeiren et al., 2016; Gray et al., 2018; Yan et al., 2019).

Ao entrar nesses ecossistemas, fatores como correntes de marés, altura e densidade da vegetação podem favorecer a retenção desses materiais por longos períodos (Ivar do Sul et al., 2014). Sacos plásticos, cordas e destroços de madeira prendem-se a raízes e outras estruturas próximas as margens dos rios, enquanto que objetos menores são transportados para o interior de áreas vegetadas (Debrot et al., 2013; Mohamed Nor e Obbard, 2014; Smith e Edgar, 2014).

Apesar de pesquisas recentes realizadas em estuários (Cordeiro e Costa, 2010; Possatto et al., 2015; Kurniawan e Imron, 2019; Yao et al., 2019; Zhao et al., 2019), a compreensão no que diz respeito ao comportamento de resíduos nessas localidades ainda são incipientes, necessitando assim de mais estudos sobre o estado em que se encontra a poluição nesses ecossistemas (Mazarrasa et al., 2019). Principalmente aqueles próximos as cidades, pois essas áreas são mais afetadas (Vendel et al., 2017; Vincent et al., 2017; Martin et al., 2019; Riascos et al., 2019).

2. OBJETIVO

2.1 Objetivo geral

Investigar o acúmulo de resíduos sólidos nas margens do rio Pará, a jusante de um grande centro urbano e realizar uma análise comparativa entre áreas vegetadas e não vegetadas.

2.2 Objetivos específicos

- Determinar a composição dos resíduos sólidos no estuário do rio Pará;
- Quantificar em número e peso os resíduos sólidos;
- Comparar quantitativamente os resíduos sólidos coletados em áreas vegetadas e não vegetadas.

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3. Capítulo 1

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ARTIGO

Are the tidal flooded forests sinks for litter in the Amazonian estuary?

Are the tidal flooded forests sinks for litter in the Amazonian estuary?

Myckey Goncalves[a], Kurt Schmid[a], Marcelo C. Andrade[a], Ryan Andradesa[a,b], Tamyris Pegado[a], Tommaso Giarrizzo[b]

[a] *Núcleo de Ecologia Aquática e Pesca da Amazônia, Universidade Federal do Pará, Av. Perimetral 2651, Terra Firme, 66077830 Belém, Pará, Brazil.*
[b] *Laboratório de Ictiologia, Universidade Federal do Espírito Santo, Av. Fernando Ferrari, Goiabeiras, 29075-910 Vitória, Espírito Santo, Brazil.*

Abstract

Pollution in aquatic ecosystems is rapidly becoming one of the world's greatest ecological challenges. Given their intermediate position between terrestrial and marine environments, estuarine systems are especially vulnerable to human pollution. Amazonian estuaries have unique characteristics, such as heterogeneous landscape intercalating tracts of vegetation with sandbanks and beaches. In the present study, we provide the first qualitative and quantitative data on litter retention in an Amazonian estuary, comparing vegetated and bare substrate areas. Overall, 12,003 items were recovered, with a mean ± SD density and weight of 1.69 ± 2.16 items/m^2 and 78.08 ± 93.11 g/m^2, respectively. Plastic was the principal material (80.97%) found. The highest number of items was found in the vegetated habitats (73.11%), indicating these areas as the most affected by plastic pollution. Our findings provide important insights for future research planning and implementation of effective public policies for conservation and management of these important ecosystems.

Keywords: Brazil; Amazon; Estuarine ecosystem; Waste retention; Plastic pollution; Missing plastic.

Litter has been recorded in aquatic environments during scientific monitoring studies since the 1970s (Carpenter et al., 1972; Carpenter and Smith, 1972; Gregory, 1977). Composed of an enormous variety of materials (e.g., plastic, glass, etc.), derived from a broad range of sources, solid waste can be found floating in the open sea or along the coastline (Constantino et al., 2019; Palatinus et al., 2019), as well as in lakes and rivers worldwide (Mani et al., 2015; Vincent et al., 2017). Despite the ubiquitous distribution of litter pollution, the majority of the available data is from the assessment of beach litter in the coastal zone (Rangel-Buitrago et al., 2018; Jang et al., 2018; Asensio- Montesinos et al., 2019; Andrades et al., 2020), while few studies have focused on freshwater systems (Wagner et al., 2014; Blettler et al., 2018; Winton et al., 2020).

Recent studies have highlighted the role of large rivers as the principal route of litter pollution to the oceans (Lebreton et al., 2017; Crosti et al., 2018; Bruge et al., 2018;

Castro-Jiménez et al., 2019). Litter of all kinds is discharged into river basins, primarily in urban zones, and then transported to estuaries and finally to the oceans (Lahens et al., 2018; Kazour et al., 2019). Estuarine systems, in particular, are hotspots of pollution, receiving waste through multiple in- puts, including fluvial discharge as well as tidal and coastal currents (Vermeiren et al., 2016; Gray et al., 2018).

Plastic is the principal component of the litter found in aquatic environments, ranging from small virgin pellets to large fragments of hard and flexible material (Cressey, 2016; Bergmann et al., 2017). Plastic litter has been observed on coastal beaches in the Amazon region (Martinelli Filho and Monteiro, 2019), and both freshwater and coastal fish from this region are known to ingest microplastics (Pegado et al., 2018; Andrade et al., 2019). So far, however, no studies have focused specifically on the composition and abundance of the litter density and distribution in the estuaries of the Amazon region.

In the present study, we conducted the first investigation of the retention of litter in an Amazonian estuary, using both qualitative and quantitative approaches. The study area encompasses a mosaic of habitats, including areas of sandy beaches and dense forests composed by flood-tolerant tropical rainforest trees (e.g., *Swartzia polyphylla*, *Virola surinamensis*, *Pseudobombax munguba*), high diversity of palms (e.g., açai - *Euterpe oleracea*, and *Mauritia flexuosa*) and perennial helophytic shrubs (e.g., *Montrichardia arborescens*), which covers a total area of 25,000–30,000 km^2 in the Amazonian estuary (Lima, 1956; Cattanio et al., 2002; Gregório and Mendes, 2009). In this scenario, we compared the composition and abundance of the litter found in vegetated and unvegetated habitats, flooded twice daily by freshwater backed up from tides.

Our study area was the estuary of the Pará River, in northern Brazil, an area that includes the metropolitan area of Belém City, several small- and medium-sized islands, and a large portion of the coastline of Marajó Island, the world's largest fluvial-marine island (Ab'Sáber, 2006). This hydrographic system is dominated by semi-diurnal tides, with intense mixing and turbulence (Prestes et al., 2017).

The data were collected between July and October 2017 at eight sites in the eastern portion of the Pará estuary (Fig. 1). These sites were selected according to the characteristics of the coastline, with four sites (Combú, Cotijuba, Jutuba, and Paraíso islands) having a coast of tidally flooded forest. These localities formed the group of sites with vegetated (VEG) habitats. The other four sites (Icoaraci, Cruzeiro, Marau, and Colares beaches) represent the unvegetated (UNV) habitats.

Fig. 1. Location of the study area in the estuary of the Pará River in northern Brazil (gray circle). White and black circles in the map represent the vegetated (Combú, Cotijuba, Jutuba, and Paraíso islands); and unvegetated sites (Icoaraci, Cruzeiro, Marau, and Colares beaches), respectively.

Each site was sampled randomly along 10 transects in the intertidal zone, perpendicular to the coastline, beginning at the high tide line and ending at the low tide line. The transects were 4 m wide, but varied in length according to the characteristics of each site. All items of litter larger than 5 mm – i.e., above the international threshold for classification as microplastics (Arthur et al., 2009) – found within the transect were collected and taken to the UFPA Laboratory of Fishery Biology and Aquatic Resource Management in Belém, Pará, for further analysis.

The items collected were counted, weighed and classified by locality, habitat type, and composition (Fabric/Fiber, Glass, Masonry, Metal, Paper, Polyethylene, PET, and Styrofoam). The effects of the factors habitat type (VEG vs. UNV) and locality (8 sampling sites) on the composition of the litter collected during the surveys were tested using a permutational analysis of variance (PERMANOVA; 9999 permutations). The PERMANOVA was run on a Bray-Curtis similarity matrix, calculated from the fourth-root transformed litter composition data (see Anderson, 2001). The patterns in the composition of the litter found on the 80 transects were explored visually using an unconstrained ordination based on a Principal Coordinates Analysis, or PCoA (Anderson

et al., 2008). A Pearson correlation of 0.3 was used as an arbitrary threshold for the display of potential correlations between individual types of litter.

A total of 12,003 items were recovered from the eight sites in the Pará River estuary, with a mean ± SD density of 1.69 ± 2.16 items/ m^2, and mean weight of 78.08 ± 93.11 g/m^2. Nine types of waste material were collected (Table 1). The vast majority of the items (80.97%) were composed by plastic (Fig. 2). These plastic items included Polyethylene with 3853 items and an average of 0.6 items/m^2, followed by Styrofoam (3471 items; 0.52 items/m^2) and PET (2395 items; 0.36 items/m^2). Plastic is the most common litter found in terrestrial, freshwater and marine ecosystems (Erni-Cassola et al., 2019; Malizia and Monmany-Garzia, 2019; Sarkar et al., 2019) and, with a few exceptions, plastic pollution is the principal challenge faced by environmentalists attempting to mitigate pollution levels around the world.

Table 1
Density of the litter (items/m^2) collected in the Para river estuary, Brazil, showing the minimum and maximum values, the mean (± SD), and the relative contribution (%) of each category of debris, by habitat (VEG and UNV). Extremely small values are shown as "<0.01".

Material type	UNV				VEG			
	min	max	mean ± SD	%	min	max	mean ± SD	%
Fabric/Fibre	0	0.01	0.01 ± 0.01	1.77	0.01	0.02	0.01 ± 0.01	0.44
Glass	< 0.01	0.43	0.19 ± 0.2	46.39	0.01	0.13	0.07 ± 0.06	2.46
Masonry	0	0.02	0.01 ± 0.01	3.04	0	0.02	< 0.01 ± 0.01	0.16
Metal	0.01	0.04	0.02 ± 0.01	6.24	0.02	0.06	0.04 ± 0.02	1.3
Other	< 0.01	0.01	0.01 ± < 0.01	1.73	0.01	0.02	0.02 ± 0.01	0.51
Paper	< 0.01	0.03	0.01 ± 0.01	2.72	0	0.03	0.01 ± 0.01	0.39
PET	0.01	0.05	0.03 ± 0.02	6.51	0.13	1.51	0.7 ± 0.6	23.61
Polyethylene	0.03	0.18	0.09 ± 0.07	21.58	0.11	2.63	1.12 ± 1.19	37.58
Styrofoam	< 0.01	0.12	0.04 ± 0.06	10.01	0.28	2.44	1 ± 1.01	33.55

We observed significant variation in the density and composition of the litter between the two habitats (VEG and UNV), and among the eight study sites (Table 2). Litter density at the UNV habitats ranged from 0.09 to 0.58 items/m^2, with a mean of 0.4 ± 0.23 items/m^2, while the density at the VEG habitats ranged from 0.61 to 5.65 items/ m^2, with a mean of 2.98 ± 2.53 items/m^2. Although our findings indicate that, the sandbanks retained a considerable amount of litter, the vegetation found in environments

such as estuaries are more effective as a sink of floating litter. This corroborates our hypothesis, that the vegetated habitats of the Pará estuary are the most impacted by litter pollution. The local vegetation acts as a natural trap, retaining drifting objects from the river discharge or tidal flooding (Ivar do Sul et al., 2014; Martin et al., 2019).

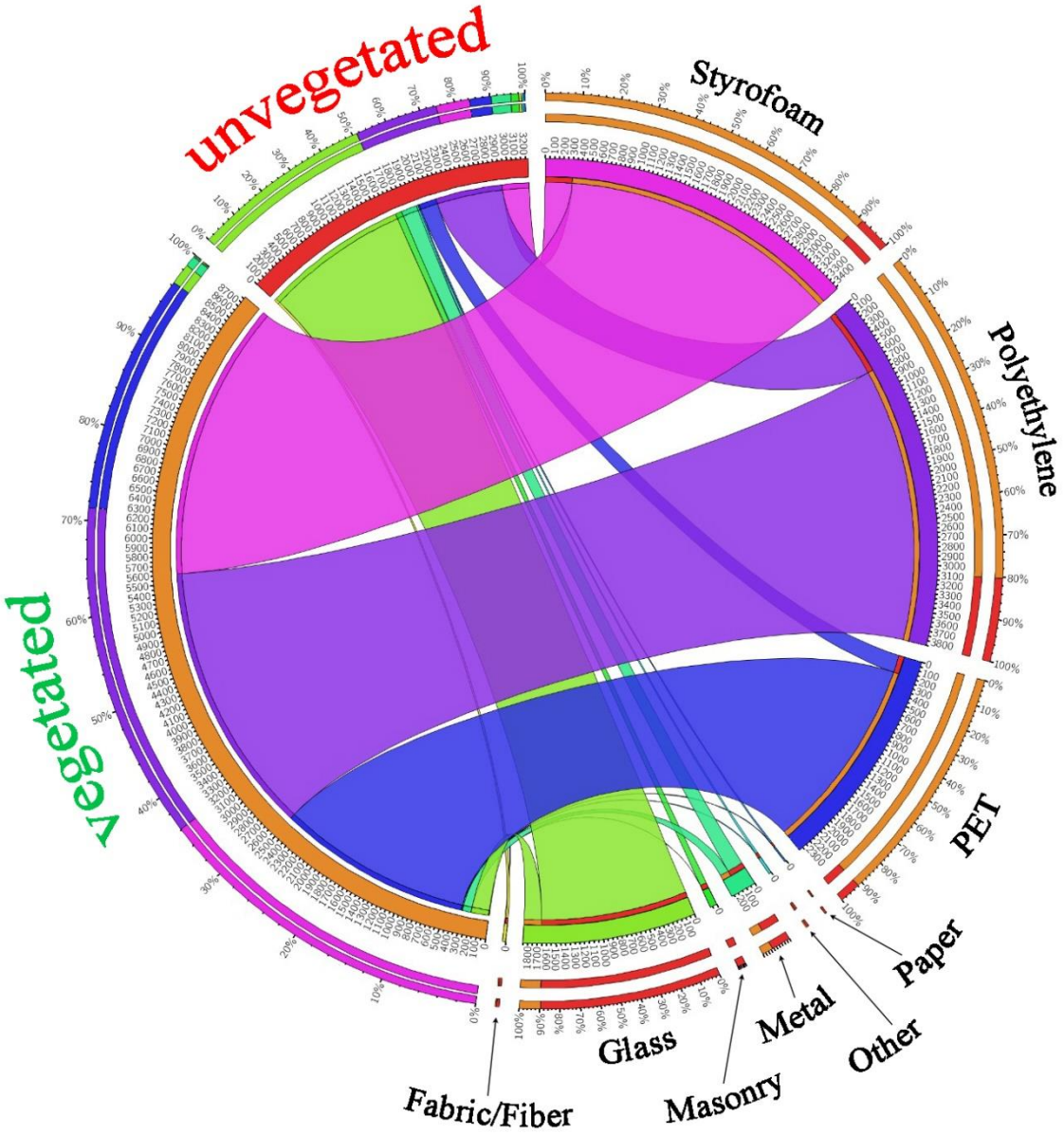

Fig. 2. Chord diagram showing the absolute and relative contributions of the different types of material to the litter collected in the two habitats (vegetated and unvegetated), in the estuary of the Pará River.

Table 2
Results of the PERMANOVA of the composition of the litter collected at the VEG and UNV habitats, and among the eight sampling sites. Significant factors ($p < 0.05$) are highlighted in bold script.

Source	DF	SS	MS	Pseudo-F	P(perm)
Habitat	1	35113	35113.00	4.1571	**0.0285**
Site	6	50680	8446.60	11.859	**0.0001**
Residual	72	51281	712.23		
Total	79	1.3707E+05			

The mean litter density recorded in VEG habitats 2.98 items/m^2 was higher than those mean values commonly recorded in tropical and sub- tropical vegetated areas. For instance, Cordeiro and Costa (2010) in the São Vicente estuary (Brazil) recorded 1.33 items/m^2 and Garcés- Ordóñez et al. (2019) in Ciénaga Grande de Santa Marta (Colombia) recorded 0.54 items/m^2. The high mean density of litter found in our study indicates that vegetated areas of estuarine regions, close to urban centers, are critical points for the accumulation of floating litter.

Plastic was the predominant type of material (96.38%) collected in VEG habitat (Fig. 2). This proportion was much higher than the value recorded by Cordeiro and Costa (2010) in the São Vicente estuary (62.81%), but similar to the (92.4%) recorded by Possatto et al. (2015) in the Paranaguá estuary, in southern Brazil. Plastic is the main type of litter found in the vegetated areas of estuarine systems, which indicates that these areas may be one of the main sinks of the "missing plastic" (Cózar et al., 2014). We found conclusive evidence, in the present study, of the role of tracts of vegetation, in the tropics, as sinks for the retention of litter pollution. Clearly, then, both mangrove forests and seagrass beds (Martin et al., 2019; Huang et al., 2020) in coastal areas, and marshes and tidally flooded forests in the Amazon estuary (the present study) are effective sinks for the retention of floating detritus in freshwater and marine ecosystems.

The PCoA of the composition of the litter supported the results of the PERMANOVA and clearly separated the samples of the VEG and UNV habitats (Fig. 3). The main type of plastic collected in VEG habitats was Styrofoam (n = 3166 items; 36.08% of the total), followed by polyethylene (n = 3093 items; 35.25%), and PET (n = 2198 items; 25.05%) (Fig. 2). The density of Styrofoam was highest in two of the four

VEG sites (Jutuba and Paraíso), which may be related to the relatively intense fishing activity observed in neighboring areas. Styrofoam is being used by artisanal fishers in floats for their nets and coolers for the storage of the catch. Both uses of Styrofoam typically result in the regular detachment of small fragments from these objects by mechanical attrition. Other studies have also shown that local fisheries, especially activities that use Styrofoam buoys, are associated with an increase in the proportion of Styrofoam in plastic litter (Hong et al., 2014; Chen et al., 2018; Ramos and Pessoa, 2019).

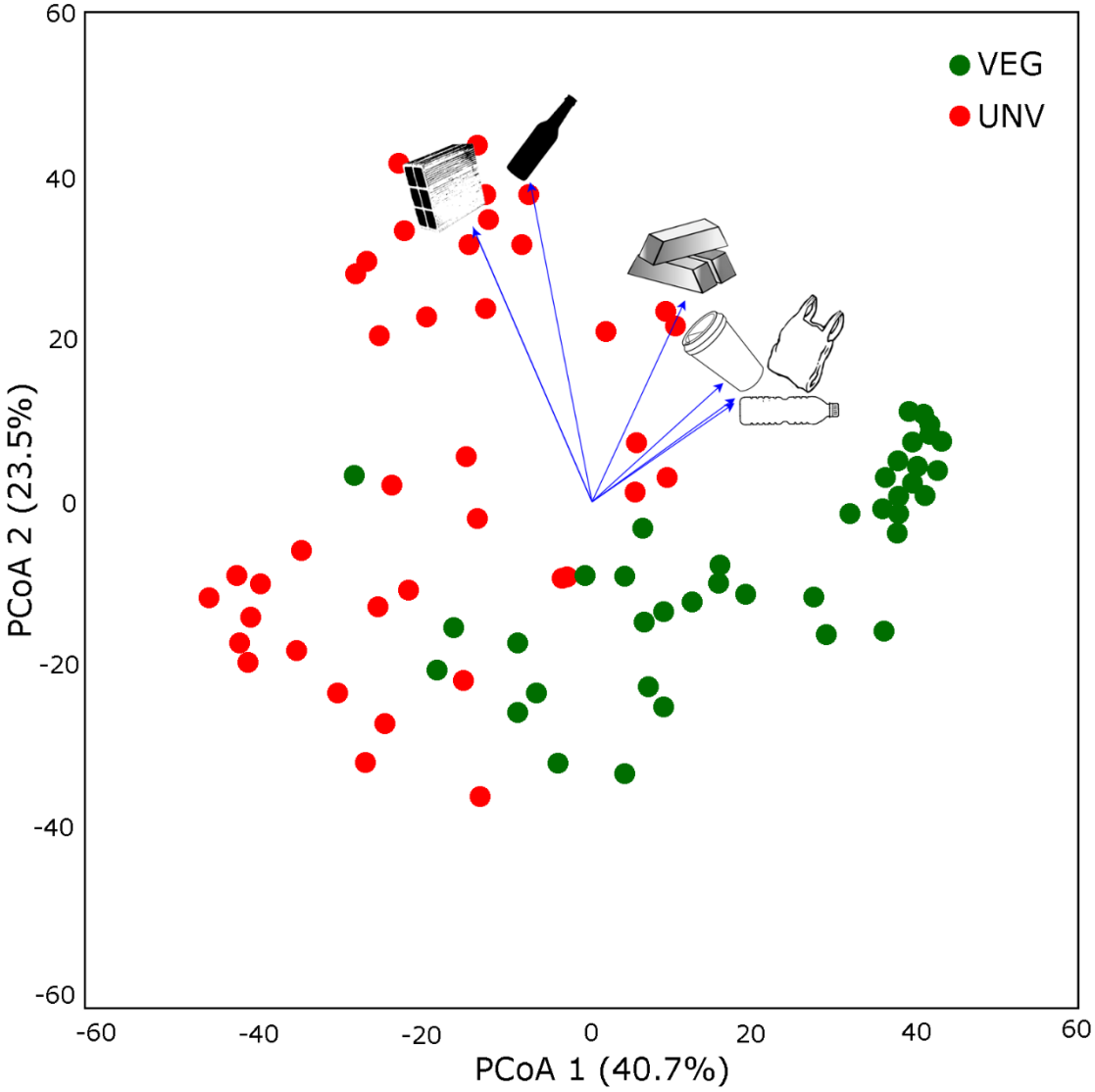

Fig. 3. Plot of the results of the Principal Coordinates Analysis (PCoA) of the composition of the litter collected in vegetated and unvegetated habitats in the estuary of the Pará River, with the litter types presenting a high correlation (> 0.3) shown in the vectors.

Yao et al. (2019) also found that the vegetation of estuaries may generate microplastics by degrading macroplastic fragments, trapped in its structures, into smaller pieces over time. As a result, smaller debris may be buried in the sediments of estuarine environments, as observed in Goiania estuary, Brazil (Costa et al., 2011), or drift on the water surface and end up floating to the ocean, as observed in the estuaries of the Pearl (Yan et al., 2019) and Changjiang (Zhao et al., 2019) rivers in China. It is thus extremely important to understand the distribution patterns of macroplastics in estuarine environments, given its potential for the secondary production of microplastics.

To the best of our knowledge, this study is the first to assess litter pollution in an Amazonian estuary. Our findings confirmed that the VEG habitats are acting as a litter sink and, as expected, plastic materials predominated in the litter. The pollution of these ecosystems by litter, primarily plastics, may have highly deleterious effects on the local aquatic and terrestrial biota. The degradation of these areas may result in a deficit in the natural flow of organic matter from the vegetation into local food webs (Duke et al., 2007), ultimately affecting also the region's fish stocks which are one of the principal sources of in come for the local riverside populations in the Amazon estuary region. These findings clearly reinforce the need to implement effective measures for the management and reduction of the amount of waste discarded in the waters of the Amazon Basin.

The most (95%) of the litter collected at the VEG habitats in the present study was derived from only three types of plastic. This indicates that regional policies aimed specifically at the reduction of the generation of these types of waste material (PET, Styrofoam, and Polyethylene), in particular by fisheries, would have considerable benefits for the protection of the aquatic ecosystem associated with the vegetation of estuaries. Our findings provide important insights into the challenges involving in managing inadequate waste disposal, in particular, plastics.

CRediT authorship contribution statement

Myckey Gonçalves: Investigation, Formal analysis, Writing - ori- ginal draft, Writing - review & editing. **Kurt Schmid:** Investigation, Writing - original draft, Writing - review & editing. **Marcelo C. Andrade:** Investigation, Writing - original draft, Writing - review & editing, Visualization. **Ryan Andrades:** Writing - original draft, Writing - review & editing. **Tamyris Pegado:** Writing - review & editing. **Tommaso Giarrizzo:** Conceptualization, Methodology, Formal ana- lysis, Investigation, Resources, Writing -

original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition.

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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