Plastic pollution risks in an estuarine conservation unit

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ABSTRACT

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Plastics enter the marine environment mostly from land-based sources, often via estuaries. However, studies related to plastic debris pollution remain rare within these environments. An estuarine beach comprised within a Marine Conservation Unit (MCU) in the Northeast coast of Brazil was studied during one year regarding plastic pollution. Petroleum derived products were >95% of all items, as commonly reported for other coastal and marine habitats. Monthly totals of marine debris presented an average of 10.8±1.63 items.100m^{-2}, much lower than reported in the literature for other estuarine beaches. Three main sources were identified: fisheries, local users and human settlements along the river basin. The most frequent (56%) size category was 11-100cm^2, but fragmented items alone were 83% of observed items. The main impact on the estuarine and visiting biota expected is the ingestion of plastic items and fragments, which was corroborated by recent works on estuarine fishes. Interactions with fishing gear are highlighted in the context of this MCU. To protect the traditional livelihoods in the Goiana Estuary, the guarantee of a healthy ecosystem, inclusive free from plastic pollution, must be included in management plans.

ADDITIONAL INDEX WORDS: *Environmental monitoring, pollution control, ecosystem management, fisheries, physical fragmentation, ingestion, nylon.*

INTRODUCTION

Coastal areas concentrate most of the World's population and, since the first human settlements, estuarine environments have been intensely used to urban, agro-industrial and recreational activities. Consequently, these regions have been heavily impacted (Ridgwaya and Shimmield, 2002), inclusive with the presence of plastic marine debris, especially since the 1930s (Spokas, 2008). The occurrence of different types of marine pollution (i.e. sewage; organic and inorganic compounds in sediments and water) is well documented in heavily occupied estuarine ecosystems (Kennish and Elliot, 2012) but, even there, the behaviour of plastics is poorly known (Thornton and Jackson, 1998; Williams and Simmons, 1997; 1999; Araújo and Costa, 2007; Browne *et al.*, 2010). Once in estuaries, plastics stand a quite high chance of reaching continental platforms and the open ocean. But also important to note is that, due to estuaries tidal regimes, plastics can stay in these environments for long periods of time, undergoing different degradation processes at different sedimentary habitats where they deposit, and during transportation among them. It is then crucial to known how estuaries contribute to increase the amounts of plastics entering the oceans. Identifying the sources of estuarine plastic debris is also a key step towards the combat of the problem before it reaches coastal waters (Santos *et al.*, 2009). The subsequent reduction of plastics entering the sea would reduce the pollution of coastal beaches, reefs, fishing grounds and other adjacent shallow areas.

However, most estuaries are not densely occupied, or have the necessary size for sustaining a large number of people and services. Some areas of the tropical coasts still hold significant numbers of pristine features that allow us to declare them of environmental interest, including the conservation of sociobiodiversity. To study plastics in relatively preserved estuarine environments, we monitored an estuary from the tropical semi-arid coast candidate for a new conservation status – Marine Extractive Reserve (Silva-Cavalcanti and Costa, 2009). The Goiana Estuary (7°S, 34°W) (Fig. 1) is on a humid coast, but is fed by rivers draining semi-arid areas (Barletta and Costa, 2009) The rainy season is from April to September (263.3±125.8mm) and the dry season from October to March (108.3±72.3mm) (Barletta and Costa, 2009). The river flow follows the same regime. This influences the transport of plastics along the river course. In the adjacent coastal area, longshore currents flow predominantly northeast (Fig. 1). Economically important species of fishes, shellfish and crustaceans are responsible for the traditional communitie's fisheries (Silva-Cavalcanti and Costa, 2009). There are two local harbours (Fig. 1) surrounded by traditional fishing villages (Barletta and Costa, 2009). These resources can be compromised, threatening traditional livelihoods of hundreds of families. In addition, the estuary holds an important natural patrimony (mangrove forests; tidal flats; seagrass meadows; beaches; coastal reefs) that are also important conservation targets.

The objective of the present study is to identify quantities, types, sources and sizes of marine debris on an estuarine beach within a MCU, describing the behaviour of plastics in this environment. To represent the depositional environments of the low estuary (Barletta and Costa, 2009) where plastic debris may accumulate, we choose a sandy beach (Ramos *et al.*, 2011).

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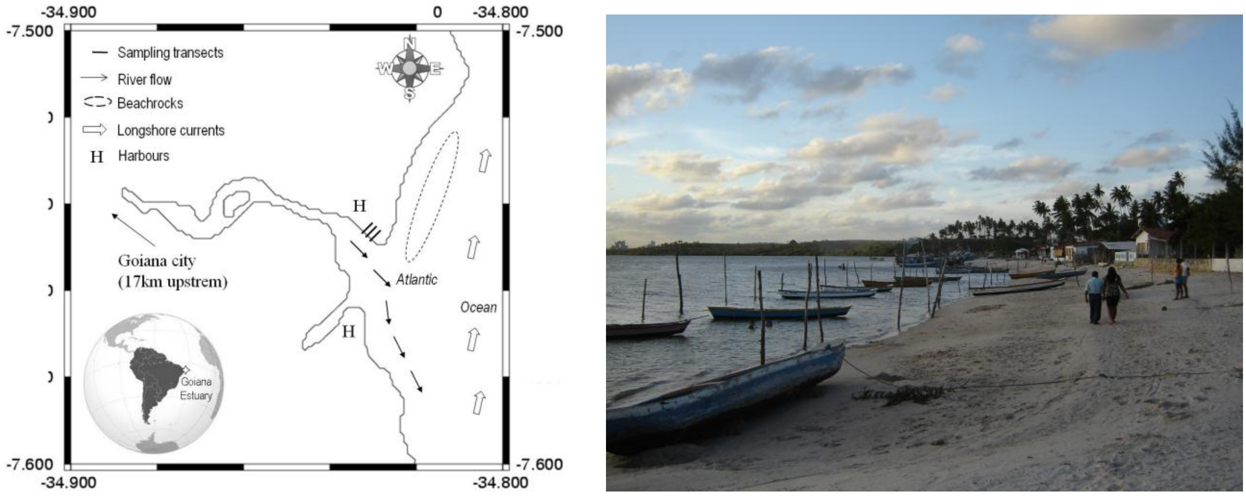

Figure 1. (Left) The Goiana Estuary in the Atlantic northeast coast of Brazil. The three replicate transects, the predominant river flow, beachrocks on the shallow adjacent coast and the main coastal currents are represented. Along the river's course, there is only one large settlement, Goiana City, 17km upstream from the river mouth. (Right) Photo showing the studied estuarine beach at the Goiana Estuary. Traditional fishing boats are also showed.

METHODS

Sandy beaches are areas of plastic marine debris deposition (Thornton and Jackson, 1998; Williams and Simmons, 1999). The studied beach was selected considering (a) main direction of longshore currents; (b) direct influence of the river flow; and (c) neutral sedimentary equilibrium of the beach. Within the area, three replicate 20m wide transects (Araújo *et al.*, 2006) were delimited from the backshore to the water line at low tide. Transects were completely cleared from marine debris in April 2006. The procedure was monthly repeated for one year.

Marine debris were collected and counted. Sampled items were classed according to material (e.g. plastic, polystyrene foam, cloth, wood, paper), specific type of item (e.g. plastic bag, PET bottle, cigarette butt, cap, fragment, buoy, net), size and most probable source. Four size categories (1-10cm², 11-100cm², 101-1000cm², >1001cm²) were used (Madzena and Lasiak, 1997; Ivar do Sul *et al.*, 2011). Micro (size) and mega (size) debris were not considered (Table 1). Three different sources, divided in two groups were adopted (Claereboudt, 2004; Santos *et al.*, 2009):

- **Local sources**, represented by: (1) fishing activities, when items are generated within the estuary at the fishing harbours and during fisheries (Guebert-Bartholo *et al.*, 2011), and (2) local users, when marine debris are *directly* discarded on the beach;
- **Non-local sources** are (3) domestic waste discarded along the river basin, including the lower estuary, represented by items that are not normally taken to the beach (e.g. margarine tubs, shampoo flasks and deodorant sticks, detergent bottles) (Araújo and Costa, 2006).

Statistical analysis

Two-way Analysis of Variance (ANOVA) was used to assess significant differences among (1) rainy and dry seasons, considering the total amount of plastics per area; (2) rainy and dry seasons, considering specific types of items related to their sources; and (3) the size categories (1-10cm², 11-100cm², 101-1000cm², >1001cm²). Statistical significance was set at a probability level of 0.05.

RESULTS

Composition and temporal patterns of marine debris

A total of 6,944 ($\bar{x}$ = 2,314.3 ± 516.5; N=36) items were sampled in the three replicate transects during one year. As expected, plastics and other synthetic materials were the majority (>95%) of items. Rigid (broken, high density polyethylene) and soft (packaging, low density polyethylene) ordinary plastic items were 72% of the samples, followed by polystyrene foam (15.9%). Nylon fibers were 5.6%, while rubber and polyurethane foam were 2.4% of the items. Non-synthetic materials (cloth, wood, metal, paper and others) represented only ~ 4% of the total items sampled.

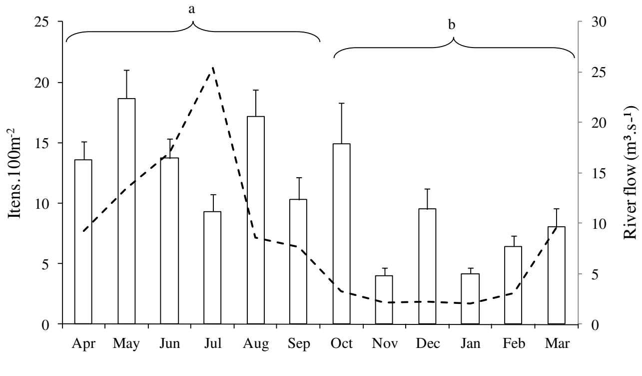

Figure 2. Temporal patterns of average marine debris during one year of sampling (white bars) compared with river flow estimates (dashed line) at the low Goiana Estuary. (a) rainy season and (b) dry season. Error bars indicate S.D.

Table 1. Comparisons of nomenclatures and size categories used in previous works on marine debris. Both, area and linear measurements were applied by different authors trying to establish a working standard.

Name	Ribic (1990)	Gregory (1990)	Ribic et al. (1992)	Gregory (1999)	Donohue et al. (2001)	Barnes et al. (2009)	Madzena and Lasiak (1997)*
Mega	2-3 cm	Visible by an onboard observer	>1 m	Visible by an onboard observer	> 25m^2	< 100 mm	-
Large	-	-	-	-	-	-	> 1001cm^2
Macro	2-3 cm; 5 mm	Fragments	≤1 ; >10 cm	Visible on beach	25 to 11 m^2	< 20 mm	1000 - 101 cm^2
Medium	< 5 mm	Plastic pellets	≤10 cm; ≥ 2.5 cm	1 cm – 5 mm	10 to 5 m^2	20-5 mm	100 - 1 cm^2
Small	-	-	-		-	-	< 1 cm^2
Micro	Invisible to the naked eye	< 5 mm	< .5 cm	500 µm - 63 µm	< 5m ^{2}	< 5mm	-

Monthly total marine debris on the beach presented an average of 10.8±1.63 items.100m^{-2}. Rainy months were significantly ($p<0.05$) more contaminated by marine debris than the dry ones (Fig. 2).

Sources

Fishing related debris (polystyrene foam buoys, ropes, nets and others) are easily identified on the field (Araújo and Costa, 2006; Santos *et al.*, 2009). Here they were 22.3% of the total items sampled (Table 2). In addition, at least 14% of the sampled items were also from local-based sources (local users), but this amount is probably higher (up to 33.6%; Table 2). To us and other authors (Claereboudt, 2004; Araújo and Costa, 2006, Santos *et al.*, 2009; Ivar do Sul *et al.*, 2011), it is not possible to recognize whether unlabeled plastic bags, PET bottles, caps, soft packaging and rigid containers come from local or non-local sources. These items remain with an uncertain final diagnosis (Table 2). Materials such as rubber, polyurethane foam and sewage-derived items (~2% of items) were directly related to domestic sources along the river basin, mainly the fishing villages of the lower estuary. Finally, rigid containers and fragments are attributed to domestic sources (Araújo and Costa, 2006). These items were significantly ($p<0.05$) more sampled during rainy months, when the river flow is higher.

Sizes and most common items

Small items (<10cm²) accounted for 26% of the total debris deposited on the estuarine beach (Fig. 3). Most were fragments of polystyrene foam (21%), cups (16%) and soft plastics (12%). Following the size classification, plastics with 11-100cm² represented the majority (56%) of all items and were significantly ($p<0.05$) more sampled during the year. Most representative types of items were fragments of plastic cups (21%), polystyrene foam (15%) and soft plastic (14%). Fifteen per cent had 101 to 1000 cm². They were mainly supermarket bags (19%), rigid containers (13%) and soft packaging (11%). Larger items (>1001 cm²) were ~3% of the sampled debris (Fig. 3). It is important to highlight that 83% of all items (of all sizes and from all sources) were fragmented plastics, the result of successive degradation process acting *in situ* (Costa *et al.*, 2010).

DISCUSSION

Comparison among studies on estuarine beaches

Few studies in estuaries and river-dominated beaches are available (Thornton and Jackson, 1998; Williams and Simmons, 1997; 1999; Acha *et al.*, 2003; Wilson and Randall, 2005; Araújo and Costa, 2007; Cordeiro and Costa, 2010; Browne *et al.*, 2010). They indicated the prevalence of plastics (42.5-91%), the same trend as in other marine environments (Ivar do Sul and Costa, 2007; Moore, 2008; Barnes *et al.*, 2009). Plastics per area identified in the Goiana Estuary are much lower than at Una River, an undeveloped river-dominated beach, and Costa do Dendê, in the northeast coast of Brazil (Table 3). When compared with beaches bordered by high populated metropolitan regions in Brazil, UK and USA, the studied estuary also present a lesser pollution level, and, consequently, smaller contamination levels (Table 3). Then, if the exportation of plastics is present in this small river of a semi-arid coast, in coastal areas where rivers have higher fluxes and land-based contamination is more severe (74.2-100%) (Table 3) the influence of estuaries on adjacent coastal areas is indubitable.

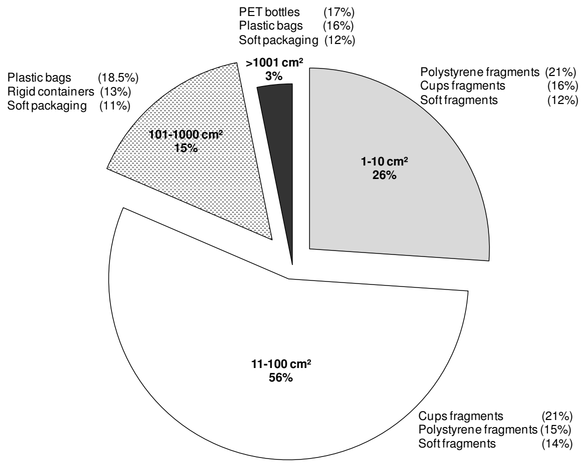

Figure 3: Size categories and most common items of plastics at the Goiana Estuary.

Sources and temporal patterns

Numerous land-based sources contribute to the generation of debris but, in the Goiana Estuary, sources are reduced to three identifiable possibilities, facilitating items classification and positive identification. Other studies (Araújo and Costa, 2006; Ivar do Sul and Costa, 2007; Moore, 2008; Santos *et al.*, 2009) related fisheries items with marine-based sources, but here they are considered to have a land-based origin. The traditional and commercial fishing fleets that uses the local harbours include gillnet, lobster traps, longline, spears and trap barriers (Guebert-Batholo *et al.*, 2011). All generated debris that could be detected during this study (Table 2). Marine sources were not recognized from the sampled items due to the absence of typical items as foreign containers of food/drinks, hygiene and cleaning products; items incrusted by marine organism and; fisheries items that could not be related to the arts used locally.

Marine debris related to recreational activities on beaches can be easily identified especially on urban and tourist beaches (Araújo and Costa, 2006; Santos *et al.*, 2009). This is not the case here, since the number of beach users is very much reduced, but restaurants along the water front contributed to the generation of plastics such as disposable cups, plates, cutlery and cigarette butts (local users; Table 2).

The river flow transports domestic plastics downstream to estuarine beaches (Williams and Simmons, 1999; Cunninghan and Wilson, 2003). High quantities of such items were observed at the study site during rainy months, indicating that large amounts of items are moved from one place to another within and beyond the estuary. Inexistent or inefficient services of collection and disposal of municipal solid wastes along the whole river basin facilitate their entrance into the aquatic environment. Three well-defined sources were identified (fishing, domestic and local users). Items that could not be safely attributed to a specific source are clearly generated by one of the above listed ones. As the area is now inserted in a Marine Conservation Unity, management actions from environmental authorities to minimize and control marine debris must target these specific sources. Adequate solid wastes disposal by the surrounding traditional communities and environmental education of fishermen are among the main actions needed. Controlling non-point sources along the river basin is also absolutely necessary.

Size categories and environmental impacts

Impacts of marine debris are related to their size (Costa *et al.*, 2010). During the last decade, efforts concentrated on the tiny fraction of plastics, known as microplastics (Thompson et al., 2004; Moore, 2008; Barnes et al., 2009). In size assessments, items are individually measured (by area or linear length) and grouped in categories or classes (µm, mm, cm, m) depending on the objectives and scale of studies (Table 1). Sizes are then used to elucidate residence times and physical degradation of plastics (O'Brine and Thompson, 2010), transport along rivers (Wilson and Randall, 2005), preferential depositional patterns (Ivar do Sul *et al.*, 2011), impacts to the biota (Thompson et al., 2004; Tourinho *et al.*, 2010), and finally beach management actions (Santos *et al.*, 2009; Moore, 2008; Costa *et al.*, 2010). Previous studies of plastics on estuarine beaches involved different environments and spatial scales, from one single transect to hundreds of kilometers. Until today, there is no consensus in the literature about the size categories and their respective nomenclature (Table 1) although initiatives exist to standardize the classification for comparison studies (i.e. Thompson et al., 2004; Barnes et al., 2009).

The prevalence of fragments is commonly observed on estuarine and river-dominated beaches around the world (Williams and Simmons, 1997; 1999; Thornton and Jackson, 1998; Santos *et al.*, 2009). They are the result of the breakdown of larger plastic debris that suffered thermal, photochemical, chemical or physical degradation (Costa *et al.*, 2010). Physical dynamics privilege plastics transport, deposition or re-mobilization and, consequently, larger residence times into the estuarine basins, promoting their ageing and fragmentation (Costa *et al.*, 2010; O'Brine and Thompson, 2010).

Impacts (ingestion and entanglement) of marine debris to the biota are important concerns, particularly at MCUs, where

Table 2. Synthetic debris sampled on a sandy beach of the low Goiana Estuary and their most probable sources: local (fishing and local users) and non-local (domestic activities along the river basin). Scores used were 3=very likely, 2=probable, 1=possible, 0=unlikely based on Whiting (1998).

Items/Most probable source	Local				Non-local		Diagnosis
	Fishing		Local users		Domestic		
	Scores	%	Scores	%	Scores	%	
Polystyrene	3	15.9	0	-	0	-	Fishing
Ropes and monofilaments	3	4.9	0	-	0	-	
Nets and nylon fragments	3	0.7	0	-	0	-	
Ice bags	3	0.5	0	-	0	-	
Plastic sashes	3	0.3	0	-	0	-	
Plastic cups, plates and fragments	0	-	3	13.5	1	4.5	Local users
Cigarette buts	1	0.2	3	0.5	0	-	
Plastic bags	2	3.3	2	3.3	2	3.3	Undefined
PET bottles and fragments	1	0.3	3	0.8	3	0.8	
Caps	1	0.6	3	1.9	3	1.9	
Soft packaging and fragments	1	3.3	3	9.6	3	9.6	
Rigid containers and fragments	1	1.8	2	5.7	3	5.7	Domestic
Rubber, foam	1	0.5	1	1	3	1.5	
Sewage (nappies and cotton-buds)	0	-	0	-	3	0.6	
Total (%)		**32.3**		**33.6**		**27.9**	

Table 3. Estuarine and river dominated beaches studied along different regions in the world. Marine debris densities and % of plastics are shown. Population density (hab/km^2) for the drainage area.

Region	Population (hab/km^2)	Marine debris densities	Plastic debris (%)	Land-based sources (%)	Reference
Una River, Brazil	87.9	11.5 - 19.7 items.m^{-2}	~80	>80[d]	Araújo and Costa, 2007
Costa do Dendê, Brazil[a,b]	38.7	~10 items.m^{-1}	91	82[d]	Santos *et al.*, 2009
River Taff, UK[a]	696.1	5.48 items.m^{-1}	49	~100	Williams and Simmons, 1999
Cliffwood Beach, USA	1,357.7	2.7 - 3.7 items.m^{-2}	42.5	74.2	Thornton and Jackson, 1998
São Vicente Estuary, Brazil[c]	496.7	1.33 items.m^{-2}	62.8	~100	Cordeiro and Costa, 2010
Goiana Estuary, Brazil	161.7	0.1 items.m^{-2}	72	100[d]	This study

[a]Marine debris density in items per linear meter; [b]River dominated beaches only; [c]Mangrove area; [d]Beach users included.

human populations depend on estuarine and marine resources. Ingestion is usually related to smaller items (Tourinho *et al.*, 2010; Possato *et al.*, 2011), while larger ropes and nets entangle invertebrates and vertebrates (Laist, 1997; Donohue *et al.*, 2001). The prevalence of fragments indicates a higher chance of an ingestion event in the Goiana Estuary. In fact, ~20% of the resident marine catfishes *Cathorops spixii*, *C. agassizii* and *Sciades herzbergii* were found with nylon fragments in their gastrointestinal contents (N=182) (Possato *et al.*, 2011). Sources of these fragments are directly related to fishing activities. In the MCU, traditional families feed on catfishes when no other resource is available (Dantas *et al.*, 2010). Also, this fish group is an important resource for larger predators as piscivorous fish, birds and mammals. In addition, ~8% of more than five hundred individuals of *Stellifer brasiliensis* and *S. Stellifer* (drums) ingested plastic fragments in this estuary (Dantas *et al.*, 2012). More recently, species of Gerreidae (mojarras) were also found with blue nylon fragments in their gastrointestinal contents (Ramos *et al.*, 2012). Fragments, once more, are directly related to fishing gear. Since juvenile catfishes, drums and mojarras (some < 3 cm in length) ingested plastics, economically important resources such as shellfish (Silva-Cavalcanti and Costa, 2009) may also be impacted filtering small and microplastics (i.e. Thompson *et al.*, 2004; Browne *et al.*, 2008). Similarly, ecologically important species such as *Chelonia mydas* and *Thichechus manatus* in the area are probably also underthreat of plastic pollution (Laist, 1997; Tourinho *et al.*, 2010, Mascarenhas *et al.*, 2002).

To humans, impacts from plastic marine debris are the loss of landscape quality, health problems for beach users, and damages to boats and fishing gear (Nash, 1992; Moore, 2008; Costa *et al.*, 2010; Guebert-Batholo *et al.*, 2011). In the MCU studied here, impacts to fishing gear and fishers themselves difficult their own survival. Gillnet is the most used gear at the Goiana Estuary (Guebert-Batholo *et al.*, 2011). Larger items can be trapped during fisheries, reducing their yield. Cleaning the gear at sea or on land is inefficient, dangerous and time-consuming. Repairing and/or replacement represent a relatively high financial investment to traditional fishing communities (Nash, 1992).

CONCLUSION

Plastics and their fragments are the majority of the marine debris items polluting estuarine beaches. Most of these fragments come from the working of items discarded within the estuary or from the river basin. The case of fisheries related items illustrates well how a large item used to its limit and inadequately discarded can fragment to small enough sizes to threat the biota in different ways (entanglement and then ingestion). Therefore, regardless sizes and types, impacts on the aquatic biota and human populations arise once plastics are disposed in the environment. To protect and confer sustainability to traditional livelihoods around the Goiana Estuary, and other MCUs, the preservation of healthy ecosystems free from plastic pollution must be a priority in management plans. Sources identification must be considered to delineate these initiatives. This will ultimately reduce the amounts of plastics within estuaries, which will result in lower quantities being exported to the ocean. The prevalence (83% of the total) of fragments <100 cm^2 suggests that ingestion is a real threat, especially for vertebrates using the estuary. As we saw, for demersal fishes this is already a real and present danger. For fisherman, impacts to their personal safety and gears are associated with larger sized plastics, which, although less common, are present in the environment. Risk of entanglement, ingestion and their consequences are not difficult to imagine for the other groups of vertebrates that use the estuary as shelter, feeding grounds and nursery.

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