Marine Pollution Bulletin 190 (2023) 114821

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Solid waste ingestion by marine megafauna on Southeast Brazilian coast

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ARTICLE INFO

Keywords:
Marine megafauna
Plastic ingestion
Foraging strategies
Feeding selectivity
Brazil

ABSTRACT

The disparities in the ecology and behavior of marine megafauna may influence their susceptibility to solid waste ingestion; however, this relationship has been underestimated along the Brazilian coast. We analyzed a dataset of 7261 marine megafauna (45 species) necropsied to investigate the influence of their foraging strategies on solid waste ingestion. A total of 1240 specimens ingested solid waste with over 55 % (689) that ingested plastic. Sea turtles were the most impacted taxa, while cetaceans present the lowest frequency. Some characteristics such as regurgitation (e.g., Suliformes and Charadriiformes seabirds) or possess complex foraging strategies (e.g., cetaceans echolocation) may mitigate the negative effects of solid waste ingestion. Also, the variability over the monitoring program likely was influenced by the volume of pollutants transported to the ocean during flood periods, and level of staff training. This study serves as a valuable baseline for solid waste management actions and marine megafauna conservation efforts.

Solid waste comprises materials of terrestrial or marine origin that are present in coastal and deep-sea ecosystems (Lavers and Bond, 2017). The most prevalent form is plastic, which has been extensively released into the environment since the 1950s, resulting in accumulation of this highly persistent material in many ecosystems for millennia (Martin et al., 2020; Pinheiro et al., 2021). It is estimated that between 4.8 and 12.7 million tons of plastic waste enters the ocean annually, which can impact a wide range of taxa globally (Jambeck et al., 2015; Kühn and van Franeker, 2020). As solid waste pollution may not immediately cause severe harm to an individual, it has the potential to accumulate over the food web, particularly at higher trophic levels such as marine megafauna (e.g., sea turtles, seabirds, and cetaceans; Kühn and van Franeker, 2020; Pinheiro et al., 2021). For example, sea turtles are at risk of feeding on solid waste pollution throughout their lives, where even small amounts can cause their death (Schuyler et al., 2014b; Santos et al., 2015a); while seabirds are prone to be impacted by solid waste pollution by the similarity between these materials and their natural prey (Jiménez et al., 2015; Roman et al., 2019b). Marine megafauna are particularly vulnerable to solid waste pollution such as plastic foam, fishing lines, and fishhooks (Jiménez et al., 2015; Kühn and van Franeker, 2020). The chronic effects of this interaction can lead to the obstruction of the digestive tract (Jacobsen et al., 2010), suffocation and entanglement, and other forms of harm, resulting in a growing number of recorded deaths among marine megafauna (Kühn and van Franeker, 2020). Most marine megafauna species along the Brazilian coast are considered endangered or at risk in the IUCN (2020) Red List. Therefore, it is crucial to determine the primary anthropogenic solid waste pollution risks (such as plastic, fishing lines and hooks, among others) for each marine megafauna species (Schuyler et al., 2014a; Roman et al., 2019a; Wilcox et al., 2018). To this end, we utilized records of marine megafauna strandings on beaches from a seven-year (2010–2017) monitoring program along the Southeast Brazilian coast to investigate whether different marine megafauna are predisposed to the impacts of various types of solid waste pollution.

This study was conducted over 763 km of shoreline along the Southern Brazilian coast, between the northern limit of Conceição da Barra (state of Espírito Santo) and the southern limit of Saquarema (state of Rio de Janeiro; 18°32′4″ S, 22°58′33″ S; Fig. 1; PETROBRAS, 2016).

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https://doi.org/10.1016/j.marpolbul.2023.114821
Received 2 November 2022; Received in revised form 3 March 2023; Accepted 5 March 2023
Available online 21 March 2023
0025-326X/

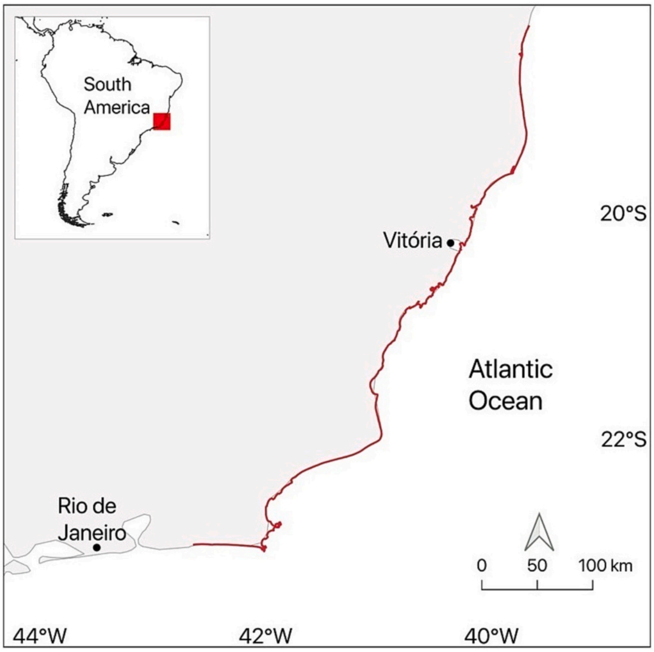

Fig. 1. Map indicating the study area on the Southeastern Brazilian coast. The red line indicates the surveyed area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The region is characterized as a transition zone between warm and temperate climates, with prevailing winds from the East and Northeast quadrants (Nimer, 1989). The area encompasses beaches with varying degrees of urbanization, from cities with 500,000 inhabitants (e.g. Serra and Campos) to small municipalities such as Presidente Kennedy (with a population of over 11,615; IBGE, 2017). The data on the presence/absence of solid waste pollution within each marine megafauna specimen used in this study was obtained from the PMP-BC/ES (beach monitoring program of Campos basin to the northern Espírito Santo coast), an impact assessment conducted by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA; PETROBRAS, 2016). The monitoring program (from October 2010 to September 2017) systematically sampled every day (from 8 a.m. to 8 p.m.) the stranded sea turtles, seabirds, and marine mammals along the coastal zone. Necropsies were performed on fresh carcasses (recently dead animals) or at the beginning of decomposition (with internal organs in good condition) during the daily coastal monitoring. All 7261 necropsies were performed using standard protocols of Work (2000, 2015), Marcondes (2005), and Hocken (2002; Supplemental Table S1).

Animals found entangled were not included in this analysis as the focus of this study was exclusively on animals that ingested marine litter. Also, the species that had less than three necropsies were excluded from the analysis as they would not provide enough sample size for statistical analysis. The dataset was analyzed within a presence/absence matrix using Euclidean distance. Since the dataset included samples of marine megafauna without the ingestion of solid waste pollution, a dummy variable was added to the matrix to account for this (weight 1, Clarke and Gorley, 2006).To evaluate the impact of different types of solid waste pollution (such as plastic, fishing lines, nylon, rubber, cloths, fishhooks, foam, aluminum, wood, and unidentified anthropogenic debris) on the 45 marine megafauna species (Supplemental Table S2), an Analysis of Similarities (ANOSIM) was performed using 999 permutations across years (2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017), species, and their feeding groups. A second-stage multidimensional scaling (MDS) was conducted using a Bray-Curtis similarity matrix to highlight these differences among taxa, while the BIO-ENV procedure was applied to relate the multivariate patterns of marine megafauna with the solid waste pollution (plastic, fishing lines, nylon, rubber, cloths, fishhooks, foam, aluminum, wood, and unidentified solid waste pollution). The Distance-based Linear Model (DistLM) routines were executed using 999 permutations to examine the influence of solid waste pollution (plastic, fishing lines, nylon, rubber, cloths, fishhooks, foam, aluminum, wood, and unidentified anthropogenic debris) on marine megafauna across a seven-year period using a stepwise procedure (selection criterion: adjusted AICc). All analyses were completed using PRIMER v 6.0 software with the PERMANOVA + add-on package (McArdle and Anderson, 2001; Clarke and Gorley, 2006; Anderson et al., 2008).

During the seven years of monitoring, a total of 7261 marine megafauna carcasses were necropsied, of which 1240 individuals (17.1 %) had ingested solid waste pollution (Table 1). All five species of sea turtles that occur on the Brazilian coast ingested solid waste pollution, accounting for over 63 % of the total number of carcasses (4608). Furthermore, the green turtle *Chelonia mydas* and the hawksbill turtle *Eretmochelys imbricata* had the highest frequency of solid waste pollution ingestion (26 % and 25 %, respectively; Fig. 2). Among seabirds, the soft-plumaged petrel *Pterodroma mollis* (44 %) and the great shearwater *Ardenna gravis* (42 %) had the highest frequency, while cetaceans had two carcasses with solid waste pollution ingestion (one for the bottlenose dolphin *Tursiops truncatus* and one for the melon-headed dolphin *Peponochephala electra* species). The number of marine megafauna carcasses with solid waste pollution ingestion increased drastically from 2010 (53 carcasses) to 2017 (2011: 568 carcasses; 2012: 1003 carcasses; 2013: 1562 carcasses; 2014: 1120 carcasses; 2015: 1401 carcasses; 2016: 1071 carcasses; 2017: 483 carcasses; Global R: 0.032, p: 0.001; Fig. 4), and the number of carcasses in 2011 and 2017 were at least 2-fold lower compared to 2012–2016.

Differences among marine megafauna were primarily influenced by their feeding groups, as well as by species-specific anatomy, feeding strategies, and behavior. Omnivorous species such as the green sea turtle (*Chelonia mydas)* and the olive Ridley sea turtle (*Lepidochelys olivacea*) had the highest frequency of ingestion of plastic, fishing lines, nylon, fishhooks, rubber, fabrics, foam, aluminum, and unidentified solid waste pollution along the Southeast Brazilian coast. This was followed by carnivorous taxa which had a lower frequency of ingestion of the same types of pollution, with the exception of aluminum. Piscivorous and molluscivore/piscivorous taxa such as the sooty shearwater *(Ardenna grisea*), great shearwater (*A. gravis*), soft-plumaged petrel (*P. mollis*), magellanic penguin (*Spheniscus magellanicus*), and masked booby (*Sula dactylatra*) were found to have ingested plastic, fishing lines, nylon, fishhooks, rubber, and fabrics, but at a lower frequency than omnivorous and carnivorous species. The molluscovore/saprophagous Atlantic yellow-nosed albatross (*Thalassarche chlororhynchos*) only ingested fishhooks and unidentified solid waste pollution. This was followed by one kelp gull (*Larus dominicanus*) with unidentified solid waste pollution, one melon-headed whale (*Peponocephala electra*) with plastic, and two slender-billed prions (*Pachyptila belcheri*) with unidentified solid waste pollution. During the seven years of monitoring, none of the planktivorous common minke whale (*Balaenoptera acutorostrata*) and

Table 1
Sampling effort. Necropsy record in marine turtles, seabirds, and marine mammals carcasses on the southeastern Brazilian coast, between the coordinates 18°32′4″ S and 22°58′33″ S. Results from October 2010 to September 2017.

	Total (n)	Total solid waste pollution ingestion (n)
Necropsied carcasses	7261	1240
Testudinata (sea turtles)	4608	1112
Procellariiforms (tubenoses)	610	64
Other Seabirds (penguins, frigate, gannets, gulls, terns)	1626	62
Cetartiodactyla (all whales)	417	2

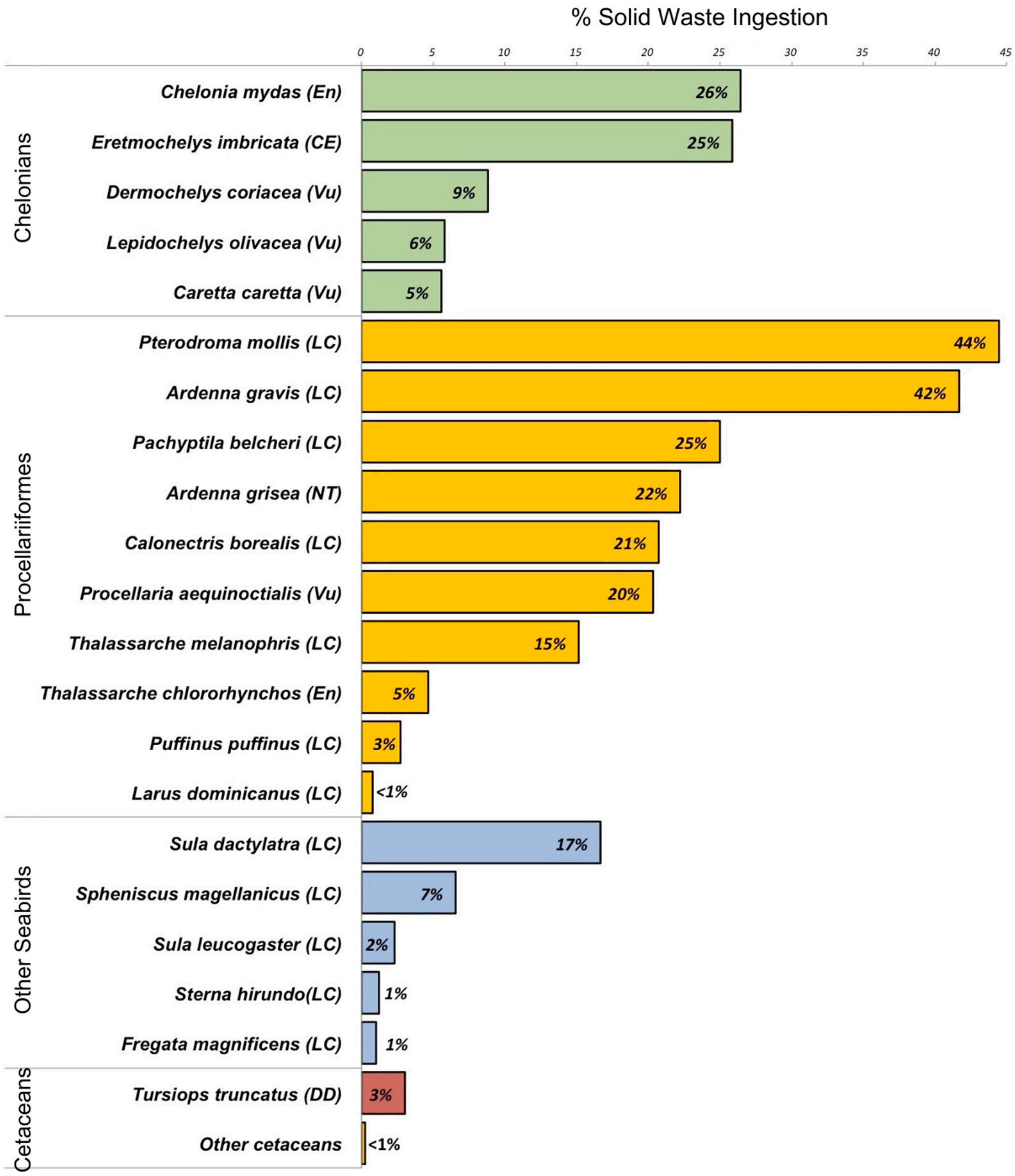

Fig. 2. Percentage of sea turtles, seabirds, and marine mammal species with a high incidence of solid waste pollution ingestion along the Southeast Brazilian coast. Acronyms in parentheses represent the degree of threat of each species according to the IUCN Red List: CE: Critically Endangered; En: Endangered; Vu: Vulnerable; NT: Near Threatened; LC: Least Concern; DD: Data Deficient. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

humpback whale (*Megaptera novaeangliae*), the carnivorous Guiana dolphin (*Sotalia guianenss*), and insectivorous cattle egret (*Bubulcus ibis*) were found to have ingested solid waste pollution. Multivariate analyses revealed that the main differences among marine megafauna and their feeding guilds were explained by plastic debris along the X-axis (total influence of 47.5 %) and unidentified solid waste pollution along the Y-axis (total influence of 27.2 %). Plastic ingestion accounted for over 45 % of the total influence among marine megafauna stranded on the Southeast Brazilian coast (all solid waste pollution explained 74.7 % of the total variation). Additionally, unidentified solid waste pollution mainly influenced sea turtles and seabirds, with a lower contribution from other types of solid waste pollution in the model (BEST, Rho: 0.485; *p*: 0.001; Supplemental Tables S3 to S8, Supplemental Fig. 1; Fig. 3).

This study revealed a drastic increase of at least 10-fold in marine megafauna carcasses that had ingested solid waste pollution from 2011 to 2017 when compared to 2010 (Fig. 4). The increase in rainfall rates from 2016 to 2017 (Servino et al., 2018; Gomes and Bernardino, 2020) likely enhanced the water fluxes along the Southeast Brazilian coast, resulting in the transport of solid waste pollution to more distant and deeper areas of the ocean and a decrease in their availability within the coastal area. Changes in rainfall patterns can greatly influence the amount of solid waste pollution transported to marine ecosystems, as well as the ingestion of solid waste pollution (Pelamatti et al., 2019). Additionally, the drastic differences between 2010 and 2011–2017 may also be a result of a combination of factors such as rainfall variability (Pelamatti et al., 2019), available resources and/or staff experience along the monitoring program (Osmond et al., 2010), marine megafauna population growth, and the rise in inefficient and/or irregular disposal of solid waste pollution that reaches the ocean (Derraik, 2002; Jambeck et al., 2015). Mazaris et al. (2017) published estimates of sea turtle population numbers, which tend to indicate a global increase rather than a decrease. It's also important to note that sea turtle population estimates are difficult to make, due to their elusive nature, nesting, feeding habits and migratory patterns making it hard to track and monitor them effectively.

The species-specific characteristics of each marine megafauna also play a significant role in their susceptibility to solid waste pollution ingestion. For example, the opportunistic feeding behavior of the green sea turtle (*Chelonia mydas*) and the leatherback sea turtle (*Dermochelys coriacea*) increases their chances of ingesting solid waste pollution as they feed on available prey and debris in the water column and on

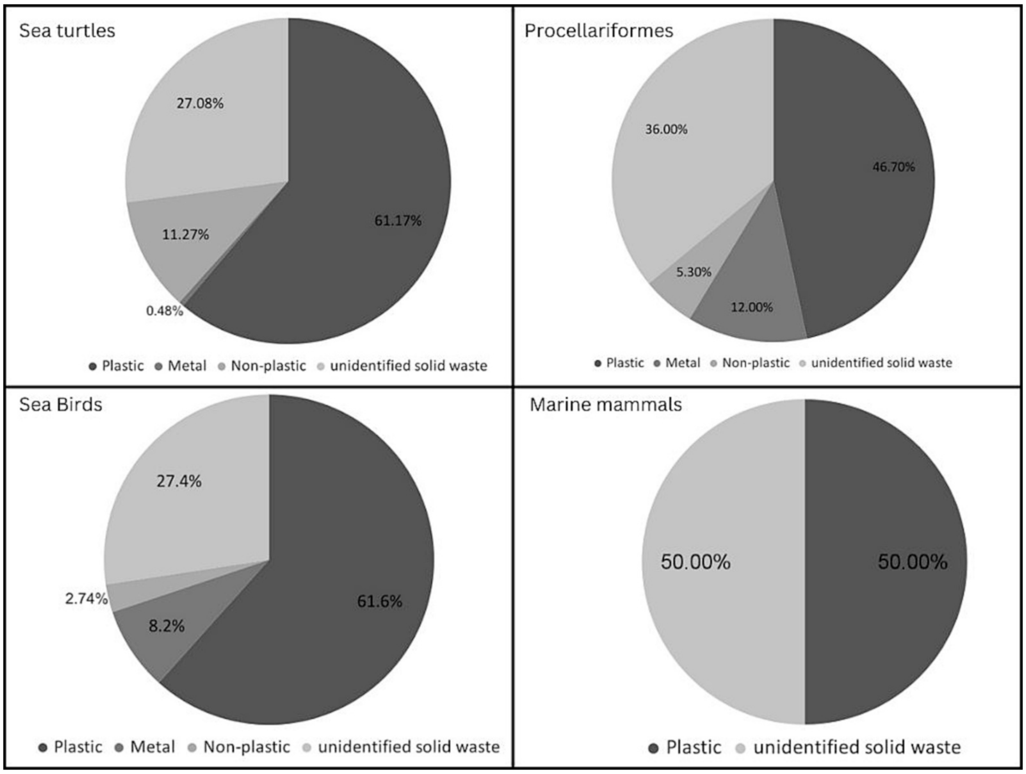

Fig. 3. Different types of solid waste pollution ingested by the 4 major groups of marine megafauna along the Southeast Brazilian coast (sea turtles, procellariforms, other seabirds and marine mammals).

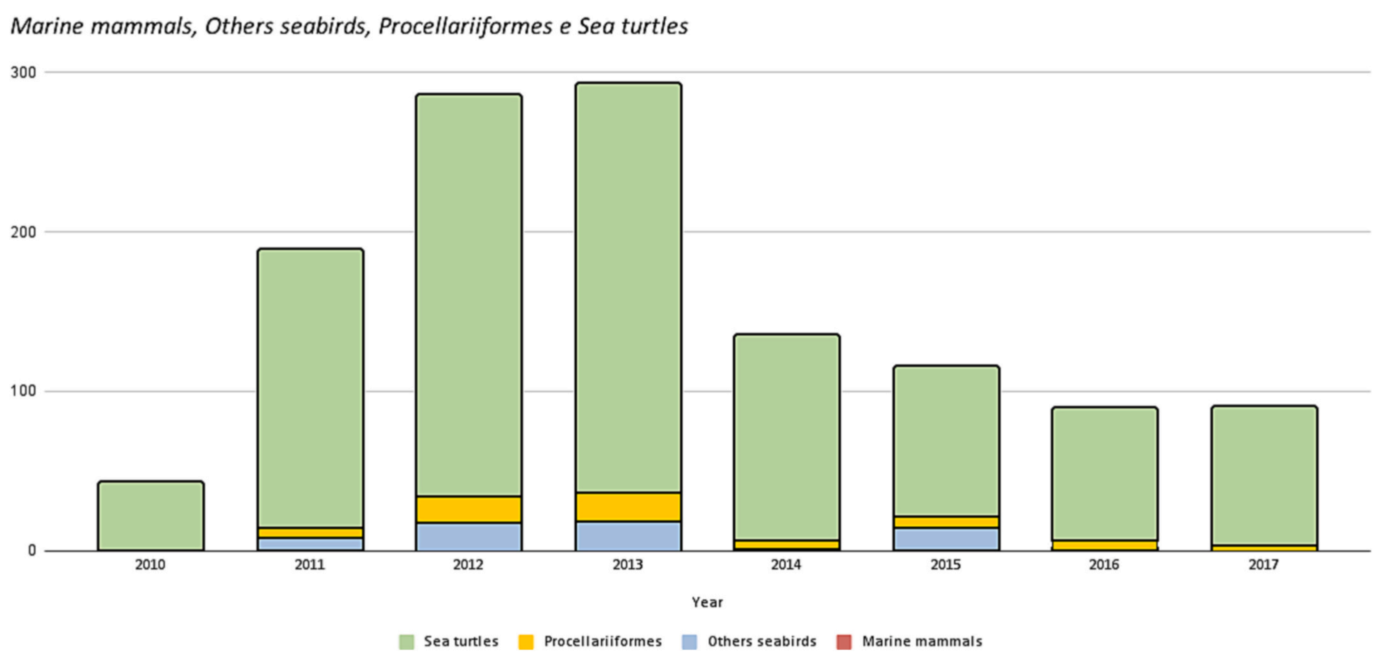

Fig. 4. Ingestion of solid waste pollution in marine megafauna along the seven years of monitoring program along the Southeast Brazilian coast.

substrates (Santos et al., 2015b; Schuyler et al., 2014a; Schuyler et al., 2014b). Additionally, their migration during the pelagic and reproductive phases also increases their exposure to solid waste pollution (Luschi et al., 1998; Tourinho et al., 2010). The presence of esophageal spines in sea turtles (Bjorndal, 1985) also limits their ability to regurgitate or expel synthetic materials, leading to the accumulation of debris in their gut and potentially causing impact, perforation, and death (Schuyler et al., 2014b; Wilcox et al., 2018). Thus, the high incidence of solid waste pollution ingestion by sea turtles is a result of their feeding strategies and anatomical/physiological limitations.

For seabirds, the ingestion of solid waste pollution is directly related to their foraging strategy. Since most of the solid waste pollution in the oceans is floating plastic (Derraik, 2002), species that feed on the water surface are most affected by plastic ingestion, such as boobies (Suliformes), terns (Charadriiformes), and albatrosses (Procellariform; Moser and Lee, 1992; Ryan, 2015). However, seabirds with different foraging strategies also show solid waste ingestion, such as penguins (*S. magellanicus*) that are divers and frigates (*Fregata magnificens*) that have a constant practice of kleptoparasitism on other seabirds (Diamond, 1973; Calixto-Albarrán and Osorno, 2000). Tubenose birds (such as Procellariiformes) also ingest up to 4 times more solid waste pollution than other groups of seabirds (Kühn and van Franeker, 2020; Tourinho et al., 2010). The main reason is that the ventricle of the Procellariiform gastrointestinal tract is a distinct organ, separated from the proventricle by a narrow and angled isthmus (Furness, 1985; Colabuono and Vooren, 2007). Therefore, unlike Suliformes (such as *F. magnificens* and *S. dactylatra*) and Charadriiformes seabirds (such as *L. dominicanus*) that can regularly regurgitate indigestible prey, the order Procellariiformes (such as *P. mollis*) have difficulty in regurgitating indigestible particles, such as synthetic materials like plastic and rubber. Despite having a higher ingestion rate, Suliformes and Charadriiformes quickly regurgitate indigestible items, resulting in lower amounts of anthropogenic debris in their stomachs (Ryan, 2015; Roman et al., 2016). Therefore, all seabirds are at risk of ingesting solid waste pollution throughout their lives.

Cetaceans are known to be more selective in their foraging habits compared to most seabirds and sea turtles (Connor, 2000; Gazda et al., 2005), which can reduce their likelihood of ingesting synthetic materials. The complexity of cetacean foraging strategies, such as echolocation, plays a significant role in the lower amount of marine debris ingested along the Southeast Brazilian coast (Connor, 2000; Gazda et al., 2005). Additionally, baleen whales like *Balaenoptera acutorostrata* and *Megaptera novaeangliae* are larger than toothed whales like *Sotalia guianenss* and other marine megafauna, making it challenging to recover, perform necropsies on, and dispose of their carcasses. This added difficulty in necropsy and stomach analysis can impede the identification of solid waste pollution within cetaceans, which are known to ingest plastic and transfer anthropogenic debris through their food chain worldwide (Nelms et al., 2021). As a result, data on solid waste pollution ingestion by cetaceans may be underestimated along the Southeast Brazilian coast.

The ingestion of solid waste pollution has been recognized as a potential threat to the conservation of sea turtle species by the International Union for Conservation of Nature (IUCN, 2020). However, the impacts of solid waste pollution ingestion on other marine megafauna, such as the yellow-nosed albatross, which is classified as "Endangered," are not widely acknowledged as a concern. This suggests that the impacts caused by solid waste pollution ingestion on most marine megafauna are likely underestimated globally. Moreover, the combination of solid waste pollution ingestion with other ongoing issues such as loss of feeding areas due to natural resources exploitation, pollution, and environmental disasters on the Southeast Brazilian coast (Santos et al., 2015b; Almada and Bernardino, 2017; Hadlich et al., 2018; Sá et al., 2021) and the intensification of climate change in the area (e.g. marine heatwaves, drought periods, intense storms; Mazzuco et al., 2019; Gomes et al., 2021; Anderson et al., 2021) will further exacerbate problems with marine megafauna conservation. Therefore, it is crucial to conduct monitoring on marine megafauna mortality rates related to solid waste pollution along the Brazilian coast (e.g. marine and coastal Long-Term Ecological Research Programs; Cordeiro et al., 2022) to update the list of threats to marine megafauna and to prioritize conservation areas considering the risks of solid waste pollution and cumulative risks for marine megafauna conservation.

In summary, the study found that sea turtles were the major group impacted by solid waste pollution ingestion, followed by tubenose seabirds. The research highlights the importance of understanding the relationship between marine organisms' characteristics and their solid waste pollution ingestion in order to develop effective strategies for marine preservation. Possible strategies for marine conservation include implementing regulations and policies to reduce marine litter, educating the public, conducting beach clean-ups, and working with businesses and industries to adopt more sustainable practices. The study also found that monitoring stranded marine megafauna can be an efficient way to evaluate the impact of marine debris on these species, and this information can be used to make management decisions and protective actions aimed at conserving marine megafauna.

CRediT authorship contribution statement

Lorena Oliveira do Nascimento: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing.

Jonathas Barreto: Conceptualization, Validation, Writing - review & editing.

Luiz Eduardo de Oliveira Gomes: Formal analysis, Statistical analysis, Writing - review & editing.

Lyla Narah Strino Bomfim: Writing - review & editing.

Agnaldo Silva Martins: Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank the PMP-BC/ES team for collecting and performing necropsies on the dead marine megafauna during the monitoring period. We would also like to extend our gratitude to IBAMA and André Barbosa for their helpfulness. Special thanks go to L. Cajaíba and J.B. Teixeira for their support from the outset. We are also grateful to A. Assis and A. P. Bernardo for their help with English editing. Thanks to A. de Paulo for the support within the graphical abstract, and to the Laboratório de Nectologia and UFES team for their helpful comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.114821.

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