



Beached seabirds as plastic biomonitors in Brazil from the Beach Monitoring Project of the Santos Basin (PMP-BS)

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ARTICLE INFO

Keywords:

Bioindicators
Marine debris
Marine pollution
Plastic ingestion
Plastic monitoring

ABSTRACT

Bioindicator species are useful to monitor wildlife exposure to plastic pollution, and responses to plastic leakage and policy interventions. Here we explore the biomonitoring potential of different seabird and shorebirds species across six years of monitoring in Brazil. Using the necropsy stranding database of the Beach Monitoring Project of the Santos Basin (PMP-BS), we evaluated i) the frequency of birds-plastic interactions in Brazil; ii) whether plastic interactions have changed through time and in different coastal regions; and iii) potential bioindicators for monitoring the exposure of seabirds to plastic in the nearshore South Atlantic Ocean. We found 37 species that had ingested plastic, including ten new records, found that the rates of tube-nosed seabirds increased through time, and suggested two potential species. We discuss the potential for biomonitoring marine pollution in the South Atlantic Ocean using PMP-BS, providing a scheme for a better plastic pollution monitoring in Brazil.

1. Introduction

Marine debris are defined as any solid material manufactured or processed by human activity that had its final destination into the marine environment (Galvani et al., 2010; Shevealy et al., 2012). There are numerous negative impacts of litter in marine environments, including posing a threat to marine species (Roman et al., 2021a). To date, >1400 species are recorded to interact with marine litter through entanglement and ingestion (Claro et al., 2019). Plastics typically comprise the majority of items littering marine environments (Galvani et al., 2015). The increase through time in marine plastic pollution (Ostle et al., 2019; Borrelle et al., 2020), caused by leakage of items from both land and sea-based sources to the ocean (Borrelle et al., 2020), is being recognized as an emerging risk for the conservation of marine species (Roman et al., 2021a). There are numerous policy actions being undertaken worldwide

to reduce leakage of waste to the oceans through addressing solid waste management (The Honolulu Strategy, Shevealy et al., 2012; The UN Environment Assembly, Carlini and Kleine, 2018; Haward, 2018).

Given that plastic pollution is a transboundary environmental challenge, there is a need for a worldwide effort to address this issue. One of the major challenges is establishing programs that monitor the presence and impacts of plastic in the environment; enabling the quantification of changes through time, in response to plastic policy change, and ultimately evaluating whether the current approaches are adequate to reach plastic pollution reduction goals. Globally, there are numerous isolated monitoring programs and published datasets on plastic pollution, but due to variable methodologies and lack of harmonization (GESAMP, 2019), it is challenging to analyze these data across broad geographies in an integrated way (Claro et al., 2019). There are theoretical models to estimate the amount of plastic in the ocean in a certain time period (e.g.

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<https://doi.org/10.1016/j.marpolbul.2023.115847>

Received 8 February 2023; Received in revised form 24 June 2023; Accepted 24 November 2023

Available online 4 January 2024

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Eriksen et al., 2014; Jambeck et al., 2015). Nonetheless, ground-truthing these models using robust methods and empirical data to monitor plastic loads and impacts in the ocean is missing across most jurisdictions.

One monitoring strategy that has been contemplated in recent decades is the usage of bioindicators, a biotic component, such as animal species, that can be collected as a passive means to sample presence, wildlife encounter or impact of plastic in the environment (Backer, 2008; Connor et al., 2011; Schlacke et al., 2011; Rapport and Hildén, 2013; Acampora et al., 2016; Matiddi et al., 2017; Fossi et al., 2018; Macali and Bergami, 2020). Since bioindicator approaches are allied to the conservation of species by considering the response of the organisms impacted when they encounter plastic in their environment, this approach further informs adequate and realistic mitigating actions for plastic-wildlife conservation interface.

To date, the only jurisdiction that applies a consolidated international monitoring program using a megafauna bioindicator to track plastic pollution through time is The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) in the North Sea, followed in all European marine areas (European Commission, 2014). In Europe, plastic pollution was recognized as a conservation issue in 2002, when member countries tasked OSPAR with including marine litter in their system of Ecological Quality Objectives (EcoQOs) (Ministerial Declaration of the Fifth International Conference on the Protection of the North Sea, 2002). The OSPAR biomonitoring program was initially developed out of an existing national monitoring program undertaken in the Netherlands, where plastic monitoring with necropsy sampling of plastic debris found in the stomach of a target species of seabird, the northern fulmar (Procellariidae: *Fulmarus glacialis*). The approach of beached seabird necropsy to quantify ingested plastic was developed for international implementation by OSPAR as one of its EcoQOs (OSPAR, 2008, 2009, 2010; Van Franeker et al., 2011).

In Brazil, the Beach Monitoring Project of the Santos Basin (Projeto de Monitoramento de Praias da Bacia de Santos, PMP-BS) is a pioneering monitoring program that daily covers an extensive coastal region in the South and Southeast Brazil in search for the stranded marine megafauna (seabirds, sea turtles and marine mammals) to perform veterinary care (PETROBRAS, 2019), including necropsy, a direct method to assess ingested plastic (Provencher et al., 2017). The PMP-BS presents a valuable opportunity for a plastic bioindicator monitoring program with occurrence, ecological and pathological data of stranded animals in a vast and daily updated database.

The major Brazilian reports about plastic ingestion in seabirds were published or have reported data from more than a decade ago (e.g. Colabuono and Vooren, 2007, Colabuono et al., 2009, 2010; Petry et al., 2008; Barbieri, 2009; Tourinho et al., 2010; Tavares et al., 2017). Daudt et al. (2022) reviewed reports on plastic ingestion by waterbirds in Brazil and highlighted that the most studies do not use standard metrics as now recommended (Provencher et al., 2019a), neither had their main objective in reporting the ingestion. Recently, some studies have published new data on seabird plastic ingestion with better standardized metrics (Vanstreels et al., 2021; do Nascimento et al., 2023), yet, more up-to-date information is needed to track the exposure of wildlife in recent years and from other coastal areas in Brazil.

Therefore, our main goal was to analyze the number of stranded birds along the entire coast monitored by the PMP-BS across 6 years to understand which marine species that are collected through this program have interacted with plastic pollution and have potential use as a plastic bioindicator for the South Atlantic. This study aims to i) assess the frequency of seabird-plastic pollution interactions in Brazil using the PMP-BS database, ii) determine whether plastic interactions have changed through time and in different coastal regions across the course of this study to evaluate PMP-BS potential as a monitoring project for plastic pollution, and iii) identify potential bioindicator seabirds for plastic monitoring.

2. Methods

2.1. Beach Monitoring Project of the Santos basin (PMP-BS)

The PMP-BS is developed as a condition of the federal environmental licensing of PETROBRAS's activities for production and flow of oil and natural gas in the Santos Basin Pre-Salt Pole, conducted by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). Its main objective is to evaluate the possible impacts of the activities on the target marine megafauna (seabirds, sea turtles and marine mammals) by monitoring the coastal extension of the South and Southeast Brazil to perform veterinary care, including necropsy and rehabilitation (PETROBRAS, 2019). All data collected by the PMP-BS is publicly available at the Aquatic Biota Monitoring Information System (SIMBA, 2022) where we extracted the data for this study.

The monitoring program is undertaken across 4 States from the South (Santa Catarina, SC; and Paraná, PR) and Southeast (São Paulo, SP; and Rio de Janeiro, RJ) Brazil and covers the municipalities of Laguna – SC (28°29'43.1"S 48°45'38.5"W) to Saquarema – RJ (22°56'08.1"S 42°29'43.9"W) (Fig. 1), covering 2013.44 km of monitoring extension (PETROBRAS, 2019). Monitoring is consistently carried out along the coastal extension with active search on a daily (768.95 km) and weekly frequency (45.47 km, areas of difficult access), embarked actions (845.74 km), partnerships with other institutions (80.97 km) and notification of occurrences of beached animals by the community (258.45 km). Beach monitoring is done preferably in the early hours of the day, with the main objective of finding stranded marine megafauna (seabirds, sea turtles and marine mammals).

Animals are taken to the facilities of a Veterinary Care Network of the Executive Institutions, composed of Stabilization Units, Marine Mammal Necropsy Units, and Rehabilitation and Depetrolization Centers; where rehabilitation, release, and destination of recovered animals are performed, as well as necropsies of animals found dead or that eventually die in care (PETROBRAS, 2019). The PMP-BS comprise a work team of 11 Executive Institutions (UDESC, Instituto Australis, Associação R3 Animal, Univali, Univille, LEC/UFPR, IpeC, Biopesca, Instituto Greomar, Instituto Argonauta, and Econservation). All logistics and protocols applied are present in the Integrated Executive Project of the PMP-BS (PETROBRAS, 2019).

2.2. Accessing marine debris ingestion

Monitoring plastic pollution is not one of the goals of the PMP-BS, however, it is possible to diagnose marine debris ingestion from its database (SIMBA, 2022). We selected only birds for this study because they are the most numerous and diverse within the marine megafauna (Croxall et al., 2012), as well as having the largest scientific record regarding plastic ingestion (Provencher et al., 2017; Kühn and Van Franeker, 2020). All species were classified according to their status in Brazil according to the Brazilian Ornithological Records Committee (Pacheco et al., 2021).

We evaluate data from necropsy records of beached individuals found dead or that eventually died in care. We only considered carcasses that were in good/fresh condition (external examination: normal appearance, no action of scavengers, firm feathers, and beaks, with normal coloring for the species; internal examination: firm musculature and fat, intact organs, no architectural changes, or consistency) and fair condition/moderate decomposition with intact organs (external examination: normal appearance, slight protrusion of cloaca, skin of abdominal region with bile soak, dried eyes, detachment of skin from legs; internal examination: organs tinged by hemolytic and biliary soaking, maintenance of the architecture and consistency of the organs and viscera, intestines dilated by gas). Carcasses that had been scavenged, individuals whose taxonomic level could not be identified due to carcass autolysis, and animals that spent more than two weeks in rehab before dying were not considered.

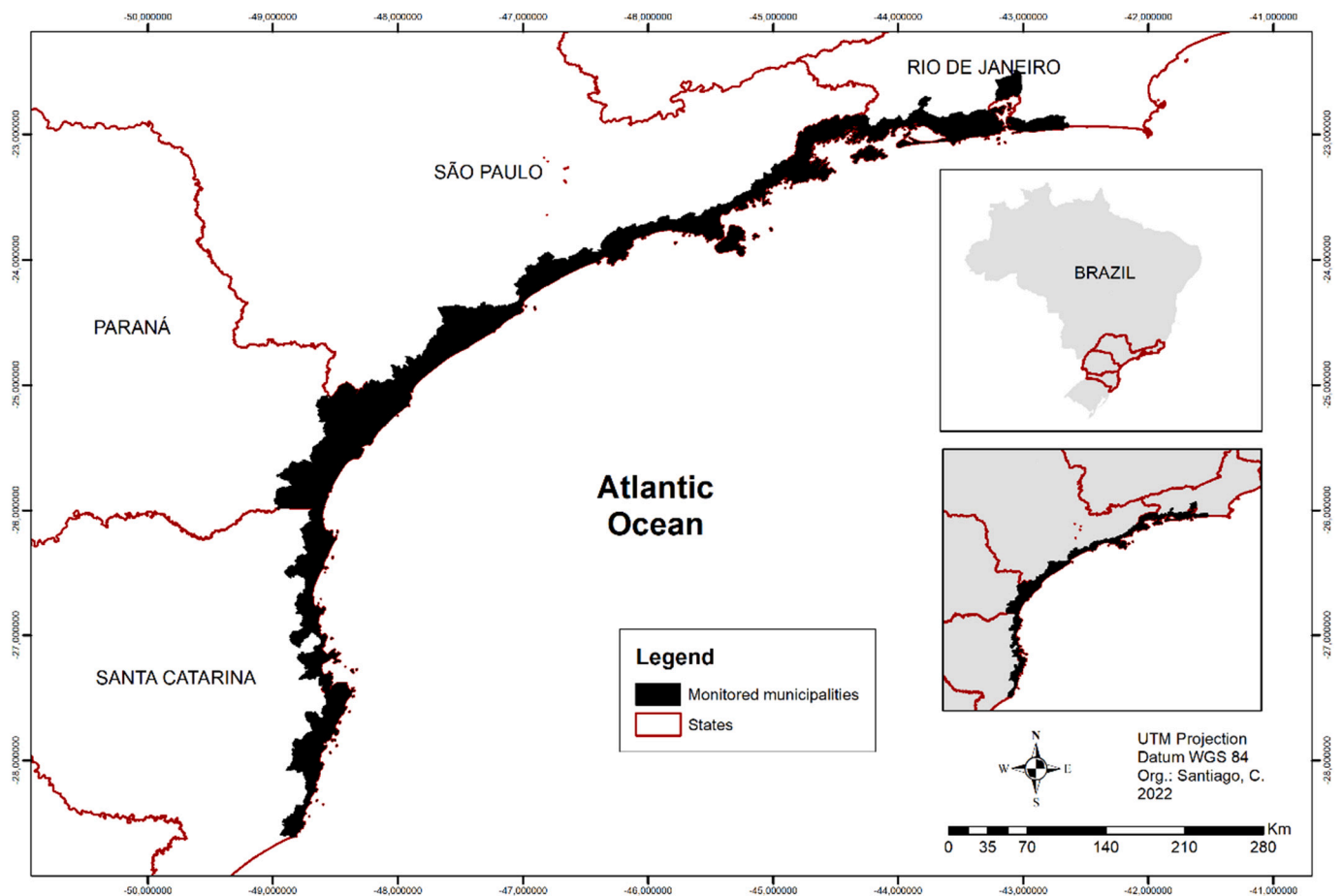


Fig. 1. Coastal extension monitored by PMP-BS comprising four Brazilian States: Santa Catarina (SC), Paraná (PR), São Paulo (SP) and Rio de Janeiro (RJ).

During necropsy procedure, the entire gastrointestinal tract of the animal is dissected, and its content is sorted in a sequence of granulometric sieves (2 mm, 1 mm, 0.5 mm) according to the PMP-BS protocol. Marine debris are visually sorted, and the Executive Institutions must assign their presence in the database. The Institutions may describe the gastrointestinal contents (not mandatory). To understand the main type of the ingested material, we searched for the description of marine debris based on the classifications provided by Provencher et al. (2017) and Roman et al. (2019a): hard plastic, flexible plastic, threadlike plastic, rope, rubber, hook, glass, foam, balloon, and metal. This information was not available for all individuals, neither there is detailed information of amount and mass (total and per type), size and color of items. Here, we could only access the proportion of animals that had ingested debris. The frequency of occurrence (FO) in percent of ingested marine debris was calculated for all species. All these data were not simply condensed in database, and we had to check it in several information from the vast necropsy dataset. How it was systematically done is presented in the supplementary material.

For the analysis, we target only Procellariiformes species from Southern Hemisphere (visitors and vagrants) related to marine debris ingestion. These animals are known to have the highest level of plastic accumulation in seabird (Roman et al., 2019b; Kühn and Van Franeker, 2020) from the pelagic habitat.

2.3. Data analysis

All analyses were performed with R statistical software (R Core Team, 2020). The variation of debris ingestion by all individuals (FO) over the years (2017 to 2022) in different states (PR, RJ, SC and SP) was analyzed by fitting a generalized linear model (GLM), assuming

Binomial error. The best statistical model applied in the analysis was chosen by comparisons between the fits of the full models and models with variable reduction using the maximum likelihood testing to compare the changes in deviances before and after the removal of variables. Interactions between variables were considered only when significant. Quality of the adjustments obtained was evaluated using “half-normal-plot” graphs with simulated envelopes at the 95 % level (Moral et al., 2016). When the effect of variables was significant, the means of the proportion of birds that ingested marine debris were compared using the maximum likelihood multiple comparisons test of the “cld” function in the “multcomp” package of the R software.

3. Results

A total of 11,017 necropsy records between 2017 and 2022 by the PMP-BS were analyzed, with 73 species assessed, of which 37 species ($n = 1437$) had ingested marine debris (FO of 13,04 %, Table 1). Among seabird species (Gaston, 2004; Provencher et al., 2019b) that had interacted with marine debris, 10,537 individuals were sampled, of which 1415 were affected (FO of 13,43 %), comprising 29 species in 4 orders (Charadriiformes, Procellariiformes, Sphenisciformes and Suliiformes) out of 46 seabird species.

Regarding the type of ingested marine debris, we found mostly plastic and other synthetic waste (Fig. 2). The most common items were flexible plastic (209 birds), threadlike plastic (197 birds), hard plastic (195 birds) and rubber (47 birds). Other items included foamed synthetic, balloon, with all items amounting to 87 % of the birds.

The reporting of Procellariiformes related to plastic ingestion increased across years ($X^2 = 49.772$, $df = 1$, $p < 0.05$) and we also detected a difference in reporting between the Brazilian States ($X^2 =$

Table 1

List of birds necropsied by PMP-BS. Total = all birds necropsied, Debris = number of birds with marine debris ingestion, FO = frequency of occurrence. Bolded species are those for which this was the first record of debris ingestion.

Order	Family	Species	Common name (ENG/PT-BR)	Status in Brazil ^a	Seabirds	Total	Debris	FO
		<i>Charadrius collaris</i>	Collared Plover/Batuíra-de-coleira	BR		3	0	0,00 %
		<i>Charadrius semipalmatus</i>	Semipalmated Plover/Batuíra-de-bando	VI (N)		8	0	0,00 %
	Charadriidae	<i>Pluvialis dominica</i>	American Golden-Plover/batuiruçu	VI (N)		4	1	25,00 %
		<i>Pluvialis squatarola</i>	Black-bellied Plover/Batuiruçu-de-axila-preta	VI (N)		1	0	0,00 %
	Haematopodidae	<i>Vanellus chilensis</i>	Southern Lapwing/Quero-quero	BR		4	0	0,00 %
		<i>Haematopus palliatus</i>	American Oystercatcher/Piru-piru	BR		18	0	0,00 %
		<i>Anous stolidus</i>	Brown Noddy/Trinta-réis-escuro	BR	x	21	0	0,00 %
		<i>Chroicocephalus cirrocephalus</i>	Gray-hooded Gull/Gaivota-de-cabeça-cinza	BR	x	1	0	0,00 %
		<i>Chroicocephalus maculipennis</i>	Brown-hooded Gull/Gaivota-maria-velha	BR	x	3	0	0,00 %
		<i>Larus dominicanus</i>	Kelp Gull/gaivotão	BR	x	1634	158	9,67 %
		<i>Onychoprion fuscatus</i>	Sooty Tern/Trinta-réis-das-rocas	BR	x	2	0	0,00 %
		<i>Rynchops niger</i>	Black Skimmer/talha-mar	BR	x	30	2	6,67 %
	Laridae	<i>Sterna dougallii</i>	Roseate Tern/Trinta-réis-róseo	VI (N), VA (E)	x	1	0	0,00 %
		<i>Sterna hirundinacea</i>	South American Tern/trinta-réis-de-bico-vermelho	BR	x	129	4	3,10 %
		<i>Sterna hirundo</i>	Common Tern/trinta-réis-boreal	VI (N, E)	x	64	3	4,69 %
		<i>Sterna paradisaea</i>	Arctic Tern/Trinta-réis-ártico	VI (N)	x	3	0	0,00 %
Charadriiformes		<i>Sterna trudeaui</i>	Snowy-crowned Tern/Trinta-réis-de-coroa-branca	BR	x	10	0	0,00 %
		<i>Thalasseus acutiflavus</i>	Cabot's Tern/trinta-réis-de-bando	BR, VI (S, N)	x	158	2	1,27 %
		<i>Thalasseus maximus</i>	Royal Tern/Trinta-réis-real	BR, VI (S)	x	34	0	0,00 %
	Recurvirostridae	<i>Himantopus melanurus</i>	White-backed Stilt/pernilongo-de-costas-brancas	BR		14	1	7,14 %
		<i>Calidris alba</i>	Sanderling/Maçarico-branco	VI (N)		10	0	0,00 %
		<i>Calidris canutus</i>	Red Knot/Maçarico-de-papo-vermelho	VI (N)		4	0	0,00 %
		<i>Calidris fuscicollis</i>	White-rumped Sandpiper/Maçarico-de-sobre-branco	VI (N)		10	0	0,00 %
	Scolopacidae	<i>Calidris himantopus</i>	Stilt Sandpiper/Maçarico-pernilongo	VI (N)		1	0	0,00 %
		<i>Gallinago paraguaiiae</i>	South American Snipe/Narceja	BR		1	0	0,00 %
		<i>Tringa melanoleuca</i>	Greater Yellowlegs/maçarico-grande-de-perna-amarela	VI (N)		2	1	50,00 %
		<i>Stercorarius antarcticus</i>	Brown Skua/Mandrião-antártico	VI (S)	x	2	0	0,00 %
		<i>Stercorarius chilensis</i>	Chilean Skua/Mandrião-chileno	VI (S)	x	2	0	0,00 %
		<i>Stercorarius longicaudus</i>	Long-tailed Jaeger/Mandrião-de-cauda-comprida	VI (N)	x	5	0	0,00 %
	Stercorariidae	<i>Stercorarius maccormicki</i>	South Polar Skua/mandrião-do-sul	VI (S)	x	1	1	100,00 %
		<i>Stercorarius parasiticus</i>	Parasitic Jaeger/mandrião-parasítico	VI (E)	x	6	0	0,00 %
		<i>Stercorarius pomarinus</i>	Pomarine Jaeger/mandrião-pomarino	VI	x	3	0	0,00 %
Coraciiformes	Alcedinidae	<i>Chloroceryle americana</i>	Green Kingfisher/martim-pescador-pequeno	BR		1	0	0,00 %
Gruiformes	Rallidae	<i>Aramides saracura</i>	Slaty-breasted Wood-Rail/saracura-do-mato	BR		1	0	0,00 %
		<i>Porphyrio martinica</i>	Purple Gallinule/frango-d'água-azul	BR		1	0	0,00 %
		<i>Ardea alba</i>	Great Egret/garça-branca-grande	BR		93	4	4,30 %
		<i>Ardea cocoi</i>	Cocoi Heron/garça-moura	BR		30	1	3,33 %
		<i>Botaurus pinnatus</i>	Pinnated Bittern/socó-boi-baio	BR		1	0	0,00 %
		<i>Bubulcus ibis</i>	Cattle Egret/garça-vaqueira	BR		6	0	0,00 %
		<i>Butorides striata</i>	Striated Heron/socozinho	BR		5	0	0,00 %
		<i>Egretta thula</i>	Snowy Egret/garça-branca-pequena	BR		28	1	3,57 %
		<i>Ixobrychus exilis</i>	Least Bittern/socó-vermelho	BR		2	0	0,00 %
		<i>Ixobrychus involucris</i>	Stripe-backed Bittern/socó-amarelo	BR		1	0	0,00 %
		<i>Nyctanassa violacea</i>	Yellow-crowned Night-Heron/savacu-de-coroa	BR		4	0	0,00 %
		<i>Nycticorax nycticorax</i>	Black-crowned Night-Heron/socó-dorminhoco	BR		92	7	7,61 %
	Threskiornithidae	<i>Phimosus infuscatus</i>	Bare-faced Ibis/tapicuru	BR		25	6	24,00 %
		<i>Thalassarche chlororhynchos</i>	Yellow-nosed Albatross/albatroz-de-nariz-amarelo	VI (S)	x	68	4	5,88 %
	Diomedidae	<i>Thalassarche melanophris</i>	Black-browed Albatross/albatroz-de-sobrancelha	VI (S)	x	56	14	25,00 %
		<i>Fregatta grallaria</i>	White-bellied Storm-Petrel/painho-de-barriga-branca	VI (S)	x	1	0	0,00 %
Procellariiformes	Oceanitidae	<i>Oceanites oceanicus</i>	Wilson's Storm-Petrel/alma-de-mestre	VI (S)	x	40	10	25,00 %
		<i>Ardenna gravis</i>	Great Shearwater/pardela-de-barrete	VI (S)	x	72	49	68,06 %
		<i>Ardenna grisea</i>	Sooty Shearwater/pardela-escuro	VI (S)	x	19	8	42,11 %
		<i>Calonectris borealis</i>	Cory's Shearwater/cagarra-grande	VI (E)	x	119	34	28,57 %
	Procellariidae	<i>Calonectris edwardsii</i>	Cape Verde Shearwater/cagarra-de-cabo-verde	VI (E)	x	1	1	100,00 %
		<i>Daption capense</i>	Cape Petrel/pomba-do-cabo	VI (S)	x	3	2	66,67 %

(continued on next page)

Table 1 (continued)

Order	Family	Species	Common name (ENG/PT-BR)	Status in Brazil ^a	Seabirds	Total	Debris	FO
		<i>Fulmarus glacialisoides</i>	Southern Fulmar/pardeão-prateado	VI (S)	x	7	4	57,14 %
		<i>Halobaena caerulea</i>	Blue Petrel/petrel-azul	VA (S)	x	2	1	50,00 %
		<i>Lugensa brevirostris</i>	Kerguelen Petrel/grazina-de-bico-curto	VA (S)	x	1	0	0,00 %
		<i>Macronectes giganteus</i>	Southern Giant-Petrel/petrel-grande	VI (S)	x	34	16	47,06 %
		<i>Macronectes halli</i>	Northern Giant-Petrel/petrel-grande-do-norte	VI (S)	x	2	1	50,00 %
		<i>Pachyptila belcheri</i>	Slender-billed Prion/faigão-de-bico-fino	VI (S)	x	2	2	100,00 %
		<i>Pachyptila desolata</i>	Antarctic Prion/faigão-rola	VI (S)	x	16	10	62,50 %
		<i>Pachyptila vittata</i>	Broad-billed Prion/faigão-de-bico-largo	VA (S)	x	3	2	66,67 %
		<i>Procellaria aequinoctialis</i>	White-chinned Petrel/pardela-preta	VI (S)	x	139	66	47,48 %
		<i>Procellaria conspicillata</i>	Spectacled Petrel/pardela-de-óculos	VI (S)	x	4	2	50,00 %
		<i>Pterodroma incerta</i>	Atlantic Petrel/grazina-de-barriga-branca	VI (S)	x	14	0	0,00 %
		<i>Pterodroma mollis</i>	Soft-plumaged Petrel/grazina-delicada	VI (S)	x	35	17	48,57 %
		<i>Puffinus puffinus</i>	Manx Shearwater/pardela-sombria	VI (E)	x	1044	209	20,02 %
Sphenisciformes	Spheniscidae	<i>Spheniscus magellanicus</i>	Magellanic Penguin/pinguim-de-magalhães	VI (S)	x	4031	588	14,59 %
	Fregatidae	<i>Fregata magnificens</i>	Magnificent Frigatebird/fragata	BR	x	645	53	8,22 %
	Phalacrocoracidae	<i>Nannopterum brasilianum</i>	Neotropic Cormorant/biguá	BR	x	785	41	5,22 %
Suliformes	Sulidae	<i>Sula dactylatra</i>	Masked Booby/atobá-grande	BR	x	1	0	0,00 %
		<i>Sula leucogaster</i>	Brown Booby/atobá-pardo	BR	x	1394	111	7,96 %

^a Status in Brazil: BR = breeding resident; VI = regular non-breeding visitor from the South (S), North (N), East (E) or West (W) and VA = Vagrant from the South (S), North (N), East (E) or West (W), or from an unspecified direction.

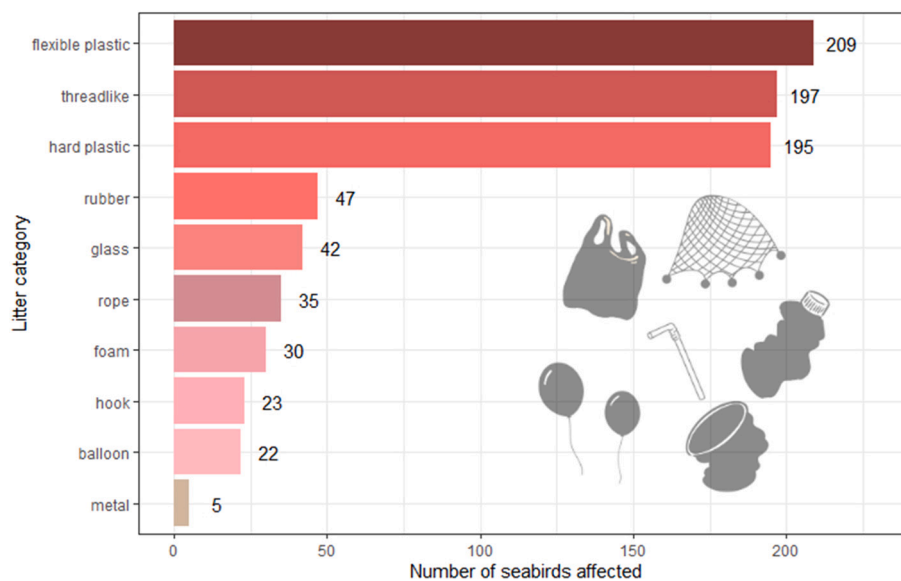


Fig. 2. Types of ingested marine debris found in necropsy of birds.

25.216, df = 3, p < 0.05). Our statistical model did not find significance for the Year:State interaction, being dropped from the model. Differences by the maximum likelihood between groups with p < 0.05 highlighted a standout of the State of PR (FO = 63.75 %) from other States. We found two similar groups encompassing the States of RJ-SC (RJ = 29.14 % and SC = 30.29 %) at the extremities, and the States of RJ-SP (RJ = 29.14 % and SP = 44.61 %) at the Northern of PMP-BS (Fig. 1). When the species are examined across each State from 2017 to 2022 (Fig. 3), PR had a great increase from 2018, RJ had an increase from 2017 to 2019, and from 2020 to 2022, SC had a continuous increase from 2017 to 2021, and SP had an increase only from 2018 to 2019, and from 2021 to 2022. All States had an increase from the initial year to the final (Fig. 3).

4. Discussion

This study used necropsy records to better understand the interaction between birds and plastic pollution in Brazil, with three key findings.

First, we found that 37 species reported by PMP-BS in Brazil interact with mostly plastic (Table 1). Second, we found that the rate of Procellariiformes interactions has increased over time in Brazil between 2017 and 2022. Finally, we identified two seabird species with plastic pollution biomonitoring potential: the Great Shearwater and the White-chinned Petrel. This research has significant implications for the state of seabird conservation and plastic pollution monitoring in Brazil and the South Atlantic.

4.1. Seabirds and plastic pollution in Brazil

The first major result of this study is the frequency of interactions between seabirds and shore birds in Brazil and plastic pollution. Among the 37 beached bird species reported here, ten possibly present their first record of marine debris ingestion from necropsy (the American Golden-Plover, the Black Skimmer, South American Tern, the White-backed Stilt, the Greater Yellowlegs, the South Polar Skua, the Cooi Heron, the Snowy Egret, the Black-crowned Night-Heron, and the Bare-faced

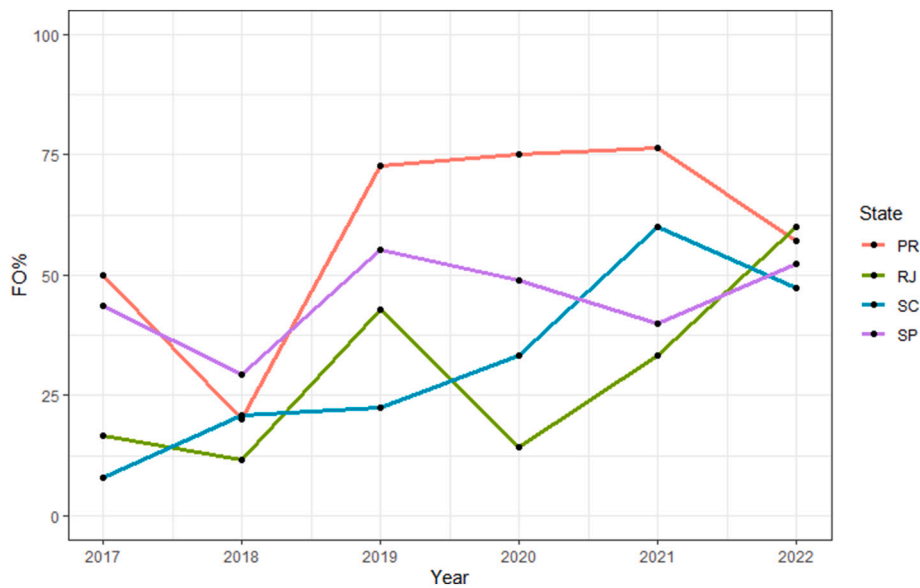


Fig. 3. Frequency of occurrence of ingested debris of Procellariiformes species in four Brazilian states (Santa Catarina - SC, Paraná - PR, São Paulo - SP and Rio de Janeiro - RJ) by year.

Ibis). Of all the seabirds, three are globally threatened: the Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos* (endangered), the White-chinned Petrel *Procellaria aequinoctialis*, and the Spectacled Petrel *Procellaria conspicillata* (vulnerable); and two near threatened: the Sooty Shearwater *Ardenna grisea* and the Cape Verde Shearwater *Calonectris edwardsii*; all of them Procellariiformes. The other species have the status of least concern (<http://www.birdlife.org>, 2022). High frequencies of ingested plastics among seabirds birds sampled, especially in Procellariiformes, raise the question of whether marine litter may pose a conservation concern for these species in Brazil.

Previous studies have reiterated our finding that plastic waste is well-represented among the main debris ingested by seabirds (Provencher et al., 2017). Some bird species can eliminate large plastic items they have ingested through their natural behavior of regurgitating indigestible solid items from the stomach. However, regurgitation is not common in all species, and others have gut physiologies that retain solid items (Rothstein, 1973). For example, Procellariiformes have a constriction between the pro-ventricle and gizzard that retains ingested plastic (Rothstein, 1973). Due to their propensity for plastic ingestion and retention, Procellariiformes are likely to be utilized as useful indicators to track plastic pollution. In our study, Procellariiformes were the taxonomic order that presented the highest FO% of ingested plastic and, within it, members of the Procellariidae family (petrels) were the birds with the highest frequency of occurrence of marine debris ingestion, with 10 species presenting a FO% of ingested plastic greater than or equal to 50 % (Table 1), reflecting the high occurrences of plastic ingested by petrels that are also seen in other studies of seabird plastic ingestion in Brazil (Colabuono et al., 2009; Tourinho et al., 2010; Vanstreels et al., 2021). Some species had low sample size (e.g. the Cape Verde Shearwater, the Cape Petrel, the Blue Petrel, the Northern Giant-Petrel) with some stating FO of 100 %. However, the fewer individuals sampled, most had ingested plastic. These species do not usually beach in Brazil, what raises the question of whether their high FO is biased or indeed these species are constantly ingesting plastic. Continuous monitoring is needed to answer this question.

Twenty-nine seabird species beached along the Brazilian coast ingested plastic pollution prior to death, raising concerns about the potential for widespread impacts on animal health and conservation (Dias et al., 2019). Ingestion of plastic can cause a direct obstruction or perforation of the gastrointestinal tract (Pierce et al., 2004; Roman et al., 2019a). Additionally, the presence of PCBs and organochlorines

associated with plastic at sea (often used in pesticides) (Colabuono et al., 2010), may lead to sublethal impacts on the reproductive condition of species (Provencher et al., 2017). Three classes of marine debris: fishing debris (ropes, nets, and tackle), flexible plastics and rubber latex/balloons have been previously identified to be responsible for the main risk of mortality when ingested in several species of seabirds (Roman et al., 2019a). Given that flexible plastic, threadlike plastic (mostly associated with fishing debris), and rubber (Fig. 2) represented in this study three of the four most common items ingested by seabirds, later found beached, the risk to these species may be reduced by addressing the mismanagement of these items. We recommend that policy actions could focus on reducing the waste through regulations, bans, and replacement of items that can cause a high risk of mortality, such as plastic bags and packaging, ropes, fishing nets and balloons. These studies can better elucidate objectives for a monitoring program considering an acceptable level of pollution that would not cause harm to the species (Fossi et al., 2018).

We also observed that the frequency of plastic ingestion varied along Brazil's coastline, with birds in some States having higher frequencies of debris than others, such as the State of PR (FO = 63.75 %) and the State of SP (FO = 44.61 %). PMP-BS encompasses many Executive Institutions working on the necropsy of beached birds and there are different staff of biologists and veterinarians working on the PMP-BS. Reporting the ingestion of debris is not the core goal and the difference in reporting the ingestion of marine debris could simply reflect too many people involved in which is difficult to standard the process, especially when it is not the main goal.

On the other hand, this difference might also be explained by a possible latitudinal influence on beached seabirds-plastic ingestion interface, in which the birds exposed to a higher load of plastic in the open ocean might strand in specific areas along the Brazilian coast. More recently, Vanstreels et al. (2021) quantified marine debris ingestion in birds stranded on the coast from Arraial do Cabo in RJ state to Conceição da Barra in Espírito Santo state (ES) between 2019 and 2021 through the Beach Monitoring Project of the Campos and Espírito Santo Basins (PMP-BC/ES), another monitoring program from the same federal environmental licensing of PETROBRAS. The study uses the same monitoring methodology of the PMP-BS and the region monitored is the continuation to the north of PMP-BS. They evaluated 126 individuals in 392 km of the coastal area, representing 19 bird species, with a total FO of 30 %, higher than found here (FO of 13.04 %, 11,017 individuals).

Considering species level, the FO in ES was also higher. The number of stranded birds from PMP-BC/ES is considerably smaller, as well as the extent of the monitored area. However, proportionally more birds seem to be ingesting marine debris, which could indicate the existence of coastal patches for plastic ingestion of stranded birds.

Such information brings new questions to evaluate plastic ingestion in seabirds on the Brazilian coast, such as the influence of latitude and ocean currents on stranded seabirds, and there is not an up-to-date survey on other Brazilian states comprehensively monitoring plastic ingestion in seabirds. This would help to target relevant coastal areas for biomonitoring efforts, for examples.

4.2. Increasing in the incidence of plastic ingestion in Procellariiformes species through years

The second major finding of this study is an increase in FO% of ingested plastic by Procellariiformes over 6 years. Here, we did not analyze the individual plastic load (mass) of ingested plastic, what is recommended to better quantify and elucidate the temporal trend over at least 10 years of recent sampling from linear regression (Van Franeker et al., 2021), because this data is not available in PMP-BS database. The FO parameter is not enough to establish a temporal trend. Nonetheless, the increased reporting of birds ingesting plastic is an interesting result and might be explained in two ways.

Firstly, it is likely to be related to the consistent increase of pollution itself in the oceans (Geyer et al., 2017; Lebreton and Andrady, 2019), which would increase the exposure of greater numbers of seabirds. In Brazil, Petry and Benemann (2017) detected an increase in FO% in White-chinned Petrels in recent decades, however, the plastic load did not show a significant change. They conducted surveys once a month during three distinct periods (1990, 1997 to 1998, and 2007 to 2014), focusing on dead beached White-chinned Petrels ($n = 114$). For a robust temporal analysis, consistent, sufficient, and standardized sampling is needed, which is done by the PMP-BS with daily monitoring and necropsy of stranded birds on the coast. However, PMP-BS do not provide the robust data needed to establish a significant temporal trend.

Secondly, the increased reporting of birds ingesting plastic might also be related to the development of the monitoring project through years and better technical performance. New directives and technical training for the PMP-BS staff are constantly happening. In the beginning of the Project in 2015, protocols were being developed and tested. In 2019, the PMP-BS executive project were integrated in a new one (PETROBRAS, 2019), in which the analysis of gastrointestinal contents became mandatory. As an example, from 2019 some States had as increase in the reporting (PR, SC and RJ, Fig. 3). Nevertheless, when the staff find marine debris in the gastrointestinal tract, its description is still poorly reported, and there is no direct instruction to report amount, mass, and type of debris in a standardized method, what ultimately hampers the potential use of PMP-BS to monitor plastic pollution from the open ocean with bioindicators.

Monitoring is important both for quantifying the current 'state-of-environment' as well as evaluating mitigation actions. Some countries with comprehensive management strategies to combat marine plastic are already beginning to report reductions. One example is the OSPAR convention for the North Sea (Van Franeker et al., 2021) which has been detected by effectively using seabirds in biomonitoring plastic pollution. Its latest time trend modeling performed indicates that the individual mass of plastic ingested by the target species from 2009 to 2018 has declined significantly, predicting that the environmental goal set by the commission may be reached in 2054 (Van Franeker et al., 2021). Many countries have undertaken management actions over the past decade to reduce plastic leakage into the environment. For example, in Australia, a variety of municipal waste management strategies, undertaken at the local government level, have been associated with a decrease in coastal plastic pollution across the whole continent, amounting to an average reduction in the coastal litter of 29 % over 6 years at the continental

scale (Willis et al., 2022). Long-term reductions of plastic litter off Australia have also been detected through seabird biomonitoring. For example, Lavers et al. (2021) found that ingested plastic retrieved by stomach-flushing of Flesh-footed Shearwaters breeding on Lord Howe Island, Australia, had decreased over the long term during 2005–2019. While further evidence is required to determine whether the reduction in coastal plastic is linked to the long-term reduction in plastic ingested by Flesh-footed Shearwaters in this specific case, Willis et al. (2022) argue that action through policy at local scales does work to reduce the coastal plastic pollution at broader scales, what would decrease plastic leakage from land into the ocean and, accordingly, the opportunity for wildlife to interact with plastic.

The opposite is seen in Brazil, where the delay in dealing with solid waste management keeps exacerbating plastic pollution in the South Atlantic. The National Solid Waste Policy of Brazil (PNRS), Law 12 305/2010 (Brasil, 2010), was ultimately implemented in the last decade. From the PNRS, municipalities are the main actors in the execution of the law, including the planning and management of services. However, there are political changes in which the decentralization proposed by the policy creates obstacles for its implementation, lacking resources and efforts of federal and state support, training of technical staff, planning and social participation (Scardua and Bursztyn, 2003; Santiago, 2016). Considering the planning for solid waste management on the coastal sphere, out of the 274 coastal municipalities, 58.8 % (153) declared they have a Municipal Integrated Solid Waste Management Plan (PMGIRS) until 2017 (Brasil, 2019). Another example is the presence of selective collection for recyclable waste in the municipalities: only 22.3 % (61) municipalities have this service (Brasil, 2019). At the national level, from 4589 municipalities, nearly half (49 %, 2268) declare to have the PMGIRS according to the PNRS (SINIS, 2022).

In this way, if we consider the increased FO as a reflection of the increasing plastic pollution, the inconsistency in the effectiveness of Brazilian public policies might be influencing our findings as well, especially the great number of species related to debris ingestion reported here (37 species). The increasing pollution may continue unless there are effective actions in Brazilian national scale, as seen in other countries. Brazil has recently developed the National Plan to Combat Litter at Sea (Brasil, 2019), but has not been implemented yet due to political challenges at national scale, being necessary specific plans for the Brazilian regions according to the national guideline. Furthermore, there is the brand-new Strategic Plan for Monitoring and Evaluation of Litter at Sea for the state of São Paulo (PEMALM, 2021) to better understand how plastic pollution is beavering through time nearshore the São Paulo state. The use of bioindicators for plastic pollution and target goals are still in their infancy, hence, continuous and better monitoring is needed to evaluate the newborn Brazilian policies that aims to face plastic pollution in the South Atlantic Ocean.

4.3. Targeting bioindicator species

The third major finding of this study is a potential suite of bioindicator seabirds that could be employed to track the change in marine pollution through time, and in response to changing policy and public behavior surrounding plastic use and disposal. Previous studies indicated that sampling 30–40 birds per year provides robust background to track plastic pollution variation through time from the necropsy of beached individuals (Van Franeker and Meijboom, 2002; Provencher et al., 2017). With the PMP-BS approach of daily monitoring, we assume that all beached seabirds are found, providing a robust assessment for debris ingestion in a continuous term.

GESAMP (2019) provides several criteria to establish good bioindicator species: regional representation; ethics (e.g., non-threatened or not protected, opportunistically sampling dead organisms); abundance in chosen environment; already use as bioindicator/biomonitoring species; cost of routine sampling/analysis, easy, practical analysis in the laboratory; commercially and ecologically important (e.

g. regional food source); species that are directly linkable to impact and effects; integration at a source; comparable globally - similar species identified worldwide. In our study, seabirds meet several of them, such as the regional representation of great Brazilian coastal zone, the abundance of seabirds beaching in Brazil, opportunistic sampling (through necropsy of beached animals), cost of sampling and easy analysis with the PMP-BS approach which is a consolidated program, species directly linked to environmental impact (Roman et al., 2019a), and globally similar species for comparison, i.e., with comparable ecological niches and behaviors.

Since Procellariiformes have a propensity for plastic ingestion and retention, we recommend two species from the Southern Hemisphere with potential for bioindicator purposes in the South Atlantic based on the number of beached individuals, FO, feeding behavior and habitat: the Great Shearwater (FO = 68.06 %, n = 72) and the White-chinned Petrel (FO = 47.48 %, n = 139). In our study, we considered only carcasses in good/fresh condition and moderate decomposition as these states of decay are mandatory for necropsy in PMP-BS. Yet, during beach monitoring, carcasses in higher level of decomposition are still found and, if the gastrointestinal tract is intact, sampling would be possible, increasing sample size to establish a temporal trend.

These species have pelagic lifestyles, so it's possible to assess their exposure to plastic pollution of the nearshore and open ocean. Shearwaters are pursuit plungers that are likely to forage at deeper depths, meanwhile petrels are surface seizers likely to explore a limited depth on the surface (Tavares et al., 2017). White-chinned petrels are also seen to explore deeper depths, diving to 16 m (Rollinson et al., 2014). In this way, tracking plastic from different species with different feeding behaviors would allow a better dimensional assessment of plastic pollution in the open ocean, not just from the near surface. Joint/comparative analyses would contribute to a broad assessment of marine plastic pollution. The Great Shearwater is a great candidate for biomonitoring and is known to have variation in plastic loads considering age, season, and location (Robuck et al., 2022), so this must be considered in further monitoring schemes for this species.

Procellariiformes usually ingest hard plastic items (Colabuono et al., 2009; Roman et al., 2019b), yet, other kinds of items can be found, such as flexible plastic, and foam synthetic (Vanstreels et al., 2021). However, not all individuals of all species in this dataset had been assessed for plastic ingestion, and we suggest that greater coverage and recording of presence or absence of ingested plastic with number, mass, type, size and color of items as suggested by Provencher et al. (2017) would add significant plastic monitoring value to the PMP-BS.

It's also of value to consider coastal species, which may ingest different kinds of debris compared to the ones found in open ocean. For example, the Magellanic Penguin *Spheniscus magellanicus* was also well-represented across years and had the highest FO of ingested plastic (n = 3911, FO = 15 %) compared to other well-represented Charadriiformes and the Suliformes species, which are the main coastal species in this region. The Magellanic Penguins are coastal visitors of southern Brazil during their winter migration from colonies in Patagonia, and mostly ingest flexible plastic as in plastic bags, and plastic threads as in nylon lines from fisheries activities (Brandão et al., 2011; Vanstreels et al., 2021). Considering what kind of debris species are ingesting in coastal and pelagic areas can tailor the monitoring purpose for specific policies of different kinds of waste management.

Overall, seabirds are suitable organisms to assess floating plastic pollution in the ocean (GESAMP, 2019), including through regular opportunistic necropsy of individuals with pelagic habits to access open ocean regions, the place of higher concentration and accumulation of marine debris due to ocean currents (Eriksen et al., 2014). This approach has already been used with a target petrel by the OSPAR Convention for the North Sea. There are similar methodologies that use other marine megafauna species as bioindicators, such as sea turtles (Matiddi et al., 2017), which are also target species in PMP-BS. However, the usage of birds seems to be more appropriate for monitoring plastic as they ingest

smaller plastic load (e.g., mean of 5.3 ± 12.5 particles for birds, Vanstreels et al., 2021; versus 38.4 ± 88.5 particles for sea turtles, Petry et al., 2021), which makes sampling and quantification easier, and more affordable. They also have great diversity and distribution of species throughout the ocean (Croxall et al., 2012), and specific bioindicator species can be established for each marine region according to their ecological attributes related to plastic pollution, such as taxonomic level, feeding behavior, diet, and plastic exposure (Roman et al., 2019b). For plastic pollution, we recommend further research with continuous sampling giving attention to the species discussed here.

4.4. Improvements to biomonitor plastic pollution in Brazil with PMP-BS approach

The PMP-BS is highlighted here with a great potential to integrate a plastic pollution monitoring program with bioindicators. We could access 37 species ingesting marine debris prior to death, mostly plastic. The only metric we could determine was FO, yet it is not enough for long-term monitoring. Additionally, there might be a technical bias in the reporting data from PMP-BS as already discussed. To establish a better monitoring scheme for plastic pollution, several factors must further be considered.

4.4.1. Standardized methods

The reporting of marine debris must follow reliable records of plastic numbers, plastic mass, and plastic type. As a minimum, reports should include location and timing of sampling, method of sampling, sample size, frequency of occurrence (FO), mean (with standard deviation and error), median and range of mass of ingested plastics/individual (including all individuals sampled), and mean (with standard deviation and error), median and range of all plastics reported by types of debris (Provencher et al., 2017). PMP-BS already meets these criteria up to FO but fails to report the main data need to establish a temporal trend. There are already protocols and recommendations to be followed to assess plastic ingestion in marine megafauna (Provencher et al., 2017), as well as specific protocols for seabirds (Provencher et al., 2019a).

4.4.2. Technical training

As PMP-BS works with 11 Executive Institutions, with different staff involved, it is difficult to ensure that all procedures are accurately followed by all people involved. The main difficulty found in the literature on marine debris ingestion related to megafauna is the lack of standardized methods (Provencher et al., 2017). To solve this problem, constant training for staff is needed. Another solution that might work in the PMP-BS scheme is centralizing stomach contents analysis in a skilled work team, either to quantify the diet of the animal as a protocol of the project, as to quantify ingested marine debris.

4.4.3. Preventing bias when targeting a bioindicator species

Within the ecological drivers of plastic ingestion, plastic ingestion may also function with age, sex, seasonality of individuals (GESAMP, 2019). During necropsy, these ecological parameters are accessed, especially seasonality as PMP-BS has a daily monitoring frequency and must be considered. This ultimately provides constant data of beached animals, what can be used to just for monitoring purposes, but to better understand how plastic ingestions is ecologically related to species through time. In the South Atlantic Ocean, there is a need to link ecological drivers to plastic ingestion in seabirds to better understand the most feasible bioindicator species to track plastic pollution through time.

4.4.4. Alignment with other conservation issues

In addition to enabling the quantification of ingested plastic with PMP-BS, it is also possible to assess the probable cause of death of the animal and its health condition until the time of death with veterinary analysis, what can evidence possible risks associated with plastic

pollution (Roman et al., 2021b) and other anthropogenic impacts, such as stranding and drowning in fishing gear (e.g. Ewbank et al., 2020) and interaction with oil (e.g., Waugh et al., 2022). It is also possible to use seabirds to detect other changes in marine ecosystems, such as fish stocks, changes in food chains/transfer of contaminants, and climate change (Provencher et al., 2019b). We highlight here that the necropsy of stranded seabirds can align with several other conservation goals besides tracking plastic pollution, and PMP-BS provides a unique dataset to contribute to the understanding of many conservation issues.

5. Conclusion

Ocean conservation and marine debris pollution are cross-cutting themes, which raises the complexity of policies to reduce marine pollution. In this scenario, monitoring is an important step to understand whether current approaches are being effective. We provided a starting point to discuss plastic pollution monitoring through seabirds in South Atlantic with a list of species ingesting marine debris, mostly from plastic pollution. Brazil has a strong scientific potential regarding the new academic trends that seek to track plastic pollution in the oceans and to understand its impact, mostly because of the high occurrence of species. In this scenario, the PMP-BS is a tool already consolidated in Brazil, with a great potential to provide this kind of data. Although there are some caveats, some improvements would add significant plastic monitoring value to the program. Other national and worldwide developing/existent policies can incorporate the approach of PMP-BS into their strategy to monitor the problem, and we highlight the encouragement of joint action of the Executive Institutions for a wider scientific database with the publication of data according to existing national and international guidelines and protocols. Our results made it possible to suggest two potential bioindicator species for the South Atlantic to be evaluated to track plastic pollution from beached seabirds. Unceasing reports are important to detect changes in plastic pollution, and further research is still needed to reveal how species in South Atlantic are interacting with plastic and, especially, how they are being impacted; with a greater goal to set the most feasible bioindicator species. For this, several actors must be considered and involved, highlighting the need for data standardization and the joint articulation as a commitment to the global problem. Finally, the monitoring of marine debris from beached seabirds with the PMP-BS approach has a great potential to outline and evaluate implemented measures to reduce pollution surrounding plastic use and disposal in the long term for the South Atlantic Ocean.

CRedit authorship contribution statement

Laura Baes: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original draft and Revision. **Cristine Diniz Santiago:** Conceptualization, Writing - Review & editing. **Lauren Roman:** Conceptualization, Formal analysis, Writing - Review & editing, Supervision. **Priscilla Carla dos Santos Costa:** Conceptualization, Writing - Review & editing. **Érica Pugliesi:** Conceptualization. **Carolina Reigada:** Formal analysis, Writing - Review & editing, Supervision.

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 are deeply grateful to the whole team of PMP-BS that daily works on monitoring and veterinary care of beached animals, especially for the Executive Institutions: UDESC, Instituto Australis, Associação R3 Animal, Univali, Univille, LEC/UFPR, IPeC, Biopesca, Instituto Greinar, Instituto Argonauta, and Econservation. This study used data from necropsy records of seabirds as part of the Beach Monitoring Project of the Santos basin (Projeto de Monitoramento de Praias da Bacia de Santos, PMP-BS). PMP-BS is one of the monitoring programs required by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), for the environmental licensing process of PETROBRAS's activities for the production and flow of oil and natural gas in the Santos Basin Pre-Salt Pole.

Funding

This study was supported by the Coordination for the Improvement of Higher Education Personnel, Brazil (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES). The corresponding author is a recipient of a master's fellowship by CAPES (grant number 88887.572685/2020-00) as part of a master's degree in the Post-graduate Program in Ecology and Natural Resources of the Federal University of São Carlos (Programa de Pós-Graduação em Ecologia e Recursos Naturais – PPGERN/UFSCar). This study is also supported by Instituto de Pesquisas Cananéia (IPeC) under the scope of the Beach Monitoring Project of the Santos Basin (Projeto de Monitoramento de Praias da Bacia de Santos, PMP-BS).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2023.115847>.

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