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High frequency of plastic ingestion in procellariiform seabirds (albatrosses, petrels and shearwaters) in the Southwest Atlantic Ocean

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ABSTRACT

Ocean pollution by plastics is a growing concern for marine wildlife conservation, and seabirds are particularly prone to ingest plastics. We report baseline information on plastic ingestion in 17 procellariiform species along the coast of Brazil and Argentina. Through a collaborative regional effort we found plastic items in 30.2 % of seabird carcasses examined (n = 192), comprised predominantly by mesoplastics (5–25 mm), user plastics, polypropylene, polystyrene and polyethylene. Considering the most representative source-site cohorts, the frequency of occurrence of plastic items varied significantly between sampling site and source of carcasses. Ingestion was highest in petrels and shearwaters. Immature birds ingested the largest number (and total mass) of plastic items followed by chicks and adults. Long-term programs applying standardized sampling protocols are needed to detect spatiotemporal patterns of plastic ingestion across species, and assess the potential effectiveness of remediation actions. Further studies are necessary to assess currently unrecognized health effects of plastic ingestion.

1. Introduction

The massive amount of plastic debris circulating in the world's oceans (Napper and Thompson, 2020; Borrelle et al., 2020; Eriksen et al., 2023) and the likewise abundant evidence of incidental ingestion by wildlife indicate that marine plastic pollution is a problem that must be urgently addressed (Wilcox et al., 2015; Kühn and Van Franeker, 2020). Studies report that >200 seabird species are affected by plastic ingestion (reviewed by Kühn and Van Franeker, 2020). Procellariiform birds, especially albatrosses and petrels, are particularly prone to incidentally ingest plastic because they tend to feed on small prey on the waters' surface, where plastics commonly float and accumulate (Ryan, 2008; Avery-Gomm et al., 2012; Roman et al., 2019a, 2020; Kühn et al., 2021). Moreover, the presence of an isthmus juncture in the gut of petrels prevents the regurgitation of indigestible items, possibly leading to the high frequency of plastics in the stomach of these species (Furness,

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1985; Ryan, 1987; Roman et al., 2019a).

The threats that plastics pose to wildlife are well documented (Kühn et al., 2015; Rochman, 2016; Roman et al., 2021; Puskic et al., 2020). Some, such as entanglement, obstruction or perforation of the gut are frequently observed (Pierce et al., 2004; Phillips et al., 2010; Senko et al., 2020). However, other less visible effects such as accumulation of plastic additives in tissues (i.e. phthalates, UV stabilizers) and the release of organic pollutants adsorbed from ambient seawater (e.g. PCBs, PAHs, organochlorine pesticides) have also been reported (Tanaka et al., 2013, 2020; Baini et al., 2017; Puskic et al., 2020). In addition, plastic ingestion can cause dietary dilution (Senko et al., 2020), starvation (Pierce et al., 2004), reduced body mass, condition and size in chicks (Lavers et al., 2014, 2019; Santos et al., 2015), decreased fat deposition (Auman et al., 2004), changes in blood chemistries (Lavers et al., 2019), and tissue damage or "plasticosis" in the proventriculus (Rivers-Auty et al., 2023; Charlton-Howard et al., 2023). Notwithstanding, there is little evidence as to what constitutes a 'safe' plastic load for seabirds, whereas a relatively large volume of plastic is needed to cause significant reductions in food intake due to false satiation, only one particularly awkward item might be sufficient to perforate or block the digestive tract (Ryan, 2019; Roman et al., 2019b).

A number of studies have reported on the occurrence of plastics in the upper digestive tract of procellariiform birds in the Southwest Atlantic, in Brazil (Petry et al., 2007; Barbieri, 2009; Colabuono et al., 2009; Tourinho et al., 2010; Tavares et al., 2017; Petry and Benemann, 2017; Baes et al., 2024) and Uruguay (Jiménez et al., 2015; Muñoz et al., 2023). Moreover, fewer studies have focused on southernmost areas, i.e. Patagonian coast, Falkland/Malvinas islands and South Georgia (Copello and Quintana, 2003; Copello et al., 2008; Phillips and Waluda, 2020). The study of plastic ingestion by birds in this region is relevant because it is expected to be higher compared to southernmost latitudes (i.e. Antarctica, Sub-Antarctic islands). Unfortunately also, many such studies were performed before the establishment of standardized protocols (Provencher et al., 2019; Uhart et al., 2020), hindering the meta-analysis of temporal, spatial, and taxonomic trends in plastic ingestion. In addition, few studies identify polymer composition which provides insights into the source of debris as well as and the potential exposure to chemical contaminants, because additives, leaching and adsorption are polymer-specific (Lithner et al., 2011; Rochman et al., 2013; Fred-Ahmadu et al., 2020).

The aim of this study was to provide baseline information on the prevalence and magnitude of plastic ingestion in procellariiform species through standardized protocols and a regional network of collaborators along the coast of Argentina and Brazil. We also aimed to characterize the polymer types in a subsample of recovered plastic items.

2. Methods

2.1. Sample collection

Through a collaborative network in Argentina and Brazil, from 2017 to 2021 we obtained 192 carcasses from 17 procellariiform species (three families), including seven species listed by the Agreement on the Conservation of Albatrosses and Petrels (ACAP) (Table 1, Fig. 1). Carcasses were regularly collected from four different sources: (a) "bycatch" (birds that were incidentally killed by fisheries), (b) "colony survey" (carcasses found at breeding colonies), (c) "beach survey" (beach-wrecked carcasses), and (d) "rehabilitation" (birds that were rescued ashore but died while under care at rehabilitation facilities). Bycatch birds were recovered from fishing vessels by on-board observer programs operating on the southern continental shelf of Argentina (Programa Marino – Aves Argentinas/BirdLife International) and Brazil (Projeto Albatroz; samples made available through the Brazilian Albatross and Petrels Biological Samples Bank – BAAP). Colony carcasses

Table 1
Summary of the occurrence of plastic ingestion (individuals examined that had plastic in the upper digestive tract /all individuals examined) across taxonomic group, species, sources (Beach survey = beach-wrecked carcasses, Bycatch = bycaught birds, Colony survey = carcasses opportunistically collected at breeding colonies, Rehabilitation = birds that died while under care at rehabilitation centers), and sampling sites (see Fig. 1: (A) Espírito Santo, (B) Santa Catarina, (C) southern Brazil continental shelf, (D) Buenos Aires, (E) Chubut, (F) southern Argentina continental shelf).

	Beach survey				Bycatch		Colony survey	Rehabilitation			Total (n)
Family/Taxonomic group/Species	A	B	D	E	C	F	E	A	B	D	
Diomedeidae											
Albatrosses											
Tristan albatross (*Diomedea dabbenena*)*	—	—	—	—	0/1	—	—	—	—	—	**1**
Southern royal albatross (*Diomedea epomophora*)*	—	—	—	—	—	0/2	—	—	—	—	**2**
Black-browed albatross (*Thalassarche melanophris*)*	—	0/3	—	—	1/14	0/27	—	—	0/1	—	**45**
Grey-headed albatross (*Thalassarche chrysostoma*)*	—	—	—	—	—	0/8	—	—	—	—	**8**
Atlantic yellow-nosed albatross (*Thalassarche chlororhynchos*)*	0/2	0/1	0/1	—	1/2	—	—	2/2	0/4	—	**12**
Procellariidae											
Fulmarine petrels											
Southern fulmar (*Fulmarus glacialoides*)	—	—	—	—	—	0/1	—	—	1/2	—	**3**
Cape petrel (*Daption capense*)	—	—	—	—	—	0/2	—	—	1/1	—	**3**
Giant petrels											
Southern giant petrel (*Macronectes giganteus*)*	—	—	—	3/3	1/1	0/2	13/24	—	1/4	2/2	**36**
Gadfly petrels											
Soft-plumaged petrel (*Pterodroma mollis*)	—	—	1/2	—	—	—	—	—	1/1	—	**3**
Atlantic petrel (*Pterodroma incerta*)	—	1/1	—	—	0/1	—	—	—	—	—	**2**
Procellarine petrels											
White-chinned petrel (*Procellaria aequinoctialis*)*	2/2	1/2	0/3	—	6/10	0/2	—	1/2	1/1	—	**22**
Prions											
Slender-billed prion (*Pachyptila belcheri*)	—	—	—	—	—	0/1	—	—	—	—	**1**
Shearwaters											
Great shearwater (*Puffinus gravis*)	—	—	1/1	—	—	—	—	—	—	—	**1**
Manx shearwater (*Puffinus puffinus*)	7/17	1/8	1/4	—	—	—	—	0/3	1/5	—	**37**
Cory's shearwater (*Calonectris borealis*)	2/2	1/5	1/2	—	—	—	—	2/3	1/1	—	**13**
Cape verde shearwater (*Calonectris edwardsii*)	—	1/1	—	—	—	—	—	—	—	—	**1**
Hydrobatidae											
Storm petrels											
Wilson's storm petrel (*Oceanites oceanicus*)	—	—	0/1	—	—	—	—	—	0/1	—	**2**
Total	**23**	**21**	**14**	**3**	**29**	**45**	**24**	**10**	**21**	**2**	**192**

Notes: *Species included in the Agreement on the Conservation of Albatrosses and Petrels (www.acap.aq).

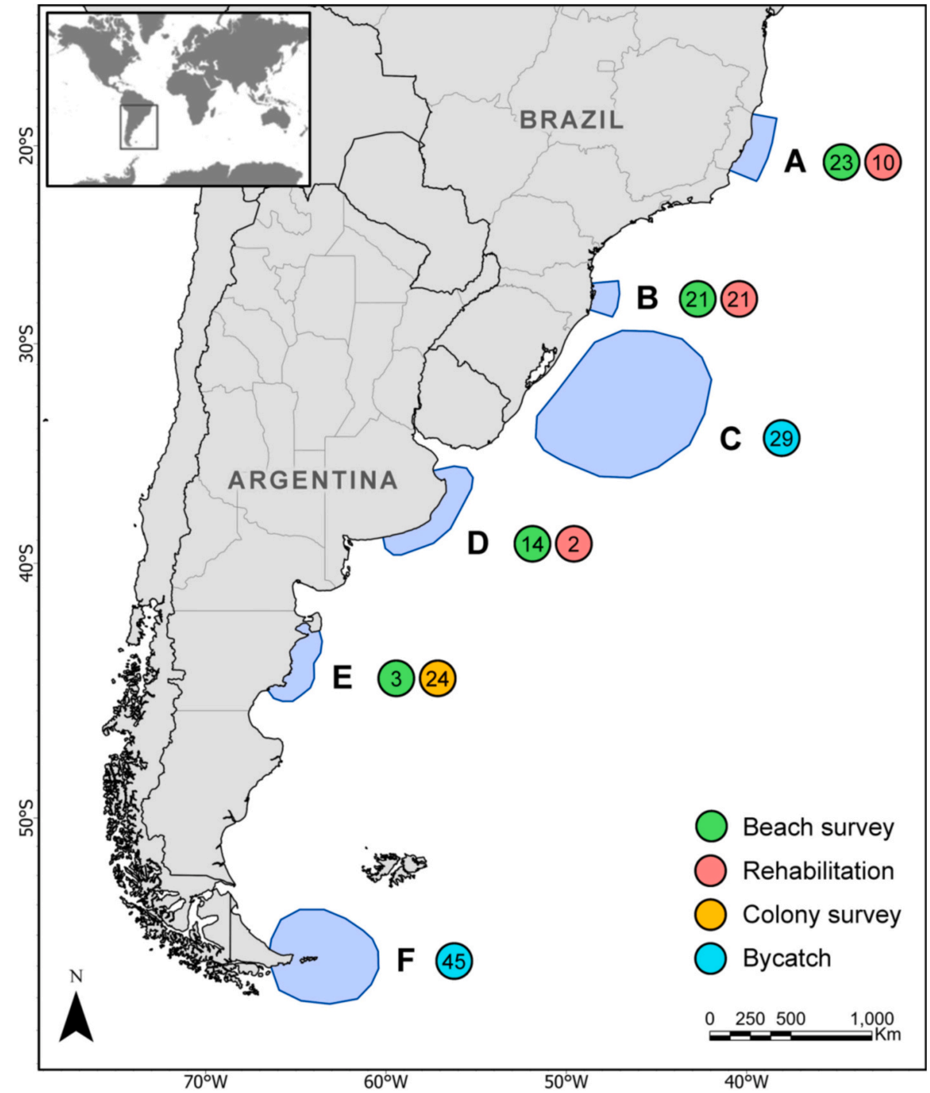

Fig. 1. Geographic distribution of sampling sites in Argentina and Brazil (blue polygons): (A) Espírito Santo, (B) Santa Catarina, (C) southern Brazil continental shelf, (D) Buenos Aires, (E) Chubut, (F) southern Argentina continental shelf. Colored circles next to letters represent the sample source (shown in legend), and the numbers within these represent the sample size (number of birds examined).

were opportunistically collected at the breeding colony of Southern giant petrel (*Macronectes giganteus*) at Gran Robredo island (45.129 S, 66.055 W), assisted by personnel from Parque Interjurisdiccional Patagonia Austral, Chubut province, Argentina. Beach carcasses were collected in Argentina through opportunistic beach surveys in Chubut province as well as systematic beach monitoring in Buenos Aires province (Fundación Mundo Marino and Equipo Costero de Observadores de Fauna y Ambiente Marinos – ECOFAM). Beach carcasses were collected in Brazil through systematic beach monitoring in Espírito Santo state (Projeto de Monitoramento de Praias das Bacias de Campos e Espírito Santo –PMP-BC/ES) and Santa Catarina state (Projeto de Monitoramento de Praias da Bacia de Santos – PMP-BS). Rehabilitation carcasses were obtained from birds that died within five days of admission at rehabilitation facilities in Argentina (Fundación Mundo Marino) and Brazil (Instituto de Pesquisa e Reabilitação de Animais Marinhos – IPRAM and Associação R3 Animal).

Carcasses were examined following training and standardized protocols locally adapted and recommended for ACAP species (Gallo et al., 2021; adapted from Provencher et al., 2017, 2019) at IPRAM, Associação R3 Animal (Brazil), Instituto de Biología de Organismos Marinos (IBIOMAR, CCT CENPAT) and Fundación Mundo Marino (Argentina). Birds were necropsied following well-established procedures and macroscopic pathological findings (ie. ulcers, lesions) were recorded along with additional metadata (species, age and sex). Sex was determined through the visual inspection of the gonads during dissection. Plumage and gonad development were used to categorized age classes as follows: "chick", "immature" (juveniles and sub-adult birds combined), "adult", and "unknown".

2.2. Detection and quantification of plastic ingestion

The upper digestive tracts from necropsied birds were stored frozen and later thawed, cut open, and their contents were thoroughly washed with running water through a 1 mm mesh sieve. This mesh size was used as pieces smaller than this are likely passed along through the pyloric sphincter and do not accumulate within the bird (Provencher et al., 2019). Any material retained was transferred to Petri dishes, air dried for at least 24 h at room temperature, and examined under stereomicroscope. To avoid misidentification and underestimation of smaller items (1–5 mm) the following criteria was utilized to guarantee proper identification: plastics had to (1) be homogeneously colored, (2) be shiny and not matte, (3) have no cellular/organic structures visible, (4) be equally thick throughout their length, and/or (5) have three-dimensional bending (Hidalgo-Ruz et al., 2012; Lusher et al., 2020).

When necessary, e.g. discolored/matte filaments of uneven thickness, the "hot needle test" (De Witte et al., 2014; Muñoz et al., 2023) and selective fluorescence under UV light (Abbasi et al., 2018; Ehlers et al., 2020; Giarratano et al., 2022) were used as complementary methods to confirm whether a suspected item was plastic.

The type of plastic items was classified into industrial pellets ("nurdles") or user plastics (all non-industrial remains of plastic items) (Provencher et al., 2017). Moreover, user plastics were differentiated in the following subcategories: (a) hard fragments (rigid pieces of larger objects), (b) sheet (flat, flexible pieces of plastic bags and packaging), (c) thread (long fibrous material that has a length substantially longer than its width), (d) foam (polystyrene and/or polyurethane; near-spherical or granular particle, which deforms readily under pressure and can be partly elastic, depending on weathering state), and (e) other plastic items (plastic material that does not fit in the previous categories, such as cigarette filters, rubber bands, balloons, etc.). All same type isolated items were weighed with a precision scale (±0.0001 g). Items were photographed against a reference background (1 mm grid) and Software "ImageJ" (Schneider et al., 2012) was used to measure their length. The length of the largest and smallest plastic item was also recorded for each individual bird when it was possible, classified by size as: 1–5 mm (microplastics), 5–25 mm (mesoplastics), >25 mm (macroplastics) (GESAMP, 2019).

2.3. Polymeric composition of a subset of plastic items

A subset of 119 plastic items recovered (25 % of total) from 16 individuals collected in Argentina (12 Southern giant petrels, 1 Soft-plumaged petrel, 1 Cory's shearwater, 1 Great shearwater, 1 Manx shearwater, see scientific names in Table 1) were evaluated using Attenuated Total Reflectance Fourier Transformed Infrared Spectroscopy (ATR-FTIR). No plastic items were stored for polymer analysis in Brazil. The number of individuals per species in the subset reflects the differential incidence of plastic per species and the unbalanced representation in our total sample. From individuals with plastics, we selected items representative of all plastic types present. For each plastic item, ATR-FTIR spectra were obtained over the 4000–400 cm^{-1} spectral region using a spectrometer (Thermo Scientific Nicolet 6700 FTIR) equipped with a Smart iTX Optical Base accessory with a zinc selenide (ZnSe) crystal. The resolution was 4 cm^{-1} and the number of scans was 64. The obtained spectra were compared with those previously reported, commercial libraries, and with our own ATR-FTIR library for polymers.

2.4. Statistical analysis

The following parameters were obtained for each bird: number of items (total, per plastic type category), mass (total, per plastic type category), size range of plastic items (minimum and maximum item length). Frequency of occurrence (FO) of plastics (%, number of birds with plastics/number of birds sampled) was calculated for each species, sample source (bycatch, beach survey, colony survey, rehabilitation) and collection site (Espírito Santo, Santa Catarina, Buenos Aires, Chubut, Southern Argentina continental shelf, Southern Brazil continental shelf). The mean and standard deviation of the number and mass of plastic items were calculated separately for (a) all individuals examined (abundance) and (b) only individuals with plastic in their upper digestive tract (intensity). The Ecological Quality Objective (EcoQO) metric (OSPAR, 2010) was re-scaled considering the body mass of each species and age class following Lavers and Bond (2016). One individual (a Southern giant petrel bycaught in Southern Brazil) had 99 plastic items in its digestive tract; thus, statistics were calculated excluding this outlier. Chi-square tests were used to compare the FO of plastics by source and sampling site (excluding colony surveys and source-site cohorts with $n < 10$).

For taxonomic groups with representative sample sizes (>20 birds), generalized linear models (GLMs) were used to explore if the following variables were predictive of the FO, total number or combined mass of plastic items: taxonomic group (albatrosses, giant petrels, procellarine petrels, and shearwaters), age class (chick, immature, adult, unknown), and sex (male, female, unknown). Models employed a binomial or negative binomial error distributions (to account for high occurrence of zero counts; quasipoisson, as the count data were overdispersed), and the taxonomic group was included as a proxy for shared ecological, anatomical and behavioral characteristics (species was omitted to prevent model overfitting). The stepwise procedure informed by Akaike's Information Criterion (AIC) was used to select the best model. Statistical analyses were conducted using R 4.1.1 (R Core Team, 2021), and significance level was 0.05.

3. Results

We examined the upper digestive tract of 192 individuals, of which 58 (FO = 30.2 %, EcoQO = 9.4 %) from 12 species contained plastics (Table 1). Despite this, we did not find evidence that any of the birds had died as a direct result of plastic ingestion (e.g. gut obstruction or perforation) nor showed macroscopic evidence of plastic-induced fibrosis (Charlton-Howard et al., 2023). Table 2 provides a detailed summary of plastic ingestion for each species and taxonomic group.

A total of 467 plastic items were recovered, with an average (mean ± SD) of 2.4 ± 9.1 items and mass of 0.0788 ± 0.2883 g per bird evaluated (Table 3). Overall, the most common plastic items found were user plastics (420 items, 90 %), with industrial pellets representing 10 % (44 items). User plastics were maily composed of hard fragments (258 items, 61 %) followed by sheet (76 items, 18 %), foam (52 items, 12 %), other types of plastic and thread (17 items, 4 % each). The size of plastic items were distributed as follows (Table S1): 1–5 mm (32 items, 36 %), 5–25 mm (41 items, 46 %), and > 25 mm (17 items, 19 %), with an average (mean ± SD) of 14.6 ± 17.2 mm.

All items analyzed by spectroscopy ($n = 119$, 60 % recovered from Southern giant petrels) were identified with some plastic polymer (Fig. S1) including: polypropylene (30 %; 33 sheet, two hard fragment, one other type of plastic), polystyrene (25 %; 28 foam, two sheet), polyethylene HDPE:LDPE 1:1 (HDPE: High density polyethylene, LDPE: Low density polyethylene, 24 %; 20 sheet, seven hard fragments, two pellets), ethylene-vinyl acetate (8 %; six sheet, three other type of plastics, one foam), polyacrylate (7 %; seven sheet, one thread), polysiloxane (3 %, three foam), cellulose acetate (2 %; two sheet), and polyethylene terephthalate (1 %; one hard fragment). Table S2 summarizes plastic polymers recovered for each species.

Excluding the colony subset due to its bias towards Southern giant petrel, and source-site cohorts with $n < 10$ individuals, the FO varied significantly among sources ($\chi^2 = 11.224$, df = 2, $P = 0.004$) and sampling sites ($\chi^2 = 25.697$, df = 4, $P < 0.001$) (Table 3). Plastic ingestion was relatively frequent in birds bycaught in southern Brazil (FO = 31 %, EcoQO = 6.9 %, $n = 29$) but not in birds bycaught in southern Argentina (FO = 0 %, EcoQO = 0 %, $n = 45$). Plastic ingestion was frequently recorded in beach-wrecked carcasses from Espírito Santo (FO = 47.8 %, EcoQO = 8.7 %, $n = 23$), followed by Buenos Aires (FO = 28.6 %, EcoQO = 14.3 %, $n = 14$) and Santa Catarina (FO = 23.8 %, EcoQO = 4.8 %, $n = 21$). In birds that died at rehabilitation facilities, plastic ingestion was more frequent at Espírito Santo (FO = 50.0 %, EcoQO = 30.0 %, $n = 10$), followed by Santa Catarina (FO = 28.6 %, EcoQO = 14.3 %, n = 21).

Generalized linear models identified the taxonomic group was predictive of FO ($\chi^2 = 39.317$, df = 3, P < 0.001; McFadden's pseudo-$R^2 = 0.18$) and number ($\chi^2 = 21.338$, df = 3, $P < 0.0001$; McFadden's pseudo-$R^2 = 0.04$) of ingested plastic items. FO was higher in giant petrels (55.6 %), followed by procellarine petrels (50.0 %), shearwaters (34.6 %) and albatrosses (5.9 %) (Table 2). Likewise, giant petrels presented the largest number (and total mass, although it was not statistically significant) of plastic items followed by procellarine petrels, shearwaters and albatrosses (Fig. 2). Age class was predictive of number ($\chi^2 = 8.097$, df

Table 2
Data summary for plastic (all types combined) found in the upper digestive tract of procellariiform birds in the Southwest Atlantic. Sample size (n), frequency of occurrence (FO), and the average number and combined mass of plastic items (mean ± SD) according to the species. Ecological Quality Objective (EcoQO) performance metric (OSPAR, 2010) was adjusted by body mass of each sampled species and age classes following Lavers and Bond (2016).

Taxonomic group	Species[a]	n	FO (%)	All individuals examined (abundance)		Individuals with plastic (intensity)		EcoQO (%)
				no. items	mass (g)	no. items	mass (g)	
Albatrosses	Tristan albatross	1	0	–	–	–	–	0 %
	Southern royal albatross	2	0	–	–	–	–	0 %
	Black-browed albatrosses	45	2.2	0.04 ± 0.3	0.0469 ± 0.3152	2.0	2.1143	2.2 %
	Grey-headed albatross	8	0	–	–	–	–	0 %
	Atlantic yellow-nosed albatross	12	25.0	2.2 ± 5.0	0.1908 ± 0.4390	8.7 ± 7.4	0.7632 ± 0.6360	16.7 %
	Subtotal	68	5.9	0.4 ± 2.2	0.0648 ± 0.3172	7.0 ± 6.9	1.1010 ± 0.8521	4.4 %
Giant petrels	Southern giant petrel*	36	55.6	6.1 ± 16.8	0.1925 ± 0.4668	16.5 ± 30.0	0.6157 ± 0.7550	16.7 %
Procellarine petrels	White-chinned petrel	22	50.0	5.2 ± 12.5	0.0536 ± 0.1721	10.5 ± 16.4	0.1073 ± 0.2364	4.5 %
Shearwaters	Great shearwater	1	100	34	0.7526	–	–	100 %
	Manx shearwater	37	27.0	1.1 ± 2.5	0.0174 ± 0.0504	4.0 ± 3.4	0.0645 ± 0.0825	10.8 %
	Cory's shearwater	13	46.2	1.2 ± 1.5	0.0145 ± 0.0320	2.5 ± 1.2	0.0314 ± 0.0426	7.7 %
	Cape verde shearwater	1	100	1	0.0233	–	–	0 %
	Subtotal	52	34.6	1.7 ± 5.1	0.0309 ± 0.1116	5.0 ± 7.7	0.0894 ± 0.1784	11.5 %
Prions	Slender-billed prion	1	0	–	–	–	–	0 %
Fulmarine petrels	Southern fulmar	3	33.3	2.0 ± 3.5	0.3000 ± 0.5127	6.0	0.8879	33.3 %
	Cape petrel	3	33.3	0.7 ± 1.2	0.0269 ± 0.0465	2.0	0.0806	0 %
	Subtotal	6	33.3	1.3 ± 2.4	0.1614 ± 0.8165	4.0 ± 2.8	0.4843 ± 0.5708	16.7 %
Gadfly petrels	Soft-plumaged petrel	3	66.7	1.0 ± 1.0	0.0030 ± 0.0044	1.5 ± 0.7	0.0045 ± 0.0051	0 %
	Atlantic petrel	2	50	2.5 ± 3.5	0.0153 ± 0.0216	5.0	0.036	50 %
	Subtotal	5	60	1.6 ± 2.1	0.0079 ± 0.0131	2.7 ± 2.1	0.0132 ± 0.0155	00 %
Storm petrels	Wilson's storm petrel	2	0	–	–	–	–	0 %
Total**		192	30.2	2.4 ± 9.1	0.0788 ± 0.2983	8.1 ± 15.2	0.2609 ± 0.5000	9.4 %

Notes: [a] Scientific species are provided in Table 1.* Results excluding one outlier (Southern giant petrel bycaught in southern Brazil): FO = 54.3 %, abundance = 3.4 ± 5.4 items, 0.1285 ± 0.2727 g; intensity = 7.3 ± 8.2 items, 0.4143 ± 0.4324 g; EcoQO = 14.3 %. ** Results excluding one outlier: FO = 29.8 %, abundance = 1.9 ± 5.8 items, 0.0665 ± 0.2456 g; intensity = 6.5 ± 9.2 items, 0.2229 ± 0.4112 g; EcoQO = 6.8 %.

Table 3
Data summary for plastic (all types combined) found in the upper digestive tract of procellariiform species in the Southwest Atlantic by source and sampling sites (including subsets with at least 10 carcasses evaluated). Sample size (n), frequency of occurrence (FO), and the average number and combined mass of plastic items (mean ± SD) according to source and sampling sites (see Fig. 1). Ecological Quality Objective (EcoQO) performance metric (OSPAR, 2010) was adjusted by body mass of each sampled species and age classes following Lavers and Bond (2016).

Source	Site	n	FO (%)	All individuals examined (abundance)		Individuals with plastics (intensity)		EcoQO (%)
				no. items	mass (g)	no. items	mass (g)	
Bycatch	C – Southern Brazil	29	31.0	5.3 ± 18.6	0.1660 ± 0.5851	17.0 ± 31.5	0.5350 ± 0.9879	6.9 %
	C – Southern Brazil*	28	28.6	1.9 ± 4.8	0.0853 ± 0.3984	6.8 ± 7.2	0.2985 ± 0.7346	3.6 %
	F – Southern Argentina	45	0	–	–	–	–	–
	Subtotal	74	12.2	2.1 ± 11.8	0.0651 ± 0.3714	17.0 ± 31.5	0.5350 ± 0.9879	2.7 %
	Subtotal*	73	11.0	0.7 ± 3.1	0.0327 ± 0.2475	6.8 ± 7.2	0.2985 ± 0.7346	1.4 %
Rehabilitation	A – Espirito Santo	10	50.0	3.0 ± 5.2	0.2391 ± 0.4711	6.0 ± 6.2	0.4783 ± 0.5969	30.0 %
	B – Santa Catarina	21	28.6	3.4 ± 12.2	0.0952 ± 0.2553	12.0 ± 21.7	0.3270 ± 0.4118	14.3 %
	Subtotal	31	34.5	3.3 ± 10.3	0.1404 ± 0.3339	9.3 ± 16.1	0.3957 ± 0.4830	19.4 %
Beach survey	A – Espirito Santo	23	47.8	1.5 ± 2.7	0.0191 ± 0.0516	3.1 ± 3.2	0.0399 ± 0.0703	8.7 %
	B – Santa Catarina	21	23.8	0.8 ± 1.8	0.0089 ± 0.0180	3.4 ± 2.3	0.0372 ± 0.0173	4.8 %
	D – Buenos Aires	14	28.6	3.1 ± 9.1	0.0598 ± 0.2004	10.8 ± 7.1	0.2093 ± 0.3637	14.3 %
	Subtotal	58	37.7	1.6 ± 4.8	0.0252 ± 0.1035	4.7 ± 7.4	0.0731 ± 0.1686	8.6 %
Colony survey	E – Chubut	24	54.2	3.8 ± 6.3	0.1261 ± 0.2444	7.0 ± 7.1	0.22328 ± 0.2950	12.5 %

Note: *Subtotal bycatch excluding one bycaught Southern giant petrel whose upper digestive tract contained 99 plastic items.

= 3, $P = 0.044$; McFadden's pseudo-$R^2 = 0.02$) and total mass ($\chi^2 = 7.892$, df = 3, $P = 0.048$; McFadden's pseudo-$R^2 = 0.83$) of plastic items ingested. Immature birds ingested the largest number and total mass of plastic items followed by chicks and adults (Fig. 3). Sex was not a good predictor of FO, number or mass of plastic items.

4. Discussion

This study describes the prevalence and magnitude of plastic ingestion in a suite of species in the Southwest Atlantic Ocean, covering a broad area from 18 to 55 degrees latitude S and a diversity of sampling sources. It also reports on the polymer composition of a subset of ingested plastics.

Overall, the frequency of plastic ingestion (30.2 %) in our study is lower than that reported for procellariiforms in northern hemisphere oceans (~75 %; Gray et al., 2012; Bond et al., 2014; van Franeker et al., 2021 and references therein) and Southwest Indian Ocean islands (50 %; Perold et al., 2020; Cartraud et al., 2019), which reflect greater exposure to floating debris in their feeding areas (Savoca et al., 2022; Clark et al., 2023). Conversely, the average FO in our study is similar to recent findings in the southern hemisphere, including Australia (32–44 %; Lavers et al., 2018; Roman et al., 2016, 2019a), South Africa (2 % only albatross; Ryan et al., 2016), and Georgias del Sur/South Georgia Islands (20–24 %; Phillips and Waluda, 2020). When comparing our results with regional studies off Brazil and Uruguay, they align closely for the majority of species, albeit with notable deviations. For example, the FO in our study was higher for Atlantic yellow-nosed albatrosses (*Thalassarche chlororhynchos*) than reported by Colabuono et al. (2009) and Baes et al. (2024) for Brazil, whereas Black-browed albatrosses (*Thalassarche melanophris*), Cory's and Manx shearwaters (*Calonectris borealis and Puffinus*

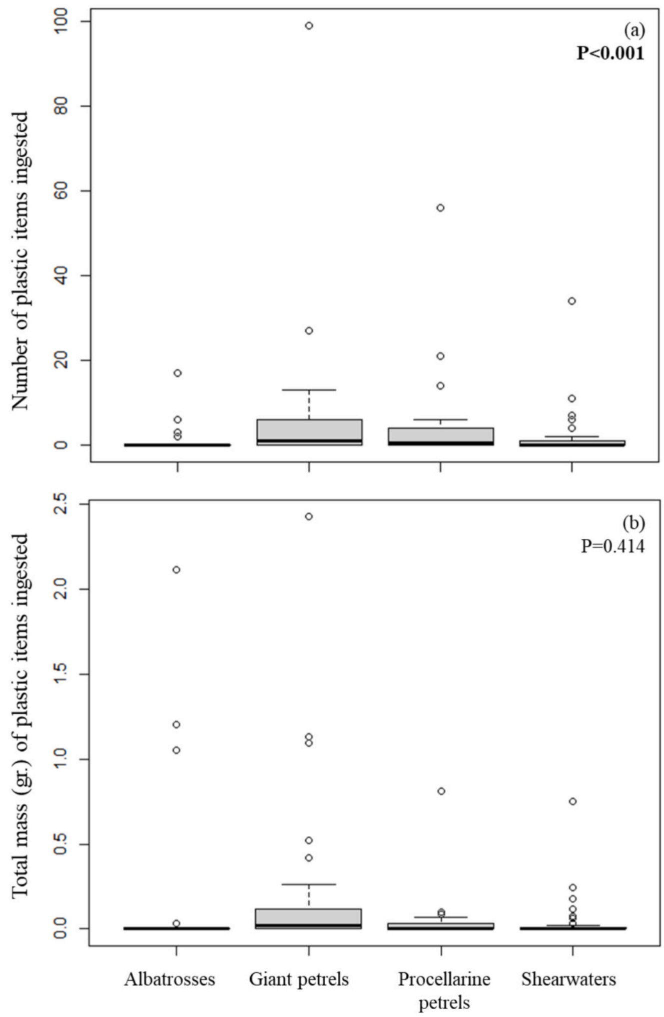

Fig. 2. Boxplot of number (a) and total mass (b) of plastic items ingested by procellariiform birds according to their taxonomic group. The area bounded by each box within the plot area shows the interquartile range (IQR) between the first quartile (Q1; bottom edge of box) and third quartile (Q3; upper edge of box). The bold line in the middle of the box shows the median. The whisker shows 1.5× IQR. Each circle represents outlier values.

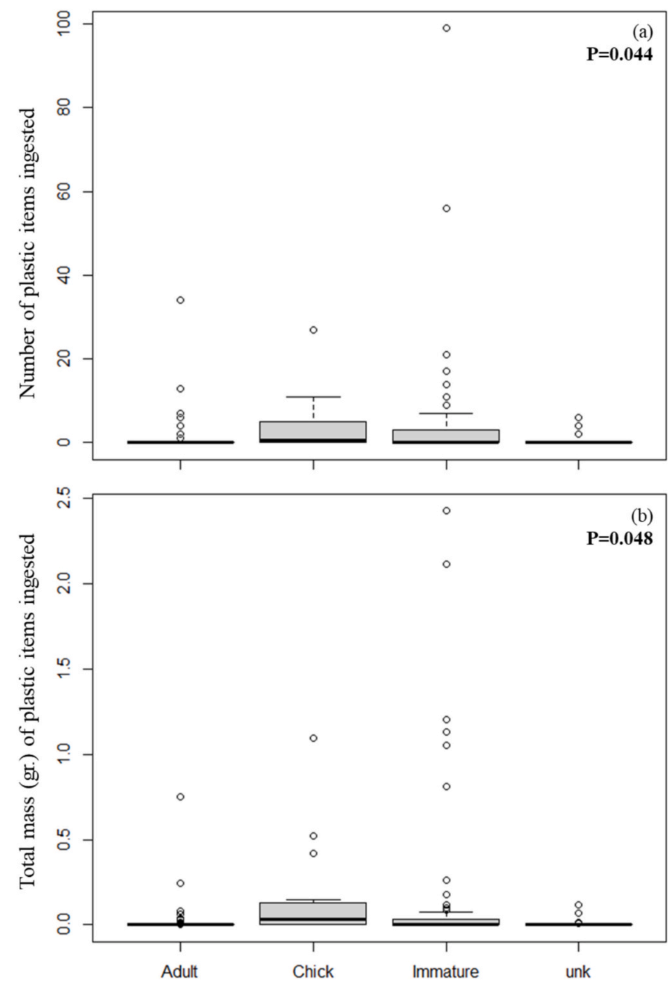

Fig. 3. Boxplot of number (a) and total mass (b) of plastic items ingested by procellariiform birds according to their age class. The area bounded by each box within the plot area shows the interquartile range (IQR) between the first quartile (Q1; bottom edge of box) and third quartile (Q3; upper edge of box). The bold line in the middle of the box shows the median. The whisker shows 1.5× IQR. Each circle represents outlier values.

puffinus) differed between our study and others (Petry et al., 2007; Colabuono et al., 2009; Barbieri, 2009; Jiménez et al., 2015; Tavares et al., 2017; Muñoz et al., 2023; Baes et al., 2024). These discrepancies emphasize that comparisons between studies should be considered with caution due to biases introduced by differences between sampling sources, years, age classes, species and/or taxonomic groups assessed, and the inconsistency in methods for data collection and analysis.

Previous studies have found that the incidence of marine debris ingestion in a species is strongly influenced by traits that are shared by taxonomic groups or closely-related species such as foraging strategies, gut morphology, and diet (Roman et al., 2019a; Muñoz et al., 2023). Our results corroborate this, as taxonomic group was predictive of the FO and number of plastic items in the upper digestive tract of birds. Giant petrels, procellarine petrels and shearwaters were more likely to have ingested plastics (and showed a higher number of plastic items) compared to albatrosses. Although our sampling effort was skewed towards Southern giant petrels and White-chinned petrels (*Procellaria aequinoctialis*), higher prevalences may be related to foraging strategies and/or feeding habits of these species (surface-seizing and scavenging) and their difficulty in regurgitating indigestible items because of the presence of an isthmus juncture in the gut (Furness, 1985; Ryan, 1987; Roman et al., 2019a). While albatrosses also feed on natural prey close to the sea surface, their gastrointestinal structure allows readily elimination of indigestible materials (Furness, 1985; Colabuono et al., 2009). In contrast, shearwaters are pursuit plungers that feed primarily on school-fish that they chase while shallow-diving (Shoji et al., 2016), hence their high prevalence is harder to explain. However, recent studies suggest that indirect ingestion through prey is possible in this species (Alley et al., 2022).

Individual drivers such as sex, age, and breeding stage can also influence plastic ingestion in seabirds (Ryan, 2015a; Roman et al., 2019a). Our results partially support this, as early life stages (chicks and immature birds) showed a higher number and total mass of plastic items compared to adults. Intergenerational plastic transfer from adults to chicks through regurgitation is common in albatrosses and petrels (Copello and Quintana, 2003; Carey, 2011; Rodríguez et al., 2012; Ryan, 2015a; Hyrenbach et al., 2017). Immature birds might still be carrying particles fed to them by their parents before fledging (Ryan, 1988; Carey, 2011; Rodríguez et al., 2012). Additionally, immature birds may be more prone to ingesting marine debris because they are naïve consumers and less discriminating foragers (Ryan, 1988; Daunt et al., 2007; Acampora et al., 2014). Moreover, competition with adults can force them to use suboptimal feeding areas and to develop different foraging strategies (e.g. feeding on fishing discards or debris released from coastal cities) (Acampora et al., 2014; Blanco and Quintana, 2014; De

Grissac et al., 2016; Blanco et al., 2022).

The incidence of plastic ingestion by seabirds may also be influenced by the extent to which their foraging range overlaps with oceanic regions polluted with marine debris (Ryan et al., 2009; van Franeker and Law, 2015; Wilcox et al., 2015; Roman et al., 2019a; Clark et al., 2023). This was evidenced in the aforementioned comparisons with studies in other oceans. In the Southwest Atlantic, fishing vessels and coastal cities have been proposed as the main source of marine debris ingested by seabirds in the last decades (Copello and Quintana, 2003; Copello et al., 2008; Jiménez et al., 2015; Phillips and Waluda, 2020; Blanco et al., 2022). Among the species with representative sample sizes in our study, the highest frequencies of plastic ingestion were for Southern giant petrels, White-chinned petrels and Cory's shearwaters. Of these, Southern giant petrels also showed the highest number and mass of plastic items. However, most of the petrels we sampled were juveniles and chicks, thus, the high frequency found may be associated with parental feeding. Likewise, the prevalence of plastic ingestion in chicks was considerably higher in Southern giant petrels from Patagonia compared with giant petrels (*Macronectes* spp.) from Georgias del Sur/South Georgia Islands (Phillips and Waluda, 2020), whose parents forage mostly in Antarctic waters (Granroth-Wilding and Phillips, 2019). The density of floating plastics in the latter is very low due the role of Antarctic Circumpolar currents in diluting, redistributing and substantially preventing the dispersal of drifting plastics in this sector (Lacerda et al., 2019; Suaria et al., 2020, 2023). In contrast, the Patagonian breeding population of Southern giant petrels overlaps extensively with areas of plastic accumulation over the Argentine continental shelf (Blanco et al., 2022). Furthermore, there is broad evidence of Southern giant petrels and White-chinned petrels foraging on fisheries discards along the continental shelf off Brazil, Uruguay and Argentina, increasing their access to plastic debris from boats (Copello and Quintana, 2009; Copello et al., 2008; Quintana et al., 2010; Bugoni et al., 2011; Favero et al., 2011; Tamini et al., 2015, 2023). In our study, most Cory's shearwaters were found dead on the Brazilian coast, and the frequency of ingested plastics resembled values reported previously in the region (23–100 %; Colabuono et al., 2009; Petry et al., 2009; Tavares et al., 2017; Baes et al., 2024). It is plausible that plastic ingestion in Cory's shearwaters is related to the diverse diet of this species in an attempt to stave-off hunger while overwintering in Brazil and being in poor condition after migration (Petry et al., 2009). Despite the small sample sizes in our study, other shearwater species also showed a high incidence of plastic ingestion (FO = 100 %) (Table 2). Of these, Cape Verde Shearwater (*Calonectris edwardsii*) does not usually strand in Brazil, which raises the question of whether their high FO is biased or indeed this species is constantly ingesting plastic. Further studies are necessary to answer this. On the other hand, high FO in Great shearwater (*Puffinus gravis*) was also reported in other studies in the region with more representative sample sizes (Colabuono et al., 2009; Tavares et al., 2017; Baes et al., 2024).

Most studies on plastic ingestion in the South-Western Atlantic Ocean have been based on beach-cast carcasses in Brazil. In this study, we expand the scope and report on both the prevalence and magnitude of plastic ingestion by broadening the geographical range and source of samples (bycatch, beach strandings, rehabilitation centers, and breeding colonies). Considering the most representative source-site cohorts (excluding the colony subset biased towards Southern giant petrel), we found significant variability among sources and sampling sites. Previous studies have noted that beach-cast carcasses of seabirds that were in poor body condition tend to have a higher frequency of plastics in their upper digestive tract, which suggests that starving birds may ingest plastics due to decreased selectivity while foraging or in a desperate attempt to avert hunger (Brandão et al., 2011). Overall, in our study, bycaught birds, which were presumably in good health when they were incidentally killed by fisheries, had generally lower frequency of plastics than birds collected ashore (beach-cast and rehabilitation; Table 3). However, given the uneven sampling effort within each source (i.e. differences in sampling sites, species, age classes, year) these results should be considered with caution. For example, Southern giant and White-chinned petrels bycaught in southern Brazil continental shelf had high frequencies of plastics (Table 1), resembling those from beach-cast birds from southern Brazil, a resemblance that may be related to the habit of petrels of foraging on garbage discarded overboard (Colabuono and Vooren, 2007; Colabuono et al., 2009). Nevertheless, including samples from different sources in the same area (and season) reflecting differential health status at time of death is a relevant approach for future studies to avoid biases in interpretation of findings and health effects of plastics ingestion.

As per the type of plastic item found in the studied birds, user plastics were the most common resembling previous reports in procellariiforms (Ryan, 2008; Barbieri, 2009; Colabuono et al., 2009; Petry et al., 2009; Tourinho et al., 2010; Petry and Benemann, 2017; Phillips and Waluda, 2020; Muñoz et al., 2023). Due to the small size of these items and the lack of inscriptions, it is often impossible to determine their source. For a small proportion of identifiable flexible items we found they were mainly food-related or medium-sized flexible packaging (Fig. S2). These types of plastics have a high surface-to-volume ratio and become less buoyant within days or weeks of discarding because of the formation of biofilms, followed by accretion of fouling organisms (Ryan, 2015b, 2020; Phillips and Waluda, 2020). They are therefore likely ingested by seabirds within a short time after arriving at the sea from land-based sources (e.g. uncovered garbage dumps or river effluents) and/or from recently discarded waste (intentionally or accidentally) by fishing vessels operating in the region (Copello and Quintana, 2003; Phillips and Waluda, 2020; Perold et al., 2020). Plastic characterization is useful to identify sources of pollution (i.e. marine or land based), which in turn enables targeted mitigation actions (e.g. proper waste-management of dumpsters on-land and practices on board vessels, including food-waste disposal). However, retention time of plastics in the stomach of birds varies with the characteristics of the items, the anatomy of the birds' gut, and the bird's life-cycle (e.g. during the breeding season plastics may be transferred to chicks more frequently, resulting in shorter retention time in adults) (Copello and Quintana, 2003; Carey, 2011; Rodríguez et al., 2012; Ryan, 2015a; Hyrenbach et al., 2017). Thus, identifying the source of plastics is complex, especially for species that migrate long distances and/or have large foraging ranges.

Concerning plastic item size, mesoplastics (5–25 mm) were the most frequent size category (46 %) recovered, which coincides with previous reports in procellariiforms off Brazil and Uruguay (Barbieri, 2009; Colabuono et al., 2009; Muñoz et al., 2023). However, these studies do not describe the lower size threshold or mesh sieve employed, so may introduce a bias in the findings reported. Previous work has found that the size of ingested particles may be correlated to the body size of birds (Ryan, 1987; Colabuono et al., 2009; Roman et al., 2019c; Muñoz et al., 2023), but this was not consistently observed across species in our study (Fig. S3). We found that 54 % of all plastic items ingested were smaller than 10 mm, which coincides with the most abundant oceanic debris size (Morét-Ferguson et al., 2010; Suaria et al., 2020) and could also reflect breakage of larger ingested debris (Terepocki et al., 2017; Roman et al., 2019c). Furthermore, it is worth noting that 41 % of plastic items in our study fall within the "danger zone" of 2–10 mm proposed by Roman et al. (2019c) for medium-small sized petrel species, which is a size that is small enough to cross the isthmus between the proventriculus and ventriculus but too large to exit the ventriculus onto the intestine. Thus, the retention of these items in the stomach poses an increased health risk for these species, since items may cause punctures or blockages that can result in death (Roman et al., 2019b). Moreover, retention of plastics in the stomachs can affect health through the release and metabolism of plastic-derived chemicals (Tanaka et al., 2015, 2020; Kühn and Van Franeker, 2020).

This study is the first to report the polymer composition of a subset of plastics ingested mostly by young Southern giant petrels and a few other procellariiform species. The most common polymer types were polypropylene, polystyrene and polyethylene, similar to findings in giant petrels from Sub-Antarctic Marion Island (Perold et al., 2020). The uptake of different plastic types and related polymers most likely reflects spatial and temporal variations in availability rather than selective ingestion by the birds (Kühn et al., 2021). Recent studies in the Southern Ocean indicate that polystyrene, polyethylene and polypropylene are the dominant plastics afloat (Andrady, 2011; Cincinelli et al., 2017; Turner, 2020; Suaria et al., 2020, 2023; Chan and Not, 2023) and may explain the ingestion/uptake by surface-feeding seabirds, such as Southern giant petrels. This is relevant because each polymer type is associated with additives that enhance different properties (e.g. flexibility, durability, UV stabilizer, etc.) (Hahladakis et al., 2018; GESAMP, 2019) and can be toxic if ingested (reviewed by Prokić et al., 2019; Puskic et al., 2020). Moreover, because the type of polymer influences the adsorption of different chemical substances (e.g. PAHs and PCBs on polystyrene; Fred-Ahmadu et al., 2020), future studies should expand on combining polymer identification of ingested plastics with measuring of plastic-derived chemicals metabolized and deposited in tissues and their potential adverse effects on seabird health.

Our study confirms that plastic ingestion is a common problem for procellariiforms in the Southwest Atlantic Ocean, but it affects species unequally. Our experience illustrates that building diverse regional monitoring networks (e.g. beach survey programs, on-board observer programs, rehabilitation centers, researchers) adds value by broadening the geographical, species, condition and life-history scope to surveillance efforts. However, although this approach allowed us to build a baseline for the area, long-term programs with balanced species representation and standardized protocols are needed to identify patterns across species at a regional level, and ultimately to understand the contribution of anthropogenic and ecological drivers to the incidence of plastic ingestion. Nevertheless, given existing evidence, efforts that address the knowledge gaps on the health effects of plastic ingestion and accumulation in seabirds are essential.

Permits

This study was conducted under permits from the Administración de Parques Nacionales, Chubut (1369), Secretaría de Desarrollo Sustentable y Ambiente, Tierra del Fuego, Antártida e Islas del Atlántico Sur (570/2012), Dirección de Fauna y Flora, Buenos Aires (DISPO-2021-1000-GDEBA-DPFAAYRNMDAGP), Dirección de Fauna y Flora Silvestre Provincia de Chubut (79/22-DFyFS-MAGIyC), Subsecretaría de Conservación y Áreas Protegidas Provincia de Chubut (76/22-SsCyAP), Autorização de Captura, Coleta e Transporte de Material Biológico (ABIO 640/2015), Sistema de Autorização e Informação em Biodiversidade (SISBIO 26896-12) and Sistema Nacional de Gestão de Fauna Silvestre (SISFAUNA/IEMA 68077610).

CRediT authorship contribution statement

Luciana Gallo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patricia P. Serafini:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Ralph E.T. Vanstreels:** Writing – review & editing, Methodology, Investigation, Data curation. **Leandro L. Tamini:** Writing – review & editing, Data curation. **Cristiane K.M. Kolesnikovas:** Writing – review & editing, Data curation. **Alice Pereira:** Writing – review & editing, Data curation. **Tatiana Neves:** Writing – review & editing, Data curation. **Gabriel D. Nascimento:** Writing – review & editing, Data curation. **Lucas S. Rodriguez Pirani:** Writing – review & editing, Formal analysis. **A. Lorena Picone:** Writing – review & editing, Formal analysis. **Rosana M. Romano:** Writing – review & editing, Resources, Formal analysis. **C. Karina Alvarez:** Writing – review & editing, Methodology, Data curation. **Sergio A. Rodriguez Heredia:** Writing – review & editing, Methodology, Data curation. **Leandro N. Chavez:** Writing – review & editing, Data curation. **Ruben F. Dellacasa:** Writing – review & editing, Data curation. **Marcela M. Uhart:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117094.

Data availability

Data will be made available on request.

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