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Ingestion of plastics and other debris by coastal and pelagic birds along the coast of Espírito Santo, Eastern Brazil

Ralph Eric Thijl Vanstreels[a,b,*], Luciana Gallo[c], Patricia P. Serafini[d], Allan P. Santos[a], Leandro Egert[a], Marcela M. Uhart[b]

[a] Institute of Research and Rehabilitation of Marine Animals, Rodovia BR-262 km 0, Jardim América, Cariacica, Espírito Santo 29140-130, Brazil
[b] One Health Institute, School of Veterinary Medicine, University of California, Davis, 1089 Veterinary Medicine Drive, VM3B, Davis, CA 95616, USA
[c] Instituto de Biología de Organismos Marinos, Consejo Nacional de Investigaciones Científicas y Técnicas, Boulevard Brown 2915, Puerto Madryn U9120ACD, Chubut, Argentina
[d] Centro Nacional de Pesquisa e Conservação de Aves Silvestres, Instituto Chico Mendes de Conservação da Biodiversidade, Rodovia Maurício Sirotski Sobrinho SC 402, km 02, Florianópolis, Santa Catarina 88053-700, Brazil

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ABSTRACT

Although the ingestion of plastics and other anthropogenic debris by seabirds is a global problem, few studies have employed standardized protocols to quantify and classify the debris ingested by seabirds in the Southwest Atlantic. We evaluated the ingestion of marine debris (items >0.1 mm) by 126 coastal and pelagic birds (19 species) along the coast of Espírito Santo, Eastern Brazil. Debris were found in 30% of birds examined (11 species). Particles <1 mm accounted for 35% of all debris items. Most ingested debris were plastics (97%). Ingestion of >0.1 g of plastic debris was recorded in five species: Atlantic yellow-nosed albatrosses (*Thalassarche chlororhynchos*), Cory's shearwaters (*Calonectris borealis*), Manx shearwaters (*Puffinus puffinus*), brown boobies (*Sula leucogaster*), and Magellanic penguins (*Spheniscus magellanicus*). Our findings suggest that the ingestion of marine debris, especially plastics, is a common problem for coastal and pelagic birds in tropical Southwest Atlantic waters.

1. Introduction

Plastic pollution is one of the greatest challenges for marine conservation in the 21st century (Wilcox et al., 2015). Modeling studies validated by global sampling efforts demonstrate that debris are concentrated in subtropical convergence zones (commonly known as "garbage patches") and along the coastal margins near human population centers (Lebreton et al., 2018; Wilcox et al., 2015). Large items (>50 cm) are the greatest contributors in terms of mass to these accumulation zones, especially fishing gear remnants (Lebreton et al., 2018). Outside of these accumulation zones, however, the majority of plastic debris floating in the ocean corresponds to smaller items, especially between 1 and 5 mm (Cózar et al., 2014; Suaria et al., 2020; Uchida et al., 2016).

Although the ingestion of plastics by marine animals was recorded as early as the 1960s, the last two decades have seen a rapid increase in studies reporting the interaction between wildlife and plastics, with plastic ingestion having been recorded in 180 of 226 seabird species studied (Kühn et al., 2015; Kühn and Van Franeker, 2020; Provencher et al., 2017). When adjusting for biases in study effort with regards to time and species, the actual rate of plastic ingestion by seabirds could be as high as 90% of individuals (Wilcox et al., 2015). The health effects of the ingestion of plastics and other debris are relatively self-evident when they cause the obstruction or perforation of the gastrointestinal tract (Phillips et al., 2010; Ryan, 2016; Senko et al., 2020). However, sub-lethal effects of debris ingestion, especially nano (<0.001 mm) and microplastics (0.001 to 5 mm), are poorly documented and consequently the true extent of their health impacts is likely underestimated (Puskic et al., 2020). For example, ingested plastics are known to release plastic additives (e.g. plasticizers, flame retardants) and organic pollutants (e.g. PCBs, PAHs, organochlorine pesticides) when ingested by marine fauna (Baini et al., 2017; Hardesty et al., 2015; Puskic et al., 2020; Rios et al., 2010; Tanaka et al., 2013). Other sub-lethal effects of debris ingestion are dietary dilution, malnutrition, delayed chick growth, and changes in

* Corresponding author at: Institute of Research and Rehabilitation of Marine Animals, Rodovia BR-262 km 0, Jardim América, Cariacica, Espírito Santo 29140-130, Brazil.
E-mail address: ralph_vanstreels@yahoo.com.br (R.E.T. Vanstreels).

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blood chemistries (Auman et al., 2004; Lavers et al., 2019, 2014; Ryan, 2016; Senko et al., 2020).

Previous studies have found that the prevalence and magnitude of plastic ingestion can vary considerably among avian taxa according to their diet and foraging techniques (Kühn and Van Franeker, 2020; Moser and Lee, 1992; Roman et al., 2019; Ryan, 1987). Thus, it is important to consider local differences in species composition of avian communities when assessing the impacts of plastic ingestion in seabirds. Although there is an abundance of studies on the ingestion of plastics by seabirds in the northern hemisphere (Avery-Gomm et al., 2013; Baak et al., 2020; Moser and Lee, 1992; Provencher et al., 2014), modeling studies suggest that plastic ingestion might be most impactful to seabirds in the southern hemisphere due to the avian community composition in that region (Wilcox et al., 2015), with a high richness of Procellariiformes species (Davies et al., 2010). Many procellariiform birds are highly susceptible to plastic ingestion, since they feed preferably on small prey on the waters' surface, where plastics tend to float and accumulate (Titmus and Hyrenbach, 2011).

Several studies have quantified debris ingestion in seabirds (beach-cast or killed by fisheries) in Brazil, especially in southernmost areas (Barbieri, 2009; Colabuono et al., 2009; Jiménez et al., 2015; Petry et al., 2009; Petry and Benemann, 2017; Tourinho et al., 2010). However, little is known about the prevalence and magnitude of plastic ingestion by coastal and pelagic birds in the Eastern Brazil ecoregion (Brandão et al., 2011; Pinto et al., 2007; Tavares et al., 2017). In this study, we employ standardized methods (Galgani et al., 2019; Kershaw et al., 2019) to characterize and quantify the ingestion of plastics and other debris by coastal and pelagic birds (19 species) along the coast of Espírito Santo, in tropical waters of Eastern Brazil.

2. Methods

The coastline of Espírito Santo state (Fig. 1A) extends approximately 392 km from Riacho Doce stream (18.35S, 39.67 W) to Itabapoana River (21.31S, 40.96 W). This region is characterized by oligotrophic tropical-subtropical transitional waters of the Eastern Brazil ecoregion in the Tropical Southwestern Atlantic province (Schmid et al., 1995; Spalding et al., 2007). Wildlife rescued or found dead in this region is routinely brought to the Institute of Research and Rehabilitation of Marine Animals (IPRAM). These animals are either collected by the Projeto de Monitoramento de Praias das Bacias de Campos e Espírito Santo (PMP-BC/ES) during daily beach surveys or are submitted by the general public and local authorities on a voluntary basis. In this study, we evaluated coastal and pelagic birds admitted over a 26-month period (20 April 2019 to 20 June 2021). Species were classified by size according to their average adult body mass (Dunning, 2007; Sick, 2001): small (<300 g), medium (300–1000 g), and large (>1000 g). Species were also classified according to their status in Brazil (resident or visitor) according to the Brazilian Ornithological Records Committee, their global conservation status according to the International Union for the Conservation of Nature (IUCN), and their habitat and foraging techniques (Table 1; derived from BirdLife International and Handbook of the Birds of the World, 2019; Piacentini et al., 2015; Shealer, 2002; Sick, 2001).

Animals were classified according to their condition of decomposition (adapted from Geraci and Lounsbury, 2005): code 1 (live animal), code 2 (carcass in good condition; fresh/edible), code 3 (carcass in fair condition; decomposed, but organs basically intact), code 4 (carcass in poor condition; advanced decomposition), and code 5 (mummified or skeletal remains). Live birds that died within five days of admission and carcasses codes 2 to 4 whose digestive tract was intact were evaluated for plastic ingestion. Carcasses were necropsied following standard protocols (Work, 2000), and macroscopic pathological findings (e.g. perforations, ulcers, bleeding, etc.) were recorded along with additional relevant metadata (latitude and longitude of collection site, date of collection, species, age, sex and body mass). The upper digestive tract (proximal esophagus to pyloric sphincter) was removed intact and placed in a sealed plastic bag and stored at −20 °C.

Digestive tracts were later thawed, cut open, and their contents and mucosa were thoroughly washed with running tap water through a 0.1 mm mesh sieve. Any material retained was transferred to Petri dishes and examined under a stereomicroscope (7.5 to 35× magnification), and debris were removed with forceps or a fine brush (with natural bristles, i.e. bovine hair). In this study, we employed a 0.1 mm mesh sieve, enabling the detection of microparticles (0.1–5 mm), mesoparticles

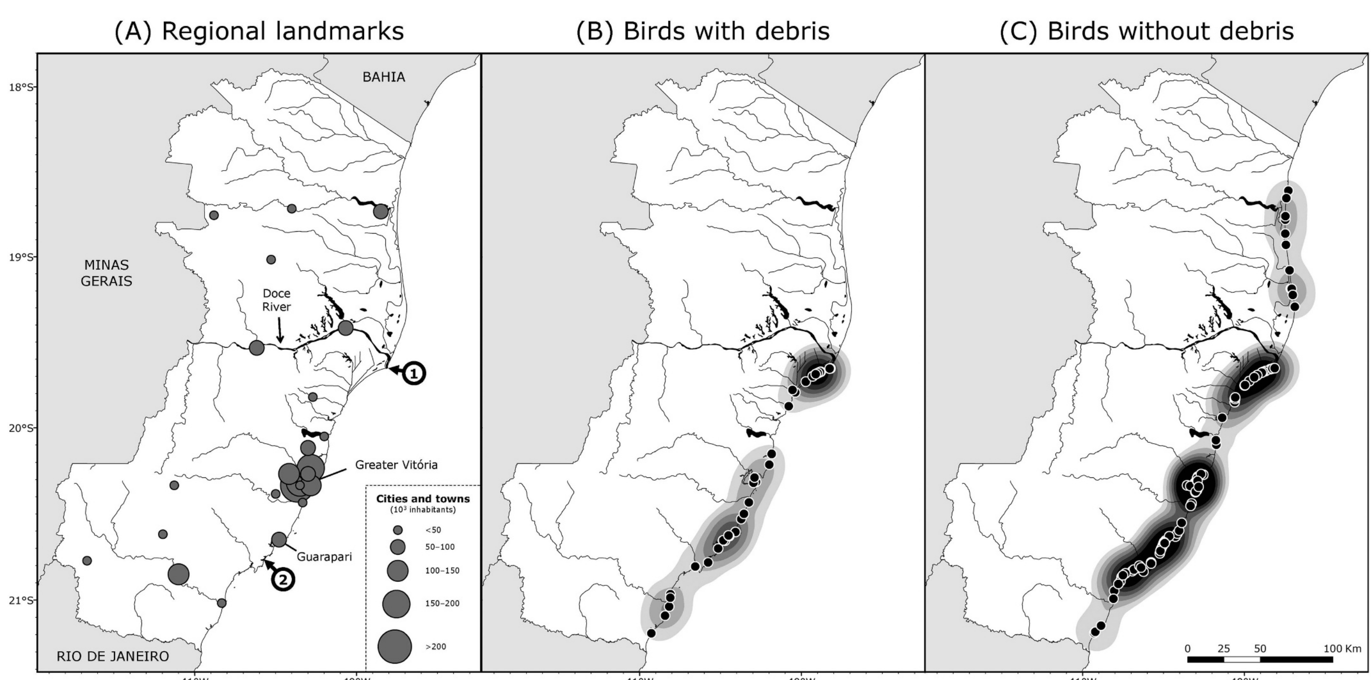

Fig. 1. Regional landmarks and geographic distribution of coastal and pelagic birds collected along the coast of Espírito Santo, southeast Brazil, with or without debris in their upper digestive tract. Study region was divided as follows: "North" from the border with Bahia to marker 1 (Doce River mouth), "Center" from marker 1 to marker 2 (Maembá), and "South" from marker 2 to the border with Rio de Janeiro.

Table 1
Biological characteristics and conservation status of the studied species.

Species	English name	Code	Body size	Foraging habitat[a]	Foraging technique[b]	Status in Brazil	IUCN[c]
Haematopus palliatus	American oystercatcher	AMOY	Medium	C	P	Resident	–
Anous stolidus	Brown noddy	BRNO	Small	P	PL,D,KP	Resident	–
Larus dominicanus	Kelp gull	KEGU	Medium	C	P,KP,SC,D,SS	Resident	–
Sterna hirundinacea	South American tern	SATE	Small	C	PL,D,KP	Resident	–
Sterna hirundo	Common tern	COTE	Small	C	PL,D,KP	Resident	–
Thalasseus acuflavidus	Cabot's tern	CATE	Small	C	PL,D,KP	Resident	–
Arenaria interpres	Ruddy turnstone	RUTU	Small	C	P,SC	Visitor	–
Ardea alba	Great egret	GREG	Medium	F,C	P	Resident	–
Nycticorax nycticorax	Black-crowned night heron	BCNH	Medium	F,C	P	Resident	–
Phaethon aethereus	Red-billed tropicbird	BCTR	Medium	P	PL	Resident	–
Tachybaptus dominicus	Least grebe	LEGR	Small	F,C	PD	Resident	–
Thalassarche chlororhynchos	Atlantic yellow-nosed albatross	AYNA	Large	P	SS,KP,SC	Visitor	EN
Calonectris borealis	Cory's shearwater	COSH	Medium	P	PD,SS,D	Visitor	–
Procellaria aequinoctialis	White-chinned petrel	WCPE	Medium	P	PD,SS,D	Visitor	VU
Puffinus puffinus	Manx shearwater	MASH	Medium	P	PD,SS,D	Visitor	–
Spheniscus magellanicus	Magellanic penguin	MAPE	Large	C,P	PD	Visitor	NT
Fregata magnificens	Magnificent frigatebird	MAFR	Large	C,P	D,KP	Resident	–
Nannopterum brasilianus	Neotropic cormorant	NECO	Medium	F,C	PD	Resident	–
Sula leucogaster	Brown booby	BRBO	Large	C,P	PL,PD	Resident	–

[a] Foraging habitat: F = Freshwater, C = Coastal/estuarine, P = Pelagic.
[b] Foraging techniques: P = Pecking and peck-digging, D = Dipping, SS = Surface-seizing, PL = Plunge-diving, PD = Pursuit-diving, KP = Kleptoparasitism, SC = Scavenging.
[c] Global conservation status according to the International Union for the Conservation of Nature (IUCN): EN = Endangered, VU = Vulnerable, NT = Near Threatened, "—" = Least Concern.

(5–25 mm) and macroparticles (>25 mm) (classification adapted from Kershaw et al., 2019). However, studies on debris ingestion by seabirds often employ 1 mm mesh sieves (e.g. Baak et al., 2020; Codina-García et al., 2013; Van Franeker et al., 2011); to allow comparison with such studies, we further categorized microparticles as smaller (0.1–1 mm) or larger microparticles (1–5 mm).

To prevent any cross-contamination with microparticles, several precautions were considered during laboratory procedures. All glass/metal containers and instruments used were previously rinsed with tap water and detergent using a brush with natural bristles. All working surfaces were cleaned with ethanol and tissue paper. Air flow was interrupted by turning off air condition, fans and keeping the room closed. Samples of potential contaminant materials (tissue paper, brush bristles, lab coat, nitrile gloves, human hair, etc.) were examined under the stereomicroscope to determine their morphology so that items with similar characteristics could be recognized and excluded if they were found in the samples (although this did not occur). Before processing samples, we placed clean Petri dishes with a small quantity of tap water near the working benches (one near the tap where samples were washed and one next to the stereomicroscope), and at the end of the day these dishes were checked for contaminants (none were found).

For particles larger particles (≥1 mm), visual inspection under the stereomicroscope is generally reliable to differentiate natural materials from anthropogenic debris (Van Franeker et al., 2011; Lusher et al., 2015; Avery-Gomm et al., 2018, 2016; Gil-Delgado et al., 2017; Provencher et al., 2014, 2018). To avoid misidentification and underestimation of smaller particles (<1 mm) it is necessary to standardize the plastic particle selection, following certain criteria to guarantee proper identification. For smaller particles to be classified as debris, they 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 (5) have three-dimensional bending (Hidalgo-Ruz et al., 2012; Lusher et al., 2020). In most cases, the smaller debris items had physical properties (density, texture, color) identical to those of larger items in the same sample, corroborating that they were fragments that broke down from larger, more identifiable debris.

Debris items were classified as recommended by the United Nations' Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (Kershaw et al., 2019), with some adaptations as employed by the European Marine Observation and Data Network (Galgani et al., 2019). Accordingly, each debris item was classified by type: fragment/pellet (hard particles with trapezoidal, spherical, cylindrical, smooth or granular shape), filament (long fibrous material with a length substantially greater than its width), film (flat, flexible particle with smooth surface), foam (polystyrene and/or polyurethane), and other/unclassified (metal, glass, paper, rubber or any other non-plastic anthropogenic debris). Fragments and pellets, which are usually classified separately, had to be pooled because they could not be reliably distinguished. Non-filamentous debris items were classified by shape (angular, sub-angular, sub-rounded, rounded, cylindrical, ovoid, flat, and other/unclassified). Filamentous debris items were classified by subtype (monofilament, ribbon, and braided thread). Additionally, debris were classified by color and grouped into eight categories (black/grey, brown/tan, blue/green, yellow, orange/pink/red, white/cream, colorless, multicolor, and metallic). A "kind" was defined as a collection of debris items with similar characteristics (density, texture and color), i.e. possibly fragments of the same item that broke down due to digestion or handling. The total mass of debris for each individual was measured with a scale (precision ±0.01 g); when the total mass was lower than 0.01 g, total mass was inferred as 0.01 divided by the square root of 2 for calculations of mean and standard deviation (Tekindal et al., 2017). Debris items were individually photographed with an 18 MP digital camera coupled to the stereomicroscope, and software-assisted image analysis with ImageJ (Schneider et al., 2012) was used to measure the length (widest dimension) of each item. Each debris item was classified into four categories (0.1–1 mm, 1–5 mm, 5–25 mm, >25 mm) according to its maximum length. The length of the largest debris item was also recorded for each individual bird. All processing, classification and measurement of debris were conducted by the same individual (R.E.T. V.) to avoid inter-observer differences.

Prevalence (no. individuals with debris/no. individuals evaluated), mean abudance (no. debris items/no. individuals evaluated) and mean intensity (no. debris items/no. individuals with debris) were calculated. The proportion of individuals with total mass of debris greater than 0.1 g was calculated for each species (OSPAR, 2010). Supplemental Files S1 and S2 provide the complete dataset for this study.

The geographic coordinates of the beach collection site were recorded for each bird, and the collection site was classified into three regions (North, Center, South; see Fig. 1A). The Chi-square test was used to compare the presence of debris in birds collected in each region. Nearby human settlements and population density were obtained from Global Population of the World v4 (GPWv4) (Doxsey-Whitfield et al., 2015); this 30-arc second resolution image was aggregated by a factor of 5, and then the human population at the point of beach collection site was interpolated for each bird. Kernel density heat maps (cell size = 0.001 km^2, search radius = 25,000 km^2) were used to illustrate the spatial density of studied birds. A binomial generalized linear model (GLM) was used to determine which of the following variables were predictive of the presence of debris in the upper digestive tract of a bird: species size (small, medium, large), habitat (binary variables: freshwater, coastal, pelagic), foraging strategy (binary variables: pecking/peck-digging, dipping, surface-seizing, plunge-diving, pursuit-diving, kleptoparasitism, scavenging), species status (resident, visitor), region (North, Center, South), year (2019, 2020, 2021), age group (juvenile, adult, unknown), sex (male, female), carcass condition (dead within 5 days of admission, freshly dead beach carcass, beach carcass in moderate decomposition, beach carcass in advanced decomposition), human population at beach collection site. The stepwise procedure informed by Akaike's Information Criterion (AIC) was used to select the best model.

3. Results

We evaluated the upper digestive tract of 126 individuals representing 19 species. Of these, 38 individuals (30% of individuals) representing 11 species (58% of species) had ingested debris (Table 2). If only debris items larger than 1 mm were considered, these numbers would change to 34 individuals (27%) and 10 species (53%) with debris. Fig. 1B and C compare the geographic distribution of birds with and without debris in their upper digestive tract. None of the birds collected in the North region had ingested debris ($n = 11$), compared to 33% in each the Center ($n = 88$) and South regions ($n = 27$); however, this apparent difference was not statistically significant ($\chi^2 = 5.206$, df = 2, $P = 0.074$). Fig. 2 presents the temporal distribution of birds found with ingested debris during the study period.

Table 3 provides a detailed summary of the distribution and characteristics of debris item for each bird species. A total of 212 debris items were recovered, with a mean abundance of 1.6 ± 7.1 items per bird evaluated ($Q_1 = 0$; median = 0; $Q_3 = 1$) and an intensity of 5.3 ± 12.5 items per bird with debris ($Q_1 = 2$; median = 2; $Q_3 = 4$; maximum = 79). Debris items were distributed by size category as follows: 0.1–1 mm (75 items, 35%), 1–5 mm (63 items, 30%), 5–25 mm (46 items, 22%), and >25mm (28 items, 13%). When debris smaller than 1 mm are omitted from the analysis (for comparison with studies using a 1 mm mesh sieve), debris prevalence is 27%, average abundance is 1.0 ± 2.7 items per bird evaluated and average intensity is 3.6 ± 4.2 items per bird with debris.

Polystyrene foam was the most frequent item type (81 items, 38%); however, this was due to 79 polystyrene foam items recovered from a single bird (an Atlantic-yellow nosed albatross *Thalassarche chlororhynchos*). When this outlier is removed, the most frequent item types were: filaments (66 items, 50%), fragments/pellets (34 items, 26%), and films (24 items, 18%), followed by natural fibers/rubber (4 items, 3%), non-plastic items (3 items, 2%), and polystyrene foam (2 items, 1.5%). The natural fibers/rubber category comprised two fragments of white sulfite pulp paper (both from an Atlantic yellow-nosed albatross) and two fragments of onion skin (both from another Atlantic yellow-nosed albatross). The non-plastic items category comprised a fishing hook (from a brown booby *Sula leucogaster*) and two fragments of aluminum foil (each from a common tern *Sterna hirundo* and a white-chinned petrel *Procellaria aequinoctialis*).

White/cream was the most frequent item color (113 items, 53%); however, this was also largely driven by the 79 white polystyrene foam items from a single bird. When this outlier is removed, the most frequent item colors were: black/grey (45 items, 34%), white/cream (34 items, 26%), and blue/green (28 items, 21%), followed by colorless (13 items, 10%), brown/tan (9 items, 7%), metallic (3 items, 2%), and yellow (1 item, 0.7%). Similarly, a rounded shape was most frequent (79 items, 41%) among non-filamentous items ($n = 146$), but this was driven by 79 polystyrene foam items recovered from a single bird. Removing this outlier, the non-filamentous items were most frequently flat (60 items, 90%), whereas other shape categories were rare: cylindrical (2 items, 3%), other/unclassified (2 items, 3%), sub-angular, sub-rounded, and ovoid (1 item each, 1.5% each).

Filamentous items ($n = 66$) were predominantly monofilaments (32 items, 48%) and ribbons (31 items, 47%), with a minority of braided threads (3 items, 5%). At least 19 monofilament items (29% of filaments) had thickness and/or knot pattern consistent with that of fishing nets. Four items had inscriptions, of which two were numbers and one was a single letter. The only item with sufficient text to be recognizable showed "CE DE AM" and "EDIENTES", which likely corresponds to "doce de amendoim" (in Portuguese: peanut sweet) or "doce de amêndoas" (almond sweet) and "ingredientes" (ingredients); it is thus

Table 2
Sample size and frequency of occurrence (FO%) of marine debris found in the upper digestive tract of seabirds collected on the coast of Espírito Santo state, southeast Brazil, 2019–2021.

Species[a]	Samples evaluated	Debris items >0.1 mm, FO%	Debris items >1 mm, FO%	Debris items by size category, FO%				Debris items by size category, n			
				0.1–1 mm	1–5 mm	5–25 mm	>25 mm	0.1–1 mm	1–5 mm	5–25 mm	>25 mm
AMOY	2	50%	50%	–	–	50%	50%	–	–	2	4
BRNO	5	–	–	–	–	–	–	–	–	–	–
KEGU	2	50%	–	50%	–	–	–	1	–	–	–
SATE	3	–	–	–	–	–	–	–	–	–	–
COTE	9	22%	22%	–	22%	–	–	–	3	–	–
CATE	27	15%	11%	4%	4%	4%	4%	1	1	2	2
RUTU	1	–	–	–	–	–	–	–	–	–	–
GREG	4	50%	50%	–	50%	25%	50%	–	6	1	4
BCNH	2	–	–	–	–	–	–	–	–	–	–
BCTR	1	–	–	–	–	–	–	–	–	–	–
LEGR	1	–	–	–	–	–	–	–	–	–	–
AYNA	5	60%	60%	40%	20%	40%	20%	63	17	3	2
COSH	5	80%	80%	–	20%	80%	20%	–	2	7	1
WCPE	4	75%	50%	25%	25%	50%	50%	1	1	4	2
MASH	20	35%	35%	5%	20%	20%	5%	2	14	12	1
MAPE	16	50%	50%	13%	19%	44%	38%	2	15	14	9
MAFR	4	–	–	–	–	–	–	–	–	–	–
NECO	2	–	–	–	–	–	–	–	–	–	–
BRBO	13	23%	15%	15%	15%	8%	8%	5	2	1	2
Total	126	30%	27%	8%	13%	18%	13%	75	61	46	27

[a] Species codes are the same as provided in Table 1.

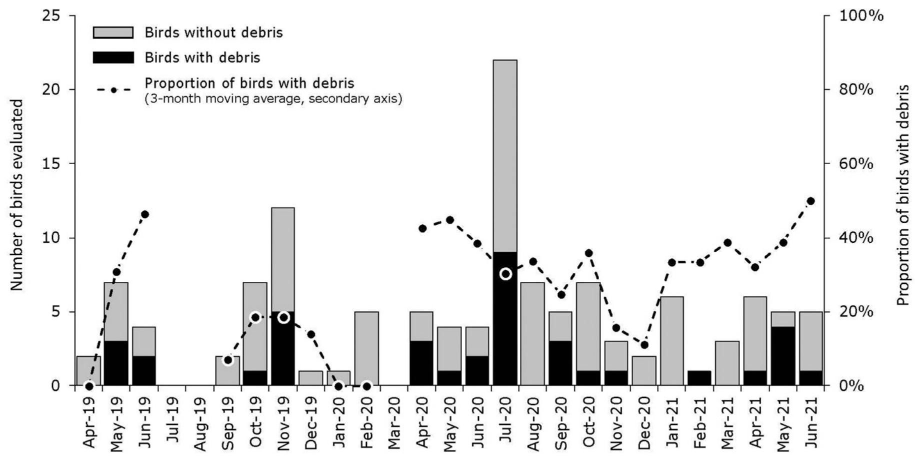

Fig. 2. Temporal distribution of coastal and pelagic birds collected along the coast of Espírito Santo, southeast Brazil, with or without debris in their upper digestive tract.

presumed to be a fragment of food packaging. Other items with identifiable origin comprised: three fragments of black rubbish bags, two fragments of shoelaces, and two fragments of a bottle tamper-evident band. The only bird that had necropsy lesions consistent with having died from debris ingestion was an adult male brown booby that was emaciated and had a heavily eroded fishing hook lodged in a firm mass of necrotic-purulent material adhered to the ventricle wall, which presumably triggered chronic pain and discomfort that ultimately caused the bird to starve.

GLM identified three variables (species size, species status and sex) were significantly predictive of debris ingestion (McFadden's pseudo-R^2 = 0.127; intercept = 2.693 ± 0.581, $P < 0.001$). Birds were more likely to ingest debris if they were a medium-sized species (coefficient = 1.448 ± 0.603, $P = 0.016$) relative to small-sized species (reference category). A similar but not statistically significant effect was seen for large-sized species (coefficient = 1.094 ± 0.594, $P = 0.065$). Birds of migratory species were more likely to ingest debris (coefficient estimate = 1.026 ± 0.459, $P = 0.025$) than resident species (reference category). Although the effect was not statistically significant, males were slightly more likely to ingest debris (coefficient estimate = 0.788 ± 0.454, $P = 0.083$) than females (reference category). The remaining variables (habitat, foraging technique, region, year, age group, carcass condition, human population) were poor predictors of plastic ingestion (all $P > 0.1$) and therefore were not included in the final model.

4. Discussion

Every year, eight million metric tons of plastics enter our ocean, adding to the estimated 150 million metric tons accumulated and circulating in our marine environments (Jambeck et al., 2015). Given the magnitude of this problem, it is urgent to understand the impacts of these plastics on marine wildlife and ocean health.

Studies on marine plastic pollution traditionally differentiate between nanoplastics (<0.001 mm), microplastics (0.001 to 5 mm), mesoplastics (5 to 25 mm), macroplastics (25 to 1000 mm), and megaplastics (>1000 mm) (Gibb et al., 2017; Kershaw et al., 2019). Studies on plastic ingestion by seabirds often employ 1 mm mesh sieves (Baak et al., 2020; Codina-García et al., 2013; Van Franeker et al., 2011) or do not provide details on the lower size threshold, presumably relying on naked eye visualization of debris during dissection (Colabuono et al., 2009; Jiménez et al., 2015; Tavares et al., 2017). In this study, we employed a 0.1 mm mesh sieve and thoroughly examined all retained material under a stereomicroscope, which allowed for the detection of items smaller than 1 mm that could otherwise have been missed. For this reason, caution is warranted when comparing our results to those of previous studies. When only fragments larger than 1 mm are considered, the prevalence of debris ingestion in this study remains approximately the same (27% down from 30%) but intensity decreases substantially (3.6 items per bird with debris, down from 5.3). Because all items smaller than 1 mm were below the 0.01 g weighing threshold, estimated debris mass remains unchanged. These results suggest that the evaluation of debris items larger than 1 mm, which is less laborious and time consuming (and less likely to misclassify natural vs. anthropogenic items), may produce reasonably accurate estimates for the prevalence and mass of debris ingested by seabirds, but is likely to substantially underestimate the number of debris items per bird (therefore inaccurately estimating debris abundance and intensity).

The high prevalence of debris ingestion in albatrosses, shearwaters, brown boobies and Magellanic penguins (*Spheniscus magellanicus*) is consistent with previous studies on the Atlantic coast of South America (Brandão et al., 2011; Colabuono et al., 2009; Copello and Quintana, 2003; Jiménez et al., 2015; Petry et al., 2009; Petry and Benemann, 2017; Pinto et al., 2007; Tavares et al., 2017; Tourinho et al., 2010). In the case of albatrosses, petrels and some shearwaters, their high susceptibility may be largely related to them feeding on small prey that they seize on the ocean's surface, where plastics tend to float and accumulate (Roman et al., 2019; Titmus and Hyrenbach, 2011). Additionally, recent studies have shown that the biofilm that forms on the surface of plastic debris produces an olfactory signature that resembles that of the natural food of procellariform birds, which may also explain the high frequency of debris ingestion in this group (Savoca et al., 2017, 2016).

However, Manx shearwaters (*Puffinus puffinus*) feed primarily on school-fish that they chase while diving (Brown et al., 1978; Shoji et al., 2016), hence their predisposition to plastics ingestion is harder to explain. Likewise, Magellanic penguins also employ a pursuit-diving foraging technique (Gómez-Laich et al., 2018; Peters et al., 1998; Sala et al., 2014). However, because the high prevalence of debris ingestion in Magellanic penguins is biased towards juveniles during winter migration, higher exposure may result from a poorly selective diet in an attempt to stave-off hunger as they acquire fishing skills (Brandão et al., 2011; Tourinho et al., 2010). In fact, juvenile Magellanic penguins consume a more diverse diet and with a greater proportion of items with low caloric density (especially cephalopods) during wintering in Brazilian waters than do adults at the breeding grounds (Di Beneditto et al., 2015; Fonseca et al., 2001; Pinto et al., 2007). It is plausible that Manx shearwaters also ingest plastics while overwintering in Brazil, where they too have a more diverse diet and higher proportion of low calorie items (especially cephalopods and insects) (Petry et al., 2008). The body mass of the Manx shearwaters evaluated in this study (mean ± SD = 269 ± 59 g, range = 204–430 g; see Supplemental File S1) was generally lower than that of healthy individuals (350–575 g) (Lee et al., 2020), which further supports the hypothesis that debris ingestion in this

Table 3
Measurements and visual characteristics of marine debris found in the upper digestive tract of seabirds collected on the coast of Espírito Santo state, southeast Brazil, 2019–2021.

	AMOY[a]	KEGU[a]	COTE[a]	CATE[a]	GREG[a]	AYNA[a]	COSH[a]	WCPE[a]	MASH[a]	MAPE[a]	BRBO[a]	Total
Prevalence												
Samples evaluated	2	2	9	27	4	5	5	4	20	16	13	107
Samples with debris	1	1	2	4	2	3	4	3	7	8	3	38
Debris FO%	50%	50%	22%	15%	50%	60%	80%	75%	35%	50%	23%	36%
Birds with >0.1 g plastics	0%	0%	0%	0%	0%	40%	20%	0%	15%	13%	15%	9%
Items per bird (intensity), n												
Mean	6	1	1.5	1.5	5.5	28.3	2.5	2.7	4.1	5	3.3	5.5
SD	–	–	0.7	0.6	3.5	43.9	1	1.2	3.7	6.6	2.1	12.8
Minimum	–	–	1	1	3	2	2	2	1	1	1	1
Maximum	–	–	2	2	8	79	4	4	11	21	5	79
Item kinds per bird, n												
Mean	1	1	1.5	1	3	1.3	2.3	2	2.3	2.3	1.7	1.9
SD	–	–	0.7	0	0	0.6	0.5	0	1.6	1.4	1.2	1.1
Minimum	–	–	1	1	3	1	2	2	1	1	1	1
Maximum	–	–	2	1	3	2	3	2	5	5	3	5
Total debris mass, g												
Mean	<0.01	<0.01	<0.01	0.01	<0.01	44.13	0.13	0.03	0.21	1.38	2.68	4.04
SD	–	–	<0.01	0.02	<0.01	72.25	0.23	0.05	0.45	3.79	3.2	20.68
Minimum	–	–	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Maximum	–	–	<0.01	0.04	<0.01	127.51	0.46	0.08	1.23	10.77	6.22	127.51
Largest debris length, mm												
Mean	108	0.85	1.81	26.41	38.3	22.04	15.47	24.71	11.04	45.48	18.78	26.17
SD	–	–	0.22	40.29	3.25	28.13	12.6	20.64	9.52	31.17	21.29	28.53
Minimum	–	–	1.65	0.72	36	3.12	5.86	1.32	1.47	8.78	3.04	0.72
Maximum	–	–	1.96	85.7	40.59	54.37	33.25	40.4	29.38	83.4	43	108
Debris type, FO%												
Fragment/pellet	–	50%	11%	7%	50%	20%	60%	25%	20%	13%	8%	17%
Filament	50%	–	–	4%	50%	–	40%	50%	15%	25%	15%	16%
Film	–	–	11%	4%	25%	–	40%	25%	5%	31%	8%	12%
Foam	–	–	–	–	–	20%	–	–	5%	–	–	2%
Non-plastic	–	–	11%	–	–	–	–	25%	–	–	8%	3%
Natural fiber/rubber	–	–	–	–	–	40%	–	–	–	–	–	2%
Debris shape, FO%												
Sub-angular	–	–	–	–	–	–	20%	–	–	–	–	1%
Sub-rounded	–	–	–	–	–	–	–	–	5%	–	–	1%
Rounded	–	–	–	–	–	20%	–	–	–	–	–	1%
Cylindrical	–	–	–	–	–	–	40%	–	–	–	–	2%
Ovoid	–	–	–	–	–	–	20%	–	–	–	–	1%
Flat	–	50%	22%	11%	50%	40%	80%	50%	25%	44%	15%	28%
Other/unclassified	–	–	–	–	–	20%	–	–	–	–	8%	2%
Filament subtype, FO%												
Monofilament	–	–	–	4%	25%	–	40%	50%	15%	19%	–	11%
Ribbon	50%	–	–	–	25%	–	–	–	–	19%	8%	6%
Braided thread	–	–	–	–	–	–	–	–	–	6%	8%	2%
Debris color, FO%												
Black/grey	–	–	–	4%	50%	–	40%	–	20%	25%	8%	13%
Brown/tan	–	–	–	–	–	20%	20%	25%	5%	25%	–	7%
Blue/green	–	–	11%	–	50%	20%	60%	50%	5%	–	15%	11%
Yellow	–	–	–	–	–	–	–	–	5%	–	–	1%
White/cream	50%	50%	11%	11%	25%	40%	20%	50%	10%	25%	–	17%
Colorless	–	–	–	–	25%	–	20%	–	5%	19%	8%	7%
Metallic	–	–	11%	–	–	–	–	25%	–	–	8%	3%

[a] Species codes are the same as provided in Table 1.

species was associated with poor nutritional status. Further studies are therefore warranted to assess potential associations between the plastic ingestion by seabirds and dietary shifts related to factors such as age/experience and prey availability.

The only previous study on the ingestion of plastic debris by seabirds in the study region used publicly-available data for 2010-2013 from the same beach monitoring program as this study (PMP-BC/ES) (Tavares et al., 2017). In that study, which included data from northern Rio de Janeiro, debris ingestion was recorded in 16% of individuals ($n = 622$) and 55% of species examined ($n = 22$). Procellariiformes experienced the highest frequency of debris ingestion in that study: 57% of black-browed albatrosses (*Thalassarche melanophris*, $n = 7$), 56% of great shearwaters (*Ardenna gravis*, $n = 16$), 50% of white-chinned petrels ($n = 10$), 33% of Atlantic yellow-nosed albatrosses ($n = 6$), 24% of Cory's shearwaters ($n = 38$), and 13% of Manx shearwaters ($n = 32$). Debris ingestion was also relatively frequent in some non-procellariiform birds: 18% of brown boobies ($n = 44$), 15% of Magellanic penguins ($n = 365$) and 4.5% of common terns ($n = 22$). Our results show a similar pattern in the susceptibility of these different species, but the prevalence of plastic ingestion in this study was nearly double (see Table 2). This difference could be reflective of a worsening of environmental conditions, considering that the population of Espírito Santo has increased by *c.* 40% from 2010 to 2020 (IBGE, 2020), combined with the global increase of anthropogenic marine debris (Lebreton et al., 2019). However, it could also reflect differences in methodology, since PMP-BC/ES did not have standardized protocols for processing of digestive tract contents in 2010-2013, and the thoroughness of this analysis would have varied considerably among professionals and organizations involved.

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) established an Ecological Quality Objective (EcoQO) for levels of plastics in the stomach of northern fulmars (*Fulmarus glacialis*) (OSPAR, 2010), which has been widely used in the northern hemisphere (Avery-Gomm et al., 2012; Bond et al., 2014; Kühn and van Franeker, 2012; Provencher et al., 2010; Trevail et al., 2015). EcoQO performance is defined as the percentage of birds in a sample that have 0.1 g or more plastic mass in the stomach, and the OSPAR target is to reduce that percentage to under 10%. Ingestion of 0.1 g or more of plastics was recorded in 9% of the birds examined in this study. However, when each species is considered separately, five species surpassed the 10% target: Atlantic-yellow nosed albatross (40%), Cory's shearwater (20%), brown booby (15%), Manx shearwater (15%), and Magellanic penguin (13%). Because fulmarine petrels are absent in the study region, it is unclear how to interpret our results relative to the OSPAR target. If we consider other Procellariiformes as comparable indicators, our results suggest a failure to meet the OSPAR target since the EcoQO performance for birds in this group was between 15 and 40% in this study (except for white-chinned petrels, for which only four individuals were examined and none had >0.1 g plastics). Future research towards the development of ecological quality indexes and targets comparable to the OSPAR EcoQO that are specific for the species in the Southwest Atlantic would therefore be valuable to guide policies for the conservation of marine environment and seabirds in this region.

Interestingly, our linear model suggests that belonging to a medium-sized and non-resident species is associated with an increased probability of debris ingestion. This may reflect that a high frequency of debris ingestion was recorded for Procellariidae (shearwaters and petrels), and representatives of this family evaluated in this study happened to all be medium-sized and migratory. Previous studies have noted that the gizzard of procellariform birds, except for albatrosses, is separated from the proventriculus by a narrow isthmus juncture where hard items become lodged and are not easily regurgitated, which may explain why these species (most of which are medium-sized) often present a higher frequency of plastic debris (Furness, 1985; Jiménez et al., 2015; Ryan, 1987).

Plastic fragments/pellets and filaments were the most frequently occurring types of debris. Unfortunately, due to grinding by the avian gizzard, we were not able to confidently differentiate between pellets (raw industrial material) and fragments (fragmented final products), as is usually done in plastic pollution surveys at beaches and in the ocean (Galgani et al., 2019; Kershaw et al., 2019). For filamentous items, nearly half of them were monofilaments, the majority of which were consistent with fragments of fishing nets. Among other recognizable items, we found several items that were presumably used for packaging such as plastic membranes, polystyrene foam and ribbons, in addition to rubbish bags and a bottle tamper-evident band. This suggests that single-use plastics are a significant contributor to the debris ingested by coastal and pelagic birds, highlighting the need to adopt policies to reduce their production and use (Xanthos and Walker, 2017).

Concerning the color, the highest frequency of occurrence was observed for white/cream, black/grey and blue/green. Not all studies quantify the color of debris ingested by coastal and pelagic birds, but some have found 'white/beige' items were most frequently ingested by oystercatchers (Rossi et al., 2019), 'yellow' by fulmars (Avery-Gomm et al., 2018), 'dark' by shearwaters and 'light' by coastal birds (Codina-García et al., 2013), 'orange-brown' by various species (Baak et al., 2020), 'brown' and 'beige' by various species (Barbieri, 2009), among others. In light of these varied results, it is unclear whether these birds actively select some colors, as is known to occur in sea turtles (Santos et al., 2016), or if the color of the ingested items is largely driven by their abundance.

We found no apparent geographic pattern in plastic ingestion within the study area. Most birds in this study, both with and without ingested debris, were collected near the mouth of the Doce River. The Doce River basin covers 83,400 km^2 including several large cities with a combined population of more than 1,000,000 inhabitants (IBGE, 2020). The sediment plume formed at Doce River's mouth is a key source of nutrients in this otherwise oligotrophic region, with a high significance for coastal cetaceans (Mayorga et al., 2020; Siciliano et al., 2002) and coastal and pelagic birds (Bugoni, 2019). Our results suggest that plastic ingestion may also be a problem in this area, and therefore the reduction of plastic pollution in the Doce River basin could benefit seabirds that forage on the Espírito Santo coast. Other key areas where a reduction in plastic pollution could benefit seabirds are the Greater Vitória metropolitan area (with a population of 2,000,000 inhabitants; IBGE, 2020) and Guarapari (which receives up to 600,000 tourists each summer; Rodrigues, 2019). It is worth highlighting that pollution reduction in this region would also benefit migratory species arriving from the northern hemisphere (e.g. Cory's and Manx shearwaters), the southern tip of South America (e.g. Magellanic penguin) and remote oceanic islands (e.g. Atlantic yellow-nosed albatross). These results highlight the need for further studies that identify hotspots of marine debris release and accumulation in coastal and offshore waters in this region and their overlap with the areas used by resident and migratory seabirds.

There was an apparent reduction in the frequency of debris ingestion during the summer (December to March, see Fig. 2). However, this may be due to seasonality of these species' presence in the region since the species with highest prevalence (i.e. procellariform birds and penguins) are seasonal migrants in Brazil (Sick, 2001). There was no apparent increase in debris ingestion that could be associated with the COVID-19 pandemic (first human case in Espírito Santo was recorded on 5 March 2020 and business and school activities were intermittently interrupted from 20 March 2020 to 4 April 2021). In other parts of Brazil, beach pollution by protective facemasks was noted from June to October 2020, with at least one Magellanic penguin dying due to the ingestion of a PFF-2 mask (Neto et al., 2021).

In conclusion, debris ingestion is relatively common in coastal and pelagic birds in Eastern Brazil, but it affects species disproportionately, with procellariform birds and juvenile Magellanic penguins experiencing a greater susceptibility. Despite nearly one-third of the studied birds having ingested debris, most items were small enough that they probably would not have caused digestive tract obstruction or perforation. Still, further studies are needed to assess subtler or indirect health effects of plastic ingestion such as damage to microscopic features of the digestive tract (e.g. proventricular glands, intestinal villi), interference with the gut microbiota, release of toxic chemicals, among others. Regardless of the health effects of plastic ingestion, our results confirm that seabirds are useful indicator species to monitor marine plastic pollution in the Southwest Atlantic Ocean.

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CRediT authorship contribution statement

Ralph Eric Thijl Vanstreels: Conceptualization, Data curation, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Luciana Gallo:** Conceptualization, Data curation, Investigation, Methodology, Formal analysis, Writing – review & editing. **Patricia P. Serafini:** Conceptualization, Investigation, Methodology, Resources, Writing – review & editing. **Allan P. Santos:** Data curation, Investigation, Writing – review & editing. **Leandro Egert:** Data curation, Investigation, Writing – review & editing. **Marcela**

M. Uhart: Conceptualization, Project administration, Resources, Supervision, Writing – review & editing.

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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