Marine Pollution Bulletin 203 (2024) 116400

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Regurgitated skua pellets containing the remains of South Atlantic seabirds can be used as biomonitors of small buoyant plastics at sea

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ARTICLE INFO

Keywords:
Biomonitor
Plastic ingestion
Polymers
Seabirds
South Atlantic Ocean
Storm petrels

ABSTRACT

Using seabirds as bioindicators of marine plastic pollution requires an understanding of how the plastic retained in each species compares with that found in their environment. We show that brown skua *Catharacta antarctica* regurgitated pellets can be used to characterise plastics in four seabird taxa breeding in the central South Atlantic, even though skua pellets might underrepresent the smallest plastic items in their prey. *Fregetta* storm petrels ingested more thread-like plastics and white-faced storm petrels *Pelagodroma marina* more industrial pellets than broad-billed prions *Pachyptila vittata* and great shearwaters *Ardenna gravis*. Ingested plastic composition (type, colour and polymer) was similar to floating plastics in the region sampled with a 200 μm net, but storm petrels were better indicators of the size of plastics than prions and shearwaters. Given this information, plastics in skua pellets containing the remains of seabirds can be used to track long-term changes in floating marine plastics.

1. Introduction

The global surge in plastic production has resulted in a rapid increase in the amounts of mismanaged plastic waste (Geyer et al., 2017; Lebreton and Andrady, 2019). In 2016, an estimated 19–23 million tonnes of plastic waste entered the marine environment, and if urgent global efforts are not implemented to curb emissions, this amount is expected to increase to 53 million tonnes by 2030 (Borrelle et al., 2020). Recent escalations in research outputs and public concern have propelled governments to implement policies and mitigation measures aimed at curbing the leakage of plastic waste into the environment (Walker, 2021). For example, the United Nations' Agenda 2030 and Sustainable Development Goal (SDG) 14.1 aim to significantly reduce marine pollution by 2025 (https://www.un.org/sustainabledevelopment/). To evaluate the effectiveness of waste reduction policies and mitigation measures, baseline data on plastic densities must be available for comparison (Ryan et al., 2009; Morét-Ferguson et al., 2010; Lebreton et al., 2017; Ryan et al., 2020). Numerous studies have attempted to measure the abundance of buoyant plastics in the ocean, which can be used to evaluate the effectiveness of mitigation efforts (e.g. Maes et al., 2017; Lebreton et al., 2018; Garcia et al., 2020; González-Fernández et al., 2022; Weideman et al., 2023). However, at-sea sampling poses several challenges, and considerable effort and resources are required to obtain robust results.

Most studies determine the abundance of floating plastic items at sea by towing a fine-meshed net along the surface of the ocean. The density of plastic is calculated from the number of plastic items collected within the sampled area (Ryan et al., 2009; GESAMP, 2019). However, this is time-consuming and expensive, and each net tow only samples a tiny area (typically <0.001 km^2). Ekman circulation creates local convergence patterns, causing variability and clustering of floating plastics at small spatial scales (van Sebille et al., 2020), and this, coupled with the small area sampled per tow, results in a high degree of heterogeneity in the amount of plastic sampled (Ryan et al., 2009; Law et al., 2014). To address this uneven distribution requires large numbers of surface net tows covering extensive areas. In addition, high winds and waves cause vertical mixing of plastics at the sea surface, reducing the likelihood of sampling floating plastics with a shallow surface net (Kukulka et al., 2012; Reisser et al., 2015). Adverse weather also can prevent net deployments (Law et al., 2014). Together, these factors make it

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https://doi.org/10.1016/j.marpolbul.2024.116400
Received 22 December 2023; Received in revised form 15 April 2024; Accepted 18 April 2024

challenging to detect temporal or spatial changes in floating plastic abundance from surface net tows (Ryan et al., 2009).

Plastics ingested by biota such as fish, turtles, and seabirds provide an alternative to at-sea sampling as they forage over large areas, are abundant and generally inexpensive to sample (Ryan, 2008; Ryan et al., 2009; van Franeker and Law, 2015; Bray et al., 2019; Savoca et al., 2022; Thibault et al., 2023). Albatrosses and petrels (Procellariiformes) are surface feeders that often ingest plastic fragments, but seldom regurgitate plastics, except when feeding chicks. Petrels retain plastics for longer than other seabirds as they have a narrow pyloric sphincter linking the stomach to the small intestine, which traps plastics and other indigestible remains in the hind-stomach or ventriculus (Furness, 1985). This retention means that the types and quantities of plastics in the environment are integrated over space and time, and as a result, petrels have been used to monitor temporal variation in the amounts and types of plastics floating at sea (Furness, 1985; Ryan, 2008; Ryan, 2015a; Ryan, 2016; van Franeker et al., 2011; Avery-Gomm et al., 2018; Perold et al., 2020). For example, plastic loads in the northern fulmar *Fulmarus glacialis* have been adopted as an indicator of marine litter in the northeast Atlantic Ocean, where an Ecological Quality Objective for marine litter states that no >10 % of fulmars should contain >0.1 g of plastic (OSPAR, 2010).

The large plastic items that petrels store in their stomachs are mainly ingested directly by the birds as they forage at sea, and which they presumably mistake for prey items. This is indicated by the fact that they mimic certain characteristics resembling food or prey items e.g., type, size, buoyancy, colour or conspicuousness (Ryan, 1987; Ryan, 2016; Santos et al., 2016; Roman et al., 2019a). Small microplastics consumed secondarily with their food are probably excreted soon after ingestion, but retention times are still undetermined for most species (Ryan, 2015a; Provencher et al., 2018; Bourdages et al., 2021). To better understand what types of plastics are ingested by seabirds at sea, we need to compare the characteristics (type, size and colour) of these plastics with what is available in their marine environment. This would allow us to assess for which types of plastics seabirds select, which in turn allows us to interpret their preferences in context with what is available at sea. Such information can help us better understand the use of seabirds as biomonitors of temporal and spatial heterogeneity in environmental plastics (Vlietstra and Parga, 2002; Kain et al., 2016; Hidalgo-Ruz et al., 2021; Lavers et al., 2021; Shugart et al., 2023).

The frequency of occurrence (FO) of plastic ingestion varies among seabird taxa (Ryan, 1987; Kühn and van Franeker, 2020), and is influenced by factors including foraging strategies (e.g. surface seizing versus plunge diving; Ryan, 1987; Poon et al., 2017; Roman et al., 2019a), body size (Ryan, 1987; Roman et al., 2019b), age and breeding status (Ryan, 1988a, 2016; Tulatz et al., 2023), foraging area (van Franeker and Law, 2015; Clark et al., 2023) and retention and egestion rates (Ryan, 2015a). In addition, the sampling method (e.g. sampling from carcasses, inducing emesis or from prey remains) as well as the cause of death of dead birds could influence the number and size of plastics collected (Ryan, 1987; Ryan and Fraser, 1988; Rodríguez et al., 2018; Lavers et al., 2021). In order to use seabirds as indicators of marine plastics, we need to understand how these factors influence the amounts and types of plastics retained in seabirds (Ryan, 2016). Plastics ingested by seabirds are collected either directly from their stomachs through dissection (e.g. Ryan, 1987; van Franeker et al., 2011; Robuck et al., 2022), or by inducing emesis (Bond and Lavers, 2013). Less invasive techniques include collecting regurgitated items at nests (Perold et al., 2020; Phillips and Waluda, 2020) or take advantage of regurgitations of predators that include the indigestible remains of prey, including their ingested plastic (Furtado et al., 2016; Acampora et al., 2017; Diaz-Santibañez et al., 2023). The large skuas (*Catharacta*) are predatory seabirds that frequently eat burrowing seabirds at their breeding sites. Their regurgitations have been used to report plastic loads in their seabird prey (e.g. Ryan, 1987; Ryan and Fraser, 1988; Hammer et al., 2016; Ibañez et al., 2020; Lenzi et al., 2022) and to assess temporal variation in plastic amounts and composition in multiple seabird taxa (Ryan, 2008). However, to assess how well regurgitated skua pellets represent what is ingested by their prey, a comparison between the types of plastics collected directly from prey carcasses (stomachs) to those sampled from pellets is still needed.

In this study, we compare the plastics ingested by seabirds breeding on Inaccessible Island in the central South Atlantic Ocean with those available within their marine environment. We use regurgitated brown skua *Catharacta antarctica* pellets to sample plastics ingested by four seabird taxa: *Fregetta* storm petrels, white-faced storm petrels *Pelagodroma marina*, broad-billed prions *Pachyptila vittata* and great shearwaters *Ardenna gravis* and compare these to floating plastics collected with a fine-meshed surface net within the seabirds' foraging ranges (Ryan, 2023a). We assess if skua pellets bias against certain plastics, especially smaller pieces that could be excreted by skuas or go undetected in their pellets. We then assess the characteristics of plastics ingested by the four seabird taxa, and compare them to the plastic items available in the marine environment. Finally, we evaluate the suitability of using skua pellets containing the remains of South Atlantic seabirds as biomonitors of small buoyant plastics at sea.

2. Methods

2.1. Buoyant plastics at sea

Buoyant plastics were collected during nine oceanographic research voyages from December 2016 to November 2019 in the South Atlantic and southwest Indian Ocean (Fig. 1; Table S1). All voyages were aboard the R.V. *S.A. Agulhas II*, except the Antarctic Circumnavigation Expedition (ACE), which was on the R.V. *Akademik Tryoshnikov*. Floating plastics were collected with surface net tows following a standardised sampling procedure across all voyages and stations (Suaria et al., 2020; Suaria et al., 2023; Weideman et al., 2023). A neuston net (Aquatic BioTechnology) with a rectangular frame (0.8 m wide x 0.2 m high) and a 2.5 m long 200 μm nylon mesh net was used to collect all samples. The net was lowered from the starboard side of the foredeck onto the surface of the water using a long-armed crane and positioned approximately 15 m away from the side of the ship, beyond the ship's bow wave. As soon as the net was in position, the start coordinates were recorded using a GPS (Garmin eTRex 20, USA). The net was towed at ~2 knots for 15 min, after which it was lifted out of the water and the end coordinates recorded. The area of sea surface sampled (km^2) was calculated as the width of net (0.8 m) x distance towed (estimated from the two GPS positions). After retrieval, the net was rinsed down from the outside using freshwater to ensure that all material was collected in the cod end. The contents of the cod-end were frozen in glass jars until processing. During processing, samples were defrosted and carefully sorted under a bright light by the same experienced observer (VP) to remove all visible anthropogenic litter ~ ≥1 mm. Litter items were stored in glass vials or aluminium packets until further processing.

In the laboratory, items were counted and classified into five categories: industrial pellets, and four types of user plastics: hard fragments, flexible plastics (e.g. food packaging, plastic bags), thread-like plastics (from rope, netting or fishing line) and foamed plastics (e.g. expanded polystyrene, other foamed plastics) and assigned to eight colour groups (white/clear, black, orange/brown, green, blue/purple, red/pink, grey/silver and yellow) following Provencher et al. (2017). The maximum length of items (flexible items and thread-like plastics were straightened) was measured to the nearest 0.01 mm either with digital calipers or from digital images. All items were weighed on a precision electronic balance to the nearest 0.1 mg. For samples collected on the Gough Island Relief, SEAmester III and IV, SCALE WINTER and SPRING and Marion Island Relief voyages (Table S1), polymer types were determined by ATR-FTIR using an iD7 ATR Nicolet iS5 (ThermoScientific) instrument under absorbance mode with spectral region from 400 to 4000 cm^{-1} and at a resolution of 4 cm^{-1}. OMNIC Spectra Software with Hummel

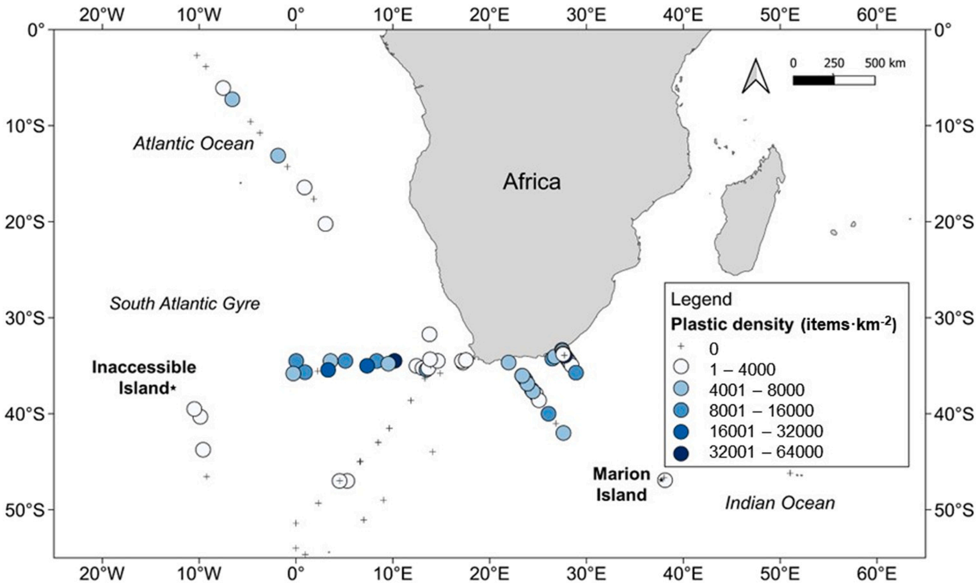

Fig. 1. Density of plastic (items·km^{-2}) in surface net trawls in the South Atlantic and southwest Indian Ocean relative to Inaccessible Island, Tristan da Cunha archipelago.

Polymer- and HR Nicolet Sampler Libraries were used for automated identification of polymers. Samples collected on the ACE voyage, Marion Island Relief 2017 and SEAmester II, were characterized using a LUMOS stand-alone FTIR microscope (Bruker Optik GmbH). ATR spectra were recorded by averaging 64 scans per particle with a spectral resolution of 4 cm^{-1} (range 650–4000 cm^{-1}). Spectra were processed and analysed using the OPUS 7.5 software (Bruker) and polymer identification was performed by comparison with commercially available libraries and an additional custom library compiled within the framework of the JPI-Oceans project BASEMAN (Primpke et al., 2018). Polymer identities were assigned if there was ≥70 % match.

2.2. *Plastics ingested by seabirds*

Plastic items ingested by seabirds were collected from regurgitated brown skua pellets containing the undigested prey remains (bones, feathers, etc.) of burrowing seabirds at Inaccessible Island, Tristan da Cunha, central South Atlantic Ocean (37.3°S, 12.7°W; Fig. 1). Pellets were collected from 13 September to 24 November 2018 at a large skua club at the West Point of the island, where 50–100 non-breeding skuas congregate (Ryan and Moloney, 1991; Ryan, 2008; Ryan et al., 2019). All pellets were processed by the same observer (PGR). Each pellet was air dried and then broken apart in a sorting tray to identify the prey remains. Bird prey species were identified from their bones and/or feathers, in comparison with reference sets of bones from known carcasses. Until recently, it was assumed that only white-bellied storm petrels *Fregetta grallaria* breed at Inaccessible Island, but genetic evidence shows that both *F. grallaria* and a white-bellied form of the black-bellied storm petrel *Fregetta tropica* breed on the island (Robertson et al., 2016). The two species are treated together here because their remains in skua pellets cannot be discriminated reliably (Ryan, 2023b).

Storm petrels are usually swallowed whole, making it easy to attribute the plastics to a particular prey species. However, some pellets contained the remains of more than one bird (Ryan and Moloney, 1991); such pellets were discarded from this study. Pellets from prey like broad-billed prions and great shearwaters that are too large to be swallowed whole, sometimes result in multiple pellets per prey item (e.g. the legs in one pellet, head in another, and balls of feathers with no bony remains at all). Pellets containing bony remains were counted as representing a bird as long as they contained some additional material (i.e. they were classed as pellets rather than loose skulls or leg bones). Pellets comprised solely of feathers were not counted unless they contained indigestible stomach contents (mainly cephalopod beaks and plastics, but also pumice, seeds, fish otoliths and fish and/or cephalopod eye lenses). Pellets containing the remains of burrowing seabird chicks were readily identified by their poorly-developed bones. However, this made it hard to identify the prey species, and to tell whether a pellet contained the remains of more than one chick. Chick pellets were assumed to be from broad-billed prions because they are by far the most common petrel species with chicks during September–November (Ryan, 2007). Broad-billed prions were the only taxon to include chicks in the analyses. All plastic items ≥1 mm from each pellet containing the remains of only one avian prey item were stored in a labelled Ziploc bag. To assess if skua pellets accurately reflect plastic loads or fail to include the smaller items ingested by their seabird prey, we opportunistically collected intact carcasses of burrowing seabirds found during routine surveys and removed all plastic items from the proventriculus and ventriculus (hereafter referred to as stomach). Some of these birds had been predated (but not yet eaten) by skuas or Tristan Thrushes *Turdus eremita*, whereas the cause of death of others was not known. Plastics in these birds were processed in the same manner as those collected from skua pellets.

In the laboratory, plastics were sorted and classified by VP into the same categories and colour groups as plastics collected at sea. The length (longest dimension) of each item was measured to the nearest 0.01 mm using digital calipers. Flexible and thread-like plastics were straightened to record their maximum length. All items were weighed; most to the nearest 1 mg, but samples weighing <2 mg were weighed to the nearest 0.1 mg.

Due to the large number of ingested plastic items, we subsampled items for polymer analyses. As industrial pellets and hard fragments were the most numerous items ingested by all four taxa, we selected 100 industrial pellets and 100 fragments from each taxon for polymer analyses. To avoid selection bias, we blindly removed a single bag (representing an individual bird) from a bag containing all the samples collected (per taxon) within a specified month (starting with the first sample month, September). All hard fragments and industrial pellets within each bag were processed, until 100 of each were sampled per taxon. For *Fregetta* storm petrels, only 20 industrial pellets were ingested over the study period, and of these, only 18 delivered a polymer match (Table S2). Many fewer flexible items, thread-like plastics and foamed pieces were collected, so all of these items were analysed using FTIR.

Polymer types were determined with a Bruker Alpha II compact FTIR spectrometer. Samples were cleaned with 70 % ethanol (to remove any residues) prior to analysis. We used absorbance mode with spectral region from 400 to 4000 cm^{-1} at a resolution of 4 cm^{-1} and 32 scans. OPUS 8.7 Spectra Software with Bruker Optics ATR-Polymer Library and the KIMW ATR-IR Polymer Library were used for automated identification and assigned a polymer if there was a ≥70 % match.

2.3. Data analysis

The density of marine buoyant plastics was calculated per sampling station, and overall, as the number and mass (g) of items·km^{-2}. To determine if all plastics ingested by seabirds were detected in skua pellets, we compared the size range of plastics from carcasses to plastics in skua pellets, using Mann-Whitney U tests and violin plots. To increase the sample size of great shearwater carcasses, we augmented our dataset with data from adult great shearwater carcasses ($n = 15$) killed on fishing gear in the central South Atlantic during March–April 2018 (Robuck et al., 2022). We also compared the mean mass and length of items collected in carcasses in other studies to our study. All data were assessed for normality using Shapiro-Wilks normality tests.

Chi-squared tests of independence were used to compare the ratios of plastic types (categories), colour groups and polymer types between plastic collected at sea and ingested by seabirds. Groups with few observations were pooled to ensure that no more that 20 % of expected counts were <5. We used correspondence analysis and a contribution biplot to visualize differences in the types and colour of plastics (rows) and seabirds/marine (columns) using the "*FactoMineR*" and "*factoextra*" packages in R (Lê et al., 2008; Kassambara and Mundt, 2020; R Core Team, 2023). The relative distance between types (or colour groups) of plastics ingested by seabirds (or collected at sea) tells us how characteristic that type (or colour group) is for that seabird (or marine plastics). The more acute the angle of the arrows are between rows and columns, the stronger the relationship is. We also wanted to determine the degree of individual variation in plastic types. To do this we performed a correspondence analysis for individuals that had ingested ≥20 items, to assess if there were patterns in the types of items ingested.

We used violin plots of mass and length (log transformed to improve visualization) to present the length and mass data among seabirds and marine plastics. Because the mass and size of ingested plastic items are generally skewed, we report the median (and range) for mass (mg) and length (mm) of plastics overall, and within each category, unless stated otherwise. Differences in the mass and length of plastics among seabirds and between ingested and marine plastics, were assessed with Kruskal–Wallis (KW) tests, and post-hoc Dunn's tests (with Bonferroni corrections to reduce the chance of committing Type 1 errors) were used to assess which groups differed. We tested for differences in the mass and length of items between broad-billed prion adults and chicks with Mann-Whitney U tests. All results were considered significant where $P < 0.05$. All data analyses were performed in R version 4.2.3 (R Core Team, 2023).

3. Results

3.1. Floating plastics at sea

We collected 392 plastic items during 116 surface net tows that sampled a total of 0.09 km^2 of sea surface (Fig. 1; Table S1). The average density was 5025 ± 9001 (SD) plastic items·km^{-2} and 60 ± 154 g·km^{-2} (Table S1). Most marine plastics were hard fragments (92 %), with small proportions of flexible pieces, industrial pellets, thread-like and foamed plastics (Table 1). Hard fragments were not restricted to specific areas of the South Atlantic and southwest Indian Ocean (Fig. S1A), but all industrial pellets were found in the South Atlantic (Fig. S1A), and 75 % of foamed and 50 % of flexible items were sampled within ~200 km of the coast (Fig. S1B). Marine plastics were mostly white/clear, blue/purple, or black while other colours, such as orange/brown or yellow, were seldom found (Table 2). Polymer type was assigned to 93 % of items; 4 % could not be identified due to poor spectral matches and 3 % of items were either too small to analyse or crushed/lost during FTIR processing. Most hard fragments (72 %), industrial pellets (100 %), flexible pieces (70 %) and thread-like plastics (57 %) were made of polyethylene (PE) (Table S3). Polypropylene (PP) was the next most common polymer (25 % of hard fragments; 30 % of flexible pieces; 29 % of thread-like plastics). Polystyrene (PS), polypropylene/ethylene-propylene-diene monomer (PP/EPDM), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA) and ethylene-propylene rubber (EPM), contributed 3 % overall (Table S3). The few foamed items were composed of PS (75 %) and PP/EPDM (25 %). Marine plastics had a median mass of 3 mg (range 0.1–624 mg; Table 3) and length of 3.1 mm (1–435 mm; Table 4), but half of all of marine plastic items weighed ≤2 mg and a third were ≤2 mm in length.

3.2. Plastics ingested by seabirds

We collected 5310 plastic items in 569 skua pellets containing the remains of 103 *Fregetta* storm petrels ($n = 210$ plastic items), 147 white-faced storm petrels (767), 207 broad-billed prions (99 adults [406], 108 chicks [1347]), and 112 great shearwaters (2580) (Table 1). The frequency of occurrence of plastic ingestion varied among taxa, the most frequent being broad-billed prion chicks (87 %, although this might be inflated by multiple chicks being sampled in some pellets), followed by white-faced storm petrels (75 %) great shearwaters (73 %), broad-billed prion adults (62 %) and *Fregetta* storm petrels (38 %) (Table 1). The median and interquartile masses of plastic items collected from great shearwater carcasses were almost identical to those collected from skua

Table 1

Composition of floating plastic in surface net tows in the South Atlantic and southwest Indian Ocean (marine plastics) and the numbers of birds, plastic items, the proportions of plastic categories and the overall frequency of occurrence (% FO) of plastic ingested by four seabird taxa sampled in brown skua pellets on Inaccessible Island. Chick samples were only included for broad-billed prions.

Source	n tows or birds (n plastics)	% hard Fragments	% industrial Pellets	% flexible Pieces	% thread-Like plastics	% foamed	% FO
Marine plastics	116 (392)	92 %	2 %	3 %	2 %	1 %	
All seabirds	569 (5310)	88 %	10 %	1 %	1 %	<1 %	
Fregetta SP[a]	103 (210)	81 %	10 %	<1 %	9 %	0 %	38 %
White-faced SP	147 (767)	79 %	20 %	<1 %	1 %	0 %	75 %
Broad-billed prion							
Adults	99 (406)	87 %	11 %	1 %	<1 %	0 %	62 %
Chicks	108 (1347)	87 %	12 %	1 %	<1 %	0 %	87 %
Great shearwater	112 (2580)	92 %	6 %	2 %	<1 %	<1 %	73 %

[a] SP = storm petrel.

Table 2
Proportion (%) of colour groups recorded for plastics collected at sea and those ingested by four seabird taxa. Chi-square test results compare the ratios of ingested items to marine plastics (df = 6, yellow and grey/silver items pooled due to low numbers). Chick samples were only included for broad-billed prions.

	White/clear	Blue/purple	Orange/brown	Green	Black	Red/pink	Grey/silver	Yellow	Significance
Marine plastics	71 %	11 %	1 %	4 %	8 %	2 %	2 %	1 %	
All seabirds	61 %	11 %	9 %	7 %	5 %	5 %	1 %	1 %	$\chi^2 = 47.11$, Π < 0.001
Fregetta SP[a]	55 %	14 %	5 %	10 %	5 %	6 %	4 %	1 %	$\chi^2 = 31.54$, Π < 0.001
White-faced SP[a]	63 %	5 %	11 %	2 %	7 %	9 %	2 %	2 %	$\chi^2 = 72.95$, Π < 0.001
Broad-billed prion									
Adult	58 %	14 %	10 %	7 %	4 %	4 %	2 %	<1 %	$\chi^2 = 45.41$, Π < 0.001
Chicks	62 %	13 %	7 %	7 %	6 %	5 %	<1 %	<1 %	$\chi^2 = 43.95$, Π < 0.001
Great shearwater	61 %	11 %	9 %	9 %	5 %	4 %	1 %	1 %	$\chi^2 = 49.90$, Π < 0.001

[a] SP = storm petrel.

Table 3
The median (range) mass (mg) of plastic items (all items and per category) collected during surface net tows (marine plastics) and ingested by seabirds breeding on Inaccessible Island in the central South Atlantic Ocean. Significance indicates the post-hoc Dunn's test results comparing the mass of ingested plastics (all items) in adult birds to the mass of marine plastics. Chick samples were only included for broad-billed prions.

	All items Median (range)	Hard fragments	Industrial pellets	Flexible pieces	Thread-like	Foamed plastics	Significance
Marine plastics	3 (0.1–624)	3 (0.1–624)	12 (1–22)	3 (0.2–26)	2 (0.3–6)	1 (0.1–1)	
All seabirds	14 (0.3–990)	13 (1–990)	20 (2–63)	6 (0.3–59)	2 (1–122)	7 (1–12)	
Fregetta SP[a]	6 (1–302)	6 (1–302)	18 (6–41)	2	2 (1–24)	–	Z = −5.32, *P* < 0.001
White-faced SP	5 (0.3–201)	4 (1–201)	13 (2–52)	5 (2–8)	2 (1–25)	–	Z = −4.18, *P* < 0.001
Broad-billed prion							
Adults	17 (0.3–190)	16 (1–190)	23 (5–49)	3 (0.3–23)	6 (1–11)	–	Z = 17.07, P < 0.001
Chicks	21 (1–719)	21 (1–719)	23 (3–58)	6 (3–18)	2 (1–3)	–	
Great shearwater	15 (1–990)	14 (1–990)	21 (6–63)	7 (1–59)	2 (1–122)	7 (1–12)	Z = 20.21, P < 0.001

[a] SP = storm petrel.

Table 4
The median (range) length (mm) of marine plastic items (overall and per category) collected during surface net tows in the South Atlantic and southwest Indian Oceans and those ingested by seabirds breeding on Inaccessible Island. Significance indicates the post-hoc Dunn's test results comparing the lengths of ingested plastics (all items) in adult birds to the lengths of marine plastics. Chick samples were only included for broad-billed prions.

	All items Median (range)	Hard fragments	Industrial pellets	Flexible pieces	Thread-like	Foamed plastics	Significance
Marine plastics	3.1 (1–435)	3 (1–435)	3.2 (1–4)	9.4 (2–22)	20.4 (2–8)	3.8 (3–5)	
All seabirds	5.0 (1–104)	5.3 (1–33)	3.8 (2–6)	10.9 (3–44)	20 (3–104)	6.9 (5–7)	
Fregetta SP[a]	3.6 (1–104)	3.5 (1–19)	3.6 (3–5)	6.5	20.7 (3–104)	–	Z = −2.78, P = 0.05
White-faced SP	3.3 (2–32)	3.2 (2–13)	3.5 (2–6)	6.6 (6–8)	7.3 (5–32)	–	Z = 2.44, *P* = 0.15
Broad-billed prion							
Adults	5.2 (2–100)	5.5 (2–17)	3.8 (2–5)	10.9 (7–31)	56.5 (13–100)	–	Z = 12.25, P < 0.001
Chicks	5.8 (1–21)	6.2 (1–18)	4.0 (2–6)	6.7 (6–15)	10.4 (1–21)	–	
Great shearwater	5.5 (1–86)	5.6 (1–33)	3.9 (2–6)	12.2 (3–44)	21.1 (6–86)	6.9 (5–7)	Z = 17.35, P < 0.001

[a] SP = storm petrel.

pellets (Fig. 2A), but there were fewer very small items in skua pellets, resulting in a significantly lower mass per item in carcasses (Z = −5.47, *P* < 0.001). The same pattern occurred in white-faced storm petrels, with lower mass items recorded from carcasses (Z = −4.14; *P* < 0.001; Fig. 2C). However, there was no significant difference between the length of items recorded in carcasses and skua pellets in either great shearwaters (Z = −0.51, *P* = 0.61; Fig. 2B) or white-faced storm petrels (Z = 0.47, *P* = 0.64; Fig. 2D). When compared to plastics collected from carcasses in other studies, our skua pellet plastics fell well within the reported size ranges (Table S4). Instances where mean mass and length differed between plastics collected from skua pellets in our study, compared to stomach plastics, could be explained by the modest sample sizes from stomach samples (Table S4).

Most ingested plastic items from skua pellets were hard fragments (88 %) followed by industrial pellets (10 %) and flexible pieces; thread-like and foamed plastics each contributed ≤1 % (Table 1). Among adult seabirds, the proportions of categories of ingested plastics differed (χ^2 = 186.39, df = 6, *P* < 0.001; flexible pieces, thread-like plastics and foam pooled). *Fregetta* storm petrels ingested more thread-like plastics (9 %) than any other species (all <2 %) and white-faced storm petrels consumed the greatest proportion of industrial pellets (20 %) (Table 1). Broad-billed prion adults and chicks did not differ in the proportions of ingested plastic categories (χ^2 = 5.05, df = 1, *P* = 0.08; Table 1). Great shearwaters were the only species that contained foamed plastics and they ingested slightly more flexible items than other taxa (Table 1). These differences were reflected in the correspondence analysis (Fig. 3).

The most frequently ingested colour groups overall were white/clear (61 %) followed by blue/purple (11 %) and orange/brown (9 %) (Table 2). The ratios of colour groups differed among seabirds (χ^2 = 165.86, df = 24, P < 0.001; yellow and grey/silver pooled), because *Fregetta* storm petrels, broad-billed prions and great shearwaters ingested more blue/purple and green items while white-faced storm petrels

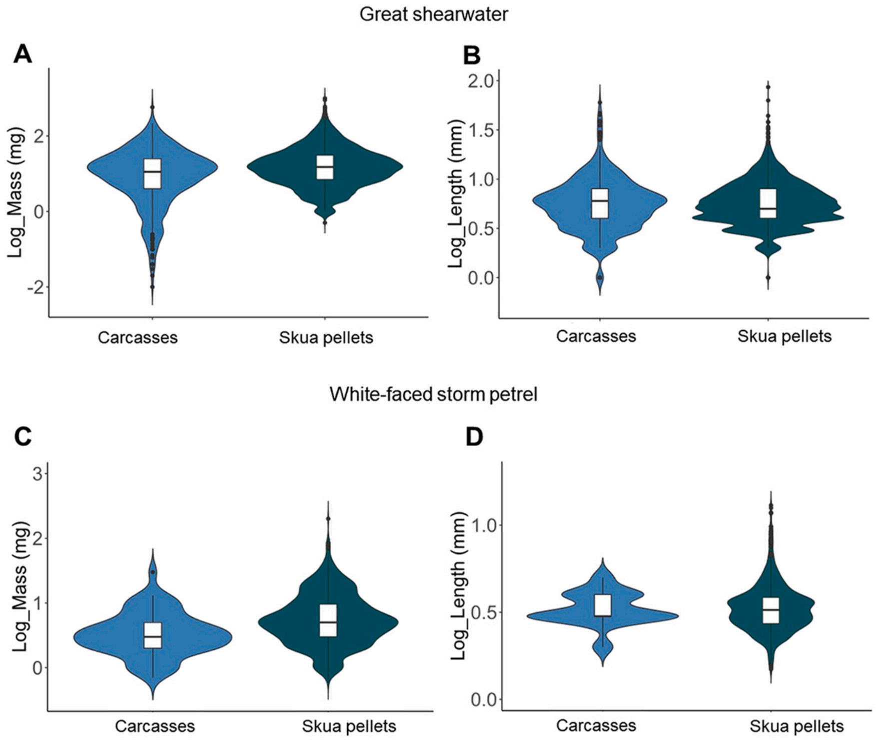

Fig. 2. Plots comparing the log transformed masses (mg) (A and C) and lengths (mm) (B and D) of plastic items recorded in carcasses and in skua pellets for great shearwaters ($n = 17$ carcasses (433 items), $n = 112$ skua pellets (2580 items) (A and B)) and white-faced storm petrels ($n = 2$ carcasses (54 items), $n = 147$ skua pellets (767 items) (C and D)).The boxplot indicates the median (dark line) and interquartile range while the violin plot indicates the kernel probability density at different values where the width of each curve corresponds to the frequency of data points in that region.

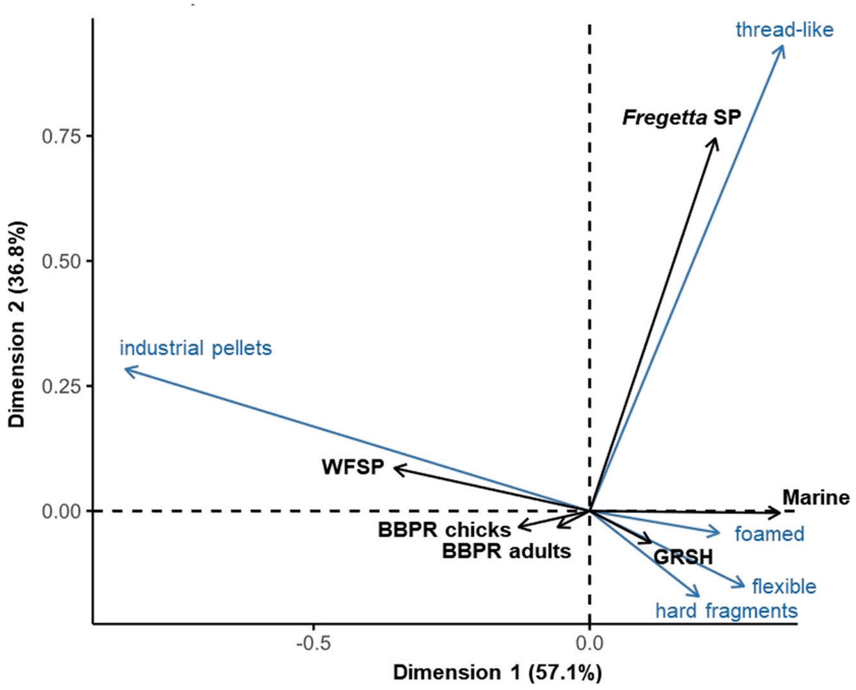

Fig. 3. Correspondence analysis indicating the relationships between the composition of plastic types sampled at sea (marine) and ingested by seabirds: SP = storm petrel, WFSP = white-faced storm petrel, BBPR = broad-billed prion, GRSH = great shearwater. Dimensions 1 and 2 together explain 93.9 % of the variation.

ingested greater proportions of red/pink and yellow items (Table 2; Fig. 4).

A total of 797 items (93 %) sub-sampled from skua pellets delivered a polymer match ≥70 % (Tables S2 and S3). There was no significant difference in the ratios of polymer types among seabird species ($\chi^2 = 5.87$, df = 3, $P = 0.14$; PP and other polymers pooled) and most hard fragments (78 %), industrial pellets (83 %) and thread-like plastics (71 %) were composed of PE, followed by PP (Table S3). Most flexible items

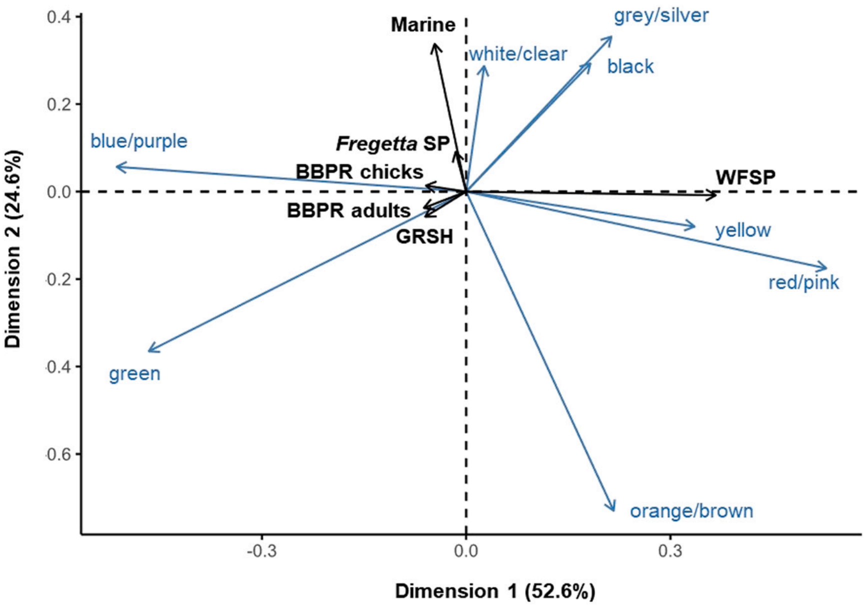

Fig. 4. Correspondence analysis indicating the relative relationship between the colour groups of plastics sampled at sea (marine) and ingested by seabirds: SP = storm petrel, WFSP = white-faced storm petrel, BBPR = broad-billed prion, GRSH = great shearwater. Dimensions 1 and 2 together explain 77.2 % of the variation.

were composed of PP (62 %; Table S3). PS was only recorded in industrial pellets, PP/EPDM in industrial pellets and thread-like plastics, and PU was only recorded in foamed plastics, and combined these polymers only accounted for 1 % of polymer types overall (Table S3).

The size of items differed among adult seabird taxa (mass: KW $\chi^2 = 529.8$, df = 3, $P < 0.001$, Table 3; Fig. 5A; length: KW $\chi^2 = 809.6$, df = 3, $P < 0.001$; Table 4; Fig. 5B), with the two storm petrels ingesting smaller items than prions and shearwaters. There was no significant difference in the mass of ingested items between the two storm petrel taxa ($Z = 2.62$, $P = 0.05$; Fig. 5A), but white-faced storm petrels ingested slightly smaller items (median = 3.3 mm, range 1.5–31.8 mm) than *Fregetta* storm petrels (3.6 mm, 1.3–104 mm; $Z = 5.16$, $P < 0.001$; Table 4; Fig. 5B), possibly due to their slightly smaller size (mass: 40–60 g) compared to *Fregetta* storm petrels (45–65 g; Ryan, 2023a). Adult broad-billed prions and great shearwaters did not show any significant differences in the mass or length of ingested items (mass: $Z = 2.17$, $P = 0.1$, Fig. 5A; length: $Z = -1.46$, $P = 0.90$, Fig. 5B), despite their size differences (broad-billed prions = 160–230 g; great shearwater = 750–1100 g). Broad-billed prion chicks contained slightly larger items than adults in terms of both mass (adult media*n* = 17 mg, range 0.3–190 mg, chicks = 21 mg, range 1–719 mg; $Z = -3.77$, $P < 0.001$) and length (adults = 5.2 (1.6–99.9) mm, chicks = 5.8 (1.3–21.4) mm; $Z = -4.05$, $P < 0.001$; Tables 2 and 3).

Some variation in the types of plastic ingested between individuals of the same species was recorded, but in general, most individuals (where $\geq$20 items were recorded) ingested similar proportions of items (Fig. S2). For example, white-faced storm petrels typically ingested larger proportions of industrial pellets than other taxa, and 80 % of birds that had ingested $\geq$20 items ($n = 5$) ingested 24–38 % industrial pellets (Fig. S2). Broad-billed prions ($\geq$20 items; n = 1 adult and 19 chicks) mostly ingested hard fragments and industrial pellets, and only three individuals included thread-like plastics (Fig. S2). There are a couple of considerations when using chicks for this analysis. One is the potential presence of multiple chicks in a single pellet, and the other is that they are likely fed plastics by both parents, which hinders individual comparisons. Most great shearwaters were similar in the types of plastics ingested, but a few individuals contained more thread-like plastics, foam and flexible pieces (Fig. S2). *Fregetta* storm petrels (which ingested more thread-like plastics than any other taxa) did not have any individuals who ingested >20 items, but across all individuals, 16 % ingested 1–2 thread-like plastics. These results indicate that among individual variation was not large, and that trends observed within taxa are characteristics of the taxon overall.

3.3. *Comparison between the characteristics of ingested and marine plastics*

Hard fragments were the type of plastic recorded most frequently in both ingested (88 %) and marine plastics (92 %). However, the proportion of plastic types differed ($\chi^2 = 35.59$, df = 3; $P < 0.001$; thread-like plastics and foamed pieces pooled) due to the greater proportions of industrial pellets ingested by seabirds (10 %) than sampled with nets (2 %; Table 1). Great shearwaters ingested plastic in proportions closest to the spectrum available in the environment because they contained more flexible pieces than other species and were the only species to contain foamed plastics (Fig. 3).

White/clear and blue/purple items were recorded more frequently than other colours in both ingested (61 % and 11 %) and marine (71 % and 11 %) plastics, but the overall proportions of colour groups differed, because seabirds ingested more red/pink and orange/brown and less white/clear/silver/grey/black items than found on the environment (Table 2; Fig. 4).

PE was the most frequently recorded polymer type in both ingested (78 %) and marine (72 %) plastics (Fig. 6). Polymer types of ingested plastics (all seabirds combined) differed from the marine environment ($\chi^2 = 9.49$, df = 2, $P < 0.05$; PS, PP/EPDM, PVC, PMMA, EPM and PU pooled), mostly because PVC, PMMA and EMP were only recorded in marine samples, and PU only recorded in ingested plastics (Table S3). However, polymer types ingested by broad-billed prions and great shearwaters did not differ significantly from those collected at sea (Table S3). Seven of the eight polymer types ($\geq$ 70 % match) recorded were found in marine plastics, whereas only five were found in ingested plastics, despite having nearly double the sample size for ingested plastics. Polymers denser than seawater (PVC and PMMA) were only recorded in marine samples, with the exception of one pellet composed of PS (unexpanded) from a great shearwater (Table S3). When only comparing hard fragments, polymer type did not differ significantly between ingested and marine plastics ($\chi^2 = 3.27$, df = 1, $P = 0.07$) and PE remained the most frequently recorded polymer (72 % marine; and 78 % ingested), followed by PP (25 % marine; 21 % ingested; Fig. 6).

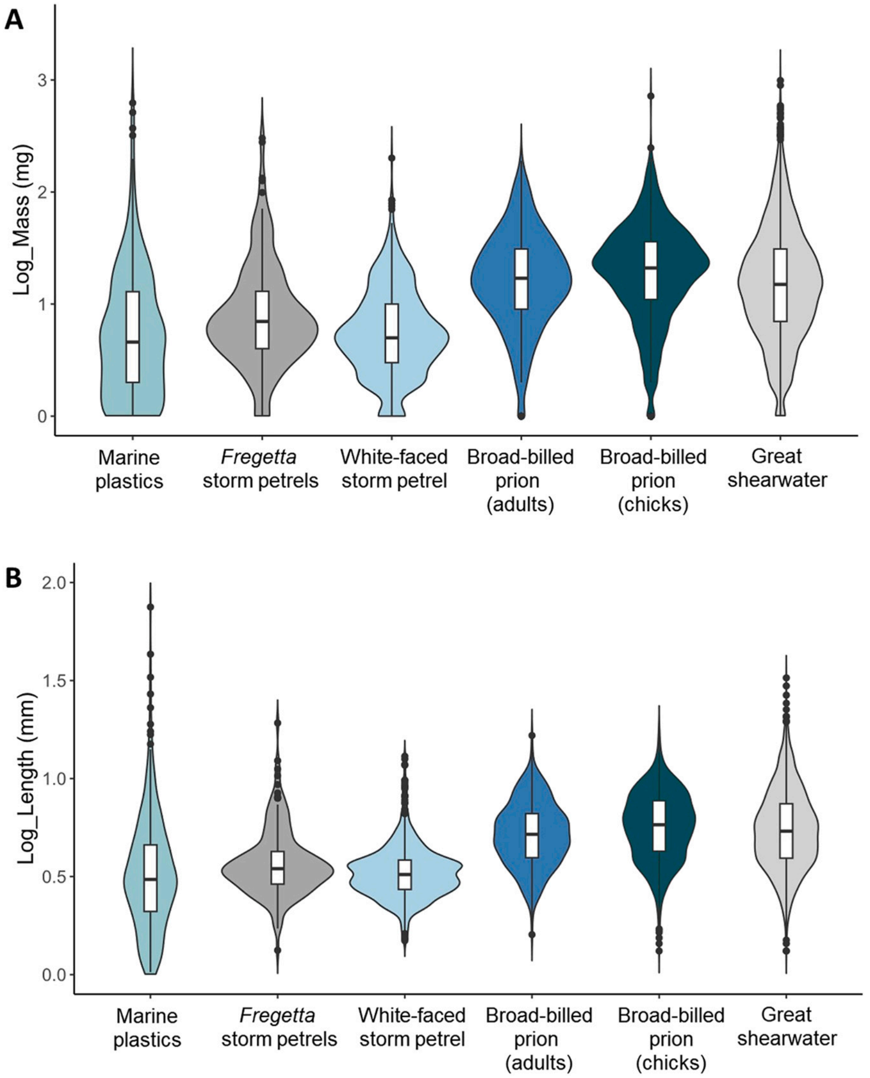

Fig. 5. Plots of the log transformed masses (A) and lengths (B) of hard fragments and industrial pellets collected at sea (marine plastics) and ingested by four seabird taxa based on skua pellets. The boxplot indicates the median (dark line) and interquartile range while the violin plot indicates the kernel probability density at different values where the width of each curve corresponds to the frequency of data points in that region.

The size of plastic items differed significantly between marine and ingested plastics across all adult seabirds (mass: KW $\chi^2 = 789.6$, df = 4, $P < 0.001$, Table 3; length: KW $\chi^2 = 927.9$, df = 4, $P < 0.001$, Table 4). Marine plastics generally were substantially lighter (3 [0.1–624] mg vs 14 [0.3–990] mg) and smaller, averaging barely half the length (3.1 [0.5–435] mm vs 5.0 [1.3–103.5] mm) of all ingested plastics (Table 3; Table 4). However, differences in length were not marked between marine plastics and those ingested by white-faced storm petrel (3.3 [2–32] mm; $Z = 2.44$, $P = 0.15$; Table 4) but showed a trend toward significance when compared to *Fregetta* storm petrels (3.6 [1–104] mm; $Z = -2.78$, $P = 0.05$; Table 4).

4. Discussion

4.1. What types of marine plastics are available to South Atlantic seabirds?

Small buoyant plastics are abundant in the marine environment, and are primarily composed of hard fragments that originate from the fragmentation of larger user items into increasingly smaller pieces (Law et al., 2010; Eriksen et al., 2014; Cózar et al., 2014; Andrady, 2015; Suaria et al., 2023). Surface net tows are used to estimate their densities (Morét-Ferguson et al., 2010; Law et al., 2014; Hänninen et al., 2021; Courtene-Jones et al., 2021) and while numerous studies have focused on the Northern Hemisphere, only a few have examined plastic densities in the South Atlantic and southwestern Indian Ocean (Ryan, 1988b; Eriksen et al., 2014; da Rocha et al., 2021; Zhao et al., 2022; Suaria et al., 2023). Our study sampled this area with 116 surface net tows over three years. The most commonly sampled plastic type was white/clear hard PE fragments, affirming that these are currently the items most likely to be encountered by seabirds foraging in this marine environment. The abundance of white/clear items at sea could be related to the process of photo-oxidation which causes discoloration of plastics, potentially explaining the greater numbers of white plastics, which appear to increase with distance from land (Martí et al., 2020). During the late 1970s, industrial pellets dominated floating plastics in the South Atlantic (Morris, 1980; Ryan, 1988b), compared to only 2 % in our study. The proportions of hard fragments were also considerably lower (0–27 %) compared to our study (92 %). This increase in the proportions of plastic fragments relative to industrial pellets floating at sea has been noted globally in both net samples (Law et al., 2010; Morét-Ferguson et al., 2010; van Franeker and Law, 2015) and in seabirds (Vlietstra and Parga, 2002; Ryan, 2008). The implementation of awareness campaigns in the early 1990s, (e.g. Operation Clean Sweep, www.opcleansweep.

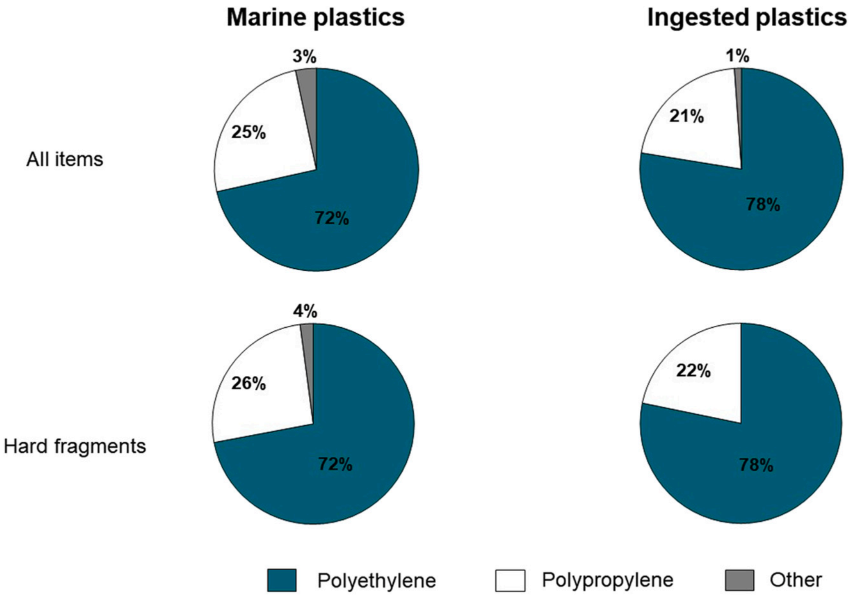

Fig. 6. The proportions of polymers recorded for marine and ingested plastics. Other = polystyrene, polypropylene/ethylene-propylene-diene monomer, polyvinyl chloride, polymethyl methacrylate, ethylene propylene rubber and polyurethane.

org) likely contributed to a decline in pellet loss and, consequently, reduced densities at sea. Flexible items such as plastic bags were less common, because they are usually found at lower densities and in closer proximity to source areas (e.g. coastlines). This is because the higher surface area to volume ratios of these items leads to increased biofouling rates, impacting their buoyancy, dispersal ability and the probability of being sampled with a surface net at sea, as they are removed at a faster rate from the sea surface compared to items with lower surface area to volume ratios (Ryan, 2015b; Fazey and Ryan, 2016; Naidoo and Glassom, 2019; Ryan, 2020; Maclean et al., 2021; Weideman et al., 2023). Foamed items also were scarce, possibly because their high buoyancy promotes stranding for items deriving from land-based sources shortly after entering the marine environment (Maclean et al., 2021). In our study, flexible and foamed items collected at sea were mostly sampled close to coastal areas, and the few items collected far from land may have originated from ships (Fig. S1B), as there has been a marked increase in litter inputs from ships crossing the South Atlantic (Ryan et al., 2019).

4.2. Do skua pellets underestimate plastic loads in seabirds?

Sampling ingested plastics from seabird stomachs ensures that all plastic items are removed, whereas skua pellets may underestimate the number and size of plastics as smaller pieces may fail to be incorporated into the pellet, or be lost before or during collection (Ryan and Fraser, 1988). Ryan and Fraser (1988) found that compared to stomach samples, plastic items <8 mg were underrepresented in skua pellets, but this was due to observer bias while processing pellets (Ryan, 2008), and careful processing retains items as small as 1 mm and weighing as little as 1 mg (this study). Although some smaller plastic items could pass through the skuas' intestines and be excreted in their guano, and thus go undetected (Ryan and Fraser, 1988; Ryan, 2016; Provencher et al., 2018), hard items >1 mm are seldom found in skua faeces (Ryan, 1987), suggesting that it is unlikely to influence the results. In our study, skua pellets included plastics ≤1 mg and ≤2 mm, and generally exhibited overall similar size ranges to those found in the stomachs of great shearwaters and white-faced storm petrels. Even though the mass of items collected from carcasses were smaller than those from skua pellets, lengths did not differ. This suggests that the risk of overlooking or losing small items is negligible, and that skua pellets are a reliable tool to sample plastics stored in the stomachs of their seabird prey. Storm petrels provide the best measure of plastic loads in the seabirds studied, because they are swallowed whole. Pellets containing the remains of great shearwaters and broad-billed prions might underestimate plastic loads because the plastics from one bird might be spread over several pellets. However, the stomach and gizzard contents are likely to be ingested together and thus be regurgitated in the same pellet. We reduced the risk of counting multiple pellets from the same prey item by only counting pellets containing squid beaks and other indigestible prey typically found in petrel stomachs.

4.3. Interspecific variation in ingested plastics

The likelihood of seabirds ingesting plastics is largely determined by the amount and types of plastic litter available within their foraging areas, where higher surface plastic densities result in a higher risk of ingestion (Clark et al., 2023). Furthermore, seabirds are more likely to ingest plastics that resemble food items, or lighter items that are more conspicuous, and thus are more readily detected at the sea surface (Ryan, 1987; Shaw and Day, 1994; Lavers and Bond, 2016; Santos et al., 2016). The greater proportions of black items in marine plastics compared to ingested plastics further supports the notion that seabirds select for plastics that resemble prey, or colours that are more conspicuous. Although some plastic may be ingested secondarily through prey, most surface-feeding seabirds ingest plastic items directly from the ocean surface (Ryan, 1987; Ryan, 2016; Santos et al., 2016; Roman et al., 2019a). As a community, the types, colours and polymer types of plastics ingested by seabirds were overall similar to that collected at sea; white/clear hard fragments, composed of PE were the most numerous in both. At a species level however, interspecific variation in the types and colours of plastics ingested were evident. Most noteworthy was the greater proportions of industrial pellets in white-faced storm petrels, thread-like plastics in *Fregetta* storm petrels, and flexible and foamed plastics in great shearwaters.

There are few data on the at-sea distribution of storm petrels breeding on Inaccessible Island, but it is thought that white-faced storm petrels mostly forage north of the island in areas overlapping with the South Atlantic Gyre (Ryan, 2023a; Fig. 1). Here, litter densities and plastic exposure risk are higher than the waters south of the Sub-tropical Front (Ryan, 1988b; Eriksen et al., 2014; Ryan et al., 2014; Clark et al., 2023). The greater proportions of industrial pellets ingested by white-faced storm petrels could be influenced by foraging area, as many pellets may have been drifting for a long time and thus tend to accumulate within the South Atlantic Gyre (Olivelli, 2019; Zhao et al., 2022). However, it is also likely influenced by species preferences as white-faced storm petrels preferred hard fragments and industrial pellets that were white/clear in colour and between 3.2 and 3.5 mm in length (likely resembling fish eggs), which is similar to the size of fragments and pellets recorded at sea (3.0–3.2 mm, 88 % white/clear). They also ingested more red/pink and orange/brown items than the other seabirds, as these likely resemble crustacean prey items (Ryan, 1987). In the Northeast Atlantic, white-faced storm petrels breeding on the Selvagens Archipelago also ingested mostly white/clear items composed primarily of PE, but only 8 % of items were industrial pellets (Furtado et al., 2016), possibly influenced by the greater distance from a subtropical gyre, compared to Inaccessible Island.

Fregetta storm petrels likely forage south of the Sub-tropical Front (Ryan, 2023a), where floating plastic loads are generally lower (Ryan, 1988b; Eriksen et al., 2014; Ryan et al., 2014; Clark et al., 2023). Waters just south of the Sub-tropical Front have high industrial fishing intensity (Kroodsma et al., 2018), which may be a source of thread-like plastics (e.g. rope or fishing line), potentially accounting for the greater proportion of thread-like plastics recorded in *Fregetta* storm petrels. However, they seemed to prefer blue/purple and green items (14 %), which is generally also the predominant colour of ingested (78 %) and marine thread-like plastics (63 %). Broad-billed prions also mostly forage in waters south of the Sub-tropical Front (Jones et al., 2020), but generally did not exhibit a preference for a particular type of plastics like the storm petrels. This is because they are filter-feeders (Ryan, 1987; Klages and Cooper, 1992; Dell'Ariccia et al., 2017), and thus likely to be less discriminating in the types of plastics that they ingest than other seabirds in this study. Similar types of plastics were recorded in both adult and chick broad-billed prions, although the items recorded in chicks averaged slightly larger. Nania and Shugart (2021) found that juvenile Cassin's auklets *Ptychoramphus aleuticus* contained larger plastic particles than adults, and Cartraud et al. (2019) also showed that juvenile Barau's petrels *Pterodroma baraui* and tropical shearwaters *Puffinus bailloni* contained plastic items that are heavier than those found in adult birds. It is unclear why plastics in chicks average larger than those in adults, but possible longer retention periods in adults, where plastics are eroded into smaller sizes over time, may contribute to the size variation of plastic items among different age groups (Ryan and Jackson, 1987; Ryan, 1988a; Nania and Shugart, 2021).

Great shearwaters ingested a wider array of the types of plastics found floating at sea, likely influenced by their foraging areas and their greater tendency to scavenge behind vessels than other species in this study. Great shearwaters undertake an annual trans-Equatorial migration to winter in the northwest Atlantic (Robuck et al., 2022). This region borders highly industrialized coastal margins with high human population densities, litter concentrations and plastic exposure risk (Eriksen et al., 2014; Robuck et al., 2022; Clark et al., 2023). Here, they are likely to encounter more items with a higher surface area to volume ratio (e.g. flexible plastics like bags), which is inversely related to the likelihood of dispersal and longevity at sea (Ryan, 2015b; Fazey and Ryan, 2016; Ryan, 2020). These items are also likely to be encountered during their commute back to the South Atlantic via the coastal waters of Brazil and southwest Africa (Powers et al., 2022; Robuck et al., 2022), or ingested while scavenging at fishing vessels.

5. Conclusions

We found interspecific differences in the types, colours and sizes of plastics ingested by seabirds in the South Atlantic Ocean. Storm petrels ingested items more similar in size to plastics sampled with a surface net at sea, but were more selective for thread-like plastics and industrial pellets than the larger prions and shearwaters. Great shearwaters sampled plastics that were more similar in composition to marine plastics than the other taxa, but generally ingested larger plastics than recorded in net samples. As a community, seabirds breeding on Inaccessible Island reflected the overall composition of small buoyant plastics in the region, although scarce polymers were found more frequently in marine samples than ingested by seabirds.

Using skua pellets to sample ingested plastics is a simple method that delivers robust results through large sample sizes. It also eliminates the need to sample birds specifically for this purpose, avoiding harm to live birds and reducing sampling costs. Regurgitated skua pellets provide a valuable tool to monitor plastics, which could be used to assess the efficacy of mitigation measures aimed at reducing the prevalence of floating plastic in the marine environment.

CRediT authorship contribution statement

Vonica Perold: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maëlle Connan:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Giuseppe Suaria:** Writing – review & editing, Project administration, Methodology, Investigation. **Eleanor A. Weideman:** Writing – review & editing, Methodology, Investigation. **Ben J. Dilley:** Writing – review & editing, Methodology, Investigation. **Peter G. Ryan:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

Acknowledgements

We thank Tristan Conservation, the Island Council and Administrator for approving the visits to Inaccessible Island. Anna Robuck, Lindsay Agvent and Gwen Emery kindly shared data on plastic ingested by great shearwaters. This work was supported by the South African National Antarctic Programme through the National Research Foundation (grant no. 110738). The ACE expedition was carried out under the auspices of the Swiss Polar Institute, supported by funding from the ACE Foundation and Ferring Pharmaceuticals. Logistical support was received from Ovenstones Fisheries, Tristan Investments and the Tristan government. We are especially grateful to James Glass from Tristan Fisheries Department and Captains Clarence October and Cecil Poleman for assisting with transport to and from Inaccessible Island. We also thank the South African Department of Forestry, Fisheries and the Environment, the crew and officers of R.V. *S.A. Agulhas II* and *Akademik Tryoshnikov*, the Swiss Polar Institute (SPI) as well as Isabelle Ansorge, Marcel van den Berg, the SEAmester South Africa's class afloat Programme and Tammy Morris (Agulhas System Climate Array) for their logistic support before and during the cruises. We also thank Marcello Vichi and Tommy Ryan-Keogh for the support during the SCALE (Southern oCean seAsonaL Experiment) voyage. Finally, we thank Stefan Schoombie (Marion relief voyage 2017) and Mike Daniels (SCALE Spring cruise) for assisting with sample collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.marpolbul.2024.116400.

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