Long-term changes in the incidence and characteristics of plastic ingested by White-chinned Petrels

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Abstract

Environmental plastic floating at sea is difficult to measure due to its high spatial and temporal variation. White-chinned Petrels *Procellaria aequinoctialis* are surface-foraging seabirds found in the Southern Ocean that often ingest plastic. They are susceptible to being caught on fishing gear, providing large numbers of carcasses that can be used to monitor changes in the incidence and characteristics of plastic floating at sea. Of the 2477 White-chinned Petrels caught off South Africa between 1979 and 2023, 56% contained plastic. Data were grouped into time periods to determine temporal variation while accounting for unequal yearly sample sizes. The proportion of birds containing plastic has remained between 47% and 63% since 1979. Changes in the number of plastic items ingested were determined by fitting the data with a negative binomial regression model. The number of plastic items ingested has significantly increased since 1979, although not consistently, with the lowest average load in 1979–85 (1.86 ± 3.79 items per bird) and the highest in 2017–23 (6.81 ± 18.51). Although the average ingested plastic load was greatest in the last 7 years, the sample size is smallest for this period due to reduced bycatch rates, so more data are needed to confirm the recent increase in ingested plastic. The proportion of pellets declined from 25% to 14%, with the average number of pellets per bird following a similar trend until two highly impacted birds were found in 2022 and 2023 containing 48 and 22 pellets respectively, possibly reflecting recent large pellet spills at sea off South Africa. The proportion of flexible plastics (fibres and films) ingested is high compared to other seabirds and has increased over time, potentially due to their behaviour of scavenging behind ships. Some birds contain fibrous gastroliths up to 20 mm in diameter. Recording plastic loads in White-chinned Petrels killed accidentally on fishing gear offers a useful method to monitor long-term changes in floating plastic at sea.

Acknowledgements

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Introduction

Despite the worldwide alarm, like many threats faced by our planet, the relentless influx of plastic into the environment shows no signs of stopping. Since 1950, plastic production has increased to more than 370 million tonnes (Mt) per year (Geyer et al., 2017). The most common plastics are made from fossil fuels and are not biodegradable (Barnes et al., 2009), unsustainably accounting for 8% of global oil production (Thompson et al., 2009). To make matters worse, the largest market for plastic production is packaging, most of which is single-use and disposed of shortly after use (Jambeck et al., 2015; Geyer et al., 2017). Mass production and poor waste management of this persistent and easily dispersed material has led to its abundance on the surface and seabed of all oceans (Furness, 1985; Barnes et al., 2009). However, many variables limit our understanding of how much is accumulating. Wind conditions, currents, and multiple entry points cause considerable temporal and spatial variation in floating marine debris, making it difficult to measure (Ryan et al., 2009). Limited knowledge of accumulation rates in the deep sea, a major sink for marine debris (Barnes et al., 2009; Woodall et al., 2014), also limits our understanding. Crude production models estimate that 4.8 to 12.7 Mt of plastic entered marine environments in 2010 and this is expected to increase by an order of magnitude by 2050 (Jambeck et al., 2015). More recently, Borrelle et al. (2020) estimated 19-23 Mt entered aquatic systems in 2016 and predicted on a business-as-usual trajectory that 90 Mt will be emitted in 2030. With still little known about their long-term threats to both marine biota and humans (Galloway, 2015), plastics are reaching unprecedented levels in the environment (Eriksen et al., 2023).

Threats of plastic pollution to marine biota

As plastic becomes more pervasive in marine environments, the risk of exposure to marine biota increases (Ryan, 2016). Kühn and van Franeker (2020) reported that 914 marine species are affected by the ingestion of or entanglement in marine debris. The impacts of entanglement are obvious and most often result in death (Gall and Thompson, 2015). Ingestion of marine debris is believed to pose a more serious threat (Kühn et al., 2015), affecting a broader range of species, and at times impacting almost entire populations within a species (Ryan, 1987a). The documented consequences of ingestion are, however, less obvious, including reduced stomach volume and blockage, false satiation, reduced fitness, and increased exposure to toxic chemicals (Ryan, 1987b; Ryan, 1988; Colabuono et al., 2010; Ryan, 2015a; Yamashita et al., 2021).

Ingestion of litter by marine organisms was first recorded in the late 1960s by Kenyon and Kridler (1969), who found large plastic loads in Laysan Albatrosses *Phoebastria immutabilis* (Ryan, 2016). Today, seabirds are one of the most affected biotas (Gall and Thompson, 2015; Petry and Benemann, 2017), with 78% of species studied found to ingest plastics (Ryan, 2016). Procellariiformes, particularly petrels, are among the most affected birds (Petry and Benemann, 2017), with more than half of individuals in many species containing ingested plastic (Kühn et al., 2015). This is attributed to their surface foraging behaviour, leading to frequent encounters with floating plastic (Ryan, 1987), coupled with their unique anatomy that largely prevents them from regurgitating ingested plastic due to a narrow and angled isthmus connecting their proventriculus and gizzard (Furness, 1985; Ryan, 1988; Ryan, 2016).

Monitoring plastic floating at sea

While species attributes (tendency to regurgitate, foraging behaviour, diet, etc.) largely determine plastic loads in seabirds, it is also related to exposure, suggesting that with increasing plastic entering the ocean, a proportional increase will be found ingested in seabirds (Wilcox et al., 2015; Ryan, 2016; Roman et al., 2019; Clark et al., 2023). Consequently, seabirds provide an opportunity to monitor changes in the amount and type of plastic floating at sea (Ryan et al., 2009; van Franeker et al., 2011; GESAMP, 2019). This insight into changes in plastic abundance can help us understand its impact and support the development and evaluation of mitigation measures (GESAMP, 2019; Lavers et al., 2021). For example, Northern Fulmars *Fulmarus glacialis* have been adopted as indicators of marine debris pollution by the European Union, who in need of quantifiable policy aims, created a standard that less than 10% of beached Northern Fulmars should contain more than 0.1 g plastic (OSPAR, 2010; van Franeker et al., 2011). The effectiveness of Operation Clean Sweep (www.opcleansweep.com), aimed at reducing spillage of industrial pellets, has been demonstrated by several studies showing a decrease in the proportion of pellets among ingested plastics in seabirds over the last few decades (Vliestra and Parga, 2002; Ryan, 2008; van Franeker et al., 2011, van Franeker and Law, 2015).

Despite effort in monitoring trends in marine plastics, there is a large mismatch between what is estimated to be entering the marine environment and what is found at sea (Ryan et al., 2020). The rate of plastic production, combined with its persistent and durable properties, suggests an inevitable rise in the amount accumulating in the marine environment (Andrady, 2011). However, for the last few decades, studies have reported varying trends in the amount of floating and ingested plastic, which has led to uncertainty about whether the amount of plastic is increasing in the ocean and whether mitigation measures have been effective (Thompson, 2004; Law et al., 2010; Ryan, 2008; van Franeker et al., 2011; van Franeker and Law, 2015; Lavers at al., 2021). While studies have shown a stable trend in floating plastics since the 1980 and 1990s (Thompson et a., 2004; Law et al., 2010), a growing number of recent reports show increasing concentrations of floating plastic at sea (Lebreton et al., 2018; Wilcox et al., 2020; Eriksen et al., 2023). Law et al. (2010) reported that there was no change in floating plastics in the North Atlantic subtropical gyre between 1986–2008, however with more recent data, Wilcox et al. (2020) found an increasing concentration mirroring global production. Another recent report by Eriksen et al. (2023) found that global floating plastics are no longer stable and increasing rapidly since the turn of the century, calling for urgent action. These reports of increasing floating plastic have coincided with reports of increased ingestion by marine biota, particularly Procellariiformes in the southern hemisphere (Petry and Benemann, 2017; Perold et al., 2020; Phillips and Waluda, 2020; Baes et al., 2024). Most recently, Baes et al. (2024) found an increasing occurrence of plastic ingestion in Procellariiformes off the coast of Brazil between 2017–2022. Perold et al. (2020) reported an increase in non-fishery related plastic items at the nests of Grey-headed Albatrosses *Thalassarche chrysostoma* and Giant Petrels *Macronectes* spp. between 1999–2008 and 2009–2018, with an almost doubling amount at Grey-headed Albatross nests. In a similar study, Phillips and Waluda (2020) found a significant increase in litter surrounding the nests of Wandering *Diomedea exulans* and Black-browed *Thalassarche melanophris* Albatrosses from 1994–2019.

White-chinned Petrels as bioindicators

Procellariiformes, especially petrels, are useful in detecting changes in debris over large spatial scales, retaining plastic in their stomach for months at a time (Ryan and Jackson, 1987; Ryan, 2015a). White-chinned Petrels are opportunistic, omnivorous (a mixed diet of fish, cephalopods, and crustaceans) surface-foraging seabirds, making them especially susceptible to the ingestion of plastic (Ryan, 1987a). They have a circumpolar distribution (Berrow et al., 2000), and travel northward after breeding at sub-Antarctic islands during the austral summer (Phillips et al., 2006;

Rollison et al., 2018). They are listed as Vulnerable by the IUCN, mainly due to high rates of incidental mortality on long-line fishing gear (BirdLife International, 2018). White-chinned Petrels are the species of seabird most often killed on fishing gear in the Southern Ocean (Phillips et al., 2016; Rollison et al., 2017). Threatened species with a high frequency of plastic ingestion like the White-chinned Petrel (Ryan, 1987; Colabuono and Vooren, 2007; Ryan, 2008; Colabuono et al., 2009; Colabuono et al., 2010; Petry and Benemann, 2017; Baes et al., 2024) are of particular concern, as ingestion may be contributing to their eventual risk of extinction (Gall and Thompson, 2015).

Like the Northern Fulmar, the White-chinned Petrels is a suitable indicator of marine pollution due to frequent plastic ingestion, long retention periods of ingested plastic, and easily accessible carcasses (Baes et al., 2024). However, to date, only two studies have documented temporal changes in plastic ingestion in this species. Ryan (2008) compared data between 1983–85 and 2005/6 and found no significant difference in the number of plastic items ingested, but a three-fold decrease in industrial pellets. Petry and Benemann (2017) reported a significant increase in the frequency of plastic ingestion off the coast of Brazil between 1990 (14%, n = 14) and 2007–2014 (63%, n = 65) and a decrease in industrial pellets but lacked statistical power due to small sample sizes. Other studies have reported a singular snapshot of the frequency of ingestion (Ryan 1987; Petry and Fonseca, 2002; Colabuono and Vooren, 2007; Colabuono et al., 2009; Colabuono et al., 2010; Muñoz et al., 2023; Baes et al., 2024), with many containing small sample sizes (≤ 10 birds) and reporting data over a decade old (Ainley et al., 1990a; Ainley et al., 1990b; Nel and Nel, 1999; Tourhino et al., 2010; Tavares et al., 2017; Vanstreels et al., 2021).

Long-term studies are urgently needed to monitor changes in ocean plastics (Lavers et al., 2021). Variability across time and space are both characteristics of plastic pollution, reflected in large intraspecific variability of plastic ingestion in seabirds (Furness, 1985; Ryan, 1988; Provencher et al., 2010; Ryan et al., 2016). This study revisits the non-breeding population of White-chinned Petrels off the coast of South Africa, providing further insight into the long-term trends of plastic ingestion in terms of abundance and composition. I examined the amount of plastic ingested in White-chinned Petrels caught as bycatch on long-line fishing boats off the coast of South Africa between 2007–2023 and compared this with revisited data from previous studies on the species in the same region (Ryan, 1987; Ryan, 2008) to assess temporal changes in the occurrence, number and/or types of plastic items ingested from 1979–2023. Characteristics of ingestion such as size, colour, and polymer type were quantified. These data are useful considering different plastic resins have varying properties regarding contamination (Teuten et al., 2009), and the ingestion of different plastic types is linked to varying threats (Roman et al., 2019). Due to the large sample sizes, long-term data, standard metrics (Provencher et al., 2019), and species attributes that align with GESAMP (2019) indicator requirements (Baes et al., 2024), this study provides valuable insight into changes in floating plastics in the Southern Ocean. This is the first long-term test of the hypothesis that increasing plastic production of this persistent and easily dispersed pollutant will result in increasing ingestion in White-chinned Petrels off the coast of South Africa. Determining the incidence and characteristics of plastic ingestion over time is the aim of this study and may help in the implementation and monitoring of mitigation measures.

Methods

White-chinned Petrels accidentally caught on long-lines set to catch tunas and other large pelagic fish primarily within the South African Exclusive Economic Zone were returned to port by fishery observers (Fig. 1). Foreign fishing vessels operating under license in South African waters must have an independent fishery observer on board who is responsible for monitoring catches, including bycatch of seabirds (Petersen et al., 2009; Rollison et al., 2017). Birds were labelled with the date, location and name of the fishing vessel before being frozen. Most fishing effort occurs in the austral winter. White-chinned Petrels breed in the austral summer, therefore the risk of intergenerational transfer of plastic to chicks, which greatly affects the results (Ryan, 1988), is largely avoided. White-chinned Petrels caught by the Prince Edward toothfish fishery were not included in this study due to most fishing efforts being conducted during the breeding season (October-April) when plastic is offloaded to chicks, resulting in a smaller proportion of birds containing plastic.

Once ashore, birds were defrosted and dissected to determine their species identity, age, sex, and stomach contents. Age and moult were noted, but birds were not weighed because they were waterlogged after being drowned on long-lines. The stomach contents were washed from the proventriculus and ventriculus into a small metal bowl, and agitated to separate plastics and prey remains. Most ingested plastics float, and even those that don't have a density close to that of seawater and can readily be separated from other dietary remains. This approach has been used by the same observer since the 1980s (Ryan, 1987; Ryan, 2008), allowing for accurate comparison of results. Plastics found within each bird were counted and sorted into four types following GESAMP protocols: industrial pellets, hard fragments, flexible or film fragments (mostly pieces of plastic bags and food packaging), and fibres (thread-like items, including fishing lines; GESAMP, 2019). The number of each type was recorded upon dissection.

Plastics were dried and stored at room temperature in plastic Ziplock bags labelled by year, with samples of individual birds stored separately from 2014–23. In some of the years being examined not all ingested items were retained. In particular, smaller flexible fragments (< 2 mm), which were often present in large numbers, seemingly as a result of fragmentation of one or more larger items, were often discarded. To assess the characteristics of ingested plastics, the size, weight, and colour of all the plastics kept were recorded. The maximum length, width, and breadth were taken to the nearest 0.01 mm using digital calipers. Items were weighed using a precision electronic balance to the nearest 0.1 mg. Following Provencher et al. (2017), the colour and colour group were recorded with multicoloured pieces assigned to multiple colour groups. Items discoloured due to ingestion or weathering were grouped according to their assumed original colour, particularly tarnished clear/white items. The proportion of colours ingested was compared with data taken from at-sea surveys conducted in the South Atlantic and southwest Indian Ocean on nine oceanographic research voyages between 2016 and 2019 (Perold et al. subm.).

A subset of the plastics (15% of the total hard fragments, pellets, fibres, and flexible items collected from 2007–2023) was analysed with FT-IR spectroscopy to determine polymer composition. One hundred pellets (11% of the total pellets collected in the given time period) and one hundred hard fragments (4%) from 2007–2011 were chosen randomly. Additionally, fifty hard fragments (12%) and fifty pellets (49%) from 2012–2016, as well as another fifty hard fragments (13%) and fifty pellets (52%) from 2017–2023 were selected. The proportion of samples that were randomly selected from each year was based on their contribution to the total number of plastics in that time period. Industrial pellets and hard fragments were selected for FT-IR spectroscopy using a numbered 50 × 50 cm square grid and random number generator, with the pieces collected that year scattered over the grid. If a piece was present on the square selected, it was chosen only if most of the piece was present on that square, which reduced bias towards larger pieces that overlapped multiple squares. Random numbers were generated until the number of pieces to select for that year was selected. Because flexible items and fibres were less abundant, all of those retained were analysed. Polymer types were determined using a Bruker Alpha II compact FT-IR spectrometer. Each sample was cleaned thoroughly using 70% ethanol to remove residue and a small piece of each item – to not destroy the entire sample – was cut off for analysis. The FTIR base was cleaned with 70% ethanol between scans to prevent contamination of samples. The spectrometer was run in absorbance mode with a spectral region of 400 to 4000 cm^{-1} and a resolution of 4 cm^{-1} and 32 scans. Spectrums were run through OPUS 8.7 Spectra Software with Bruker Optics ATR-Polymer Library and the KIMW ATR-IR Polymer Library, to identify and match with a polymer. Only results with a 70% or higher correlation score with a specific polymer were used.

To assess whether hard prey material and plastic pass through the stomach into the intestine, the entire intestinal tracts of 52 White-chinned Petrels (collected in 2017) were also dissected. The contents of the intestines were washed with filtered water through 3 mm, 1 mm, and 0.1 mm stainless steel sieves. The contents were then floated again with filtered water to check for plastic. Plastics as well as the top 10 largest hard items were measured.

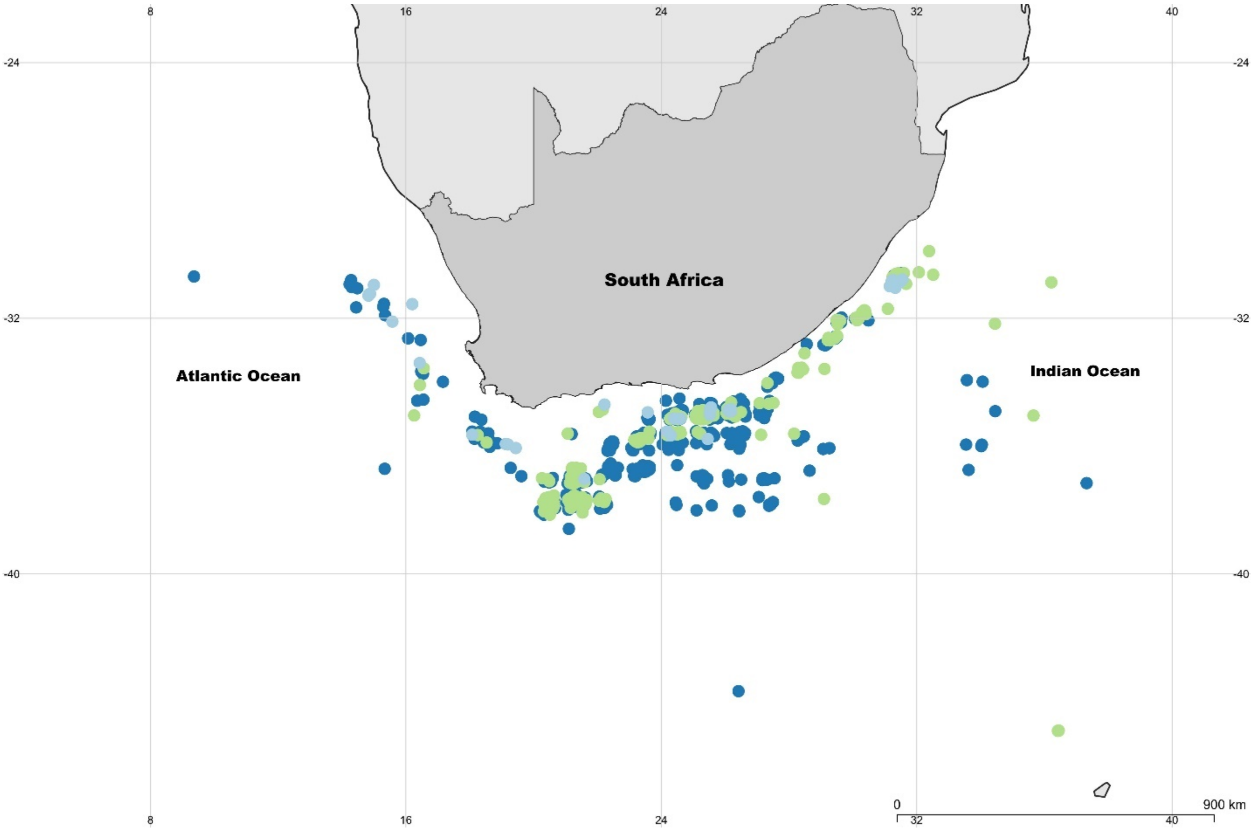

Figure 1. Locations where White-chinned Petrels were caught on long-lines during three time periods: 2007–11 (dark blue), 2012–16 (green), and 2017–23 (light blue).

Data analysis

Data collected from 2007–2023 were analysed with the raw data from Ryan (2008), which were non-breeding bycatch birds caught off the coast of South Africa from 2002–06, and Ryan (1987), which were non-breeding birds collected at sea off the coast of South Africa for diet studies from 1979–85 (Jackson, 1988). Annual averages have been reported as impractical in other long-term studies due to small sample sizes and short-term variations (van Franeker, 2011). Therefore, due to the considerable variation in the number of birds killed each year as well as the gap between 1985 and 2002, data were compared in the following time periods to obtain sufficient sample sizes (following van Franeker, 2011): 1979–85 (n=189), 2002–06 (n=599), 2007–11 (n=1169), 20012–16 (n=421), 2017–23 (n=99). However, to ensure there is no bias resulting from grouping the data, it is explored at a finer temporal scale (1979–85, 2002–06, 2007–08, 2009–10, 2011–12, 2013–14, 2015–17, 2019–23) or per year where needed.

First, the frequency of occurrence of plastic ingestion, meaning the proportion of birds containing plastic, was calculated across each time period. The change in frequency of occurrence over time was tested using a Chi-squared test for independence. This analysis was conducted both across the specified time periods and again at a finer temporal scale (1979–85, 2002–06, 2007–08, 2009–10, 2011–12, 2013–14, 2015–17, 2019–23) to further investigate trends. Throughout each analysis, a statistical significance level of $\alpha = 0.05$ was used.

The amount of plastic ingested was measured by the number and then the mass of plastic ingested. The number of plastic items ingested was measured by averaging the plastic load 1) of all birds and 2) of birds containing plastic (mean ± SD). To explore the changes in the number of plastic items ingested, the data was fit (both in time periods and per year) with a negative binomial regression model after determining non-equal variance (see Appendix 1 for model selection). An ANOVA was run on the output to determine overall significance. The mass of plastic items ingested was taken by averaging the amount of plastic by mass in birds between 1979–85 (where individual item weights were recorded for each bird upon dissection) and comparing it with birds from 2017–23. Only these time periods were included in this analysis because plastic items were not stored separately per individual bird from 2007–2014, making it impossible to determine mass per bird between 2007–11 and 2012–16. The change in mass of plastic load was tested with a Mann Whitney U Test to account for the non-normally distributed data being compared between two independent groups. The proportion of birds with > 0.1 g of plastic ingested, which is the OSPAR ecological quality indicator used for Northern Fulmars, was tested for a significant change using a Chi-squared test for independence. To further investigate the changes in the composition of ingested plastic mass, all items retained from 2007–2011, 2012–16, and 2017–23 were weighed. The proportion in mass of each plastic type (excluding fibrous gastroliths due to their high proportion of organic material by mass - see Appendix 2), relative to the total mass of plastic during each time period was assessed with a Chi-squared test for independence with pairwise analyses to determine where significance lies.

The frequency of occurrence of different plastic types per time period were assessed using a Chi-squared test for independence and a pairwise analysis to see where significance lies. The frequency of occurrence of industrial pellets was visualised and analysed at a finer temporal scale. The change in the number of industrial pellets ingested was tested using a negative binomial regression model after determining non-equal variance. An ANOVA was run on the output to determine overall significance. The change in the number of pellets ingested was further investigated per year to confirm trends.

Lastly, the characteristics of plastic items were assessed to gain further insight into changes in plastic floating at sea. The change in mass and length of individual items across time periods was tested using Kruskal-Wallis tests, with post-hoc Dunn's tests to show where differences were significant. Changes in the polymer composition were determined using Chi-squared test for independence. Lastly, the frequency of occurrence of colours of plastic ingested was compared to plastic floating at sea using a Chi-squared test for independence. Data were analysed using R version 4.2.2, using the following packages: dplyr, ggplot2, ggpubr, MASS, car, tidyr, chis.posthoc.test, and dunn.test.

Results

Frequency of occurrence of plastic ingestion

Plastic and other anthropogenic litter was found in 56% of 2477 White-chinned Petrels shot at sea (1979-85) or caught on long-line fishing gear (2002–2023). There was a significant difference ($\chi^2 = 29.75$, df = 4, $P < 0.001$) in the frequency of ingestion among time periods due to the low value (47%) in 2002–06, but there was no trend to the incidence in subsequent years (Table 1). At a finer temporal scale, an overall significant trend in the frequency of occurrence was also observed ($\chi^2 = 35.58$, df = 6, $P < 0.001$) but this was again due to the low incidence in 2002–06 (Fig. 2).

Table 1. Long-term trends in the number and characteristics of plastic items found in White-chinned Petrels at sea off South Africa. The total number of birds examined with the number of ingested plastic items (in parentheses), the proportion of birds containing plastic and each type of plastic (%FO), maximum and mean plastic loads (n items ingested) out of all birds and only birds containing plastic (plastic only), and pellet load with and without outliers (mean ± SD), df = 4.

Variable	**1979–85***	**2002–06****	**2007–11**	**2012–16**	**2017–23**	**Significance**
Sample size (n plastics)	189 (351)	599 (824)	1169 (4593)	421 (901)	99 (674)	
%FO	56%	47%	60%	55%	63%	χ^2=29.75; P < 0.001
Mean load (all birds)	1.86 ± 3.79	1.33 ± 3.24	3.93 ± 9.29	2.14 ± 5.17	6.81 ± 18.5	χ^2=168.58; P < 0.001
Median (all birds)	1.0	0	1.0	1.0	1.0	
Mean load (plastic only)	3.31 ± 4.57	2.94 ± 4.23	6.56 ± 11.3	3.88 ± 6.46	10.90 ± 22.4	χ^2=162.09; P < 0.001
Median (plastic only)	2.0	2.0	3.0	2.0	3.0	
Maximum load	24	37	88	55	122	
Pellet load	0.66 ± 1.67	0.22 ± 0.88	0.78 ± 2.33	0.24 ± 0.86	0.98 ± 5.33	χ^2 =76.03; P < 0.001
(excluding outliers)	-	-	-	-	0.28 ± 0.93	χ^2= 77.77; P < 0.001
%FO industrial pellets	25%	11%	22%	13%	14%	χ^2 = 47.59; P < 0.001
%FO hard fragments	13%	27%	38%	31%	32%	χ^2 = 58.03; P < 0.001
%FO flexible fragments	17%	8%	12%	16%	27%	χ^2 = 37.51; P < 0.001
%FO fibres & fibrous gastroliths	30%	18%	23%	24%	38%	χ^2 = 30.19; P < 0.001

*Revised data from Ryan, 1987

** Revised data from Ryan, 2008

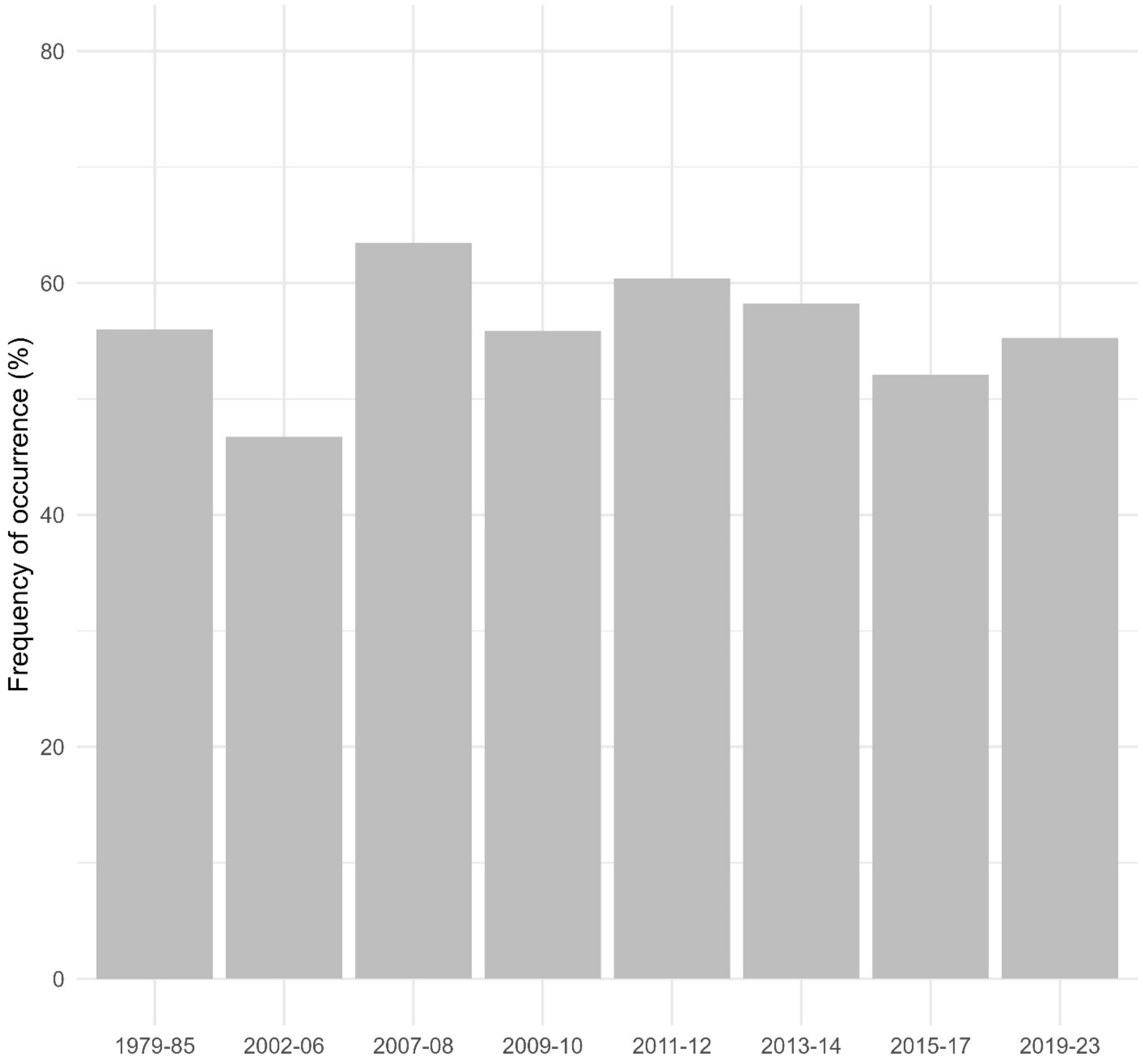

Figure 2. Long-term trends in the frequency of occurrence of plastic ingestion in White-chinned Petrels killed at sea off the coast of South Africa.

Plastic loads by number

A total of 7410 anthropogenic items were recorded in White-chinned Petrels, of which 99.1% were plastic. The few non-plastic items were mostly metal hooks, mainly from the hake-long-line fishery, which presumably were in discarded fish heads scavenged by the petrels. Twelve latex balloon fragments were also ingested. The overall average plastic load between 1979–2023 was 2.96 ± 8.02 items in all birds (5.32 ± 10.01 in birds containing plastic). Of the 99 samples from the latest time period (2017–23), only eight were collected in 2022 and 2023. Seven of these birds contained plastic, two with over 100 pieces, and an average load of 36 ± 49 pieces. A significant increase in plastic loads was detected, despite fluctuations from 1979 to 2023 (Figs. 3 and 4). The significant increase occurred, both when comparing data in time periods (LR χ^2= 168.86, df=4, $P < 0.001$; Fig. 3), and per year ($Z = 4.497$; $P < 0.001$; Fig. 4). With the two outliers in the latest time period excluded, a significant increase in plastic load was still detected when analysed in time periods (LR $\chi^2 = 147.42$, df = 4, $P < 0.001$) and per year ($Z = 3.293$, $P < 0.001$).

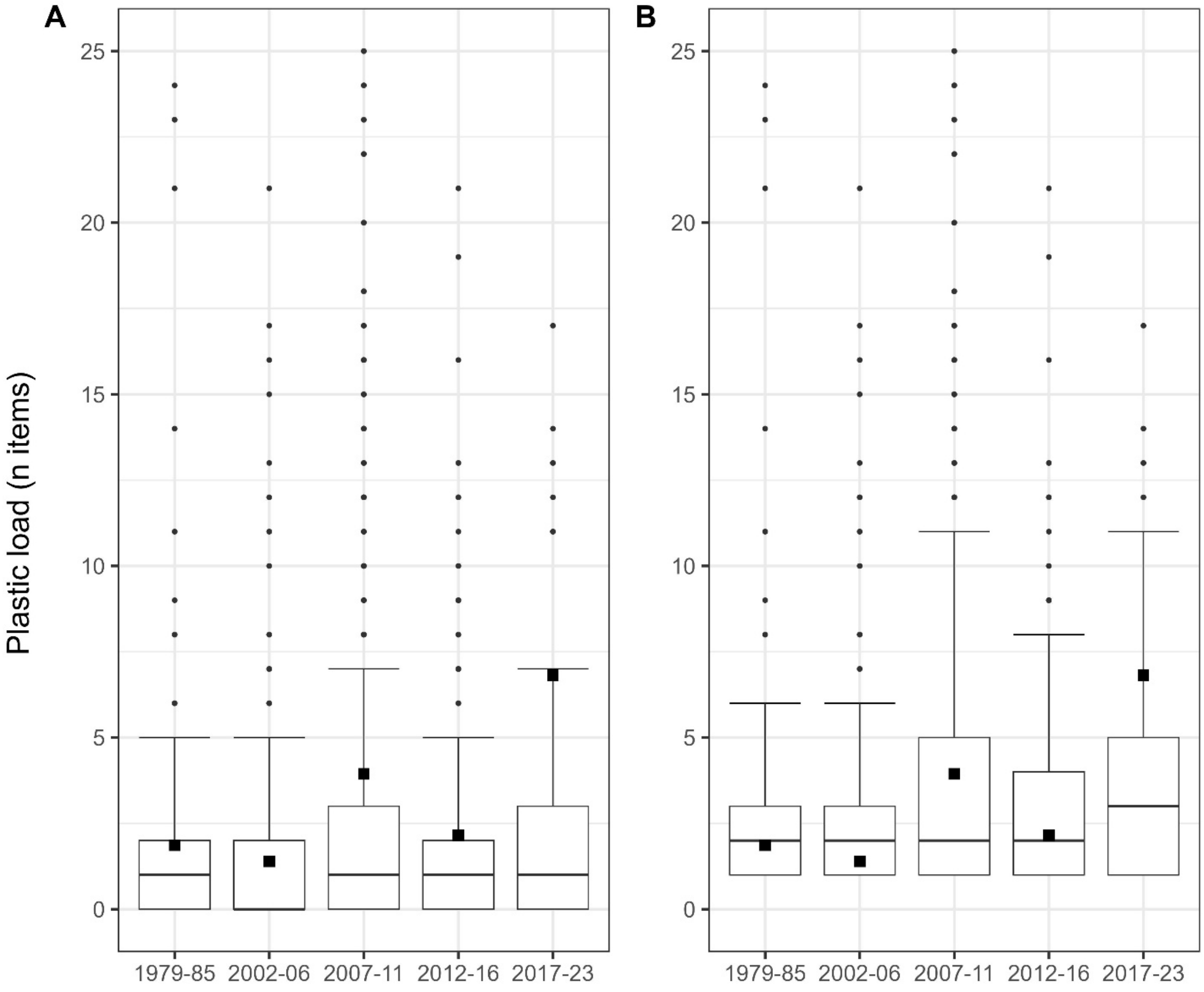

Figure 3. Boxplots displaying plastic loads in White-chinned Petrels over three time periods, including total birds (A) and only birds with plastic (B). The median (black line), average (square), interquartile range (box), values 1.5 times the interquartile range (whiskers), and outliers (circles) are displayed, with outliers greater than 25 not displayed.

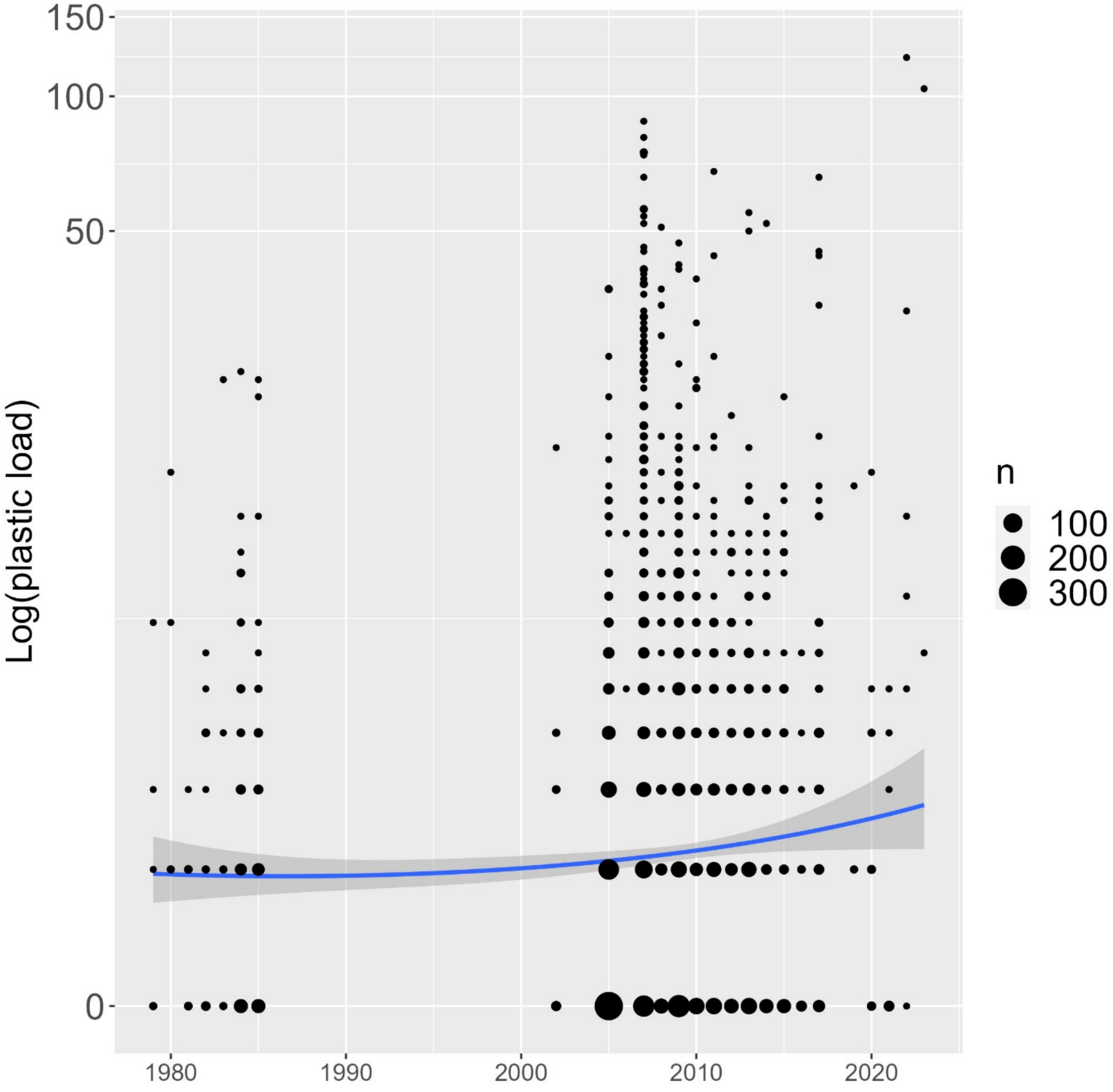

Figure 3. Plastic load (log-transformed) in White-chinned Petrels killed by fisheries off the coast of South Africa from 1980 to 2023. Fitted line (blue) follows a negative binomial regression with a polynomial effect allowing for a non-linear relationship with 95% confidence interval indicated (grey band). The size of each point indicates the number of individual birds represented by that data point. The relationship between plastic load and year shows a significant positive effect ($Z = 4.497$; $P < 0.001$).

Plastic loads by mass

The average plastic load (by mass) of birds containing plastic did not change significantly between 1979–85 and 2017–23 in all birds (W = 7032.5, P = 0.46) or in birds with plastic (W = 2389, P = 0.36) despite more than doubling in average loads (Fig. 5). The proportion of birds containing > 0.1 g of plastic increased from 5% of birds in 1979–85 to 13% in 2017–23, but not significantly ($\chi^2 = 3.108$; df = 1; P = 0.07). There was, however, a significant difference in the composition of the types of plastic items (by mass) between time periods ($\chi^2 = 56.56$, df = 9, P < 0.001: Fig. 6). There was a significant decrease in contribution by mass of industrial pellets between 1979–85 (44%) and 2012–16 (16%), followed by a significant increase, surpassing 1979–85 amounts, from 2012–16 to 2017–23 (49%). The proportion of hard fragments (by mass) significantly increased from 1979–85 (26%) to 2012–16 (50%) and then dropped back to 37% as pellets increased in 2017–23.

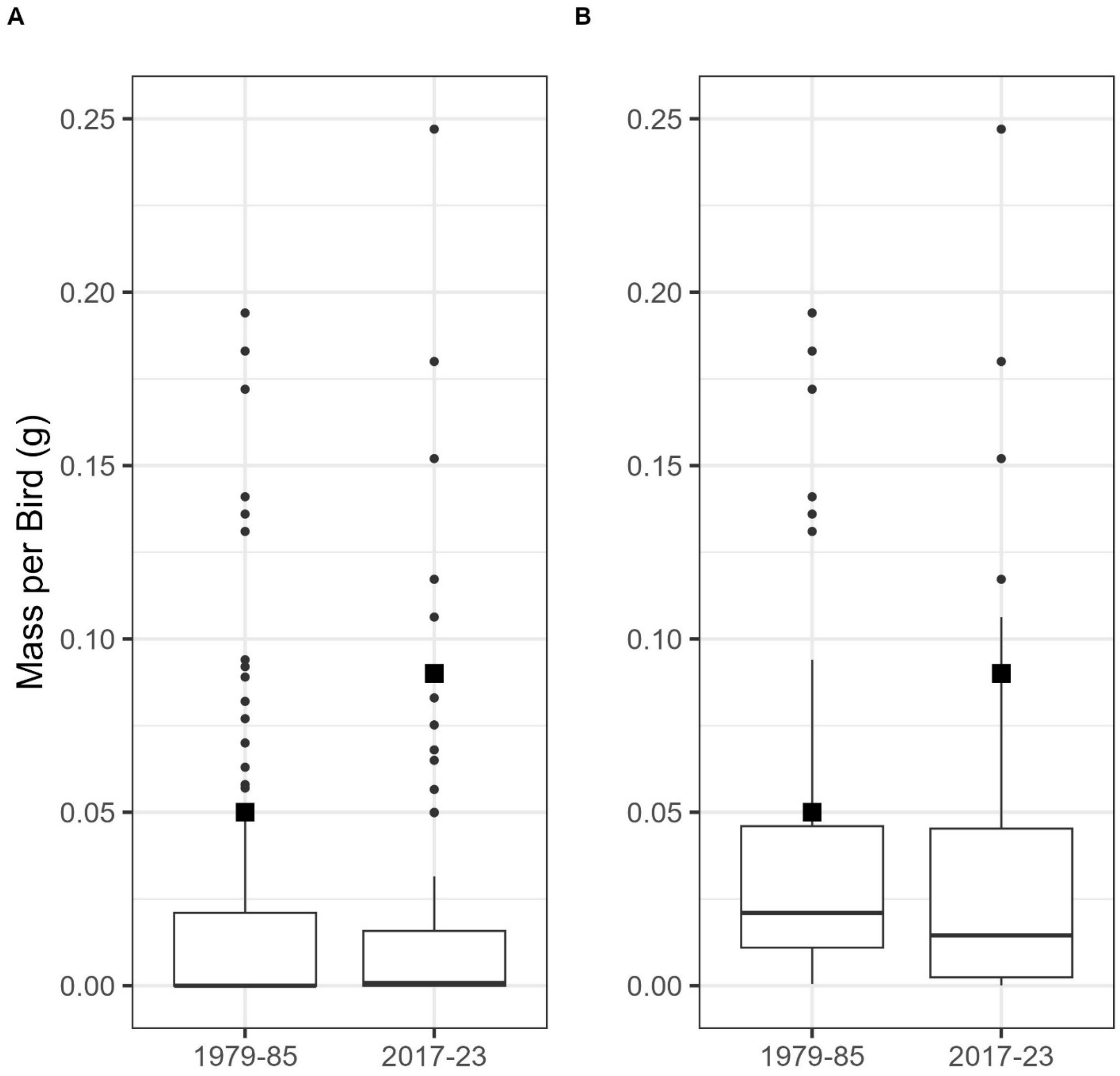

Figure 4. Boxplots displaying the average mass of plastic loads in White-chinned Petrels killed at sea out of total birds (A) and birds with plastic (B). Data from Ryan (1987) compared with new data from 2017–2023 when plastic was stored separately for individual birds allowing for plastic load weights to be determined. The median (black line), average (square), interquartile range (box), values 1.5 times the interquartile range (whiskers), and outliers (circles) are displayed, with outliers greater than 25 items not displayed.

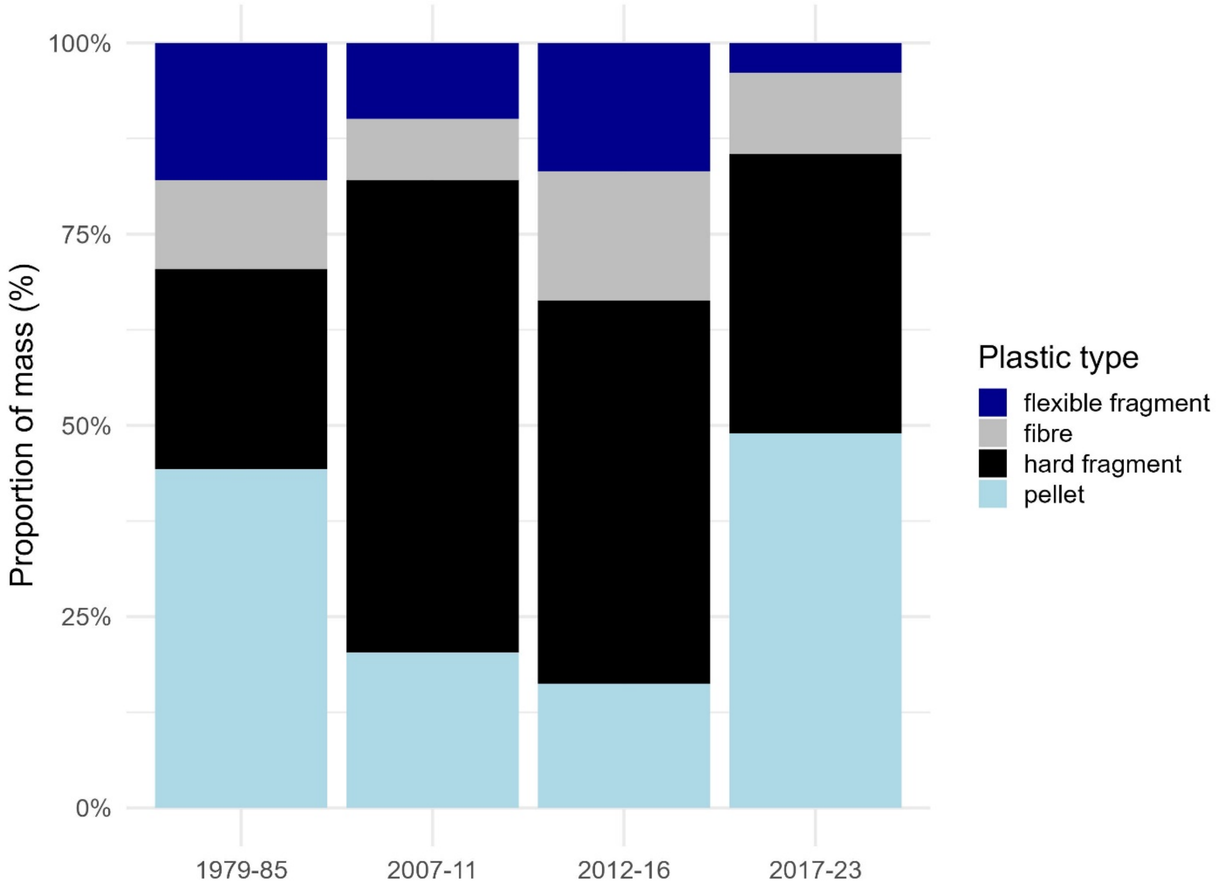

Figure 5. The proportion of plastic types that make up the weight of plastic ingested in each time period. Fibrous gastroliths are not included, only individual fibres. The relationship between year and proportion of mass by each plastic type shows a significant change ($\chi^2 = 56.56$; df = 9; $P < 0.001$) in the proportion of plastic item types making up overall mass ingested in each time period.

Characteristics of ingested plastic

A total of 7343 plastic items were recorded between 1979–2023. Most of the total plastics ingested were hard fragments (57%), followed by industrial pellets (19%), flexible fragments (13%), fibres (6%), fibrous gastroliths (5%), and polystyrene (<1%). The frequency of occurrence (%) of industrial pellets ingested fluctuated over time, mostly due to a drop in overall plastic ingested in 2002–06. There was a significant decrease from 1979–85 (25%) to 2012–16 (13%; P = 0.007). The proportion of 14% in 2017–23 was not significant most likely due to a smaller sample size, but combining the last two time periods results in a significant decrease from 1979–85 to 2012–23 ($P = 0.003$). An overall decreasing trend can be seen when portrayed at a finer scale (Fig. 7).

Data collected in 2007–2023 showed that the average number of pellets ingested decreased from 2007–11 to 2012–16, but an average load in 2017–23 of 0.98 ± 5.33 reversed the trend (Table 1). The increase in the latest time period was due to two birds: one in 2022 containing 48 pellets and one in 2023 containing 22 pellets. Excluding these individuals reduced the average load in 2017–2023 to 0.28 ± 0.93 pellets per bird, resulting in a significant decrease ($\chi^2 = 40.28$, df = 2, $P < 0.001$). When comparing to earlier data, the average pellet load was 0.66 ± 1.67 in 1979–85, and there was a significant decrease from 1979–85 to 2012–16 ($Z = -3.56$, $P < 0.001$), but in 2017–23 the decreasing trend remains only if the outliers are removed ($Z = -2.13$, $P < 0.05$). The change in pellet load was also analysed per year to further investigate overall trends, and there was a non-significant decrease over time ($Z = -0.65$; $P = 0.52$). However, when the two outliers in 2017–23 were removed, there was an overall significant decrease ($Z = -2.70$; $P < 0.05$).

The frequency of occurrence of hard fragments increased significantly from 1979–85 across each time period after 2002–06. Flexible fragments showed an increasing trend as well. Birds containing either individual fibres or fibrous gastroliths were combined in this analysis and the incidence of ingestion did not show any real trends when compared to 1979–85 data, but in the latest time period there was a high frequency of occurrence (38%: Table 1). Fibrous gastroliths are described in further detail in Appendix 2.

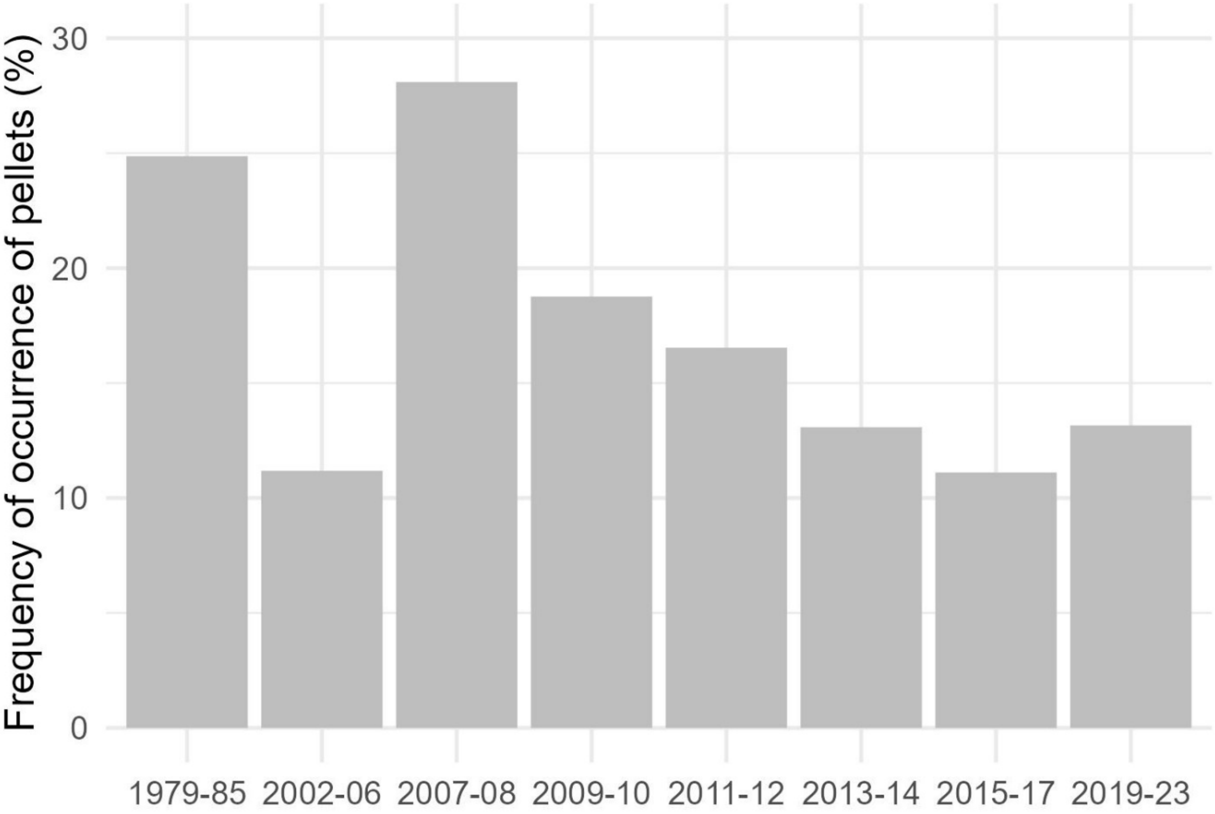

Figure 6. The frequency of ingestion of industrial pellets in White-chinned Petrels caught off South Africa between 1979 and 2023.

The average mass of plastic pellets significantly increased from 15.2 mg ± 7.9 to 25.4 ± 23.8 mg between 1979–85 and 2017–23 ($\chi^2 = 46.08$, df = 3, $P < 0.001$; Fig. 8). The average length of pellets increased from 3.9 ± 0.8 mm to 4.1 ± 0.8 mm ($\chi^2 = 14.36$, df = 2, $P < 0.001$: Fig. 9). The average mass of individual hard fragments in White-chinned Petrels decreased between 2007–11 (24.2 ± 48.4 mg) and 2017–23 (12.3 ± 19.5 mg; $\chi^2 = 67.45$, df = 2, $P < 0.001$: Fig. 8). When comparing data from 1979–85 (12.2 ± 14.7 mg) there was no change. However, only 86 hard fragments were analysed in the 1979–85 data compared to 3646 analysed between 2007–2023. Hard fragments significantly decreased in length from 5.9 ± 3.7 in 2007–11 to 4.7 ± 2.0 mm in 2017–23 ($\chi^2 = 48.29$, df = 2, $P < 0.001$: Fig. 9). Bag fragments decreased from an average length of 21.2 ± 15.9 mm in 2007–11 to 10.9 ± 8.9 mm in 2017–23 ($\chi^2 = 63.83$, df = 2, $P < 0.001$), but this could be partially due to bias resulting from differing data collection methods across time periods, such as only saving larger plastic pieces in earlier years. Individual fibres, excluding fibrous gastroliths, decreased from 53.08 ± 88.1 mm in 2007–11 and 50.8 ± 77.8 mm in 2012–16 to 18.6 ± 43.4 mm in 2017–23 ($\chi^2 = 30.36$, df = 2, $P < 0.001$), but the standard deviations are large. The high means in the first two periods are strongly influenced by polyamide hake long-line snoods, which are 190.7 ± 122.3 mm long (n = 20), and presumably are scavenged from fish heads discarded by hake long-line vessels. The length of individual fibres comprising fibrous gastroliths are explored in Appendix 2.

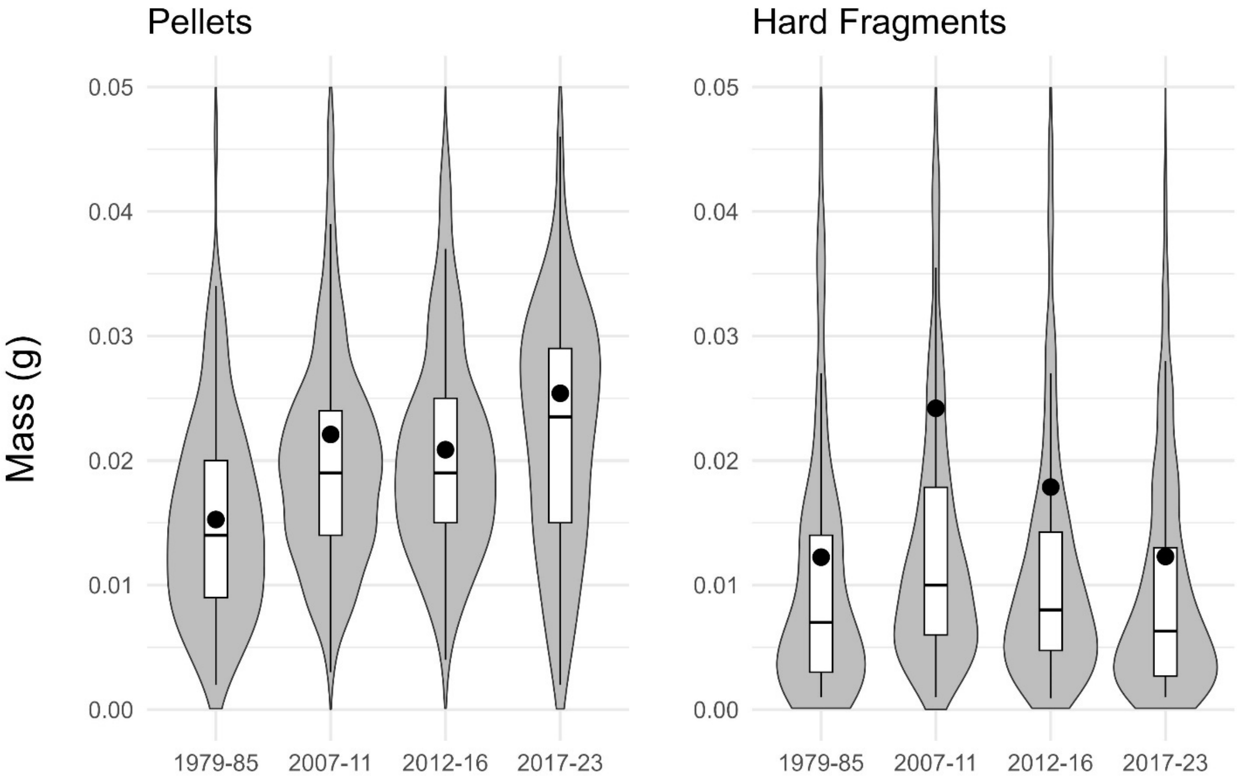

Figure 7. Violin plots of mass on pellets and hard fragments ingested by White-chinned Petrels over four time periods. Raw data from Ryan (2008) did not include the mass of individual items and was excluded from this analysis. The data density (width of plot), mean (circle), median (black line), quartiles (box), and range (whiskers) are represented.

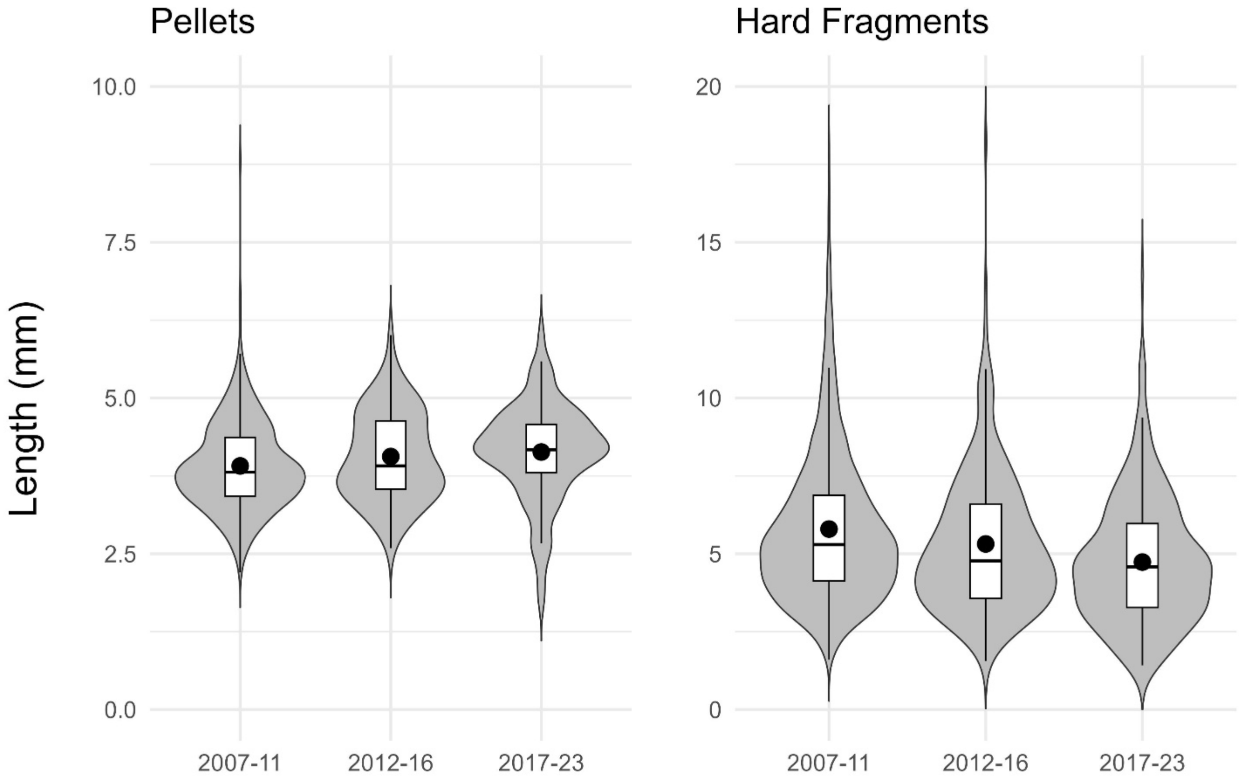

Figure 8. Violin plots on length of pellets and hard fragments ingested by White-chinned Petrels over three time periods, as raw data from Ryan (1987) and Ryan (2008) did not include lengths of individual items. The data density (width of plot), mean (circle), median (black line), quartiles (box), and range (whiskers) are represented.

Most ingested items were clear/white (49%) and orange/brown (23%: Table 2) in colour. Compared to the proportion found in net samples collected off the coast of South Africa from 2016–2019 (71%), White-chinned Petrels ingested fewer clear/white items and more dark items ($\chi^2 = 18.56$, df = 1, $P < 0.01$). The only marked temporal change in the colour of ingested items was among industrial pellets, which increased from 36% clear/white prior to the two major pellet spills off South Africa in 2018 and 2020, to 63% after these spills.

Table 2. The number and proportion (%) of colours for plastic items collected at sea and ingested by White-chinned Petrels.

Time/type	white/clear	black	orange/brown	red/pink	blue/purple	yellow	green	grey/silver
Marine Plastics	71%	8%	1%	2%	11%	1%	4%	2%
All samples	1500 (49%)	396 (13%)	696 (23%)	48 (1%)	124 (4%)	29 (1%)	225 (7%)	52 (2%)

Most industrial pellets were polyethylene; the proportion of polypropylene pellets increased from 8% in 2007–11 to 17% 2017–23 (Fig. 10). The only significant difference over time among plastic types occurred in hard fragments, which varied from 2% polyblend in 2007–11 to 24% in 2012–16 and 5% in 2017–22 ($\chi^2 = 45.12$, df = 4, $P < 0.01$). Around 50% of the flexible fragments were made of polypropylene, while the remaining proportion was distributed between polyethylene and polyblends. Some flexible fragments could be recognised as pieces of black refuse bags and food wrappers, but spectral matches > 70% could not be achieved. Fibres were between 50-60% polyethylene with polyamide ranging from 7-25%. Polyamide, mostly constituting fishing lines and snoods (monofilament lines connecting hooks to fishing lines), is the only polymer found ingested that does not float.

Intestine contents

Only 2 of 52 intestinal tracts contained any plastic. Each contained a single item: one semi-flexible piece of high-density polyethene (2.91 × 1.37 × 0.28 mm), longer than 8% of hard fragments but wider than only 2% of hard fragments, and a thin bag fragment (2.14 × 0.65 × 0.01). Both birds with plastic in their intestines had plastic present in their stomachs, 11 and 6 pieces respectively. Of the 52 dissected birds, 63% had plastic present in their stomachs, with an average of 4.7 pieces and a maximum of 66 pieces. In the bird containing 66 pieces of plastic, 60 were hard fragments, with 13 measuring < 2 mm in length and more than 30 measuring < 2 mm in width. The only other hard material found in the intestines were fragments of squid beaks (Table 3).

Table 3. The length, width, and breadth (mm) of the ten largest squid beak fragments found in the intestines of 52 White-chinned Petrels caught off long-line fishing boats in 2017.

Squid beak number	Length × width × breadth (mm)	
1	2.61 × 1.88 × 0.59	
2	2.57 × 0.9 × 0.7	
3	2.23 × 1.58 × 0.2	
4	2.13 × 1.17 × 0.46	
5	1.62 × 1.4 × 0.04	
6	1.57 × 1.43 × 0.27	
7	1.51 × 1.24 × 0.28	\
8	1.49 × 0.93 × 0.83	
9	1.39 × 1.25 × 0.11	
10	1.17 × 0.77 × 0.05	

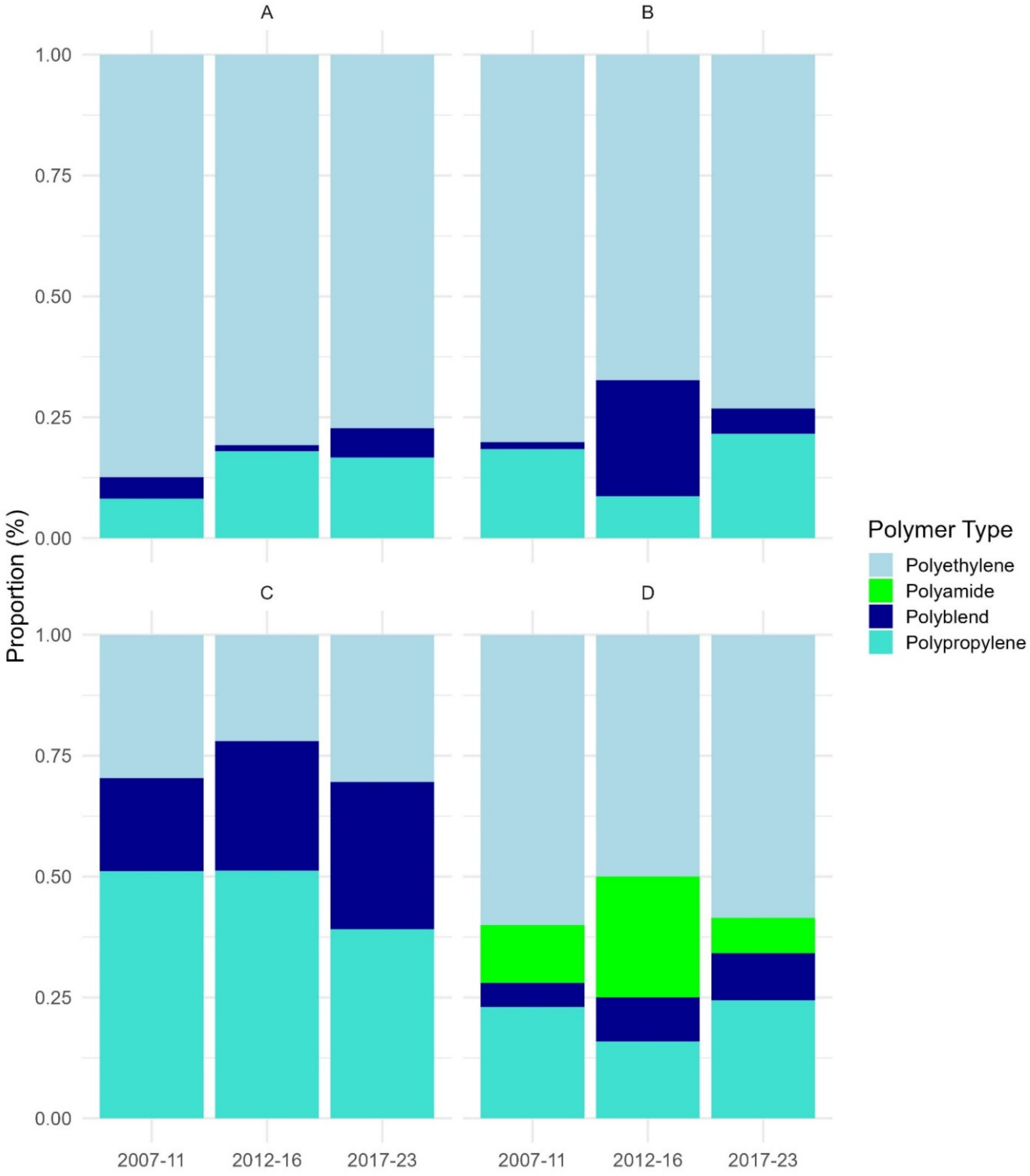

Figure 9. The proportion of polymer types of pellets (A), hard fragments (B), flexible fragments (C), and fibres (D) ingested by White-chinned Petrels over three time periods.

Discussion

Industrial-scale plastic production started in the 1950s, and since then, there has been a steady annual growth in production (Geyer et. al., 2017). Due to poor waste-management policies and a general lack of accountability, large amounts of mismanaged plastic waste are produced annually (Geyer et al., 2017). Plastics are long-lasting and dispersed easily once in the environment, often ending up in our oceans. We therefore expect to see an increase in the density of mismanaged plastic litter at sea over time (Jambeck et al., 2015; Geyer et al; 2017; Borrelle et al., 2020). The characteristics of plastics, namely the type, size, mass, and polymer type can also influence their density and longevity at the sea-surface, and analysing these features could be applied to interpret temporal and spatial variation in plastics loads and types.

This study investigates trends in marine plastic pollution over time by examining the temporal variation in the amount and characteristics of plastic ingested by White-chinned Petrels off the coast of South Africa. This species is known to frequently ingest plastic at sea, and since South Africa is a significant contributor to land-based plastic inputs (Jambeck et al., 2015; Ryan, 2020; Verster and Bouwman, 2020), the water off the South African coast is predicted to have high litter densities and therefore ingestion rates.

Temporal variation in the ingestion of plastic

The data analysed in this study indicated that the frequency of ingestion remained relatively stable over time. Although the proportion of birds that contained plastic showed no clear trend, there was a significant increase in the number of plastic items ingested over time. However, the opportunistic sampling method used in this study has led to fewer birds being examined as bycatch mitigation has improved (Rollinson et al., 2017). The average plastic load more than tripled from 1.86 ± 3.79 in 1979–85 to 6.81 ± 18.5 in 2017–23, but only 99 birds were examined in this period, two of which contained plastic loads of over 100 pieces (the first such loads recorded). Excluding these two birds reduced the average load to 4.63 ± 10.30, still the highest of the time periods and a significant increase over time. However, excluding these birds is not an accurate representation of the data, as they are observations representing the increasing threat posed by plastic pollution and they are therefore included in the analysis.

While there was an overall significant increase in the number of items ingested from 1979 to 2023, there were significant variations when the data was split into time periods. Between 2007–11 and 2012–16, there was a significant decrease in the average plastic load before increasing in 2017–23. The variable patterns observed emphasise the importance of examining extended timelines to discern overall trends beyond short-term variations. Lavers et al. (2018) reported a similar trend in the amount of ingested plastic in Wedge-tailed Shearwaters *Ardenna pacifica* on Lord Howe Island between 2005 and 2018, with fluctuating amounts ingested over time and a potential increase in 2017/18.

Fluctuations in plastic ingestion highlight the challenges associated with measuring this pollution type, as well as the limitations of using seabirds as monitors. The high spatial and temporal variation in plastic floating at sea affects the exposure of seabirds to floating plastics. In addition, factors including age, health, time of year and region, and year of collection can cause intraspecific variation (Ryan, 2016). In this study almost all of the birds were caught outside the breeding season (collected during winter months), indicating that their plastic load was not affected by offloading to chicks (Ryan, 1988; Ryan, 2015a). The sampling method used – collecting birds caught on long-lines – has less of an effect on plastic load than sampling birds found dead on beaches, where plastic may have contributed to their death (Ryan, 2016; GESAMP, 2019; Lavers et al., 2021). Additionally, the entire stomach contents of the bycaught birds were evaluated. This provides a more robust methodology compared to induced regurgitations or sampling of pellets, which may underestimate plastic load, or birds found dead on beaches, which may overestimate plastic loads (Ryan, 1987; Ryan et al., 2009; Lavers et al., 2021).

Although there was a significant increase in the plastic load by number, the weight did not show any significant change ($W = 7032.5$, $P = 0.46$). van Franeker and Law (2015) reported no change in the number of plastic items over time in Northern Fulmars, but a decrease in the amount of plastic by weight. The weight of plastic ingested, as opposed to the number of items is used as the Ecological Quality Objective (EcoQO) by OSPAR (2010), which – although only an arbitrary choice based on pollution levels in environments with low anthropogenic impact – states that no more than 10% of birds should have 0.1 g of plastic ingested. In this study, the frequency of birds containing > 0.1 g of ingested plastic increased from 5% in 1979–85 to 13% in 2017–23, which indicates an increasing risk over time. Examining the proportion of birds exceeding this threshold betters our understanding of the evolving risks associated with plastic ingestion in this species and can help to create and monitor future policy aims.

The characteristics of ingested plastic

It has been assumed, with few evidence-based reports (Ryan and Jackson, 1987), that plastic particles are retained in the stomachs of petrels for at least 3-6 months until they have been worn down sufficiently to pass through the narrow and angled pyloric sphincter (Ryan, 1988; Ainley et al., 1990; Ryan, 2015a). White-chinned Petrels particularly have been reported to retain plastic items < 1 mm in their stomachs (Ryan, 1987), although the smallest hard fragment recorded in this study was 1.22 mm long. Combined with their ability to cover distances up to 8000 km in 15 days (Berrow et al., 2000), and their tendency to travel throughout the area between South Africa and Antarctica in winter months (Rollison et al., 2018), this long retention time suggests that stomach contents may provide insight into the characteristics of plastic floating at a large regional spatial scale. The presence of a semiflexible plastic item (2.91 × 1.37 mm) in the intestines, longer than 8% of the rigid items measured in this study, calls into question the accuracy of reported retention rates, which suggests such items may not be able to pass through the narrowly angled pyloric sphincter. However, the width was smaller than 98% of rigid items found in the stomach contents, which, combined with its semi-flexible characteristics may have played a role in its passage into the intestines. A limited understanding of the retention time of plastics does to some extent affect the usefulness of White-chinned Petrels as indicators of floating plastics (Ryan, 2015a). However, their inability to regurgitate indigestible items – though also contested (van Franeker and Law, 2015; Terepocki et al., 2017) – along with documented long retention times of plastic (Ryan and Jackson, 1987), offers valuable insight into changes in the amount and characteristics of plastic ingested over time.

Understanding the polymer types of plastic ingested is necessary to evaluate potential health risks, because different plastic types contain distinct additives and differing leaching and adsorption properties (Lithner et al., 2011). In regard to the polymer composition of plastic ingested, most of the analysed plastics were made up of polyethylene (PE), polypropylene (PP) and polyblends (PP-EPDM). The exceptions were some polyamide (PA) fishing lines and the gastroliths reported in Appendix 2, which had high proportions of polyethylene terephthalate (PET). PE and PP make up over 50% of produced plastic resins globally by mass (Geyer, 2017). These oil-derived polymers are buoyant (0.88-0.96 $g \cdot cm^{-3}$), and items made from these polymers tend to dominate floating litter in convergence zones such as the Great Pacific garbage patch (Lebreton et al., 2018), leading to their interaction with surface-foraging seabirds. As is the case with other seabirds such as the trans-equatorial migrant the Great Shearwater *Ardenna gravis* (Robuck et al., 2022) and the Northern Fulmar (Kühn et al., 2021), PE was the most prevalent polymer for ingested hard fragments and pellets. This poses a risk to seabirds, because toxic plasticizers and flame retardants are added to long-life items – products designed to be used over extended periods such as household goods and electronics – during manufacture, making up 7% of their mass (Geyer et al., 2017). In addition, persistent organic pollutants (POPs) floating at sea tend to sorb onto plastics (Colabuono et al., 2010). PE has a greater sorption for POPs floating in the ocean than other types of plastic (Teuten et al., 2009). The high prevalence of ingested PE may therefore influence the degree to which seabirds are exposed to POPs.

The size of plastic items also plays a role in toxic exposure. As plastics gradually fragment into smaller pieces from UV radiation or mechanical breakdown (Andrady, 2011), the surface area increases (Ryan, 2015b). With smaller fragments containing higher surface area ratios, they may contain a higher concentration of POPs adsorbed from the water, posing a greater risk by releasing these chemicals into the wider range of organisms that consume them (Barnes et al., 2009; Teuten et al., 2009). Between 2007–2023, hard fragments significantly decreased in length. While this has been documented in other long-term studies (van Franeker and Law, 2015), suggesting that the size of plastics in the ocean is getting smaller over time, when compared to data from Ryan (1987), hard fragments have shown no change in size.

Previous studies have reported that the resemblance of plastic items to prey species may influence the frequency of ingestion of a specific colour, or that seabirds ingest lighter coloured items due to contrast with darker water (Ryan, 1987; Lavers et al., 2014; Lavers and Bond, 2016; Phillips and Waluda, 2020). However, in this study White-chinned Petrels exhibited an avoidance of clear/white items. The incidence of ingestion of clear/white items is much lower than expected by chance, considering the high frequency of clear floating items found at sea (71%). Of items found floating at sea, 1% were orange/brown and 8% of items were black. Ingested plastics were 23% orange/brown and 13% black, suggesting a selection of darker-coloured conspicuous items.

White-chinned Petrels exhibit opportunistic scavenging behaviour, a trait that leads to a high frequency of ingestion (Ryan, 2016). Because of their well-documented ship-following behaviour (Griffiths, 1982), White-chinned Petrels are especially vulnerable to plastic debris discarded by vessels. Fluctuations in fishing efforts and practices may therefore affect the amount and types of plastic ingested. The proportion of birds with ingested fibres, either individual or in a ball, have fluctuated across time periods, but a similar proportion of birds from 1979–85 (30%) to 2017–23 (38%) was found. A proportion of the fibres found in this study were made of PA (15%), a polymer commonly used in fishing lines. An increasing trend was found for flexible fragments, mostly bag fragments, commonly found submerged in the water column (Ryan, 2014). This suggests that they may have been consumed shortly after being discarded from vessels. A high frequency of ingestion of these items may pose a risk as fibres and bag fragments may form compact balls in the stomach (see Appendix 2). Softer items are also resistant to peristalsis and may obstruct the gut (Roman et al., 2019).

While mitigation measures have not reduced overall plastic emissions into the environment, there has been a decrease in the proportion of birds ingesting industrial pellets, similar to other reports in seabirds (Vliestra and Parga, 2002; Law et al., 2010; van Franeker et al., 2011; Lavers et al., 2018; Robuck et al., 2022) and particularly White-chinned Petrels (Ryan, 2008; Petry and Benemann, 2017). A decreasing trend was detected in the frequency of occurrence of birds with ingested pellets over the study period. There is, however, fluctuation over time, with a similar proportion of birds with pellets in 2007–11 (22%) and 1979–85 (25%), which was prior to the launch of Operation Clean Sweep in the early 1990s. Despite these fluctuations, it seems that the frequency of ingestion has stabilised to around 14% in the last decade. This could be due to their slow degradation, especially when ingested, where they have been found to only lose 1.1% of their mass after 12 days (Ryan and Jackson, 1987), or it could be due to continued contamination.

The number of ingested pellets does not show the same downward trend due to two birds found in 2022 and 2023 with high pellet loads. The high intensity of ingestion can be seen in both the number of pellets ingested (Table 1) and the proportion of pellets to total plastic (by mass) ingested compared in 1979–85 (44%) and 2017–23 (45%: Fig. 6) This is likely the consequence of two pellet spills: In Durban in 2017, a storm blew at least two containers of approximately 49 tonnes of industrial pellets into Durban harbour, spreading a plume of pellets over 2000 km along the South African coast in 8 weeks (Schumann et al., 2019). A less well-known spill occurred in 2020 off the southern Cape coast near Plettenberg Bay. The two birds with high pellet loads in 2022 (48) and 2023 (22) may illustrate the widespread effects of the release of industrial pellets.

Reasons for varying trends in the literature

The estimates of increasing plastic emissions into marine systems are not commonly observed in studies on floating and ingested plastic. Various factors may account for this mismatch. First, due to the tendency of plastic to disperse long distances via currents, wind, and weather patterns, it is suggested that increases in plastic production will lead to a global increase in the concentration of floating plastics (Thompson et al., 2009). However, there may be other factors that play a role in regional pollution levels, limiting our ability to come to a global consensus. Factors affecting emissions, such as waste management strategies, poverty levels, and policy implementation, may significantly affect regional pollution levels. Willis et al. (2020) reported a decrease in litter strandings from 2013–2019 on Australian coastlines following the implementation of improved waste management in surrounding areas. Although a large proportion of litter off the coast of Australia originates from Indonesia (Galaiduk et al., 2020), the decrease in local emissions of plastic may contribute to the stable plastic loads reported in one of the few long-term studies of ingestion found in shearwaters off the coast of Australia (Lavers et al., 2021). Another long-term study reported that over three decades there was no change in microplastics in species of plankton and planktivorous fish (Beer et al., 2018). However, the main plastic items ingested were textile fibres, potentially originating from laundry outputs from the community surrounding the Baltic Sea, which has remained unchanged in population level over the last three decades.

Other reasons for this mismatch between estimates and observations may be an overestimation of emission (Ryan et al., 2020) or the removal of marine debris from the sea surface at a similar rate to which it enters. This removal from the sea surface could be due to biota consuming it, sinking due to biofouling or lack of buoyancy, coastal deposition, or fragmentation into particles too small to sample (Wilcox et al., 2020). Reporting trends in quantities of plastic, either floating or ingested by biota, should not be done on short time scales. These reports may be misleading, as there are many variables, some potentially unknown, that could be affecting the fluctuations in plastic ingestion.

Due to their frequent plastic ingestion, long retention time, and the accessibility of carcasses, long-term data from White-chinned Petrels offers valuable insight into trends in plastic pollution in the Southern Ocean. Comparing data from 1979–85 to a more recent time series allows us to see past the inherent short-term variability in plastic ingestion and detect an increasing trend in the amount of plastic ingested. The increasing intensity of ingestion, high frequency of occurrence, and two recent occurrences of plastic loads of over 100 pieces and weighing 0.98 and 2.69 g each, 10-25 times higher than the ecological quality indicators set in the North, provide evidence that the coastal waters around South Africa are suffering from severe plastic pollution. Implementing new mitigation efforts and monitoring these efforts using the ingestion rates in the White-chinned Petrel should be a part of a holistic approach to managing the plastic pollution crisis.

Conclusions

This study highlights the usefulness and challenges of using petrels as monitors of marine plastics, as well as the importance of long-term datasets in determining overall trends. Assessing the carcasses of bycaught birds, although it may introduce a bias towards individuals with fishery-related items ingested, allows for a complete analysis of their stomach contents. In contrast, inducing regurgitation or examining regurgitated pellets only allows for a partial examination. The approach used in this study offers valuable insight into the occurrence and types of plastic floating in the open ocean. A key finding in this study was the significant increase in plastic load per bird, with more than a threefold increase in the average number of items ingested from 1979–85 to 2017–23. The recent increase in plastic ingestion in White-chinned Petrels combined with the stable but high frequency of occurrence of ingestion is a cause for concern and should be further explored with more samples collected from the last few years. Similar to other studies, these results show a long-term reduction in the frequency of occurrence of industrial pellets ingested, showing that in some cases, industry initiatives can be successful in reducing industrial plastic at sea. However, there are still instances of birds containing large numbers of pellets, showing that catastrophic losses at sea may be a large contributor that must be addressed. Although there have been successful efforts in other parts of the world to reduce the amount of plastic in the sea, the exposure of marine biota in the Southern Ocean is almost certainly increasing. In the absence of adopting new policies and practices, increasing amounts of plastic in the marine environment and biota seems inevitable. While implementing policy aims to reduce the amount of plastic in the Southern Ocean is the first step, this dataset and the continued use of White-chinned Petrels as an indicator species offers a useful tool for monitoring changes in floating marine plastic.

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Appendix 1. Model selection

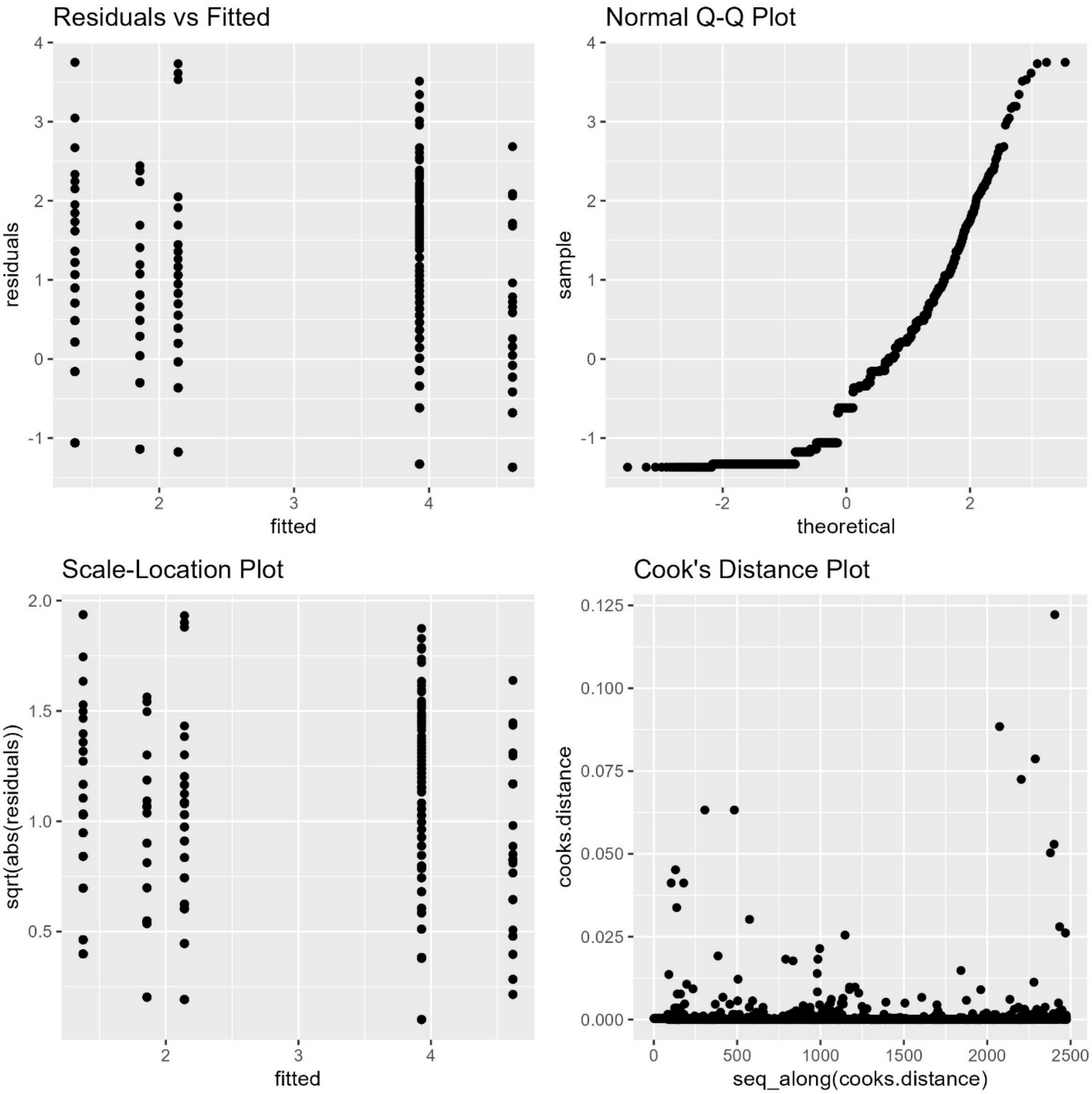
To examine the changes in the number of plastic items ingested I used a regression model to interpret the data. To determine the most appropriate model, I used a model selection process by fitting various generalized linear models to the data – followed by assessing the residual plots and using an Akaike's Information Criterion (AIC) as a model selection tool.

First, I fit a Poisson model due to the observed Poisson distribution of the data. However, the model output showed a mean lesser than the variance, indicating overdispersion of the data and thus violating model assumptions. Furthermore, Poisson model's residuals plots indicate a number of influential observations that fall outside the cook's distance (Fig. A1-1). Due to the overdispersion of the data, the Poisson model would be inappropriate, therefore I subsequently fit both a negative binomial regression model and a Generalized Additive Model (GAM) and compared these models using the respective AIC values.

The negative binomial model has by far the smallest AIC value, and moreover holds the entire Akaike's weight (ω_i) (Table A1-1). Therefore, there is strong evidence to suggest that the negative binomial model is comparatively the most appropriate model for the data.

Table A1-1. Model selection table for generalized linear models for the changes in the number of plastic items ingested across time. The models compared here are (1) Poisson model, (2) Negative Binomial model, and (3) Generalized Additive Model (GAM). The table indicates the difference in the Akaike's Information Criterion values (ΔAIC), as well as the Akaike's Weights (ω_i) and Deviance Explained (%).

Model	ΔAIC	ω_i	Deviance Explained (%)
(1) Poisson	13332	0.00	7.4
(2) Negative Binomial	0	1.00	6.7
(3) GAM	7322	0.00	6.3


Residuals vs Fitted

Normal Q-Q Plot

Scale-Location Plot

Cook's Distance Plot

Figure A10. Residual plots for Poisson regression model for the changes in the number of plastic items ingested across time.

Appendix 2. Fibrous gastroliths in the stomachs of White-chinned Petrels

Abstract

Compact balls of fibre, bag fragments, and organic material such as squid beaks found in the stomachs of White-chinned Petrels *Procellaria aequinoctialis* have not been well described in the literature. The characteristics of 10 of the largest gastroliths were explored, including their size, weight, contents, and the polymer composition of plastic items. Each of the 10 fibrous gastroliths dissected contained plastic, ranging from 0.179 to 1.422 g total. Polyamide and Polyethylene Terephthalate (PET), a polymer not found ingested in Chapter 1, composed 35% of the total mass of the 10 fibrous gastroliths collectively.

Introduction

The formation of indigestible items into compact masses has been identified across many species of birds. For example, albatross regurgitate indigestible prey remains, such as squid beaks, in a bolus (Perold et al., 2020). Other birds such as owls, skuas, gulls, and terns regurgitate pellets made of bones and other indigestible material (Perold et al., 2020; Yorio et al., 2020; Nessi et al., 2022; Carrillo et al., 2023). As plastic debris has become more prevalent in the environment, some of these regurgitated loads, especially in seabirds or birds that eat seabirds, have been found to contain plastic items (Ryan, 2008; Hyrenbach et al., 2017; Perold et al., 2020; Nessi et al., 2022). Occasionally ingested plastic and other anthropogenic items form compact ball-like structures in the stomachs of terrestrial and marine species. Parslow and Jefferies (1972) reported the formation of tightly knotted balls of elastic band threads in the gizzard of Atlantic Puffins *Fratercula arctica*, around 10 mm in diameter. Wernery et al. (2021) reported gastroliths composed of rope, plastic bags, and other litter in the stomachs of camels. The compaction of these plastic items can cause blockages in the digestive tract, the leaching of toxic chemicals into the blood stream, and starvation due to reduced stomach volume and false satiation (Parslow and Jefferies, 1972; Mrosovsky et al., 2009; Wernery et al., 2021). This appendix describes fibrous gastroliths in the stomachs of White-chinned Petrels, which were first found in 1979 when Ryan (1987) reported a high incidence of ingested fibres (30%), many being in the form of gastroliths.

Methods

The collection methods and protocol for fibrous gastroliths were conducted as per the methods section in the main report. A total of 99 fibrous gastroliths were found in the stomachs of the 1689 White-chinned Petrels analysed between 2007–23. Each was weighed with an electronic balance to the nearest 0.1 mg, and length and width were measured to the nearest 0.1 mm with electronic calipers. Fibrous gastroliths were placed in a jar filled with filtered water to assess buoyancy. For the exploratory purpose of this study, I selected the 10 largest fibrous gastroliths by mass, which constitutes three-quarters of the available sample mass. Each of the selected fibrous gastroliths was photographed using a Nikon SMZ1500 stereo microscope with NIS-Element imaging software before and after being teased apart. The fibrous gastroliths were soaked in a mixture of 70% ethanol and filtered water for two days to soften and be pulled apart for further inspection. The fibrous gastroliths were rinsed with filtered water and teased apart to remove organic debris. They were then dried at 30° C for 48 hours. Each fibrous gastrolith was re-weighed to record the mass without organic debris. The length of individual fibres that could be pulled apart were measured and the average and median fibre lengths were recorded for each fibrous gastrolith. Fourier-Transform Infrared Spectroscopy was used to identify the polymer composition and other anthropogenic material of fibres composing the 10 largest fibrous gastroliths (see main report for methods).

Data Analysis

The mass of 48 fibrous gastroliths found in the stomachs of White-chinned Petrels shot off the coast of South Africa for diet studies in the 1980s (Ryan, 1987; Jackson, 1988) were compared to the mass of fibrous gastroliths from 2007-23 to assess whether the size has changed since 1979. A Kruskal-Wallis with a post-hoc Dunns test was used to detect significant changes. The proportions of organic material and polymer types constituting the overall mass of the 10 fibrous gastroliths was calculated.

Results and Discussion

Fibrous gastroliths were found in 13% of the 1689 White-chinned Petrels caught on long-line fishing boats off the coast of South Africa and used for this study between 2007–2023, compared to 22% of the 189 birds sampled from 1979–85. The mass of fibrous gastroliths from 1979–23 ranged from 0.002 to 2.423 g, with a median mass of 0.0473 g, and an average of 0.1753 g. The mass fluctuated over time, but the mass of fibrous gastroliths were significantly less in 1979–85 than 2007–23 (Fig. A2-1: $\chi^2 = 7.42$, df = 1, $P < 0.01$).

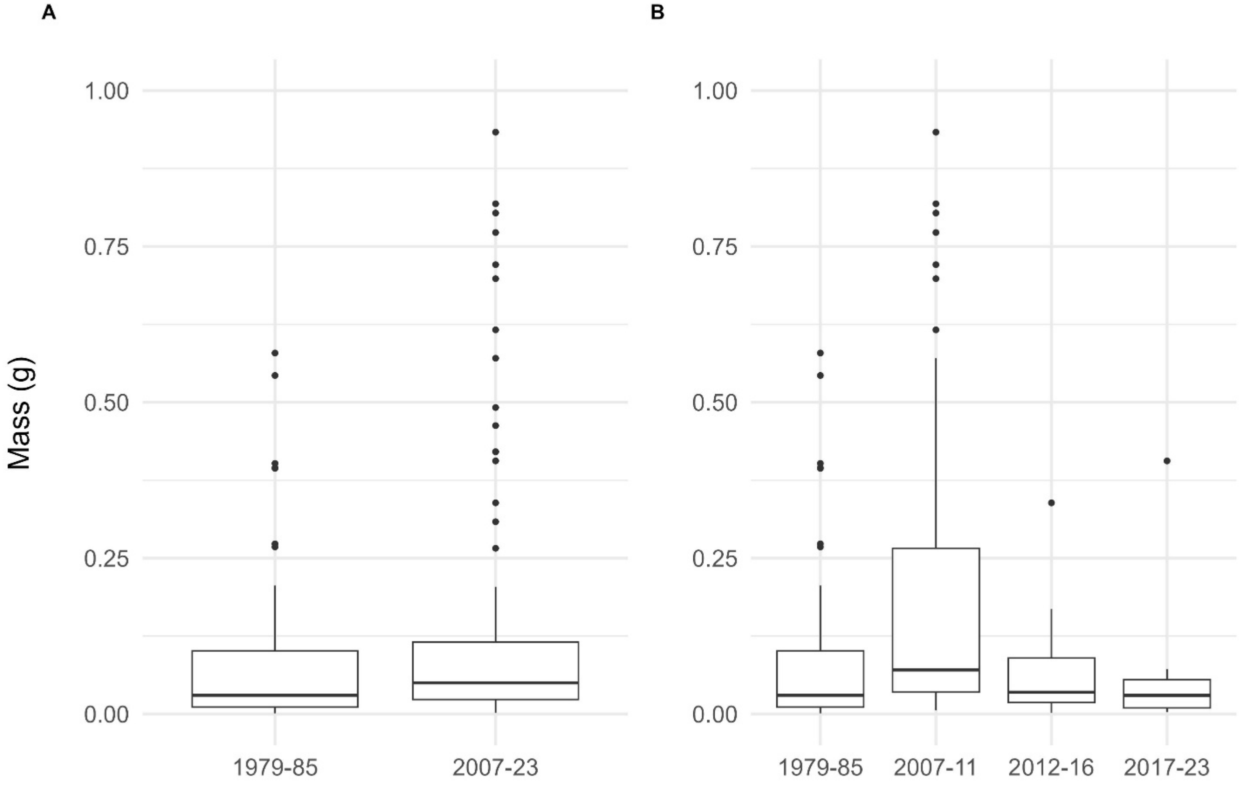


Figure A2-1. The mass of fibrous gastroliths found in White-chinned Petrels compared between 1979-85 and 2007-23 (A) and across time periods used in Chapter 1 (1979-85, 2007-11, 2012-16, and 2017-23; B)

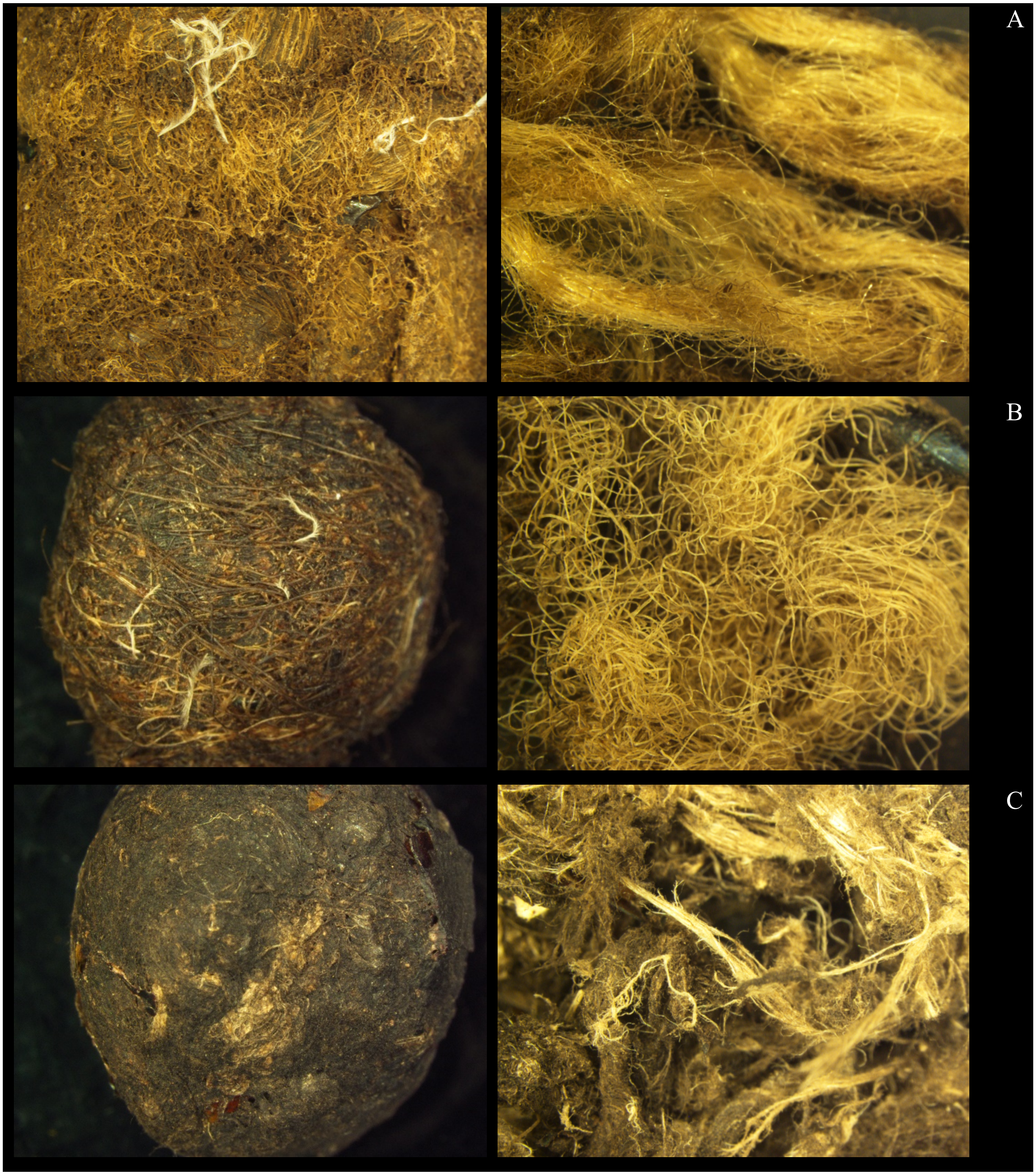
Of the total mass of the 10 fibrous gastroliths dissected, 52% was organic material. Squid beaks were present in every fibrous gastrolith, with two containing more than 20 squid beaks each. Each of the 10 fibrous gastroliths contained plastic, ranging from 0.179 to 1.422 g (Table A2-1). A proportion of 2% (by mass) of the fibres could not be identified with a spectral match > 70% and were therefore categorized as unknown. Polyamide – mostly in the form of thin fibres that have been woven together to make a rope (Fig. A2-2: A & J) or fragments of thicker fishing lines (Fig. A2-2: F & I) – constituted the greatest proportion of plastics out of the total mass (Table A2-2). Polyethylene terephthalate (PET) was found in five of the fibrous gastroliths either as thin fibres also used to make rope (Fig. A2-2: F, G & H) or in the form of fibres resembling the stuffing of pillows or dolls (Fig. A2-2: D & E). Polyamide and PET have higher densities than sea-water and do not float in sea water. This suggests that they are consumed shortly after being discarded into the water prior to sinking, potentially from vessels, which White-chinned Petrels often scavenge behind (Griffiths, 1982). They could also be secondarily ingested from prey that consume the fibres deeper in the water column, or possibly the fibres stay in the water column at a depth still accessible to foraging White-chinned Petrels, which can dive up to 16 m (Rollison et al., 2014). Polyblend, a mix of both PE and PP, made up 7% of the mass and was found in two fibrous gastroliths (Table A2-2). Six of the 10 fibrous gastroliths contained more than one plastic type, with an average of 2.1 ± 1.3 types of plastic per fibrous gastrolith. One of the fibrous gastroliths contained five different types of plastic: polypropylene (PP), low and high density polyethylene (LD & HD PE), polyblend, and PET (Fig. A2-2: D). All of the fibrous gastroliths were buoyant when placed in a jar of water, meaning that they would also be buoyant in denser sea-water. However, after the fire balls were cut into and water was able to penetrate through the material, most of the contents lost their buoyancy.

Table A2-1. The weights, measurements, and total plastic found in the 10 largest fibrous gastroliths found in the stomachs of White-chinned Petrels caught on long-line fishing gear off the coast of South Africa from 2007-23.

Sample	Total dry mass (g)	Total Plastic (g)	Buoyant (Y/N)	Length (mm)	Width (mm)	Depth (mm)	Avg. fibre length (mm)	Median fibre length(mm)
A	2.095	1.117	Y	19.50	19.13	17.78	55.9 ± 10.4	55.0
B	0.616	0.304	Y	13.29	10.66	10.35	19.0 ± 5.2	17.5
C	0.804	0.413	Y	14.20	11.85	11.13	26.7 ± 5.4	26
D	0.721	0.234	Y	11.72	11.59	10.19	28.3 ± 16.5	22.8
E	0.571	0.179	Y	13.64	11.29	10.54	28.3 ± 2.7	28.0
F	1.776	0.765	Y	18.11	16.16	13.93	37.4 ± 24.2	27.0
G	0.698	0.269	Y	16.22	14.39	11.06	52.5 ± 29.3	45.5
H	0.772	0.296	Y	13.09	12.26	11.75	97.8 ± 39.2	104
I	0.819	0.187	Y	17.72	11.96	8.45	36.6 ± 31.0	29.0
J	2.423	1.422	Y	17.72	17.45	14.54	92.2 ± 66.3	94

Table A2-2. The total mass, proportion, and incidence of the materials making up the 10 largest fibrous gastroliths found in the stomachs of White-chinned Petrels caught on longline fishing gear off the coast of South Africa from 2007-23.

Material	Total Mass (g)	Proportion of Total Mass (%)	Proportion of Polymers (%)	Incidence n=10
Organic Material	5.996	52	-	100%
Polyamide	3.276	29	63	40%
Polyethylene terephthalate	0.668	6	13	50%
Polyblend	0.798	7	15	50%
Polypropylene	0.317	3	6	20%
Polyethylene	0.127	1	3	40%
Unknown	0.299	2	-	20%


A
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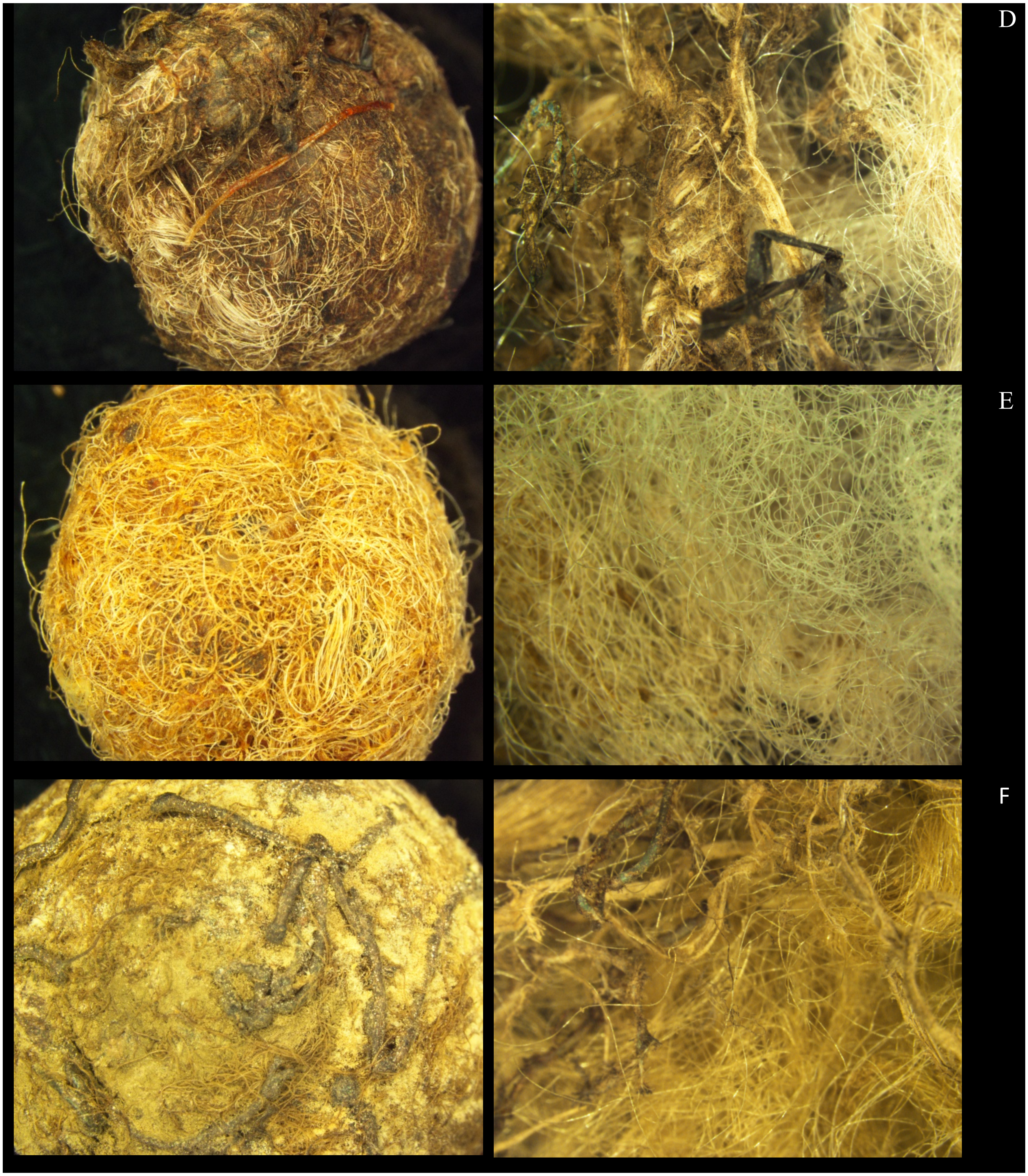
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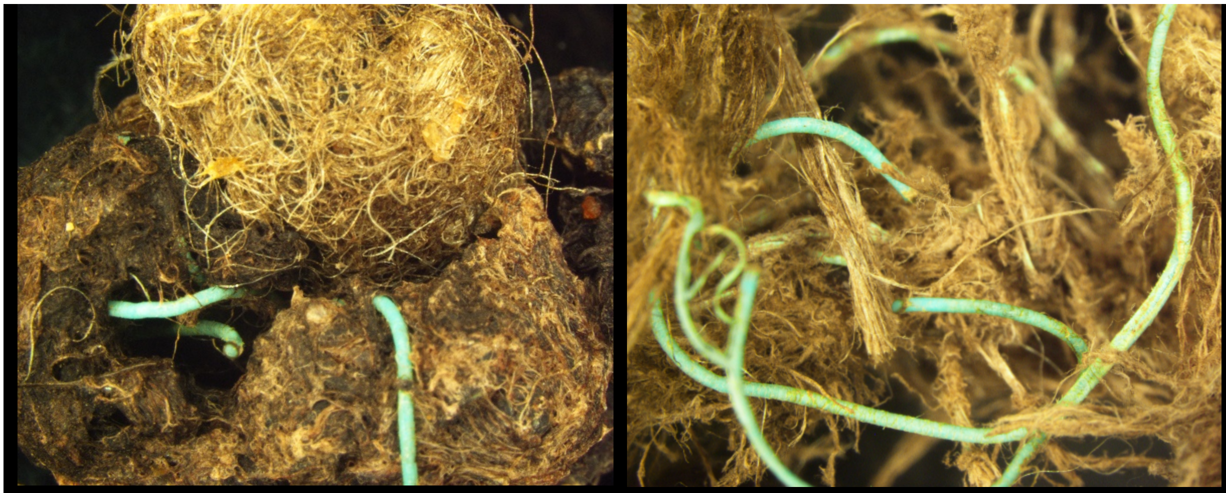
F



G

H

I

Figure A2-2. Images of the top ten largest (by mass) fibrous gastroliths found in the stomachs of White-chinned Petrels caught on long-line fishing boats off South Africa. Images were taken before (left) and after (right) soaking and dissecting them for further inspection.

While almost of the fibrous gastroliths could be visually identified as being made of mostly fibres, some had large amounts of bag fragments present. Two in particular (Fig. A2-3) were mostly composed of bag fragments and weighed 0.108 and 0.933 g each. Bag fragments were not analysed using FT-IR spectroscopy but appear to be fragments from black refuse bags dumped off vessels. Some of the fibrous gastroliths contained portions of ropes while others appeared to be fibres of ropes already pulled apart by mechanical abrasion within the gizzard. These observations lead me to believe that the high frequency of fibrous gastroliths found within White-chinned Petrels, and not in other seabirds, may be due to their behaviour of scavenging from vessels, making them susceptible to the ingestion of discarded items (Griffiths, 1982). The source of the stuffing-like PET fibres found in some of the fibrous gastroliths should be further investigated.

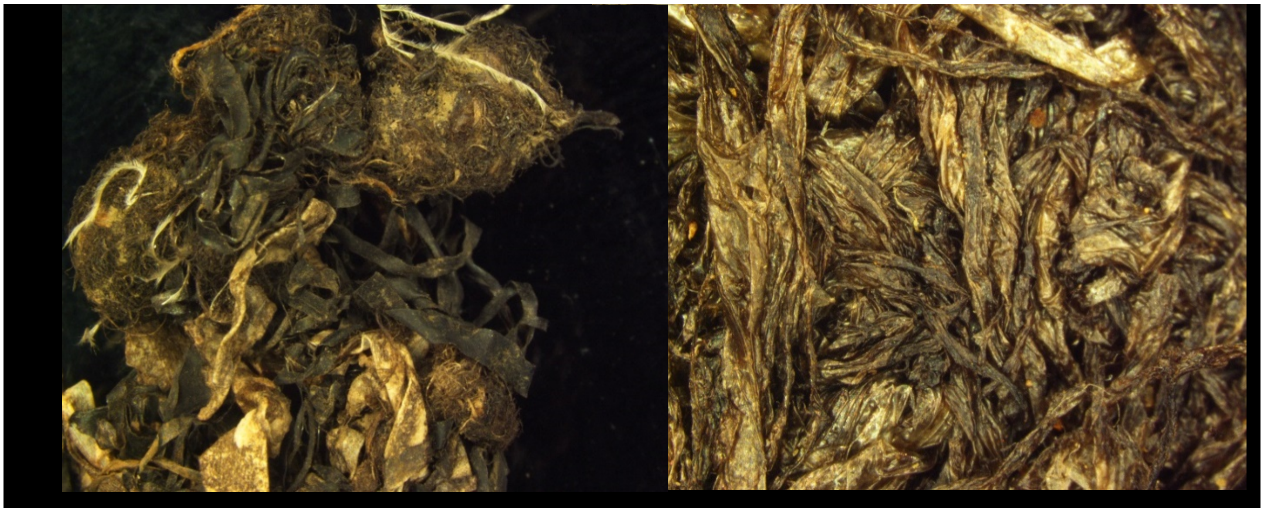


Figure A2-3. Two fibrous gastroliths found in the stomachs of White-chinned Petrels off the coast of South Africa with large amounts of bag fragments, compared to the previously documented fibrous gastroliths which mostly contain fibres and organic material.

The large amounts of plastic found in fibrous gastroliths may pose a risk to the health of White-chinned Petrels. Reduced stomach volume, false satiation, blockages, and exposure to toxic chemicals are risks that come with the ingestion of plastic (Ryan, 2016; Yamashita et al., 2021). The formation of this debris into fibrous gastroliths, which were found to weigh up to almost 2.5 g and up to 19.5 mm wide may occupy substantial gizzard volume. Whereas the average length of hard fragments described in the main report varied between 4.7–5.9 mm across time periods, and averaged < 2 mm in depth, spherical fibrous gastroliths could pose a much greater threat in terms of reduced gizzard volume than other types of plastic. Further investigation into these novel threats, as well as the changes in their composition over time, could provide additional information into changes in fibres floating at sea. Improved waste management practices on vessels may help to decrease the occurrence of fibrous gastroliths forming in the stomachs of White-chinned Petrels.

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