Marine Pollution Bulletin 192 (2023) 115038

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Short-tailed shearwater (*Ardenna tenuirostris*) plastic loads and particle dimensions exhibit spatiotemporal similarity in the Pacific Ocean

Gary W. Shugart[a,*], Cheyenne L. Waters[b], John D. FitzPatrick[b], Robert S.A. Kaler[c], Lucy S. Vlietstra[b]

[a] *Slater Museum of Natural History, University of Puget Sound, Tacoma, WA, United States of America*
[b] *Department of Marine Science, U.S. Coast Guard Academy, New London, CT, United States of America*
[c] *U.S. Fish and Wildlife Service, Anchorage, AK, United States of America*

A R T I C L E I N F O

Keywords:
Pacific Ocean
Seabird
Ardenna tenuirostris
Plastic

A B S T R A C T

Short-tailed shearwater (*Ardenna tenuirostris*) stomach contents provide some of the earliest documentation of oceanic plastic pollution, one of the longer data series of seabird stomach samples, and the species' wide range in the North and South Pacific provides comparative data for the Pacific Ocean. A mortality event in the North Pacific in 2019 provided additional data for spatiotemporal comparisons. In the North Pacific the percent occurrence, mass, and number of pieces were similar since the first records in the 1970s. Particle size increased slightly reflecting a transition from uniform pre-manufactured pellets in initial reports to irregular user fragments in recent reports. Contemporary North and South Pacific plastic loads and particle dimensions were similar. A lack of temporal or spatial difference affirms previous conclusions that plastic retained in short-tailed shearwaters and other Procellariiformes is related to body size, gastrointestinal structure, and species' preferences rather than the availability of oceanic plastic.

1. Introduction

Marine plastic pollution is a pressing environmental issue (Wilcox et al., 2015, 2020) with large plastic debris and small plastic particles spreading throughout oceans including deep-sea sediments and Arctic sea ice (Cózar et al., 2017; Collard et al., 2021; Bergmann et al., 2022). While plastic input into the ocean is increasing, particles fragment with age and environmental exposure leading to an increase in the relative number of small particles, which eventually sink (Shaw and Day, 1994; Morét-Ferguson et al., 2010; Law et al., 2014; Eriksen et al., 2014; Cózar et al., 2017; Wang et al., 2020; Wilcox et al., 2020; Pabortsava and Lampitt, 2020; Miyazono et al., 2021).

Faunal impacts of ingested and retained plastic may be physical and physiological and are assessed using quantifications such as percent of stomachs with plastic, plastic loads based on average mass and the number of pieces, type of plastic, and color (reviewed in Puskic et al., 2020; Savoca et al., 2022). Procellariiform seabirds are focal species in many assessments having gastrointestinal tract (GIT) structure that retains some ingested plastic (Furness, 1985; Terepocki et al., 2017; Roman et al., 2019a). Plastic is usually found in the caudal portion of the stomach, the ventriculus, while the cranial portion received ingested plastic that passes into the ventriculus or is regurgitated. The ventriculus does the mechanical grinding of food while the proventriculus has storage and digestive functions.

Initially, premanufactured pellets (PMPs) predominated plastic samples removed from shearwater GITs and afforded some consistency to consideration of passage through GITs versus what was retained (Day, 1980; Furness, 1985; Skira, 1986; Ogi, 1990). However, as the amount of plastic in the marine environment has increased over time, aged and fragmented into progressively smaller pieces, and spread throughout oceans, the range of particle size has increased along with the number of particles available (Wilcox et al., 2020; Miyazono et al., 2021). This necessitates quantification of particle dimension in seabird diets to assess associated risk to this group, gauge what plastic is retained relative to passage through constrictions in gastrointestinal tracts (Furness, 1985; Roman et al., 2019a), and determine if stomach-based sampling could track changes in the dynamic oceanic plastic mass.

The size of plastic particles relative to body size has been established for some seabird species (Furness, 1985; Ryan, 1987; Roman et al., 2019a, 2019b). Roman et al. (2019a) extended body size correlations

* Corresponding author.
E-mail address: gshugart@pugetsound.edu (G.W. Shugart).

https://doi.org/10.1016/j.marpolbul.2023.115038
Received 22 February 2023; Received in revised form 2 May 2023; Accepted 5 May 2023
Available online 17 May 2023

and established that retention of rigid anthropogenic material, mostly hard plastic, in Procellariiformes was correlated with head or gape size and structure of GITs, especially the constriction at the proventricular-ventricular junction. Plastic retained in GITs and the resulting sample used for quantification, therefore, appears to be determined by the physical characteristics of species' GITs along with species' preferences for color, size, and shape perhaps related to similarity to food (Day, 1980; Furness, 1985; Ryan, 1987; Ogi, 1990; Roman et al., 2019a, 2019b).

In this paper, we investigate the size of plastic loads and the range of plastic particle sizes in GITs of the short-tailed shearwater (*Ardenna tenuirostris*). Short-tailed shearwaters range throughout the Pacific Ocean breeding in Australia beginning at the end of September until April when they begin a circum-Pacific migration and spend the boreal summer in the North Pacific and Bering Sea (Ogi, 1990; Carey et al., 2014). Studies of this species provide some of the earliest documentation of oceanic plastic pollution (Day, 1980; Ogi, 1990), provides one of the longer data series of seabird stomach samples (see Table 1 in Puskic et al., 2020), and the wide range in the North and South Pacific provide comparative data for the Pacific Ocean.

2. Methods

In August 2019, 42 short-tailed shearwater carcasses were salvaged from the beach of Sarichef Island, Alaska (66° 14′ 41″ N, 166 ° 6′ 25″ W), a 6 km^2 barrier island located on the Chukchi Sea coast, 11 km off the Seward Peninsula (Fig. 1). Three additional carcasses were collected from Point Hope, AK (68° 20′ 49″ N, 166° 45′ 47″ W; USFWS Permit #MB025076-1). Point Hope is located approximately 750 km north of Sarichef Island and is situated on the northwestern end of the Lisburne Peninsula, also on the Chukchi Sea coast, just above the Arctic Circle.

Collections took place during a mass seabird mortality event, affecting thousands of short-tailed shearwaters and other seabirds in the region, including horned puffins (*Fratercula corniculata*), black-legged kittiwakes (*Rissa tridactyla*), and murres (*Uria* spp.; U.S. Fish and Wildlife Service, 2019). High seabird mortality rates were observed yearly over the preceding four years. The die-off has been linked to climate-related shifts in regional prey distributions caused by high sea surface temperatures (marine heat waves) in the greater Bering and Chukchi Seas and elsewhere in the North Pacific Ocean (Jones et al., 2018; Piatt et al., 2020; Kaler et al., 2022). Short-tailed shearwaters are not typically abundant in waters north of Bering Strait (Jones et al., 2018; Piatt et al., 2020).

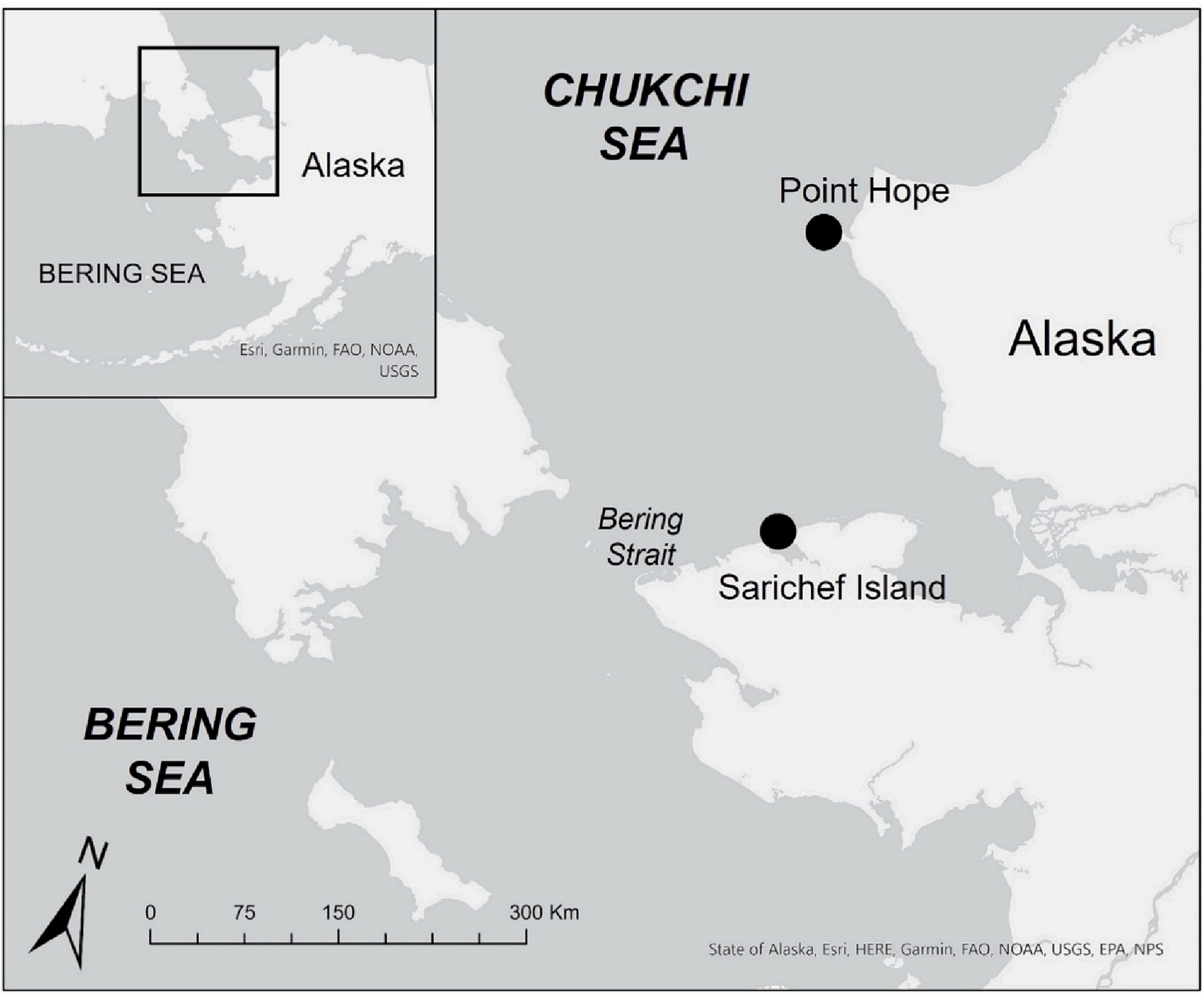

Fig. 1. Short-tailed shearwater collection sites (dark circles) in the Chukchi Sea, August 2019.

Although the 42 carcasses appeared to be intact upon collection, only 31 had intact GITs including the proventriculus, ventriculus (gizzard), and intestine. All except one of these birds were collected on Sarichef Island (Fig. 1). Carcasses were frozen and sent to the Slater Museum of Natural History at the University of Puget Sound, Tacoma, WA, for processing. There, carcasses were thawed, sand was removed from feathers with forced air while drying, and then weighed. Birds were dissected, and features of the bursa of Fabricius (Glick, 1983; Broughton, 1994), gonad inspection, and molt patterns of the primary feathers were used to determine the age class of each bird (juvenile, sub-adult/adult, adult) (see Van Franeker, 2004; Shugart and Nania, 2021). Short-tailed shearwaters appear to follow a simple basic molt strategy similar to sooty shearwaters (*A. grisea*) (Cooper et al., 1991; Shugart and Nania, 2021). Juveniles, approximately four months old, had no primary molt, unworn body feathers, and a large glandular-walled bursa of Fabricius. The sub-adult/adult category included birds with a bursa of Fabricius without glandular walls, primary molt, and a mix of worn body feathers. Adults were similar but with a diminutive thin-walled or no bursa. Body condition was evaluated following illustrations in Van Franeker's (2004, Fig. 11) index for Northern Fulmars (*Fulmarus glacialis*). The index is based on the amount of subcutaneous fat (on abdominal tracts), intestinal fat, and pectoral fullness scored 0–3 with 3 being the highest. The three scores are summed for a body condition index.

We followed standard protocol (van Franeker, 2004) for the collection of plastic from stomachs with an additional step of keeping the proventricular and ventricular plastic samples separate (see Supplementary Fig. 1). In addition, intestines were removed, stretched to full length in a trough, cut opened length-wise, and flattened, then contents were flushed into a containment vessel, then contents were processed using the standard protocol. We used a digital balance to determine the weight (mg) of each plastic particle to the nearest 0.1 mg. Digital calipers were used to measure to the nearest 0.1 mm the greatest dimension (length), the second greatest dimension (width) approximately perpendicular to the length, and the third dimension (thickness) approximately perpendicular to the plane of length and width (see Fig. 1 in Roman et al., 2019a). For this study, volume was also determined using the American Society for Testing and Materials (ASTM) D792 protocol (Mettler-Toledo, 2022). Particles were weighed dry and then again in EtOH to determine density. Density was then used to calculate volume using standard formulae (Mettler-Toledo, 2022).

Particle color was quantified following Ogi (1990) using dry particles. We reduced categories to eight because the shade (e.g., light, medium, dark) differs if particles are wet (Ogi, 1990) or dry, and status was not usually reported (Provencher et al., 2017). We also examined particles under a stereomicroscope and recorded the type as PMPs (spherical or cylindrical plastic beads), user plastic (fragments of molded consumer products), foam, film, or filament (monofilament fishing line or plastic fibers). If a particle was questionably plastic, the particle was touched with a hot needle while viewed under a stereoscope after all quantification was done to see if there was melting at the spot that was touched. Six spherical particles were tested and classified as seeds. Non-plastic material was categorized and quantified.

A comparison of the time particles spend in ventriculi could provide some evidence for the reduction of particles through wear or fragmentation (Nania and Shugart, 2021). Juveniles have a time limit for accumulation and wear and fragmentation of plastic of about six months compared to 12+ months for non-juveniles. We assume juveniles received some plastic from parental feeding during the pre-fledging period in March and April, fledged in April, and migrated to the North Pacific where they died in August. Predictions are that if wear and fragmentation were significant relative to the time in ventriculi, the non-juveniles would have relatively smaller and harder particles than juveniles (see Nania and Shugart, 2021).

Voucher specimens that document plumage-based aging along with GIT contents are archived at the Slater Museum of Natural History, University of Puget Sound, Tacoma, Washington (see Supplementary Fig. 2).

2.1. Data analysis

We used R-Studio Version 1.4.1103© 2009–2021. The mean mass and number of particles typically are right skewed and not normally distributed. Normality was tested in R by plotting residuals (ggpubr) and the Wilks-Shapiro test. Transformed data (see Van Franeker and Meijboom, 2002) failed to normalize residuals in most cases so we opted for non-parametric methods. For Mann-Whitney in R, results are reported as Mann-Whitney-Wilcoxon. With right-skewed data, median and quartiles are more appropriate, but we provide means and standard errors for comparison to literature values that lack the median and quartiles.

3. Results

Of 31 GITs examined, 29 (93.5 %) contained 227 plastic particles totaling 5318.0 mg. Most were in ventriculi (203 particles, 89.5 %; 3746.4 mg, 70.4 %,) with the remainder in proventriculi (19 particles, 1470.8 mg) and intestines (five particles, 100.8 mg) (Table 1 and Supplementary Table 1). Table 2 summarizes data comparable to previous studies that pooled proventricular and ventricular loads, did not include intestinal plastic, and included zero values (see Day, 1980; Ogi, 1990; Vlietstra and Parga, 2002). The average volume of plastic for 29 samples with plastic was 143 ± 28 mm^3 (mean ± SE, range 4–640 mm^3, median 98 mm^3).

User plastic accounted for 81 % of particles (179/222) in proventriculi and ventriculi. The rest consisted of PMPs (9 %, 19 particles in 15 ventriculi), fibers (5 %, 11 particles in six ventriculi), film (5 %, 12 particles in five ventriculi), and foam (<1 %, one particle in one ventriculus. PMPs were found only in the ventriculi. The most common colors were brown and white (Supplementary Table 2).

3.1. Body condition and plastic loads

Body weight ($\bar{x}$ = 389 g, SE = 9, range 299–510 g, $N = 26$) was correlated with the body condition index of van Franeker (2004) ($S = 571.91$, $p = 0.0000007$, $rs = 0.805$) based on 26 birds that were sufficiently intact to allow us to determine body weight and body condition index (Fig. 2). The low weight and body condition index indicate that birds probably starved except for one 510 g bird with a body condition index of seven.

We used Siegel non-parametric linear regression (mblm package, R Studio, 2022) and found no significant differences between body weight and plastic loads using mass ($V = 188$, $p = 0.99$) or the number of particles ($V = 199$, $p = 0.56$), separately. Similarly, there was no relationship between body condition index and mass ($V = 93$, $p = 0.668$) and the number of particles ($V = 5$, $p = 1$).

Factors that could influence these comparisons are the larger body size of males (Einoder et al., 2008; Carey, 2011a) or age (Acampora et al., 2014; Shugart and Nania, 2021). Comparing body weight for 14 males (median = 370 g) and 12 females (median = 391 g) and there was no difference (*Wilcoxon* $W = 77.5$, $p = 0.75$). The body condition index also did not differ by sex (medians: male = 3.0, female = 2.5) (*Wilcoxon* $W = 81$, $p = 0.90$).

In comparing age differences for 12 adults and nine juveniles, adults were heavier (medians: juvenile = 363 g, adult = 413 g, *Wilcoxon* $W = 92.5$, $p = 0.0068$) and had a higher body condition index (medians: adults = 3.5, juveniles = 1.5, *Wilcoxon* $W = 91$, $p = 0.0087$). There were no corresponding age-related differences in plastic loads using mg (medians: adult = 125, juvenile 119, *Wilcoxon* $W = 46.5$, $p = 0.62$) or the number of particles per sample (medians: adult = 4.5, juveniles = 7, *Wilcoxon* $W = 51$, $p = 0.86$).

Table 1
Summary of plastic from short-tailed shearwater gastrointestinal tracts. Two samples without plastic are not included.

	Intestine		Proventriculus		Ventriculus		Totals	
	Count	mg	Count	mg	count	mg	Count	mg
Sample size	5	5	10	10	28	28	29	29
Mean			1.9	147.1	7.3	133.8	7.8	183.4
SE			0.4	64.5	1.0	20.9	1.1	35.9
Median	1	3.6	1.0	81.6	6.0	118.4	7.0	119.9
1st/3rd quartiles			1.0/2.8	12.5/204.1	3.0/11.0	48.8/186.8	3.0/11.3	51.2/226.8
Minimum	1	0.8	1.0	3.1	1.0	4.8	1.0	4.8
Maximum	1	89.5	5.0	671.0	20.0	550.5	21.0	823.8

Table 2
Summary data for 31 samples, including two zero values, that were used for comparison to the literature.

Measurement	Number of particles	mg
Mean	7.2	168.3
Standard error	1.1	33.9
Median	5	116.8
1st/3rd quartiles	2.0/11.0	47.0/224.8
Kurtosis	−0.3	5.3
Skewness	0.7	2.2
Minimum	0	0
Maximum	21	823.8

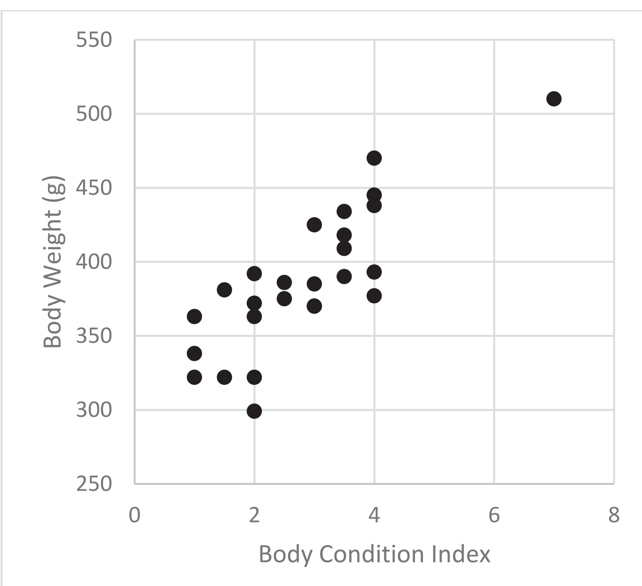

Fig. 2. Assessment of the health of beachcast short-tailed shearwaters based on body weight and body condition index from the 2019 mass mortality event. N = 26, 25 points are shown, there are two points at Body Condition Index = 3, Body weight = 370 g.

3.2. Particle weights and dimensions

Particle size was 23.5 mg using the totals of 5217.18 mg/222 particles and excluding five intestinal particles. The latter were excluded so that our data were comparable to previous studies that provide no size data for intestines. Typically, studies do include the total particles and total mg, but mean values (mean mg/mean particles), produce the same result (168.30 mg/7.16 particles = 23.5 mg. Using mean values of mg and particles for similar studies, we computed particle size from previous publications (see Discussion, Table 3).

A comparison of the type of particles, size of particles in stomach sections, and reduction relative to time in the ventriculus we based on rigid plastic (see Roman et al., 2019a). As expected, PMPs were more uniform than user fragments (Supplementary Table 3). Particles in proventriculi tended to be larger than those in the ventriculus except for thickness (Supplementary Table 4). An assessment of particle reduction using rigid particles in ventriculi of juveniles and non-juveniles found no differences in volume ($W_{59,120}$ = 3718, p = 0.5860) or density ($W_{59,120}$ = 3742.5, p = 0.5344) indicating that was minimal reduction relative to time in residence (Fig. 3) (see Nania and Shugart, 2021).

Recent particle size estimates from the South Pacific short-tailed shearwaters used only rigid particles (Roman et al., 2019a). Summarizing our data this way for comparison (Supplementary Table 5) and there were no significant differences in length, width, thickness, or mg in mean values (*Z-test means*, $p > 0.5$ for all) between the South Pacific (Roman et al., 2019a) and our North Pacific, Chukchi Sea data.

Particle dimensions provide estimates of the size of particles that could enter and pass through constrictions in GITs at the mouth, proventriculus to ventriculus, and ventriculus to the intestine. Roman et al. (2019a) found that the second greatest dimension or width of particles was probably the most significant in regulating what could pass into GITs. This assumes that the greatest dimension of particles, or length, aligns parallel with GITs. We plotted the frequency of the length and width (second greatest dimension) to assess passage and retention in GIT sections (Fig. 4). For each particle the width is shorter than the length, so any reference to width has an associated longer or equal length. Particles in the same 1 mm bins or smaller could potentially pass caudally from proventriculus to ventriculus and from ventriculus to intestine.

For intestinal particles, there were two in the >3 to ≤4 mm width bin indicating that ventricular particles of similar size or smaller (25 % or 48/191) could conceivably pass into the intestine (Fig. 4B). If the intestinal particle in >5 to ≤6 mm bin indicated what could pass into the intestine, this would include 59 % (113/191) of ventricular particles. One >7 to ≤8 mm wide intestinal particle is the maximum size so far recorded for passage through the ventricular-duodenal juncture.

For passage through the proventricular-ventriculus constriction, the greatest width was the >12 to ≤13 mm bin for ventricular particles suggesting an upper limit to the passage from the proventriculus (Fig. 4B). There were nine proventricular particles in bins smaller than the >12 to ≤13 mm bin indicating that not all particles that could pass into the ventriculus had done so. As Roman et al. (2019a) note the proventricular-ventricular constriction or, isthmus, likely regulates what could pass into the ventriculus and the maximum would appear to be 13 mm in width or less thereby regulating particle size, volume, and the resulting sample of plastic. Truncation of sizes at ≤2 mm width and ≤3 mm length probably indicates that particles of this size are not retained or were not ingested (Fig. 4).

Proventricular particle size provides estimates of the maximum of 20 × 65 mm for passage through the mouth or through flexible mandibular rami (streptognathism, Zusi, 1993) with medians 8.9 × 15.7 mm for rigid plastic particles (Supplementary Table 4).

3.3. Non-plastic

In addition to plastic, non-plastic provides additional dimensional

Table 3
Summary of short-tailed shearwater plastic studies. Pre-fledged and fledglings acquire plastic from parental feedings so are not directly comparable to non-fledglings but are useful for estimating particle size. Particle size was calculated using estimated mean mg/mean number. An "x" indicates data were not provided.

Pacific Region	Source	Year	Samples	Mean mg	Mean particles	% with plastic	Total particles	Particle size mg
Adult, immature, juvenile								
North	Day (1980, Table 5)	1969–1977	200	100	5.4	83.5	164	18.5
North	Ogi (1990)	1970–1979	324	140	8.79	82	2330	15.9
North	Vlietstra and Parga (2002)	1997–2001	330	114	5.8	84	1924	19.7
North	Tanaka et al. (2013), Supplement	2005	12	241	27	100	x	8.9
North	Yamashita et al. (2011)	2003, 2005	99	226	15.1	x	na	15.0
South	Roman et al. (2019a), Supplement	2013–2017	178	x	5.6 or 8.3[1]	Only birds with plastic	992	30.7[2]
North	This study	2019	31	168.30	7.16	93.5	222	23.5
Pre-fledgling-fledgling								
South	Carey (2011b)	2011	67	113	7.6	100	513	14.9
South	Rodríguez et al. (2018)[3]	2015–2016	140	150	7.4	98	x	21.7
South	Puskic et al. (2020)	2017	38	60	3.8	89.5	136	15.9
South	Cousin et al. (2015)	2012	171	148	6.0	96	1031[4]	24.7

[1] From Supplement Table 1, 8.3 particles/sample or 5.6 particles/sample based on 992 particles/178 samples.
[2] Not computed, from Supplement Table 1.
[3] 1 < mm greatest dimension particles excluded.
[4] 1032 in text.

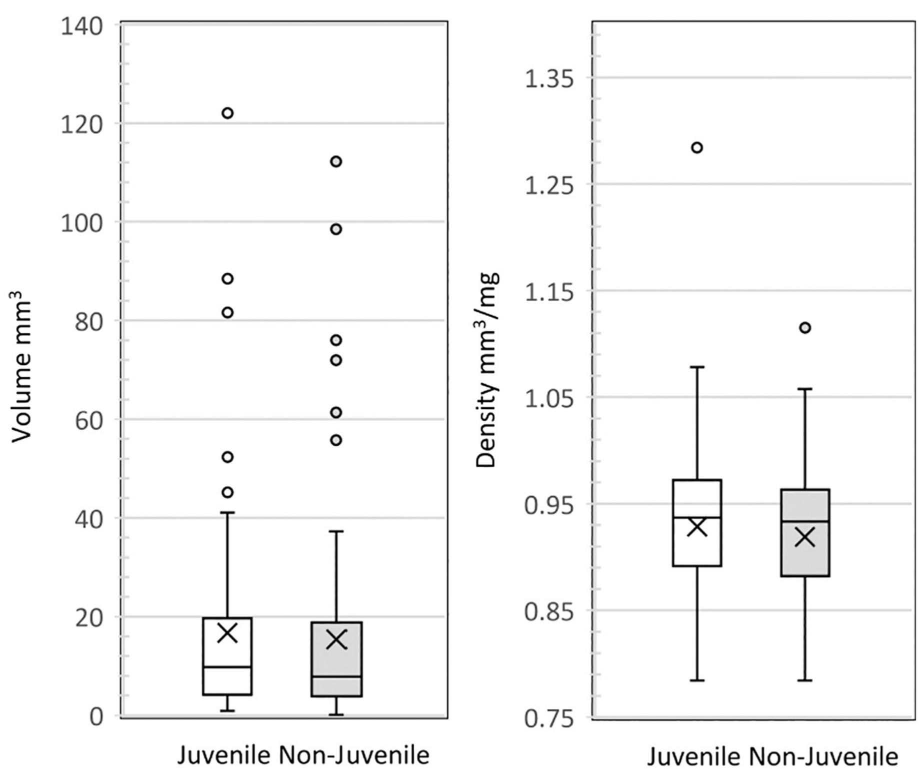

Fig. 3. Comparison of particle size and density for short-tailed shearwater juveniles and non-juveniles indicating no differences. The horizontal line in each box is the median, boxes are 1st and 3rd quartiles, and x is the mean.

information on items that could enter and presumably pass through the intestines. We found an additional 399 items in 28 of 31 GITs mostly in ventriculi (Supplementary Table 6). Notable samples included a stick 17.6 mm in length × 2.4 mm in diameter in the intestine of sample 231, two samples that contained 50 and 24 squid beaks, and a 335 mg rock with the greatest dimension of 8.5 mm.

4. Discussion

Puskic et al. (2020) in a review of short-tailed shearwater literature noted percent of birds with plastic was >80 % since first reports by Day (1980) and Ogi (1990) (see Puskic et al., 2020; this study Table 3, Supplementary Table 7). Amounts per sample ranged from 5.4 to 27 particles and 100–241 mg in non-fledglings (Table 3). The condition of birds did not appear to be related to plastic loads based on a comparison of poor-condition birds (this study) to healthier birds that were shot or bycatch from other North Pacific samples (Day, 1980; Ogi, 1990; Vlietstra and Parga, 2002; Puskic et al., 2020; Table 3 this paper). One exception from Australia found that low-weight beachcast and presumably starved birds had more plastic than normal-weight birds that had been accidentally killed (Rodríguez et al., 2018). We did note that juveniles appeared to be in poorer condition than adults similar to beachcast samples from Australia, but condition was not related to the load of anthropogenic debris in Acampora et al. (2014). There was no

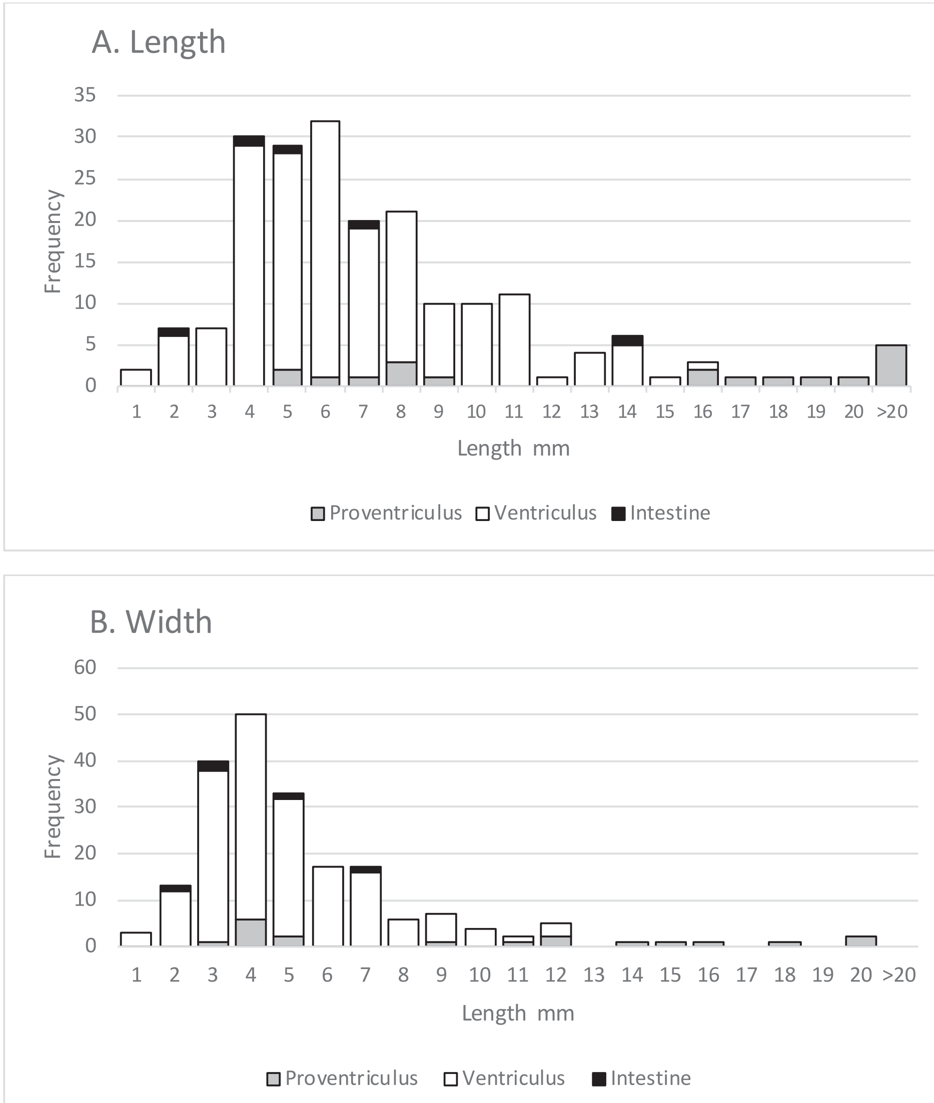

Fig. 4. Length and width of rigid particles in proventriculus, ventriculus, and intestine showing overlap of sizes. X-axis is in 1 mm increments inclusive of the number on the axis, e.g., 1 is >0 and ≤1 mm.

sex difference similar to other reports (Vlietstra and Parga, 2002). Particles were mostly lighter colors except for Roman et al. (2019a) with a predominance of black (Supplementary Table 7). This overview of the typical biomonitoring parameters suggests that there are few significant trends in stomach plastic loads in the North Pacific samples or in comparison of North Pacific to South Pacific (Fig. 5, Table 3; Supplementary Table 7).

Particle size is an important consideration in GIT-based sampling because the size of particles determines the amount of plastic retained in GITs and the resulting loads (Day, 1980; Ogi, 1990; Ryan, 1987, 1990, 2016; Van Franeker and Meijboom, 2002; Roman et al., 2019a; Nania and Shugart, 2021). A baseline for full stomach capacity for short-tailed shearwaters is 100 ml (range 70–140 ml) (Skira, 1986), which is equivalent to 100,000 mm^3 or approximately 108 g assuming a density of 0.93 mass/volume. Assuming a particle of 25 mg, the stomach, including proventriculus and ventriculus, could hold up to 4320 particles indicating that loads were far below capacity (Table 2). The greatest load recorded for a short-tailed shearwater was 101 particles weighing 590 mg for an outlier (#27) in Tanaka et al. (2013, Supplement).

Procellariiformes stomachs are two sections with a relatively large thin-walled proventriculus where chemical digestion begins and a smaller muscular ventriculus, or gizzard, where particles may be reduced through wear or fragmentation (Furness, 1985; Shugart and Nania, 2021). Items are first held in the proventriculus where particles can be regurgitated or pass into the ventriculus if small enough. Entry into the ventriculus is through a constriction (Furness, 1985) that likely limits the size of particles that enter (Roman et al., 2019a). Particles could pass into the intestine if small enough, or be retained and reduced in size through wear or fragmentation before eventually passing into the intestine. The successive sections in the procellariid GIT can be viewed as a sampler similar to nested sieves (Merkus, 2009). Filters or constrictions limit entrance at the mouth, proventriculus, ventriculus, and intestine, and particle size in the segments can be used to gauge what could enter and pass through or be retained (Roman et al., 2019a; this study, Fig. 4). Our estimates based on width for passage from mouth to proventriculus, proventriculus to ventriculus, and proventriculus to intestine passage based on maximum width were 20 mm, 13 mm, 3–4 or 3–8 mm, respectively (Fig. 4).

The mouth to proventriculus and ventriculus to the intestine are least affected by concerns for wear or fragmentation. Entry into the proventriculus of 20 mm or larger particles (see Acampora et al., 2014) can occur through flexible mandibular rami that bow outward to allow objects larger than the approximate gape to be ingested (Zusi, 1993). Particle size for passage from ventriculus to intestine is 3–4 mm wide but

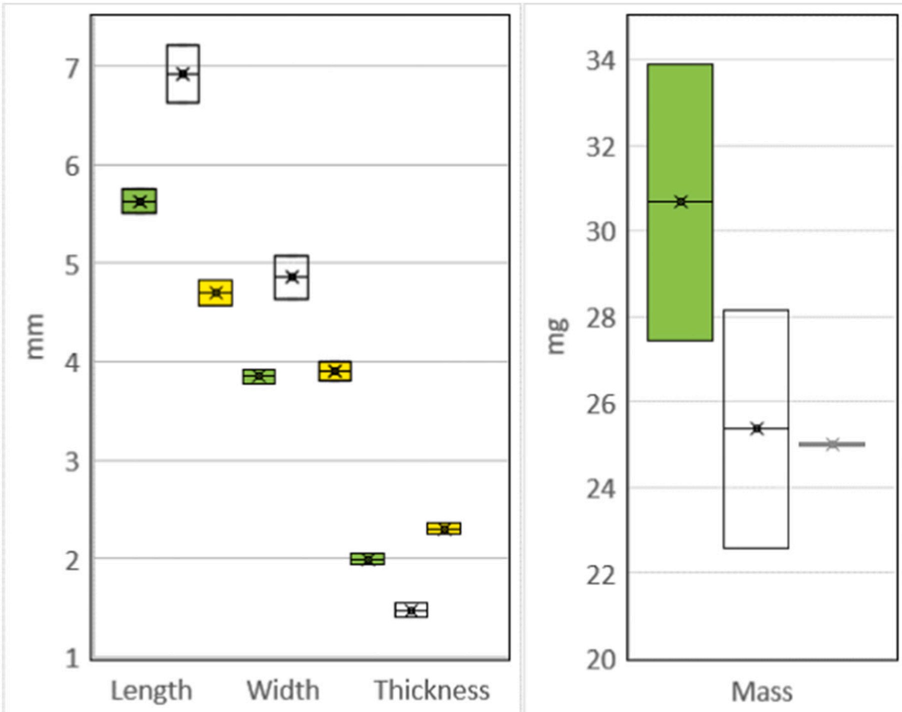

Fig. 5. Mean (-x-) ± SE (boxes) for length, width, thickness, and weight of rigid plastic particles from South Pacific, near Australia (green box, Roman et al., 2019 Supplement Table 1), North Pacific, Chukchi Sea (open box, this study), and North Pacific 1969–1977 (yellow box, Day, 1980). Means were not significantly different for Australia and Chukchi Sea. The number of particles per bird, not plotted, in South Pacific was 5.6 or 8.3, depending on the source, compared to 7.2 in North Pacific, Chukchi Sea, and 5.4 North Pacific 1969–1977 (see Table 3). B. Particle mass for Australia (green), North Pacific 2019 (open box), and North Pacific 1969–1977 (line). The latter SE was small apparently due to the uniformity of most of the plastic, which was pre-manufactured pellets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

similar sized particles were also in the ventriculus so not all in this size range pass. This is similar to Northern fulmars (Terepocki et al., 2017; Shugart and Nania, 2021) and requires additional investigation. There are few data for intestinal plastic but Ogi (1990, page 645) suggested that PMPs and similarly sized particles could pass directly into the intestine with food citing a reduction in the percent occurrence of plastic in shearwaters that had stomachs full of food (Terepocki et al., 2017). Acampora et al. (2014, Fig. 2) noted intestinal anthropocentric debris without details.

Ventricular particle size may be reduced due to fragmentation or wear from grinding so might not provide estimates of particle size that could be ingested or passed caudally (see Ryan, 1990; Nania and Shugart, 2021 for reviews). We provide the first estimates of what could pass into the ventriculus that could be remnants of larger particles. However, the lack of a difference between ventricular plastic in juveniles versus non-juveniles suggests that there is little reduction in size through wear or fragmentation (Fig. 3) which was similar to Northern fulmars (Nania and Shugart, 2021). Rather, the constriction at the entrance to the ventriculus may limit the size of particles to those that could eventually pass into the intestine with a few exceptions (Supplementary Table 4; Terepocki et al., 2017).

We confirmed that particle size in mg based on the total mg/total particles could be estimated using means values in published accounts. An overview of particle size from seven studies of non-fledglings average 8.9–30.7 mg with a grand mean of 18.9 mg. The inclusion of four studies with pre-fledglings and fledglings was 19.0 mg. Plastic in the latter group was from parental regurgitative feeding so although the mode of acquisition differs, inclusion does not significantly change particle size. Particle size may have increased slightly due to a previously documented change from PMPs to user fragments (Vlietstra and Parga, 2002). In first reports in the 1970s, PMPs comprised 72.5 % (Table 8 in Day, 1980) and 67.2 % (Table 12 in Ogi, 1990) of particles declining to 32.9 % in 1997–2001 (Vlietstra and Parga, 2002) with a further decline to 8.6 % in 2019 (this study). This occurred with little change in quantities (Vlietstra and Parga, 2002; Puskic et al., 2020). PMPs were 4.3 × 3.8 × 2.6 mm and 18.6 mg in 2019 (this study) compared to samples from Day (1980) that was 72.5 % PMPs measuring 4.7 × 3.9 × 2.3 mm and 18.5 mg. Particle size in most recent reports (Roman et al., 2019a; this paper; Table 3) appears to be slightly larger since the early instances when PMPs predominated (Day, 1980; Ogi, 1990) because user fragments have a greater size range (Supplementary Table 3) with larger pieces being retained, especially in the proventriculi (Fig. 4, Supplementary Table 4, this paper; Ryan, 1987; Roman et al., 2019a).

Our data for short-tailed shearwaters demonstrates that larger particles were found in the proventriculus (Supplementary Table 4) similar to Northern fulmars from the NE Pacific (Shugart and Nania, 2021). In addition, the proventriculus can accommodate a larger volume than the ventriculus (Furness, 1985; Shugart and Nania, 2021) so the mass and number of particles, as well as dimensions in a sample, could depend on the distribution in GIT sections (Shugart and Nania, 2021). Typically contents from the proventriculus and ventriculus are pooled, but plastic in short-tailed shearwater tends to concentrate in ventriculi (Table 1, Table 3, this study; Day, 1980; Vlietstra and Parga, 2002; Carey, 2011b; Cousin et al., 2015; Puskic et al., 2020). Therefore we feel that comparisons between studies are reasonable. Except for the shift from PMPs to user particles, we conclude that there were little differences in long term data for the North Pacific and for concurrent comparisons between the North and South Pacific.

From a biomonitoring perspective, the similarity of plastic loads and particle dimensions in time in the North Pacific and space comparing North to South Pacific indicates that plastic pollution was unchanged since Day (1980) and Ogi (1990) except for the change from PMPs to user fragments (Vlietstra and Parga, 2002; this paper). However, given a consensus that the amount of oceanic plastic has dramatically increased, the range of sizes has increased relative to PMPs, and the relative proportions in small bins have increased with age, exposure, and fragmentation (Eriksen et al., 2014; Cózar et al., 2017; Wang et al., 2020; Wilcox et al., 2020) it is unlikely that short-tailed shearwater GIT samples could track such changes. Alternatively, plastic loads reflect species' preference for some characteristics (Day, 1980; Ogi, 1990) and show little relationship to plastic that is available (Day, 1980; Day and Shaw, 1987; Shaw and Day, 1994; Acampora et al., 2014, Roman et al., 2016). A single Procellariform species the size of a short-tailed shearwater provides a relatively small plastic sample with a restricted size range with a truncation of smaller sizes <2–3 mm greatest dimension (Fig. 4) and may lack actual or relative utility for monitoring the ubiquitous, increasing, and dynamic state of environmental plastic pollution (Roman et al., 2019a; Shugart and Nania, 2021), However, GIT-based sampling is critical for risk assessment, especially in identifying populations or cohorts of species that are at risk for physical or physiological harm (Roman et al., 2016, 2019a, b; Wilcox et al., 2020; Shugart and Nania, 2021).

CRediT authorship contribution statement

GS, CW, LV, JF and RK conceived the study. GS and CW quantified plastic and analyzed data, GS and CW wrote draft, LV reviewed and revised revisions; RK provided logistics support and procured samples making the study possible.

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 Gay Sheffield, University of Alaska Fairbanks/Alaska Sea Grant, and Stacia Backensto, National Park Service, for collecting the birds used in this study.

Appendix A. Supplementary Figures and Tables for short-tailed shearwaters from the North Pacific in 2019

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115038.

References

Acampora, H., Schuyler, Q.A., Townsend, K.A., Hardesty, B.D., 2014. Comparing plastic ingestion in juvenile and adult stranded short-tailed shearwaters (Puffinus tenuirostris) in eastern Australia. Mar. Pollut. Bull. 78, 63–68.

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G.W., Provencher, J.F., Rochman, M., van Sebille, E., Tekman, M.B., 2022. Plastic pollution in the Arctic. Nat. Rev. Earth Environ. 3, 323–337.

Broughton, J.M., 1994. Size of the bursa of fabricius in relation to gonad size and age in Laysan and black-footed albatrosses. Condor 96, 203–207.

Carey, M.J., 2011a. Sexual size dimorphism, within-pair comparisons and assortive mating in the short-tailed shearwater (Puffinus tenuirostris). Notornis 58, 8–16.

Carey, M.J., 2011b. Intergenerational transfer of plastic debris by short-tailed shearwaters (Ardenna tenuirostris). Emu 111, 229–234.

Carey, M.J., Phillips, R.A., Silk, J.R.D., Shaffer, S.A., 2014. Trans-equatorial migration of short-tailed shearwaters revealed by geolocators, 2014 Emu 114 (4), 352–359.

Collard, F., Husum, K., Eppe, G., Malherbe, C., Hallanger, I., Divine, D., Gabrielsen, G., 2021. Anthropogenic particles from sediments in an Arctic fjord. Sci. Total Environ. 772, 145575.

Cooper, J., Underhill, L.G., Avery, G., 1991. Primary molt and transequatorial migration of the sooty shearwater. Condor 93, 724–730.

Cousin, H.R., Auman, H.J., Alderman, R., Virtue, P., 2015. The frequency of ingested plastic debris and its effects on body condition of short-tailed shearwater (Puffinus tenuirostris) pre-fledging chicks in Tasmania, Australia. Emu 115, 6–11.

Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., Van Sebille, E., Ballatore, T.J., Eguíluz, V.M., Gonzáles-Gordillo, I., Pedrotti, M.L., Echevarría, F., Troublè, R., Irigoien, X., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. Sci. Adv. 3 (4), e160058.

Day, R., 1980. The Occurrence and Characteristics of Plastic Pollution in Alaska's Marine Birds. University of Alaska. Master's Thesis.

Day, R.H., Shaw, D.G, 1987. Patterns in the Abundance of Pelagic Plastic and Tar in the North Pacific Ocean, 1976-1985. Mar. Pollut. Bull. 18, 311–316.

Einoder, L.D., Page, B., Goldsworthy, S.D., 2008. Sexual size dimorphism and assortative mating in the short-tailed shearwater Puffinus tenuirostris. Mar. Ornithol. 36, 167–173.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE 9 (12), e111913. https://doi.org/10.1371/journal.pone.0111913.

Furness, R.W., 1985. Ingestion of plastic particles by seabirds at Gough Island, South Atlantic Ocean. Environ. Pollut. Ser. A Ecol. Biol. 38 (261–272), 1985. https://doi.org/10.1016/0143-1471(85)90131-X.

Glick, B., 1983. Bursa of Fabricius. In: Avian Biology, 1983. Academic Press, Cambridge, Massachusetts.

Jones, T., Parrish, J.K., Peterson, W.T., Bjorkstedt, E.P., Bond, N.A., Balance, L.T., Bowes, V., Hipfner, J.M., Burgess, H.K., Dolliver, J.E., Lindquist, K., Lindsey, J., Nevins, H.M., Robertson, R.R., Roletto, J., Wilson, L., Joyce, T., Harvey, J., 2018. Massive mortality in a planktivorous seabird in response to a marine heatwave. Geophys. Res. Lett. 45, 3193–3201.

Kaler, R., Sheffield, G., Backensto, S., Lindsey, J., Jones, T., Parrish, J., Ahmasuk, B., Bodenstein, B., Dusek, R., Van Hemert, C., Smith, M., Schwalenberg, P.M., 2022. Partnering in Search of Answers: Seabird Die-offs in the Bering and Chukchi Seas. https://doi.org/10.25923/h002-4w87.

Law, K.L., Morét-Ferguson, S.E., Goodwin, D.S., Zettler, E.R., Deforce, E., Kukulka, T., Proskurowski, G., 2014. Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year data set. Environ. Sci. Technol. 48 (9), 4732–4738. https://doi.org/10.1021/es4053076. Epub 2014 Apr 24 PMID: 24708264.

Merkus, H.G., 2009. Particle Size Measurements: Fundamentals, Practice, Quality. Springer Science+Business Media B.V e-ISBN: 978-1-4020-9016-5.

Mettler-Toledo, 2022. Manual. https://www.mt.com/us/en/home/applications/Laboratory_weighing/density-measurement.html.

Miyazono, K., Yamashita, R., Miyamoto, H., Nurul Ishak, N.H.A., Kazuaki Tadokoro, K. E., Yugo Shimizu, Y., Takahashi, K., 2021. Large-scale distribution and composition of floating plastic debris in the transition region of the North Pacific. Mar. Pollut. Bull. 170, 112631 https://doi.org/10.1016/j.marpolbul.2021.112631.

Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C. M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar. Pollut. Bull. 60 (1873–1878), 50.

Nania, T.G., Shugart, G.W., 2021. Are plastic particles reduced in size in seabirds' stomachs? Mar. Pollut. Bull. 172, 112843.

Ogi, H., 1990. Ingestion of plastic particles by sooty and short-tailed shearwaters in the North Pacific. In: Shomura, R.S., Godfrey, M.L. (Eds.), Proceedings of the Second International Conference on Marine Debris, 2–7 April 1989, Honolulu, Hawaii, NOAA Technical Memo. NMFS, NOAA-TM-NMFS-SWFSC-154. U.S. Dept. Commerce, pp. 635–652, 1274 p.

Pabortsava, K., Lampitt, R.S., 2020. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean, 11. https://doi.org/10.1038/s41467-020-17932-9. www.nature.com/naturecommunications.

Piatt, J.F., Parrish, J.K., Renner, H.M., Schoen, S.K., Jones, T.T., Arimitsu, M.L., Kuletz, K.J., Bodenstein, B., Garcia-Reyes, M., Duerr, R.S., Corcoran, R.M., Kaler, R. S.A., McChesney, G.J., Golightly, R.T., Coletti, H.A., Suryan, R.M., Burgess, H.K., Lindsey, J., Lindquist, K., Warzbok, P.M., Jahncke, J., Roletto, J., Sydeman, W., 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. PLoSONE 15 (1), e0226087.

Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borelle, S.B., Bravo Rebolledo, E.L., Hammer, S., Kühn, S., Lavers, J.L., Mallory, M.L., Trevail, A., van Franeker, J.A., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Anal. Methods 9, 1454–1469.

Puskic, P.S., Lavers, J.L., Adams, L.R., Bond, A.L., 2020. Ingested plastic and trace element concentrations in short-tailed shearwaters. Mar. Pollut. Bull. 155, 111143.

Rodríguez, A., Ramírez, F., Carrasco, M.N., Chiaradia, A., 2018. Seabird plastic ingestion differs among collection methods: examples from the short-tailed shearwater. Environ. Pollut. 243, 1750–1757.

Roman, L., Hardesty, B.D., Hindell, M.A., Wilcox, C., 2019b. A quantitative analysis linking seabird mortality and marine debris ingestion. Sci. Rep. 9.

Roman, L., Paterson, H., Townsend, K.A., Wilcox, C., Hardesty, B.D., Hindell, M.A., 2019a. Size of marine debris items ingested and retained by petrels. Mar. Pollut. Bull. 142, 569–575.

Roman, L., Schuyler, Q.A., Hardesty, B.D., Townsend, K.A., 2016. Anthropogenic debris ingestion by avifauna in eastern Australia. PLoS ONE 11 (8), e0158343. https://doi.org/10.1371/journal.pone.0158343.

Studio, R., 2022. Version 1.4.1103, download. © 2009-2021 RStudio, PBC.

Ryan, P.G., 1987. Incidence and characteristics of plastic ingested by seabirds. Mar. Environ. Res. 23, 175–206.

Ryan, P.G., 1990. The effects of ingested plastic and other marine debris on seabirds. In: Proceedings of the Second International Conference on Marine Debris; 1989 April 2-7; Honolulu, Hawaii, US. Washington, D.C.: National Oceanic and Atmospheric Administration. NMFS.NOAA-TM-NMFS-SWFSC-154.199.

Ryan, P.G., 2016. Ingestion of plastics by marine organisms. In: Takada, H., Karapanagioti, H.K. (Eds.), Hazardous Chemicals Associated With Plastics in the Marine Environment: The Handbook of Environmental Chemistry 78. Springer International Publishing, Switzerland. Pp.235-226.

Savoca, M.S., Kühn, S., Sun, C., Avery-Gomm, S., Choy, C.A., Dudas, S., Hee Hong, S., Hyrenbach, K.D., Li, T., Ka-yan Ng, C., Provencher, J.F., Lynch, J.M., 2022. Towards a North Pacific Ocean long-term monitoring program for plastic pollution: a review and recommendations for plastic ingestion bioindicators. Environmental Pollution 310, 119861. https://doi.org/10.1016/j.envpol.2022.119861. ISSN 0269-7491.

Shaw, D.G., Day, R.H., 1994. Colour- and form-dependent loss of plastic micro-debris from the North Pacific Ocean. Mar. Pollut. Bull. 28, 39–43. https://doi.org/10.1016/0025-326X(94)90184-8.

Shugart, G.W., Nania, T.G., 2021. Demographic differences in the quantity, mass, and anatomical location of ingested plastic in northern fulmars (Fulmarus glacialis): a review and reconsideration of NE Pacific Ocean samples. Adv. Environ. Eng. Res. 2 (3), 023. https://doi.org/10.21926/aeer.2103023.

Skira, I.J., 1986. Food of the short-tailed shearwater, Puffinus tenuirostris, in Tasmania. Aust. Wildl. Res. 13, 481–488. https://doi.org/10.1071/WR9860481.

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., Watanuki, Y., 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69 (1–2), 219–222.

Terepocki, A.K., Brush, A.T., Kleine, L.U., Shugart, G.W., Hodum, P., 2017. Size and dynamics of microplastic in gastrointestinal tracts of northern fulmars (Fulmarus glacialis) and sooty shearwaters (Ardenna grisea). Mar. Pollut. Bull. 116 (143–150), F2005.

U.S. Fish and Wildlife Service, 2019. 2019 Alaska seabird die-off. In: USFWS Fact sheet 508C, September.

Van Franeker, J.A., Meijboom, A., 2002. In: Litter NSV; Marine Litter Monitoring by Northern Fulmars (a Pilot study). Alterra, Wageningen, p. 401.

Van Franeker, J.A., 2004. In: Save the North Sea Fulmar-Litter-EcoQO Manual Part 1: Collection and Dissection Procedures, 2004. Alterra, Wageningen, p. 672.

Vlietstra, L.S., Parga, J.A., 2002. Long-term changes in the type, but not amount, of ingested plastic particles in short-tailed shearwaters in the southeastern Bering Sea. Mar. Pollut. Bull. 44, 945–955.

Wang, S., Chen, H., Zhou, X., Tian, Y., Lin, C., Wang, W., Zhou, K., Zhang, Y., Lin, H., 2020. Microplastic abundance, distribution and composition in the mid-west Pacific Ocean. Environmental Pollution 2020. https://doi.org/10.1016/j.envpol.2020.114125.

Wilcox, C., Hardesty, B.D., Law, K.L., 2020. Abundance of floating plastic particles is increasing in the Western North Atlantic Ocean. Environ. Sci. Technol. 54 (790–796), 45.

Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. 112 (38), 11899–11904.

Yamashita, R., Takada, H., Fukuwaka, M., Watanuki, Y., 2011. Physical and chemical effects of ingested plastic debris on short-tailed shearwaters, Puffinus tenuirostris, in the North Pacific Ocean. Mar. Pollut. Bull. 62, 2845–2849.

Zusi, R.L., 1993. Patterns of diversity in the avian skull. In: Hanken, J., Hall, B.K. (Eds.), The Skull, Volume 2: Patterns of Structural and Systematic Diversity. University of Chicago Press, Chicago, pp. 391–437.