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Long-term changes in the type, but not amount, of ingested plastic particles in short-tailed shearwaters in the southeastern Bering Sea

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Abstract

We report the current (1997–1999, 2001) incidence and amount of ingested plastic in short-tailed shearwaters (*Puffinus tenuirostris*) in the southeastern Bering Sea and compare our results with plastic reported in shearwaters during 1970–1978. We also examine correlations between plastic loads and shearwater body mass. We found that 84% ($N = 330$) of shearwaters sampled in 1997–1999 and 2001 contained plastic. The incidence and amount of ingested plastic have not significantly changed since the 1970s. In contrast, the predominant type of plastic has changed over time, from industrial plastic to user plastic. Seasonal patterns in the incidence and amount of ingested plastic also changed from peak levels during early and late summer in the 1970s to mid summer in the late 1990s and 2001. We suggest that the availability of neuston plastic to seabirds in the Bering Sea has undergone a shift in composition since the 1970s. Shearwater body mass appears little if at all impaired by plastic, at least at present levels of consumption.

Keywords: Plastic ingestion; Seabirds; Short-tailed shearwaters; *Puffinus tenuirostris*; Bering Sea; Subarctic Pacific Ocean

1. Introduction

Plastics are major pollutants in the marine environment, and their ingestion by seabirds has become a global conservation concern (Coleman and Wehle, 1984; Woehler, 1993; Nisbet, 1994). The impacts of plastic on seabird health are still uncertain, but effects may include chemical exposure (Carpenter et al., 1972; Ryan et al., 1988; Mato et al., 2001) or digestion impediment leading to reduced reproductive success or starvation (reviewed by Day et al. (1985)).

Plastic ingestion was first noted in two seabird species during the 1960s (Kenyon and Kridler, 1969; Rothstein, 1973), and by the late 1980s, plastic had been found in at least 109 seabird species in the North Pacific (Sileo et al., 1989; Robards et al., 1995; Blight and Burger, 1997), North Atlantic (Moser and Lee, 1992), tropical Pacific (Fry et al., 1987; Spear et al., 1995), South Atlantic (Furness, 1985a; Ryan, 1987a), and Southern Ocean (van Franeker and Bell, 1988; Ainley et al., 1990). During the 1970s and 1980s, the incidence of plastic increased in many seabird species, but increases were especially marked among the Procellariiformes (albatrosses, shearwaters, petrels; Day, 1980; Blight and Burger, 1997; Spear et al., 1995; Moser and Lee, 1992; Robards et al., 1995). Increases in plastic ingestion have been attributed to increases in worldwide plastic production, which rose from 30 million metric tons per year in 1970 to 85 million metric tons per year by the late 1980s (Schouten and van der Vegt, 1991). By the year 2000, worldwide plastic production exceeded 150 million metric tons per year, with increases expected to continue (Young, 1994; Port, 2001).

Many authors have emphasized the need for monitoring plastic consumption by seabirds (Day, 1980; Day et al., 1985; Furness, 1985b; Blight and Burger, 1997). However, we are aware of only one published study that addresses temporal trends in plastic ingestion that includes data from the past 10 years. Auman et al. (1997) documented that the occurrence of plastic material in Laysan albatross (*Diomedea immutabilis*) chicks from Midway Atoll, Hawaii, increased from 74% in the 1960s,

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to 90% in the 1980s, to 98% in the mid 1990s. Measures of plastic ingestion by seabirds in the recent decade are of particular conservation interest because the enactment of MARPOL Annex V in 1988 was expected to significantly reduce the amount of plastic ingested by seabirds and other marine fauna.

Procellariiformes, especially shearwaters, accumulate more plastic than any other seabird group recorded to date (Ryan, 1987a; Sileo et al., 1989; Moser and Lee, 1992; Spear et al., 1995; Blight and Burger, 1997), possibly because of their foraging behavior and unique morphology. Short-tailed shearwaters (*Puffinus tenuirostris*; hereafter, shearwaters) breed in the South Pacific Ocean and spend the austral winter in the subarctic Pacific. In the Bering Sea, they are a dominant seabird in terms of number and biomass; population estimates range from 8.7 (Shuntov, 1961) to 20 million birds (Hunt et al., 1981). In the southeastern Bering Sea, shearwaters feed primarily on euphausiids (e.g., *Thysanoessa inermis*, *Thysanoessa raschii*, *Thysanoessa spinifera*) that occur at the surface and at depths up to 40 m (Ogi et al., 1980; Hunt et al., 1996). As pursuit divers, shearwaters may have trouble distinguishing between plastic and prey from the air (Day et al., 1985), and when filter-feeding, they might not distinguish between prey and plastic of similar size. Shearwaters also have a gizzard that is separated from the proventriculus by an unusually narrow passage, which is thought to prevent offloading of plastic during regurgitation (Furness, 1985a). These qualities make shearwaters useful species in which to monitor plastic ingestion because long-term data sets are available and sample sizes are adequate for statistical analyses. In addition, if plastic adversely affects body condition, then seabirds that frequently ingest plastic are most likely to exhibit negative effects, such as reduced foraging success or starvation.

In this study, we report the current (1997–1999, 2001) incidence and amount of ingested plastic in short-tailed shearwaters in the southeastern Bering Sea and compare our results with plastic reported in shearwaters in the same region during 1970–1978 (Ogi, 1990). In addition, we assess possible changes over time in seasonal patterns of plastic consumption and the characteristics of plastic consumed. When possible, we make separate assessments of changes over time in the occurrence of plastic in shearwaters collected throughout the subarctic Pacific Ocean, which includes the Bering Sea, Gulf of Alaska, and North Pacific Ocean south of the Aleutian Islands (hereafter, North Pacific Ocean). Because the basis for concern about plastic is that plastic is harmful to seabird health, we also examine the relationship between ingested plastic and shearwater body mass.

2. Methods

2.1. Sources of data

Data on the occurrence of plastic in shearwaters from 1970 to 1978 are from Ogi (1990), who collected birds

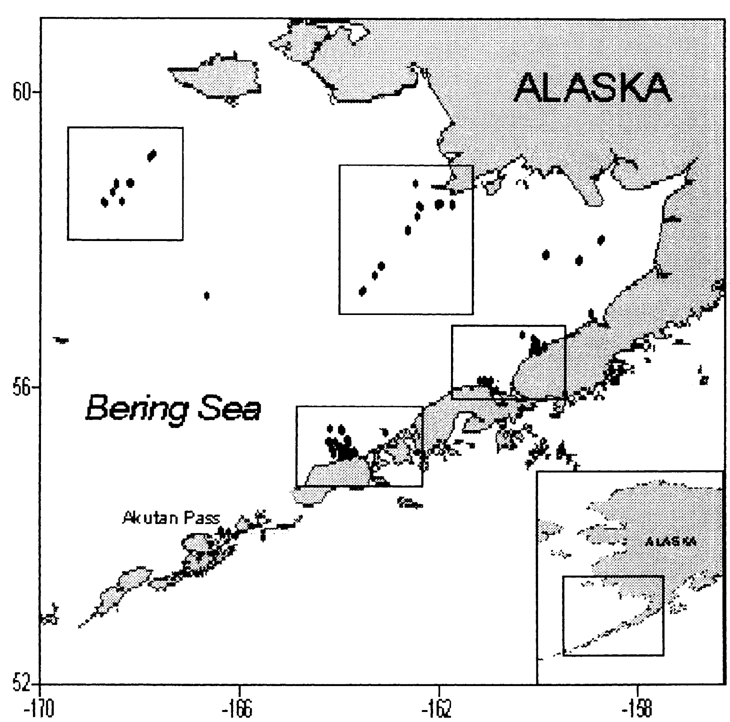

Fig. 1. Study site where short-tailed shearwaters were collected. Solid circles show locations of shearwater collections. One circle may indicate multiple collections. Large boxes indicate regions where most (76%) collections were made.

caught in high-seas drift nets in the Bering Sea and North Pacific Ocean. In our study, we collected shearwaters by shooting, as approved by federal, state, and university permits. Methods of collection and sample sizes used by other studies conducted across the subarctic Pacific that we use for comparison are described in Appendix A.

From 1997 to 2001, we collected shearwaters during seven cruises to the southeastern Bering Sea. Most (76%) collections took place in four regions of Bristol Bay and areas northeast of the Pribilof Islands. Three of these four regions were visited twice each year during 1997–1999, once in May–June and once in July–September. In 2001, we collected shearwaters during June in Akutan Pass, eastern Aleutian Islands (Fig. 1).

Because shearwaters were originally collected for a study on food web interactions, we sampled only shearwaters that were actively feeding. Within 30 min of collection, we weighed each bird to the nearest 5 g with a Pesola scale. We removed the proventriculus and gizzard and weighed the contents of each to the nearest 1 g with a Pesola scale before placing the contents in 80% ethyl alcohol. We calculated body mass for each bird by subtracting the mass of the stomach contents from the original mass of the bird. To allow for us to control for sex differences in our analysis of ingested plastic and shearwater body mass, we examined the gonads of each bird and recorded the sex as male, female, or unknown.

In the laboratory, we examined stomach contents for plastic material and noted the presence or absence of plastic in the proventriculus and gizzard of each bird. We removed the plastic from the stomach contents and used a digital balance to weigh the total amount of plastic per bird (mg). We used digital calipers to measure the dimensions (length, width, thickness, radius; mm) of each particle. Following Ogi (1990), we classified each particle by type, including industrial pellets (2–5 mm diameter polyethylene beads that are used for molding into plastic products and in cargo packaging and transport), user plastic (plastic molding, usually particles from larger objects such as buckets, bottles, etc.), and other refuse (string, rubber, vinyl). We also classified each particle by color as white, yellow, yellow–brown (light colors); brown, blue, green, red (medium colors); and dark blue, dark green, dark red, and grey–black (dark colors).

2.2. Statistical analysis

2.2.1. Temporal trends

In Ogi's (1990) study of ingested plastic in shearwaters in the 1970s, he reported the location, proportion of shearwaters containing plastic, and sample size for each collection event. We were therefore able to separate data for birds collected in the Bering Sea from those collected elsewhere (North Pacific) and recalculate the occurrence of plastic in shearwaters at each site. We used linear regression to examine changes in the occurrence of plastic among shearwaters in the Bering Sea during 1970–1978 and 1976–2001. We used 1976 as a baseline for comparison with our results because Ogi separated his observations into two periods with significantly different incidences of plastic ingestion, early (1970–1972) and late 1970s (1975–1979). The year, 1976, was the first year of the latter period that contained birds collected in the Bering Sea. We used linear regression to examine long-term trends in the mass and number of plastic particles ingested by shearwaters in the Bering Sea. Too few data were available for statistical analysis of long-term changes in the volume of ingested plastic. Analyses of mass, number, and volume (see below) of plastic particles were conducted on data from all birds that we collected in the Bering Sea, regardless of whether they contained plastic, unless otherwise noted. We also used linear regression to examine long-term trends in the occurrence of plastic in shearwaters collected across the subarctic Pacific Ocean as well as in the Bering Sea by other authors. Such comparisons were made separately from those of birds collected in the Bering Sea because the Bering Sea typically contains little neuston plastic pollution relative to the North Pacific (Day and Shaw, 1987); we therefore suspected that data on plastic ingestion collected in the North Pacific may not be directly comparable to those from the Bering Sea.

To examine seasonal trends in the occurrence and amount of plastic in shearwaters during 1997–1999 and 2001, we calculated the mean frequency of ingested plastic for birds collected in each month (May–September) and used the Kruskal–Wallis test to compare incidences among months. The mass, number, and volume of plastic particles per bird were not normally distributed; therefore, we used the Kruskal–Wallis test to compare amount of ingested plastic among summer months. We made qualitative comparisons between the proportion of plastic taken in each type and color category during 1997–1999 and 2001 with those described by Ogi (1990) and Day (1980), both of whom addressed birds from both the Bering Sea and the North Pacific.

2.2.2. Plastic and body mass

We evaluated whether we needed to control for sex-related differences in body size in our analysis of plastic ingestion and shearwater body mass. We used a t-test to determine whether body mass differed between the sexes, and we used a Mann–Whitney U-test to determine whether the mean frequency of plastic differed between the sexes. We also used a Mann–Whitney U-test to examine sex differences in the total mass, number, and volume of consumed particles per bird. We found no difference between the sexes in any of these parameters (see Section 3); therefore, we performed the following analyses on the combined sample of male and female shearwaters.

To determine whether the frequency of ingested plastic was correlated with body mass, we separated shearwaters into eight 50-g categories according to body mass (350–750 g) and calculated the frequency of ingested plastic for each category. We used Pearson's correlation to assess whether body mass was related to the incidence of plastic in shearwaters. We also used this test to assess whether body mass was related to the mass, number, or volume of ingested particles. Statistical tests were carried out using $\alpha = 0.05$. Means are presented with standard error.

3. Results

During 1997–1999 and 2001, we collected 330 short-tailed shearwaters, of which 83.9% ($n = 277$) contained plastic. Among birds containing plastic, most (94.2%) had plastic in their gizzard; plastic in the proventriculus was less common (33.2%). We found a total of 1924 plastic particles. The mean mass of plastic per bird was 114 ± 7.8 mg (136 ± 8.7 mg per bird containing plastic). The mean number of particles per bird was 5.8 ± 0.4 (6.9 ± 0.4 particles per bird containing plastic), and the mean volume of plastic per bird was 199 ± 18 mm^3 (237 ± 21 mm^3 per bird containing plastic).

3.1. Temporal variation in the frequency and amount of ingested plastic

3.1.1. Annual differences

From Ogi (1990), we calculated an increase in the incidence of ingested plastic in shearwaters in the Bering Sea from 1970 to 1978 ($r^2 = 0.84$, $F_{1,4} = 15.58$, $P = 0.029$; Fig. 2(A)). This increase was also evident when Ogi also considered shearwaters collected in the North Pacific Ocean. In contrast, we found that the occurrence of plastic in shearwaters in the Bering Sea showed no significant change from 1976 to 2001 ($r^2 = 0.39$, $F_{1,7} = 3.78$, $P = 0.100$; Fig. 2(A)). When we considered plastic found in shearwaters throughout the subarctic Pacific by other authors, we observed a slight, but nonsignificant, decline in the occurrence of plastic since 1976 ($r^2 = 0.24$, $F_{1,13} = 3.84$, $P = 0.074$; Fig. 2(A)). Among shearwaters in the Bering Sea, no significant change was evident in the mean mass of plastic per bird since 1973 ($r^2 = 0.0003$, $F_{1,5} = 0.001$, $P = 0.974$; Fig. 2(B)) or the mean number of plastic particles per

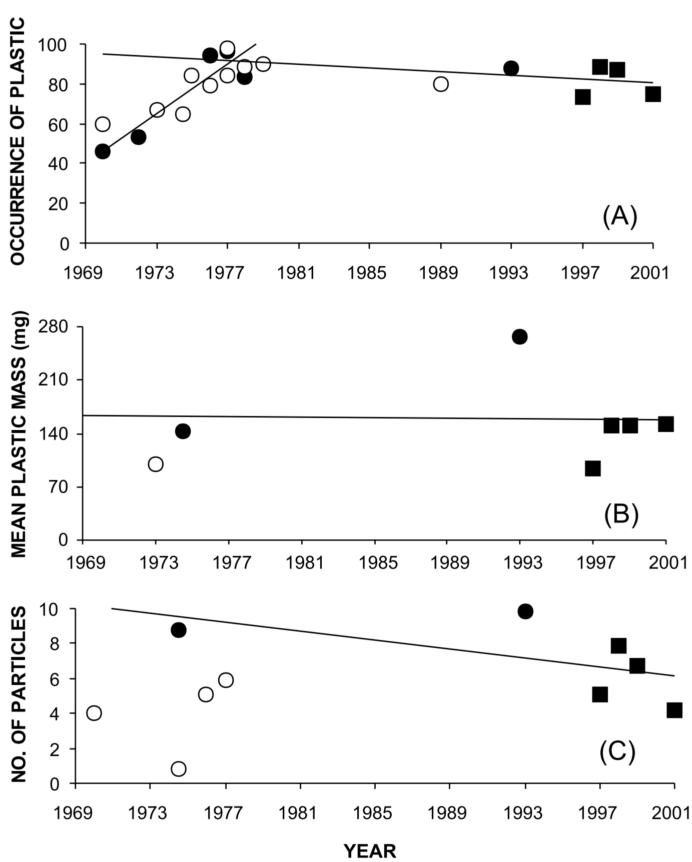

Fig. 2. (A) Incidence of ingested plastic found in short-tailed shearwaters in the Bering Sea (●; Ogi, 1990, this study) and subarctic Pacific Ocean (○; Day, 1980; Robards et al., 1995). Dashed lines indicate duration over which mean incidence of ingested plastic was derived. Solid lines are regression lines for birds collected in the Bering Sea during 1970–1979 and 1976–2001. (B) Mass of plastic and (C) number of plastic particles found in shearwaters in the Bering Sea and subarctic Pacific Ocean. See Appendix A for sample sizes.

bird since 1969–1971 ($r^2 = 0.21$, $F_{1,5} = 0.78$, $P = 0.441$; Fig. 2(C)).

3.1.2. Monthly differences

Shearwaters collected during July contained more plastic than birds collected during any other summer month. This pattern was evidenced by seasonal peaks in the incidence of ingested plastic ($\chi^2_4 = 13.68$, $P = 0.008$; Fig. 3(A)), mass of plastic ($\chi^2_4 = 23.57$, $P < 0.001$; Fig. 3(B)), number of plastic particles ($\chi^2_4 = 30.95$, $P < 0.001$; Fig. 3(C)), and volume of plastic particles present ($\chi^2_4 = 24.88$, $P < 0.001$, Fig. 3(D)).

3.2. Characteristics of ingested plastic

3.2.1. Type

The most common type of plastic found in shearwaters in this study was user plastic, followed by industrial pellets. Shearwaters contained a small proportion of other refuse, such as vinyl, rubber, and string (Table 1).

3.2.2. Color

Shearwaters contained plastics that were primarily light in color, such as white, yellow, and yellow–brown. Plastics that were medium in hue, such as brown, blue,

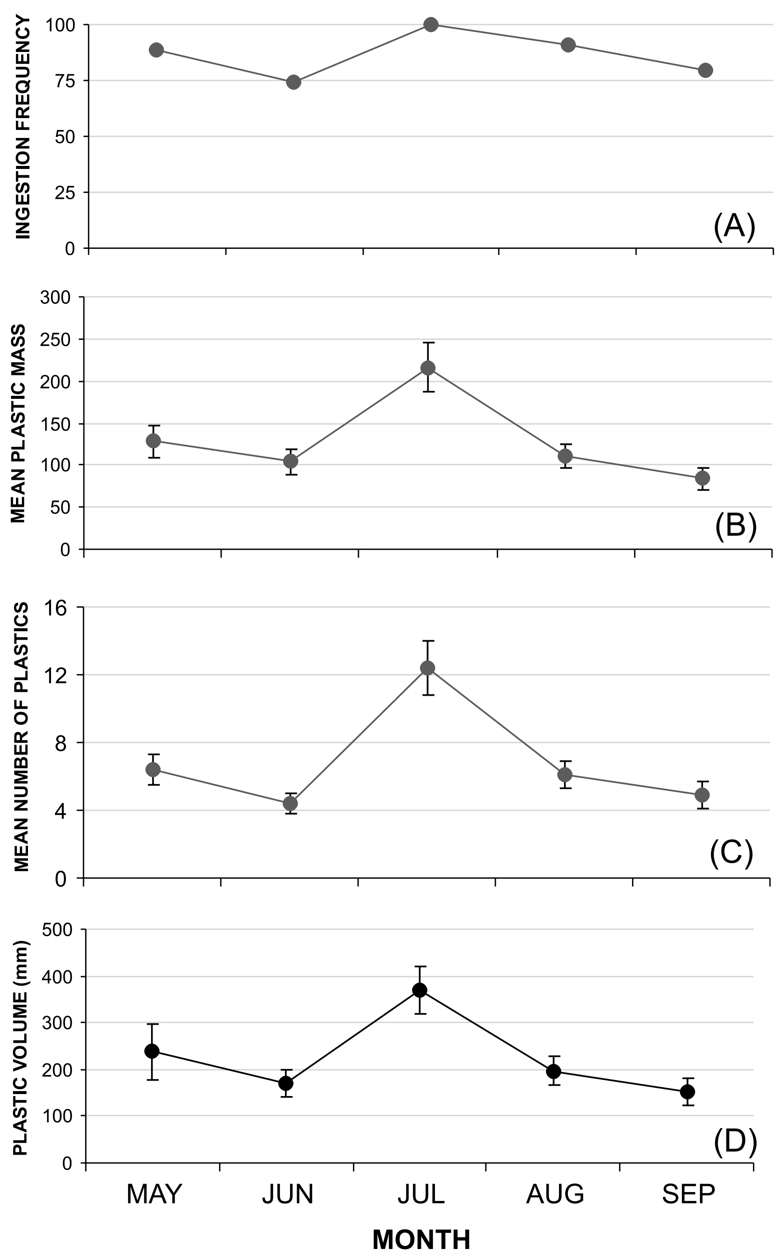

Fig. 3. (A) Monthly incidence of ingested plastic in short-tailed shearwaters collected in the southeastern Bering Sea, May–September, 1997–1999 and 2001. Numbers are sample sizes. (B) Mean (±SE) mass (C) number, and (D) volume of plastic particles per bird collected during each month.

Table 1
Type of plastic particles found short-tailed shearwaters collected in the subarctic Pacific Ocean, 1969–1977 (Day, 1980) and 1970–1979 (Ogi, 1990), and the Bering Sea, 1997–1999 and 2001 (this study)

Plastic type	% Plastic particles		
	1969–1977 (n = unk)	1970–1979 ($n = 2330$)	1997–1999, 2001 ($n = 1674$)
Industrial pellets	72.5	54.6	32.9
User plastic	25.6	39.1	63.9
Other	1.9	16.5	3.2

Table 2
Percentage of plastic particles of various color found in the stomachs of short-tailed shearwaters collected in the subarctic Pacific Ocean, 1969–1977 (Day, 1980) and 1970–1979 (Ogi, 1990), and the Bering Sea, 1997–1999 and 2001 (this study)

Color	% Plastic particles		
	1969–1977 (n = unk)	1970–1979 ($n = 2330$)	1997–1999, 2001 ($n = 1674$)
Light			
White	18.2	27.4	33.8
Yellow	0.7	2.5	11.5
Yellow–brown	55.1	35.4	19.7
Total	74.0	65.3	65.0
Medium			
Brown	11.0	16.9	13.9
Blue	4.8	2.4	2.9
Green	4.8	5.4	7.2
Red	2.4	3.0	4.1
Total	23.0	27.7	28.1
Dark			
Dark blue	na	0.3	0.4
Dark green	na	0.5	0.4
Dark red	na	0.3	1.5
Grey–black	2.9	6.0	4.7
Total	2.9	7.1	7.0

green, and red were present only a quarter of the time. Dark plastics were rarely found (Table 2).

3.3. Ingested plastic in relation to sex and body mass

3.3.1. Sex

Although we could not discern males and females during collection, we obtained individuals of each sex in approximately equal proportion (F: 44.5%, M: 44.5%, unknown: 11.0%). We found no difference in mean body mass between males and females (F: 552 g, M: 540 g; t^2-test: $t^2_{292} = 1.41$, $P = 0.158$). There were also no differences between the sexes in the occurrence of plastic (F: 83%, M: 84%; $U = 21,609$, $P = 0.877$), mean mass of plastic (F: 119 mg, M: 108 mg; $U = 21,271$, $P = 0.792$), number of particles (F: 5.6 particles, M: 6.2 particles; $U = 21,231$, $P = 0.534$), or volume of ingested plastic (F: 192 mm^3, M: 201 mm^3; $U = 20,930$, $P = 0.975$).

3.3.2. Body mass

Birds containing no plastic were similar in body mass to birds containing plastic (t-test; d.f. = 328, $t^2 = 0.21$, $P = 0.833$). Similarly, we found no correlation between body mass and the occurrence of plastic ($n = 8$, Pearson's $r = -0.41$, $P = 0.313$; Fig. 4(A)) and mass of plastic ($n = 325$, $r = -0.07$, $P = 0.197$; Fig. 4(B)). However, there was a weak, negative correlation between body mass and the number of plastic particles ($n = 325$, Pearson's $r = -0.14$, $P = 0.010$; Fig. 4(C)). We found no correlation between body mass and the volume of ingested plastic ($n = 324$, $r = -0.09$, $P = 0.118$; Fig. 4(D)).

4. Discussion

4.1. Temporal trends in the occurrence, amount, and characteristics of ingested plastic

The incidence of plastic in short-tailed shearwaters remains among the highest reported in all seabird species to date, with over 80% of individuals containing plastic (Baltz and Morejohn, 1976; Day, 1980; Ogi, 1990; Robards et al., 1995; this study). Such high levels have only been observed in recent decades. In the early 1950s and 1960s, plastic was virtually absent from shearwaters on their southern breeding grounds (as cited in Day et al. (1985)), but by the late 1970s, plastic was found in over one third of breeding shearwaters examined (Skira, 1986). Increases in plastic load in shearwaters were also observed on northern wintering grounds during this time. In the early 1970s, over half of shearwaters examined in the subarctic Pacific contained plastic (Day, 1980; Ogi, 1990), and from the early to late 1970s, Ogi (1990) noted a twofold increase in the incidence of plastic in shearwaters in the Bering Sea. Like other authors, Ogi attributed this increasing trend in plastic ingestion to increases in worldwide plastic production and subsequent pollution. By the late 1980s, many seabirds from throughout the subarctic Pacific had shown further increases (13–26%) in the occurrence and amount of ingested plastic, including northern fulmars (*Fulmarus glacialis*), Leach's storm-petrels (*Oceanodroma leucorhoa*), pelagic cormorants (*Phalacrocorax pelagicus*), mew gulls (*Larus canus*), red-legged kittiwakes (*Rissa brevirostris*), and parakeet auklets (*Aethia psittacula*; Robards et al., 1995).

Despite more than a twofold increase in worldwide plastic production between the mid 1970s and 2001 and an increase in plastic pollution in the Bering Sea from 68 particles/km^2 in 1974–1976, to 80 particles/km^2 in 1985, to 600 particles/km^2 in 1988 (Day et al., 1990), we observed no significant change in the occurrence and amount of plastic in short-tailed shearwaters in the Bering Sea from 1976 to 2001. When we considered shearwaters from elsewhere in the subarctic Pacific, we

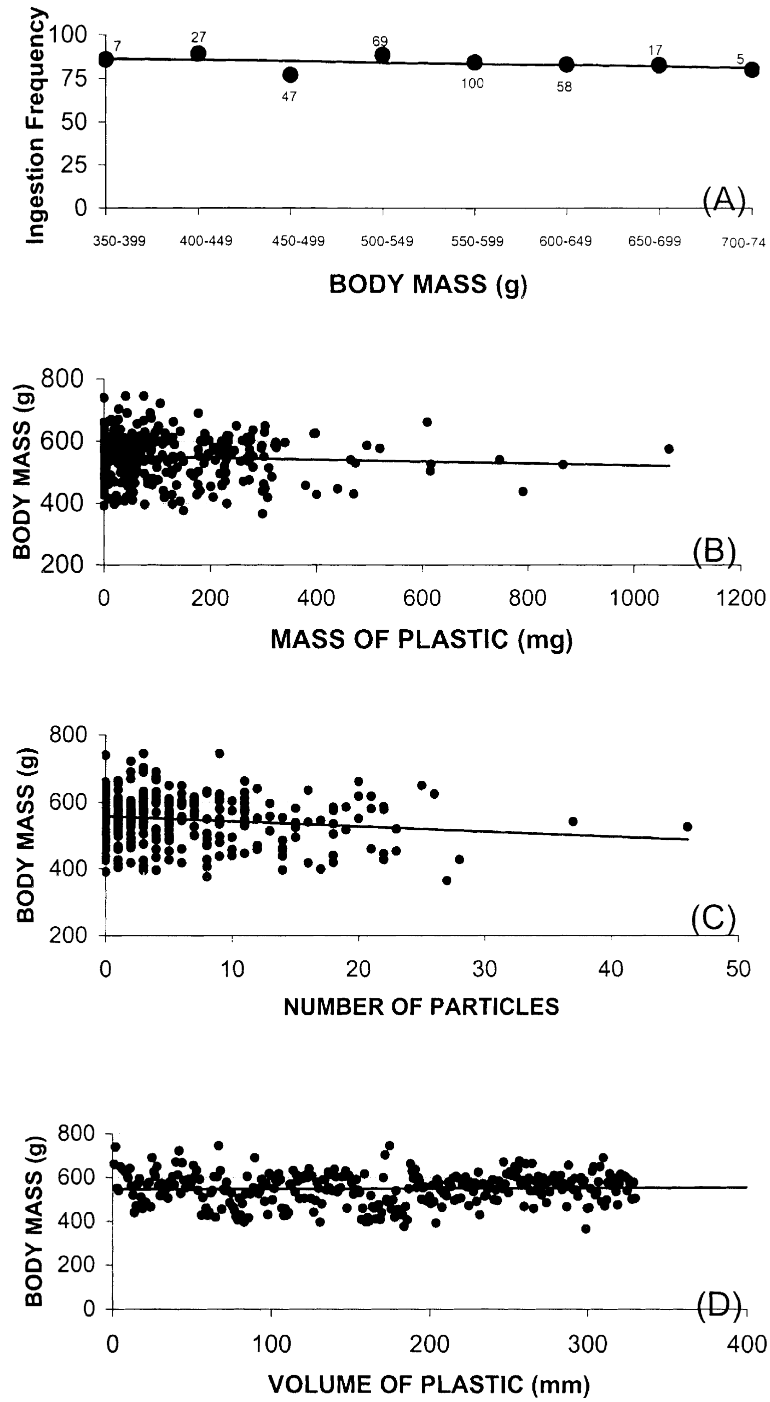

Fig. 4. (A) Incidence, (B) mass, (C) number, and (D) volume of ingested plastic particles found in short-tailed shearwaters collected in the south-eastern Bering Sea, 1997–1999 and 2001, relative to shearwater body mass. Numbers are sample sizes.

found a slight but nonsignificant decline over time in the occurrence of ingested plastic. This result is consistent with Robards et al. (1995) who found that a slightly lower proportion (3%) of shearwaters in the subarctic Pacific contained plastic in 1988–1990 than in 1969–1977. Our observations suggest that plastic ingestion has stabilized in this species in the Bering Sea and possibly elsewhere over the last decade or even as early as the late 1980s. This finding is notable because the incidence of plastic in seabirds did not reflect the observed rise in worldwide plastic production since the 1970s, but the lack of increase is somewhat consistent with expectations that plastic ingestion would decline following the enactment of Annex V of MARPOL, which prohibits the disposal of plastic material at sea. This trend may not be limited to shearwaters in the subarctic Pacific: between the mid 1980s and 1990–1991, Spear et al. (1995) reported a significant decline in the incidence of plastic in five Procellariids (not including short-tailed shearwaters) in the tropical Pacific.

In contrast to the lack of change in the incidence of plastic in shearwaters in the Bering Sea over the last three decades, we observed a shift over time in the type of plastic consumed. During the 1970s, industrial pellets were reported to be the most common type of plastic consumed by shearwaters, as they composed over half (55–73%) of plastics found in shearwaters collected throughout the subarctic Pacific (Table 1). In 1974–1975, industrial pellets also composed over 90% of plastics found in short-tailed shearwaters collected off the coast of California (Baltz and Morejohn, 1976). They also made up the majority (70–76%) of plastics found in a combined sample of 16 other seabird species, especially among diving birds, from the subarctic Pacific Ocean during the 1970s and 1980s (Robards et al., 1995). In contrast, we found shearwaters consuming predominantly user plastic (64%), such as plastic molding from buckets, bottles, and other miscellaneous products. This result is similar to that of a more recent study conducted in 1987, in which most (71%) of the plastic found in eleven seabird species (not including short-tailed shearwaters) in the North Pacific was user plastic (Blight and Burger, 1997).

The shift in the type of plastic found in shearwaters coupled with no significant change in the incidence of plastic suggests that the type of plastic available to birds in the Bering Sea has changed since the 1970s. Specifically, the regional availability of industrial pellets appears to have declined. This decline could have arisen in response to landscape-level shifts in the distribution of this type of plastic pollution in the ocean or reductions in pollution from one or both of its major sources: outflow from plastic production plants and spillage from cargo ships (Environmental Protection Agency, 1992). Reductions in pollution from these sources were also hypothesized by Day et al. (1986) after observing that the most common type of plastic caught in neuston net tows in the North Pacific changed from industrial pellets in 1972 (Wong et al., 1974) to user plastic in 1985 (Day and Shaw, 1987) and 1986 (Day et al., 1986).

It is unclear whether there has also been a decline in the availability of user plastic to shearwaters, as a decline in industrial plastic alone may have offset the expected rise in plastic ingestion by shearwaters following increases in plastic production and subsequent pollution. The primary source of user plastic in the Bering Sea is presumed to be waste disposal from cargo and fishing vessels (Environmental Protection Agency, 1992). Ship-based pollution was expected to decline following the enactment of Annex V of MARPOL in 1988, which prohibits the disposal of plastic material at sea (Edwards and Rymarz, 1990). However, there has been some question about the effectiveness of MARPOL due to difficulties in enforcement (Ijlstra, 1989). In addition, changes in the availability of plastic to marine life may vary among regions without producing a change in availability on larger scales. For example, one study documented no change in the number of Hawaiian monk seals (*Monachus schauinslandi*) entangled in user debris (e.g., fishing line and nets) in Hawaii up to six years before and eight years after MARPOL Annex V (Henderson, 2001). In contrast, Johnson (1994) observed a post-MARPOL decline in the deposition of user debris on beaches in Alaska. It is also hard to assess whether changes in the type of plastic ingested by shearwaters is related to changes in plastic pollution imposed by MARPOL, as a shift in the predominant type of neuston plastic pollution was observed in the Bering Sea as early as 1985 (Day et al., 1990). Independent surveys of plastic density in the southeastern Bering Sea are needed to determine whether long-term shifts have occurred in the composition and abundance of plastic pollution available to seabirds. Surveys of neuston plastic in the Bering Sea are available from the 1970s (Shaw, 1977) and 1980s (Day and Shaw, 1987). We are unaware of such surveys from the 1990s or thereafter.

Seasonal patterns in the occurrence and amount of ingested plastic in shearwaters also differed from those reported 30 years ago. During the 1970s, shearwaters showed a bimodal peak in the occurrence of ingested plastic during the nonbreeding season, with highest levels during June and August (Day, 1980; Ogi, 1990). In contrast, we found that shearwaters collected during July contained more plastic than those collected during any other summer month. Because plastic can remain in seabird stomachs for up to two years (Ryan and Jackson, 1987), shearwaters may have acquired their plastic on northern wintering grounds, southern breeding grounds, or both. Seasonal variation in ingested plastic therefore likely does not reflect short-term (monthly) fluctuations in plastic ingestion. Ryan (1988b) proposed an 'annual cycle hypothesis' to explain intra-annual variation in plastic consumption by seabirds, in which he specifically addressed short-tailed shearwaters. He hypothesized that birds accumulate plastic during the nonbreeding season, but plastic loads decrease during the breeding season as birds offload plastic to young during regurgitation. Skira (1986) observed that, despite proposed difficulties shearwaters have in offloading plastic to young, the incidence of plastic in shearwaters indeed decreased at her study site during the breeding season. However, we did not find a steady increase in plastic load during the nonbreeding season. We posit that seasonal variation in the incidence and amount of ingested plastic may reflect a combination of processes that are as yet unexplored, including possible age-related differences in plastic ingestion and timing of arrival to the Bering Sea. In addition, reasons for a change in the seasonal pattern of plastic load from a bimodal pattern in the 1970s to a unimodal pattern today are unclear. Factors that shape seasonal patterns in plastic ingestion by seabirds merit further attention.

Preference for plastic of a certain color has been noted in many seabirds and is presumably linked to conspicuousness of bright colors or, more often, resemblance of plastic to prey (Day, 1980). For birds with color preferences, changes in the color of plastic pollution in the ocean may influence the rate at which they consume plastic. Day (1980) suggested that the high variation in the color of plastics taken by shearwaters indicates that this species has little color preference. Conversely, our observation that they took each color in consistent proportion over three decades may indicate a general preference for plastics that are light in color. Shearwaters in the southeastern Bering Sea feed mainly on euphausiids, which are also light in color, and shearwaters might mistake plastic for prey. Of course, without direct sampling of plastic availability, it is impossible to know whether shearwaters have color preferences, as colors taken may simply reflect availability.

4.2. Ingested plastic and shearwater body mass

The primary mechanism by which plastic is thought to impair seabird health is through digestion impediment, in which plastic either simulates satiation, causes ulceration of the stomach lining, or obstructs the proper passage of food (Day et al., 1985). There is some evidence that plastic impedes digestion and slows growth in chickens (*Gallus domesticus*; Ryan, 1988a), but when white-chinned petrels (*Procellaria aequinoctialis*) were fed plastic, they showed no signs of impaired digestion (Ryan, 1987b). Field studies are also equivocal in their results, as some indicate weak correlations between ingested plastic and seabird body mass (Connors and Smith, 1982; Ryan, 1987b; Spear et al., 1995), while others show no such relationship, even when plastic is present in large amounts (Moser and Lee, 1992).

We observed a weak decline in shearwater body mass with the number of plastic particles in the stomach, but no correlation between body mass and the mass or volume of plastic. These results are similar to those of other studies of plastic in shearwaters and other Procellariiformes (Day, 1980; Ryan, 1987b; Spear et al., 1995; but see Auman et al., 1997), suggesting that shearwater body condition is little, if at all, compromised by plastic, at least at the level at which it is presently found. However, it is also possible that plastic present at levels exceeding those we observed are linked to reduced survivorship, and birds with high-plastic loads died before they were sampled. In this case, we would still expect body condition to decline with increasing plastic load (which we did not observe), unless body condition was affected only above some threshold amount of plastic. This scenario seems unlikely given the wide range of load sizes relative to gizzard size represented by our data. We agree with other authors that experimental studies are needed to determine whether or at what levels plastic ingestion adversely affects seabird health (Furness, 1985a,b; Burger and Gochfeld, 2002).

In conclusion, the incidence of plastic in short-tailed shearwaters remains high in the Bering Sea but appears to have stabilized over the past decade. In contrast, there has been a major change in the type of ingested plastic in shearwaters over time, a pattern which may be linked to a shift in the regional composition of plastic pollution. It is unknown whether the occurrence of plastic has also stabilized in other seabird species in the Bering Sea or elsewhere, as effects may differ among species with different foraging methods and among regions. For example, the Bering Sea appears to contain an order of magnitude less neuston plastic pollution than the North Pacific (Day and Shaw, 1987), and shifts in plastic availability to seabirds in the North Pacific similar to those which may have occurred in the Bering Sea may not result in similar patterns in plastic ingestion by seabirds. We recommend continued monitoring of plastic ingestion by shearwaters and other seabird species. Although plastic ingestion may have leveled off in shearwaters over the past decade, it is unclear how plastic availability and subsequent ingestion by seabirds may change in the future.

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Appendix A

Sources of data on plastic ingestion by short-tailed shearwaters

Year	Location	*N*	Type of collection[a]	Source
1969–1971	Bering Sea, Aleutian Islands, N. Pacific Ocean	14	Healthy birds	Day (1980)
1970	Bering Sea	28	Drowned birds	Ogi (1990)
1972	Bering Sea	51	Drowned birds	Ogi (1990)
1973	N. Pacific Ocean	6	Drowned birds	Ogi (1990)
1974–1975	Bering Sea, Aleutian Islands, N. Pacific Ocean	9	Healthy birds	Day (1980)
1975	N. Pacific Ocean	25	Drowned birds	Ogi (1990)
1976	Bering Sea	73	Drowned birds	Ogi (1990)
1976	Bering Sea, Aleutian Islands, N. Pacific Ocean	33	Healthy birds	Day (1980)
1977	Bering Sea	27	Drowned birds	Ogi (1990)
1977	Bering Sea, Aleutian Islands, N. Pacific Ocean	151	Healthy birds	Day (1980)
1977	N. Pacific Ocean	45	Drowned birds	Ogi (1990)
1978	Bering Sea	12	Drowned birds	Ogi (1990)
1978	N. Pacific Ocean	16	Drowned birds	Ogi (1990)
1979	N. Pacific Ocean	39	Drowned birds	Ogi (1990)
1988–1990	Aleutian Is. and N. Pacific Ocean	5	Healthy birds	Robards et al. (1995)
1993	Bering Sea	8	Healthy birds	G.L. Hunt Jr. (unpubl. data)
1997	Bering Sea	97	Healthy birds	this study
1998	Bering Sea	97	Healthy birds	this study
1999	Bering Sea	120	Healthy birds	this study
2001	Aleutian Islands	16	Healthy birds	this study

[a] Healthy birds were secured by shooting. Drowned birds were salvaged from drift nets.

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