© 1997 Springer-Verlag New York, Inc.
Marine Debris, James M. Coe,and
Donald B. Rogers editors

6■

The Highest Global Concentrations and Increased Abundance of Oceanic Plastic Debris in the North Pacific: Evidence from Seabirds

Martin D. Robards, Patrick J. Gould, and John F. Piatt

Introduction

Plastic pollution has risen dramatically with an increase in production of plastic resin during the past few decades. Plastic production in the United States increased from 2.9 million tons in 1960 to 47.9 million tons in 1985 (Society of the Plastics Industry 1986). This has been paralleled by a significant increase in the concentration of plastic particles in oceanic surface waters of the North Pacific from the 1970s to the late 1980s (Day and Shaw 1987; Day et al. 1990a). Research during the past few decades has indicated two major interactions between marine life and oceanic plastic: entanglement and ingestion (Laist 1987). Studies in the last decade have documented the prevalence of plastic in the diets of many seabird species in the North Pacific and the need for further monitoring of those species and groups that ingest the most plastic (Day et al. 1985). Plastics may be consumed because particles resemble prey items (Day et al. 1985, 1990a), or by consuming prey with plastics in their gut (Kartar et al. 1976). In turn, adult seabirds may pass plastics on to chicks by regurgitation (Fry et al. 1987).

Two classes of plastic are commonly found in seabirds (Day et al. 1985; Ryan 1987b): pellets and fragments. Plastic "pellets" (also known as nibs, resins, or cylinders) are the raw product of the plastic industry. Pellets lost at the manufacturing plant or during transportation may enter the marine ecosystem directly or via drainage systems. Plastic "fragments" or "user" plastics are small, weathered pieces of larger manufactured items (e.g., fishing floats, buckets, and bottles) that are discarded or lost at sea, particularly from fishing boats and marine shipping (Scott 1975; Merrell 1980). Other forms of ingested debris include toys, Styrofoam, monofilament line, rubber, and plastic film (Baltz and Morejohn 1976; Day 1980; Robards et al. 1995).

Day (1980) completed the first comprehensive investigation of plastic ingestion by North Pacific seabirds. He analyzed 1968 stomach samples from 37 species of seabirds collected between 1969 and 1977 throughout a wide geographic area of subarctic coastal Alaska. Most specimens were collected at major seabird colonies in the Aleutian Islands (e.g., Buldir Island), and in the northern Gulf of Alaska (e.g., Shumagin, Semidi, and Kodiak Islands). He found plastic in 15 of the 37 seabird species collected. The frequency of plastic particle ingestion varied among species and was most prevalent in surface feeders such as fulmars, some shearwaters, petrels, and phalaropes (Day 1980), as well as some planktivorous diving species (e.g., auklets). Similar results have been observed in other studies (Ryan 1987b; Moser and Lee 1992).

Distribution and abundance of small plastic particles (<25 mm) collected in neuston nets from the North Pacific and Bering Sea were

reported by Wong et al. (1974, 1976), Shaw (1977), Shaw and Mapes (1979), Takatani et al. (1986), Day and Shaw (1987), and Shaw and Day (1994). These studies found that pelagic plastic is most abundant in the central subtropical and western North Pacific, suggesting an association with tanker and general ship traffic in the western Pacific and the "downstream effects" of pollutants entering the ocean near Japan and adjacent countries. Japan and southern California are the two major petrochemical and plastic manufacturing centers in the North Pacific (Guillet 1974; Wong et al. 1976). Plastic entering the ocean in southern California probably moves south away from the subarctic North Pacific in the California Current system. However, this current runs into the Equatorial Current, travels west across the Pacific, and enters the Kuroshio Current that moves north to Japan. Plastic entering the ocean in Japan (or reaching Japan in the Kuroshio Current) probably moves eastward in the North Pacific Drift Current (Day et al. 1985). Of 109 identifiable items ingested by laysan albatrosses on Hawaii, 108 originated in Japan (Pettit et al. 1981). The North Pacific Drift Current splits to form the California and Alaska currents. Of the plastic transported into the northern Gulf of Alaska by the Alaska Current, some apparently moves inshore and is consumed by seabirds. The highest incidence of ingested particles in the subarctic North Pacific (Day 1980) was in the Aleutian coastal waters. Densities of small plastic particles in the subarctic North Pacific and Bering Sea are 26 to 400 times lower, respectively, than in subtropical waters. Of small oceanic plastic particles found in the central North Pacific, 3.7% were pellets and 96.3% were user fragments (Day and Shaw 1987). In contrast, 19% of plastic particles found off southwestern Cape Province, South Atlantic in 1977–1978 were pellets and 39% were user fragments.

Available evidence suggests that plastics are damaging to seabirds when they are consumed in sufficient quantity to obstruct the passage of food or cause stomach ulcers (Fry et al. 1987; Ryan 1987b). Other effects may include bioaccumulation of polychlorinated biphenyls (PCBs) (Aldershoff 1982; Ryan et al. 1988), toxic effects of hydrocarbons (Carpenter et al. 1972), diminished feeding stimulus (Ryan 1988b), reduced fat deposition (Connors and Smith 1982), lowered steroid hormone levels, and delayed reproduction (Azzarello and Van Vleet 1987). However, at present acute effects of plastic ingestion are rarely observed, and chronic effects on body condition are generally equivocal (Day 1980; Ryan 1987c, 1990b; Moser and Lee 1992).

In this paper we present three major findings: (1) the frequency and number of plastic particles ingested by seabirds of the subarctic North Pacific have increased during the past two decades; (2) seabirds collected in the central North Pacific have a higher incidence and quantity of plastic particle ingestion than seabirds collected in the subarctic North Pacific or elsewhere in the world; and (3) experiments to assess the effects of ingested plastic on seabirds are probably underestimating what constitutes a large plastic load.

Methods

Seabirds for this study originated from two main sources. A collection was made in the subarctic coastal area of the North Pacific (1988–1990) in the same season and areas sampled by Day (1980) for temporal comparisons of plastic ingestion. A second collection was made in the central North Pacific (1990–1991) to assess geographic variation in incidence of plastic ingestion and types of plastic ingested.

1988–1990 Sample Collection

Stomach samples of 1799 seabirds comprising 24 species were collected during May 1988 through August 1990 for ongoing long-term studies of feeding ecology. Samples were collected at seven sites in Alaska ranging over a distance of about 2800 km: at Agattu and Buldir Islands in the western Aleutian

Islands, at Aiktak Island in the eastern Aleutian Islands, and Shumagin and Semidi Islands south of the Alaska Peninsula, in Kachemak Bay (lower Cook Inlet), and in Prince William Sound (Fig. 6.1).

To ensure that samples were large enough for statistical comparisons of key species, collections were more extensive for four species: parakeet auklets, tufted puffins, horned puffins, and black-legged kittiwakes (Table 6.1 provides Latin names of sampled species). These species were chosen for intensive study because of their large populations, widespread distribution, ease of collection, and because they had been the focus of the earlier study of plastic ingestion by Day (1980). Stomachs were dissected and contents were preserved in the field.

1990–1991 Sample Collection

Seabirds were collected as part of the National Marine Fisheries Service scientific observer program to assess catch and by-catch of driftnet fisheries. The use of seabirds collected from driftnets for research provides a nondestructive method of collecting large samples of many species.

Seabirds were salvaged from nets from May 1990 until November 1991 (one bird in the database was collected in 1987). The observers worked in the central North Pacific, ranging from 28°N to 47°N and from 145°W to 141°E. After collecting birds from nets, the observers identified, counted, and froze the birds for the duration of the cruise.

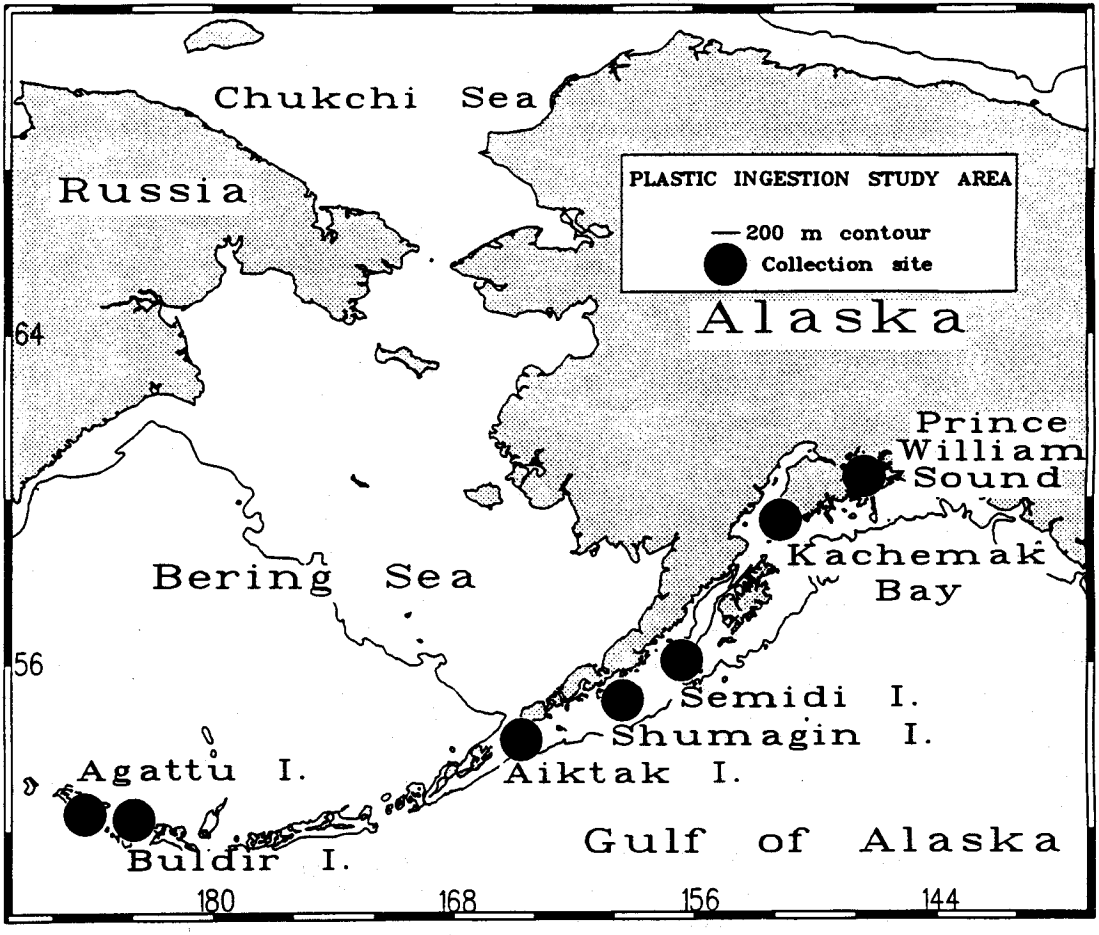

FIGURE 6.1. Location of Subarctic North Pacific sampling areas (*large circles*).

Table 6.1. Percent incidence of plastic ingestion for species collected in the North Pacific.

Common name	Latin name	*Subarctic North Pacific, 1969–1977*[a]		*Subarctic North Pacific, 1988–1990*[b]		*Central North Pacific, 1990–1991*[d]	
		Percent incidence	*n*	Percent incidence	*n*	Percent incidence	*n*
Laysan albatross	*Diomedea immutabilis*	–	–	–	–	93	167
Black-footed albatross	*Diomedea nigripes*	–	–	–	–	45	110
Northern fulmar	*Fulmarus glacialis*	58	38	84	19	88	42
Sooty shearwater	*Puffinus griseus*	43	76	–	–	85	543
Short-tailed shearwater	*Puffinus tenuirostris*	84	200	80	5	88	200
Buller's shearwater	*Puffinus bulleri*	–	–	–	–	98	118
Pink-footed shearwater	*Puffinus creatopus*	–	–	–	–	100	1
Flesh-footed shearwater	*Puffinus carneipes*	–	–	–	–	95	83
Streaked shearwater	*Calonectris leucomelas*	–	–	–	–	0	2
Dark-rumped petrel	*Pterodroma phaeopygia*	–	–	–	–	50	2
Solander's petrel	*Pterodroma solandri*	–	–	–	–	50	2
Mottled petrel	*Pterodroma inexpecta*	–	–	–	–	60	5
Fork-tailed storm-petrel	*Oceanodroma furcata*	100	8	86	21	100	12
Leach's storm-petrel	*Oceanodroma leucorhoa*	25	4	48	64	67	3
Tristam's storm-petrel	*Oceanodroma tristami*	–	–	–	–	100	4
Red-tailed tropicbird	*Phaethon rubricauda*	–	–	–	–	0	1
Pelagic cormorant	*Phalacrocorax pelagicus*	0	3	20	10	–	–
Red-faced cormorant	*Phalocrocorax urile*	0	2	0	16	–	–
Bar-tailed godwit	*Limosa lapponica*	–	–	–	–	100	1
Red-necked phalarope	*Pharlaropus lobatus*	67	3	–	–	–	–
Red pharlarope	*Phalaropus fulicaria*	–	–	–	–	100	1
Pomarine jaeger	*Stercorarius pomarinus*	–	–	–	–	0	1
Long-tailed jaeger	*Stercorarius longicaudus*	–	–	–	–	0	2
South polar skua	*Catharacta maccormicki*	–	–	–	–	50	2
Mew gull	*Larus canus*	0	10	25	4	–	–
Glaucous gull	*Larus hyperboreus*	3	33	–	–	–	–
Glaucous-winged gull	*Larus glaucescens*	0	63	0	21	–	–
Slaty-backed gull	*Larus argentatus*	–	–	–	–	0	1
Black-legged kittiwake	*Rissa tridactyla*	5	188	8	256	0	5
Red-legged kittiwake	*Rissa brevirostris*	13	46	27	15	–	–
Common murre	*Uria aalge*	0	191	1	134	–	–
Thick-billed murre	*Uria lomvia*	1	138	0	92	100	1
Cassin's auklet	*Ptychoramphus aleuticus*	40	10	11	35	–	–
Parakeet auklet	*Aethia psittacula*	75	116	94	208	33	3
Crested auklet	*Aethia cristatella*	0	85	3	40	–	–
Least auklet	*Aethia pusilla*	1	89	0	13	–	–
Whiskered auklet	*Aethia pygmaea*	0	5	0	22	–	–
Ancient murrelet	*Synthliboramphus antiquus*	0	16	0	68	–	–
Marbled murrelet	*Brachyramphus marmoratus*	0	61	0	96	–	–
Kittlitz's murrelet	*Brachyramphus brevirostris*	0	5	0	17	–	–
Pigeon guillemot	*Cepphus columba*	0	18	3	43	–	–
Rhinoceros auklet	*Cerorhinca monocerata*	0	20	0	1	44	9
Horned puffin	*Fratercula corniculata*	37	148	37	120	57	28
Tufted puffin	*Fratercula cirrhata*	15	348	25	489	88	8

[a]Day (1980).
[b]Robards et al. (1995).
[c]Robards (1993).

After the cruise, the birds were sent to seabird biologists to be used for seabird ecology studies, including diet studies. A total of 1357 stomachs from 28 species were used in this study.

Plastic Analysis

The stomachs and gizzards of the collected birds were dissected and food items sepa-

rated from nonfood items. Nonfood items included plastic objects and particles, rubber bands and gloves, cigarette filters, screws and nails, Styrofoam, fibrous wads, wire, stones, and pumice. Most plastic particles were found in the ventriculus (gizzard), and few were found in the proventriculus (stomach).

Nonfood items were analyzed in a manner consistent with previous studies (Day 1980) to allow for comparisons. The number of plastic particles in each stomach were recorded; particles were then weighed and classified according to their color, size (maximum dimension), shape, and type (pellets or user items). For this study, only the size, type, and number of particles were used. For comparison of incidence of ingestion and mean numbers of particles ingested between years and areas, we required a minimum sample size of 15 from each study to reduce potential bias from low sample sizes.

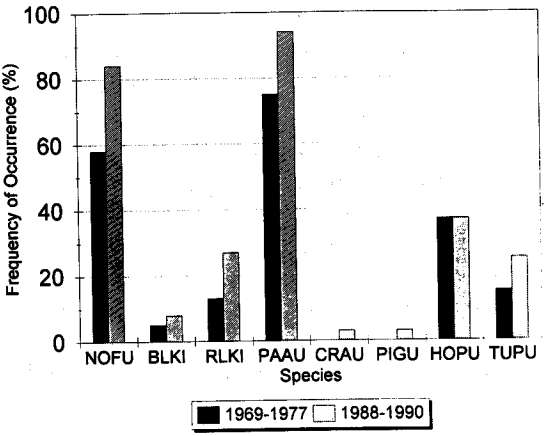

FIGURE 6.2. Temporal change in frequency of occurrence of plastic ingestion by subarctic North Pacific seabirds. *NOFU*, Northern fulmar (*Fulmarus glacialis*); *BLKI*, black-legged kittiwake (*Rissa tridactyla*); *RLKI*, red-legged kittiwake (*Rissa brevirostris*); *PAAU*, parakeet auklet (*Aethia psittacula*); *CRAU*, crested auklet (*Aethia cristatella*); *PIGU*, pigeon guillemot (*Cepphus columba*); *HOPU*, horned puffin (*Fratercula corniculata*); and *TOPU*, tufted puffin (*Fratercula cirrhata*). *Solid bars*, 1969–1977; *hatched bars*, 1988–1990.

Results

Temporal Change in Subarctic North Pacific Plastic Ingestion

Of the 24 species of seabirds that were collected in both Day's (1969–1977) and our (1988–1990) study periods, the number of species that contained plastic particles increased from 12 in the 1970s to 15 in the 1980s.

Of the 17 species found to contain plastic in either study period, plastic ingestion increased in 12 species. Overall, there was a significant (χ^2 = 1100, 16 df, $P < .001$) increase in the frequency of plastic ingestion between the period of 1969–1977 and the late 1980s. Species with high frequencies of occurrence of plastics included all procellarids (fulmar, shearwaters, and storm-petrels), black-legged kittiwakes, parakeet auklets, and horned and tufted puffins. For species with adequate sample sizes, the frequency of plastic ingestion increased over time by 0.2%–26.3% (horned puffin and northern fulmar, respectively) (Fig. 6.2).

Species that did not ingest plastic in any year of study included red-faced cormorant (n = 18), glaucous-winged gull (n = 84), whiskered auklet (n = 27), ancient murrelet (n = 84), marbled murrelet (n = 157), Kittlitz's murrelet (n = 22), and rhinoceros auklet (n = 21). Only 3 of 545 common and thick-billed murres that were examined over all years contained plastic. A low incidence of ingestion was also observed in glaucous gulls and least auklets.

The mean number of particles per bird increased significantly (Mann–Whitney U = 0.87, $P < .05$) between collections of the four key study species (parakeet auklets, tufted and horned puffins, and black-legged kittiwakes) made in 1969–1977 and those from 1988–1990. Parakeet auklets ingested, on average, the most particles of the 1988–1990 study with 17.1 particles per bird (versus 13.7 particles per bird in the 1969–1977 study). Similarly, the weight of plastic ingested by the four key study species increased significantly (Mann–Whitney U = 1.43, $P < .05$) between 1969–1977 and

1988–1990. Maximum numbers of particles varied widely among species (tufted puffin, 51; northern fulmar, 26; black-legged kittiwake, 15; horned puffin, 14; Leach's storm-petrel, 13; fork-tailed storm-petrel, 12). The largest number of particles per individual was 87 in a parakeet auklet.

Of 4417 plastic pellets examined from 15 species collected between 1988 and 1990, the majority were of the two main types: pellets (76.4%) and user plastics (21.5%). The remainder (2.1%) of items were unrecognizable plastic pieces. This was comparable with the 833 plastic particles analyzed by Day (1980), who found 70% pellets and 30% user plastic. Seven seabird species accounted for 98.9% of all particles recovered, and the composition of particles varied greatly among species. Pellets were ingested most by diving species such as tufted puffins and parakeet auklets., while user plastics were common in surface-feeding species such as storm-petrels and kittiwakes. Table 6.1 presents a summary of this study's results as well as the Latin names of each species sampled.

Geographic Variation in North Pacific Plastic Ingestion

Of the species (excluding species with only one sample) collected in the central North Pacific between 1990 and 1991, 5 species (Laysan albatross, Buller's shearwater, flesh-footed shearwater, fork-tailed storm-petrel, and Tristam's storm-petrel) had a plastic incidence of more than 90%, and 4 (northern fulmar, sooty shearwater, short-tailed shearwater, and tufted puffin) had an incidence greater than 80%. Of the 27 species collected in the subarctic North Pacific between 1988 and 1990, only 1 species had an incidence of plastic ingestion greater than 90% (parakeet auklet) and 2 an incidence more than 80% (northern fulmar and fork-tailed storm-petrel).

For the 11 plastic-ingesting species that were represented in both subarctic North Pacific and central North Pacific collections, 9 displayed a higher incidence of ingestion. For the 4 species with adequately sized samples collected in both areas (Fig. 6.3), there was a significantly higher frequency of plastic ingestion in the central North Pacific ($\chi^2 = 9$, 3 df, $P < .05$).

The highest mean number of particles for a central North Pacific seabird species with adequate sample size was 18 for northern fulmars, followed by 16 for Buller's shearwaters and 14 for Laysan albatrosses. The only bird collected in the subarctic North Pacific containing similar mean numbers was the parakeet auklet, which contained 17 particles per individual. Three of the procellariiform species from the central North Pacific had individuals that ingested more than 100 particles. A short-tailed shearwater contained the highest number of particles found in any seabird (135 particles), followed by northern fulmars (114 particles) and sooty shearwaters (108 particles). The highest number of particles ingested by any seabird collected in the

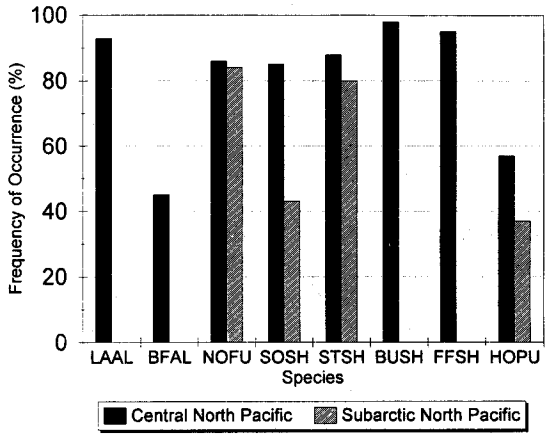

FIGURE 6.3. Frequency of occurrence of plastic ingestion by central North Pacific seabirds, with species collected in subarctic North Pacific added for comparison. *LAAL*, Laysan albatross (*Diomedea immutabilis*); *BFAL*, black-footed albatross (*Diomedea nigripes*); *NOFU*, northern fulmar (*Fulmarus glacialis*); *SOSH*, sooty shearwater (*Puffinus griseus*); *STSH*, short-tailed shearwater (*Puffinus tenuirostris*); *BUSH*, Buller's shearwater (*Puffinus bulleri*); *FFSH*, flesh-footed shearwater (*Puffinus carneipes*); and *HOPU*, horned puffin (*Fratercula corniculata*). *Solid bars*, central North Pacific; *hatched bars*, subarctic North Pacific.

subarctic North Pacific was by a parakeet auklet that contained 87 particles.

As in other studies (Moser and Lee 1992; Ryan 1987b), we found that the weight of particles ingested by central Pacific seabirds to be related to body size. Laysan albatrosses ingested the highest mean loads (1.94 g per bird with a maximum of 39.2 g), and horned puffins the least (0.18 g per bird with a maximum of 1.83 g). However, black-footed albatrosses were an exception to this. They ingested the second highest mass of plastic (11.26 g) but ingested only on average 0.32 g of plastic.

User plastic was the most abundant type of plastic ingested by seabirds in the central North Pacific (24% pellets, 76% user plastic). In contrast, seabirds in the subarctic North Pacific ingested mostly pellets (76% pellets, 22% user plastic, 2% unrecognizable plastic particles). This is consistent with the availability of different types of plastic, most (95%) of which is user type (Day and Shaw 1987). Some of the recognizable plastic objects are consistent with debris originating from dumping as opposed to fishing activities. These objects included plastic cars, game dice, a bubble gum toy case (still with enclosed toy doll), and refrigerator magnets. Debris items of unknown origin included cigarette lighters, plastic wrapping, gloves, cigarette filters, and plastic fittings. Larger plastic particles and objects were found in the larger seabirds such as fulmars and albatrosses, which was also the case in the North Atlantic (Moser and Lee 1992).

Discussion

Temporal Variation

Our study corroborates Day's (1980) finding of widespread ingestion of plastic particles by seabirds in the subarctic North Pacific. If we assume that differences in sampling intensity among species and geographic areas between Day's (1980) and our study do not bias our analyses, then it appears that although the type of ingested plastic has changed little over a 10- to 15-year period, the frequency and quantity of plastic ingestion has increased significantly.

This increase in plastic particle ingestion parallels an observed increase in plastic pollution in the North Pacific during the same time period (Day and Shaw 1987). In subarctic waters and the Gulf of Alaska, levels of small plastic pollution rose from 0–132 particles/km^2 in the mid-1970s to 12,800 particles/km^2 in the mid-1980s (Day et al. 1990b). Similar increases over these time periods were observed in the Bering Sea (68 and 600 particles/km^2, respectively) and in the subtropical waters (100 and 726 g/km^2, respectively).

Similar temporal observations of plastic pollution and ingestion of plastics by seabirds in the North Atlantic have recently been reported by Moser and Lee (1992). They analyzed the stomach contents of 1033 seabirds collected off the coast of North Carolina from 1975 to 1989. Procellariiform birds contained the most plastic, and the frequency of occurrence of plastic increased in 7 of 8 procellarid species during the study period. This increase was attributed to increasing levels of plastic particle pollution in the North Atlantic (Moser and Lee 1992).

Geographic Variation

Incidence and quantity of plastic ingested by different species are influenced by feeding method (Day 1980; Azzarello and van Vleet 1987). Numerous species throughout the world feed to a varying degree by scavenging at the sea surface (Ashmole 1971). This method of feeding is difficult to quantify and may lead to a bias in comparing the quantity of plastic ingested between different species assemblages, depending on the availability of scavengable plastic. However, a higher incidence of plastic ingestion in similar species in specific areas indicates a greater availability of plastic and thus more highly polluted oceanic waters.

Several species that we collected in the central North Pacific for this study were also collected in the same general area by Ogi

(1990). He found an 89% incidence of plastic ingestion in sooty shearwaters (n = 193), and an 82% incidence in short-tailed shearwaters (n = 265) collected in the central North Pacific between 1979 and 1987. This compares closely with our results of an 85% incidence of plastic ingestion in sooty shearwaters (n = 543) and 88% incidence in short-tailed shearwaters (n = 200).

If collection of seabirds from drift nets does not significantly bias the sample toward seabirds with higher plastic loads, then it appears that seabirds collected in the central North Pacific ingest plastic at a higher frequency than seabirds collected in the subarctic coastal area of Alaska. The composition of plastic in central North Pacific seabirds indicates a strong correlation between plastic ingested and availability of plastic in the oceanic surface waters, fragments of user plastic being the most common form of ingested plastic as well as the most common form of plastic in neuston trawls of central North Pacific surface waters (Day and Shaw 1987).

Apart from plastic ingestion studies involving only a few species, several recent studies have investigated large species assemblages around the world. The most comprehensive studies examined 36 species collected in the tropical Pacific (Ainley et al. 1990b; Spear et al. 1995); 38 species collected off North Carolina in the North Atlantic between 1975 and 1989 (Moser and Lee 1992); 15 species collected from Gough Island in the central South Atlantic Ocean (Furness 1985a); 60 species collected in the southern hemisphere, mostly off South Africa (Ryan 1987b); and 23 species collected in the Antarctic (Ainley et al. 1990a).

Four species collected in the North Pacific were also collected as part of these other studies, allowing for a direct comparison of plastic ingestion between areas (Table 6.2). These results indicate that seabirds in the central North Pacific have the highest frequency of plastic ingestion. Northern fulmars have also been collected on the European coast (Van Franeker 1985), with an incidence of plastic ingestion of 92% (n = 96), the highest known incidence of plastic ingestion for fulmars. However, these birds were collected dead off beaches, which probably biased results when comparing to collections of live fulmars. These fulmars contained a mean number of 11.9 plastic particles per bird (maximum, 96), which was less than the mean number of 18 particles (maximum, 114) found in birds collected in the central North Pacific.

Taxa at the family level were used for comparisons between areas with different species assemblages. Highest known incidences of plastic ingestion from around the world are compared with incidences in seabirds from the North Pacific in Table 6.3. For five species of South Atlantic albatross collected by Ryan (1987b), the highest incidence was only 11%, by a sample of 18 black-browed albatrosses (*Diomedea melanophris*). The species with highest incidence of ingested plastic in the seven recent studies of large species assemblages are presented in Table 6.4 The subarctic North Pacific study

Table 6.2. Percent incidence of plastic ingestion for species found in a variety of global areas.

Species	*Central North Pacific (n)*[a]	Subarctic North Pacific (*n*)[b]	Tropical Pacific (*n*)[c]	North Atlantic (*n*)[d]	South Atlantic (*n*)[e]
Northern fulmar	88 (42)	84 (19)	–	86 (44)	–
Sooty shearwater	85 (543)	43 (76)[f]	75 (36)	40 (5)	51 (63)
Leach's storm-petrel	67 (3)	48 (64)	20 (354)	38 (8)	–
Black-legged kittiwake	0 (5)	8 (256)	–	10 (41)	–

[a]Robards (1993).
[b]Robards et al. (1995).
[c]Spear et al. (1995).
[d]Moser and Lee (1992).
[e]Ryan (1987b).
[f]Day (1980) (no sooty shearwaters were collected between 1988 and 1990).

Table 6.3. Highest percent incidence of plastic ingestion and mean number of particles ingested for different seabird families collected in the North Pacific and other areas of the world.

	North Pacific[a]			*Outside the North Pacific*			
Family	*Species (n)*	Percent incidence	Mean particle number	Species (*n*)	Area	Percent incidence	Mean particle number
Diomedeidae	Laysan albatross (167)	93	14	Black-browed albatross (50)[b], *Diomedea melanophris*	South Africa	11	0.2
Procellariidae	Buller's shearwater (118)	98	16	Blue petrel (74)[b], *Halobaena caerulea*	South Africa	92	9.7
Phalacrocoracidae	Red-faced cormorant (16)	0	0	Bank cormorant (167)[b], *Phalacrocorax neglectus*	South Africa	1	<0.1
Laridae	Red-legged kittiwake (15)	27	1	Bonaparte's gull (32)[c], *Larus philadelphia*	North Atlantic	19	3.0
Alcidae	Parakeet auklet (208)	94	17	"Auks" (37)[d]	Scotland	5	–

[a]Robards (1993) and Robards et al. (1995).
[b]Ryan (1987b).
[c]Moser and Lee (1992).
[d]Bourne (1976).

contained five procellariiform species, but is unique in being the only study in which a nonprocellarid (parakeet auklet) is the most common consumer of oceanic plastic.

The family Laridae contains many surface-scavenging species. However, the maximum incidence of plastic ingestion was only 27% by red-legged kittiwakes. Glaucous-winged gulls, with a sample size of 84, displayed a zero incidence of plastic ingestion. Elsewhere in the world, the highest incidence of plastic ingestion was 19% by Bonaparte's gulls (*Larus philadelphia*). These results suggest a behavioral difference for this taxa in their selectivity at identifying food items, or a short residency time for plastic particles in the gut.

Seabirds collected in the tropical Pacific by Spear et al. (1995) indicated seabirds moving south from the North Pacific generally contained more user plastic. In contrast, seabirds migrating north from the South Pacific generally contained more pellets. This corresponds with the high volume of user plastic found in North Pacific surface waters (Day

Table 6.4. Highest incidence of plastic ingestion by seabirds in seven recent studies of large species assemblages.

Location	*Species displaying greatest percent incidence of plastic ingestion (n)*	Percent Incidence
Central North Pacific[a]	Buler's shearwater, *Puffinus bulleri* (118)	98
Subarctic North Pacific[b]	Parakeet auklet, *Aethia psittacula* (208)	94
South Africa[c]	Blue petrel, *Halobaena caerulea* (74)	92
North Atlantic[d]	Northern fulmar, *Fulmarus glacialis* (44)	86
Central South Atlantic[e]	Great shearwater, *Puffinus gravis* (13)	85
Tropical Pacific[f]	Sooty shearwater, *Puffinus griseus* (36)	75
Antarctica[g]	Blue petrel, *Halobaena caerulea* (62)	56

[a]Robards (1993).
[b]Robards et al. (1995).
[c]Ryan (1987b).
[d]Moser and Lee (1992).
[e]Furness (1985a).
[f]Spear et al. (1994).
[g]Ainley et al. (1990a).

and Shaw 1987) and in seabirds of the central North Pacific.

In conclusion, some of the highest global incidence of plastic ingestion occurs in central North Pacific seabirds, and this corresponds to high plastic concentrations in oceanic surface waters. Input of plastic to the North Pacific Ocean from mainland and shipping sources, coupled with the currents and convergencies of the region, concentrate marine debris on the ocean surface at levels that appear higher than for any other oceanic region of the world.

The only solution to remedy this problem is to reduce the density of plastic particles at sea. Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL), which came into force in 1988 and prohibits dumping of all plastic at sea, may have already reduced the input of plastic to the North Pacific. Preliminary data from work completed in the early 1990s by Spear et al. (1994) indicate that increased frequency of ingestion may be dropping slightly. Further study of procellarid species will help track continued changes in levels of oceanic plastic debris.

Effects of Plastic Ingestion

There have been several studies using birds artificially loaded with plastic particles to assess the effects of plastic ingestion (Ryan 1990b, Sileo, L., U.S. Fish and Wildlife Service, unpublished data). These investigations showed some evidence of detrimental health effects from ingested plastic particles, particularly in relationship to growth and feeding desire. However, smaller plastic loads were used than for equivalent species or for similarly sized birds found wild in the central North Pacific. To produce more conclusive evidence of chronic health effects, these experiments need to be repeated using plastic loads closer to the maxima found in wild populations of similar species. Results can then be applied to wild populations of seabirds that have known levels of plastic ingestion.

A search for correlations between plastic load and health indices for wild populations of seabirds has been generally unsuccessful in producing any more than indirect evidence of chronic health effects (Day 1980; Connors and Smith 1982; Ryan 1990b). These investigations used collections of wild birds, with maximum numbers of ingested plastic particles less than that observed for similar species in the central North Pacific. Spear et al. (1994) is the only investigation at present to show a statistically significant negative correlation between plastic loads and body weight. However, it may be impossible to demonstrate direct cause-and-effect relationships between plastic ingestion and body condition in wild seabirds because of natural variability in the environment and the fact that affected birds may quickly disappear (die) from sampled populations. Statistical confirmation of impacts using carefully controlled experiments is of primary importance for future study.

Acknowledgments. We thank Jay Pitocchelli, and the crew of the M/V *Tiglax* (Alaska Maritime National Wildlife Refuge), for logistic support and help in collection and processing of the subarctic birds [all specimens were collected under state and federal permits issued to J. Piatt]. Assistance in the field was also provided by John Wells, Andrea MacCharles, Alan Springer, Gus van Vliet, Bay Roberts, Leslie Pulcher, Mark Holmgren, John Lang, and Vernon Byrd. We thank Chris Babcock, Karen Laing, Bay Roberts, and Gerry Sanger for help during project planning and data analysis. The Marine Mammal Laboratory of the National Marine Fisheries Service and Region 7 of the U.S. Fish and Wildlife Service provided financial support for this project. We especially thank Linda Jones and Kenton Wohl of those organizations. We thank all the people who cooperated in the 1989–91 High Seas Driftnet Observer Programs for their help in obtaining the data used in this study, and especially Shannon Fitzgerald, Greg Morgan, and Dan Waldek. Larry Spear of Point Reyes Bird Observatory sorted the stomachs. Finally, thanks go to Peter Ryan, Gerry Sanger, Carolyn Gove, Mary Cody, and Cott Mignery for help with analysis of plastic particles and the preparation of this manuscript.