ELSEVIER

Marine Environmental Research, Vol. 40, No. 2, pp. 123–146, 1995

0141-1136/95/$9.50 + 0.00

0141-1136(94)00140-5

Incidence of Plastic in Seabirds from the Tropical Pacific, 1984–91: Relation with Distribution of Species, Sex, Age, Season, Year and Body Weight

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(Received 2 May 1994; revised version received 7 August 1994; accepted 16 August 1994)

ABSTRACT

The incidence of plastic in seabirds was studied (number of individuals of a species containing plastic per number inspected, and number of particles per individual), in 1574 individuals representing 36 species of seabirds collected in the tropical Pacific, mostly between 110 and 150°W longitude, from 1984 to 1991. Incidence of plastic was lower in resident species compared to those which bred to the south or north but wintered in the region, and especially when compared to species that crossed the tropics in migration between the South and North Pacific. Seasonal and age-related patterns in incidence of plastic, number of particles, and particle type (pellets versus user-plastic) among a group of five Procellariiform species (each with > 5% of the individuals containing plastic and for which samples were > 20 birds) indicated that degradation for an individual particle in the gizzard required less than one year, and that little plastic was regurgitated by parents to chicks. Two patterns emerged from this data regarding body weight: (i) heavier birds (for a given species, age-class, season and year) were more likely to contain at least some plastic, from which we hypothesize that birds in better physical condition fed more often in areas where higher densities of plastic and food are found, such as fronts and convergences; and (ii) among individuals who contained plastic (grouped by species), there was a significant negative correlation between number of

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plastic particles and body weight. This is the first solid evidence for a negative relationship between plastic ingestion and physical condition in seabirds. The likelihood that higher quality individuals are more prone to ingestplastic has serious implications regarding health of some seabird populations.

INTRODUCTION

Ingestion of plastic by seabirds was first discovered in the early 1960s (reviewed in Day, 1980; Harper & Fowler, 1987), and has since been recorded in at least 108 (approximately 35%) of the world's seabird species (Day *et al.*, 1985; Ryan, 1987*a*; Ainley *et al.*, 1990*a*; Ainley *et al.*, 1990*b*; Sileo *et al.*, 1990; Moser & Lee, 1992; Laist, in press). Incidence of plastic, often of considerable volume per stomach, can exceed 80% in species frequenting waters adjacent to urbanized areas (reviewed in Ryan, 1990). Areas where ingestion of plastic was high include the eastern and western North Pacific (Baltz & Morejohn, 1977; Day *et al.*, 1985; Ainley *et al.*, 1990*a*; Sileo *et al.*, 1990), the South Pacific off Australia and New Zealand (Day *et al.*, 1985; Harper & Fowler, 1987; Van Franeker & Bell, 1988), the eastern South Pacific (Ainley *et al.*, 1990*a*), the eastern South Atlantic, southeast Indian Ocean (Ryan, 1987*b*; Ryan, 1988) and western North Atlantic (Moser & Lee, 1992).

Despite the enormous area polluted by plastic particles, and high intake of plastic by seabirds, few studies have found evidence suggesting that ingested plastic may have a negative effect on seabird populations. Negative findings include (i) degradation of the digestive tract (Pettit *et al.*, 1981), and (ii) an (insignificant) reduction of body weight and/or fat load (Day, 1980; Connors & Smith, 1982; Furness, 1985*a*; Furness, 1985*b*; Ryan, 1987*a*). However, interpretation of correlations between plastic load and body condition is difficult without controlling for the effects of such factors as reproductive status and season (Ryan, 1990). Other studies did not find a relation between presence of plastic and body weight (Ryan, 1987*a*), assimilation efficiency (Ryan & Jackson, 1987), or stomach fullness (Moser & Lee, 1992).

Day *et al.* (1985) concluded that plastic stays in the digestive tract of seabirds until it degrades or is regurgitated, and that degradation of a particle requires about six months. However, Ryan & Jackson (1987) estimated a retention period of one to two years. Ryan (1988) also suggested that seasonal variation in plastic loads resulted mainly from breeding adults off-loading plastic when feeding young. Findings of Ainley *et al.* (1990*a*) for transequatorial seabirds migrants did not support the off-loading hypothesis, and indicated a retention time of six months or slightly longer.

To our knowledge, the study of Ainley *et al.* (1990*a*) was only the second (see Ainley *et al.*, 1990*b*) to examine incidence of plastic among seabirds collected in an area (the eastern and central tropical Pacific) devoid of urbanization and where pollution was not severe (see Results section for quantitative assessment of neuston plastic). Sampling of seabirds as they migrate through non-polluted waters provides an ideal natural experiment. Incidence of plastic can be examined as birds pass both ways between breeding and wintering areas, thus providing important information regarding (i) retention time of plastic particles and (ii) location where ingestion is occurring.

Ainley *et al.* (1990*a*) presented data on 921 seabirds of 39 species collected from 1984 to 1988. In the present paper the sample is updated to include another 720 seabirds collected during 1989-91. Incidence of plastic as related to parameters (i) and (ii) above, and three categories of 'age' is re-examined. Exploratory analyses are also presented on the relationship with sex, season, year and body weight, as well as results of a four-year study (1988–91) on distribution and quantity of neuston plastic in the study area.

METHODS

Data collection

During 12 cruises over the eight-year period, six each in spring and autumn, 1641 seabirds of 54 species were collected using a shotgun. The main aim was to study the relationship between community structure, occurrence patterns and food-web characteristics. The study area was between lat. 15°N and 15°S and long. 85° to 172°W. Most collecting was done at the same locations each year (Fig. 1), which included convergence zones between the three major current systems of the tropical Pacific, the North Equatorial Current, Equatorial Countercurrent, and the South Equatorial Current. During examination of proventriculi and gizzard contents, the presence or absence of plastic particles was noted, and except for 1984, the number of pieces was recorded. In years 1989-91, the size and type of particle was recorded. Particle types included industrial 'pellets' (the raw material shipped in bulk carriers and from which most plastic products are manufactured Heneman, 1988), and 'user fragments' from broken plastic products. Nylon fishing line or rope, or plastic bag, was

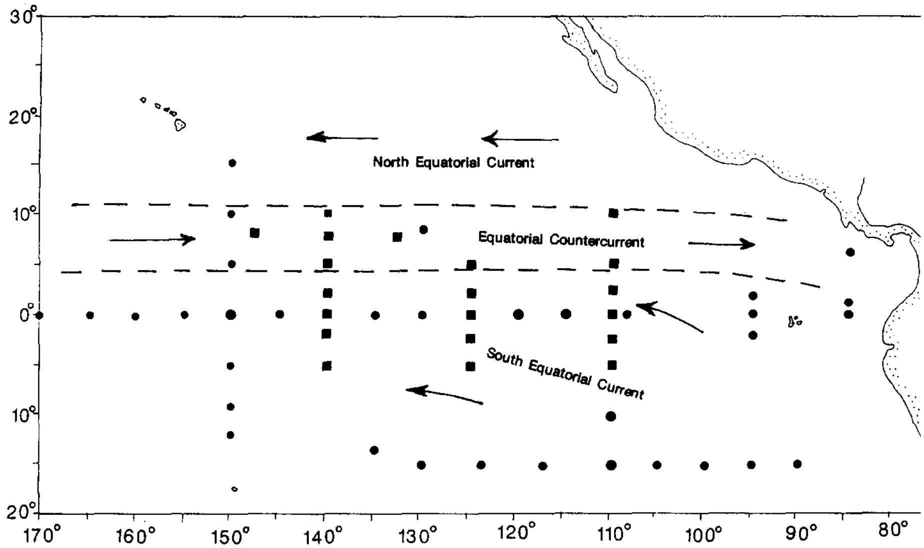

Fig. 1. Study area in the eastern and central tropical Pacific, including the three major current systems of the region. Squares denote sites where neuston tows were conducted concurrently with sampling of seabirds (small squares, on one cruise only; large squares, on two or more cruises). Circles denote sites where seabird collecting was conducted, but not neuston tows (small circles, on one cruise only; large circles, on two or more cruises).

rarely found. For most specimens the sex was also noted, and the width and length of the left testes, and diameter of the largest follicle, was measured. The method of Johnston (1956*a*), Johnston (1956*b*), and Broughton (1994) was followed for estimation of relative age of seabirds. These authors found that testes/follicle size of adults representing long-lived species with delayed age of maturity (gulls *Larus* spp. and albatrosses *Diomedea* spp.) was, for any given season, at least twice as large as that of subadults. Assuming that this relationship existed in the Procellariiformes studied, we separated 'adults' from 'subadults.'

Among subadults, fledglings (birds less than six months old) can be separated by noting plumage condition. Fledglings have fresh, unworn plumage and absence of molt during the post-fledging period whereas other members of the population have worn plumage and are in various stages of molt. For the birds studied, fledgling status was recorded only in the first four months following post-fledging dispersal of a given species.

Birds were weighed to the nearest gram (storm-petrels) or, for larger species, the nearest 5-10 g depending on size. The variable 'season' pertains to boreal unless noted otherwise.

Analyses

Species were grouped into four categories to examine incidence of plastic and patterns of plastic ingestion as related to distribution and migration in the tropics. These included: (i) year-round residents; (ii) those who bred in the South Pacific and wintered in the tropics; (iii) those who bred in the North Pacific and wintered in the tropics; and (4) those who bred in the South Pacific, migrated across the tropical Pacific, and wintered in the North Pacific. Dark- and light-phase wedge-tailed shearwaters (*Puffinus pacificus*) were treated separately because of difference between the two forms in body weight (PRBO, unpubl. data), and because the two forms have different breeding distributions. The light-phase breed primarily in the northern hemisphere and the dark-phase birds breed primarily in the southern hemisphere. Species are not reported for which the sample size was one, or for the 11 species collected on the outer edge of the Peru Current, because no additions were made to the sample reported in Ainley *et al.* (1990*a*).

Log-linear models with residual analysis (Fienberg, 1980) were used to compare proportions of types of plastic (user-fragments versus pellets) between the four species groups described above. Adjusted standardized residuals greater than 2 indicated significantly larger proportions (at $p = 0.05$) compared to the null model of equal proportions among the groups. Calculations were done using SPSS-PC+ (Norusis, 1988).

'Incidence' of plastic was defined as the proportion of individuals of a species who contained plastic. The incidence of plastic between tropical Charadriiformes/Pelecaniformes and Procellariiformes was compared with a Mann–Whitney *U*-test (Conover, 1980). Incidence of plastic in Procellariifomes of different resident/migratory status was compared with the Kruskal–Wallis test and posterior comparisons at $p = 0.05$ (Conover, 1980). Logistic regression was used to model incidence of plastic (Cox & Snell, 1989) because outcomes were binary (individuals either contained plastic or did not). The likelihood ratio statistic (LRS) is reported, which is equivalent to 'deviance' (used in generalized linear models), and therefore analogous to Sums of Squares in analysis of variance. Linear regression was used to examine the relationship of the five independent terms with the (continuous) dependent variable 'number of plastic particles,' and, to satisfy assumptions of normality, that variable was log-transformed. Regression analyses were performed on five of the more abundant species in the study area, species for which we had samples of 20 or more birds and among which incidence was greater than 5%. Species included the Leach's storm petrel *Oceanodroma leucohroa*, Stejneger's petrel *Pterodroma longirostris*, white-winged petrel *Pterodroma leucoptera*, wedge-tailed shearwater and sooty shearwater *Puffinus griseus*, in order of increasing mass. The term 'species' was included in logistic-regression analyses where species values were (1) to (5) in order of increasing mass. Species was treated as categorical in linear regression analyses.

In analyses on 'sex' and 'season', males and spring were given the value (1), and females and autumn the value (2). In analyses on 'age,' fledglings were scored as (1), subadults (2) and adults (3). Analyses for body weight were of the original, ungrouped data. Non-linearity was tested for by using a quadratic term. In addition, interactions between the term 'species' and all independent variables were tested. Means + one standard deviation are given unless noted otherwise. Significance was assumed at $p < 0.050$ unless noted otherwise. Logistic and linear regression analyses were done using STATA (Computing Resource Center, 1992).

Sampling neuston plastic

During 1988 to 1991, 36 neuston tows were conducted over an area of 85,500 m2 of ocean surface using a net 6 m in length with 1 mm mesh, attached to a rigid, rectangular bar with an opening 1.0 m wide. Tows were conducted between longitudes 110°W and 150°W (Fig. 1), at the same locations where birds were collected in the Southern Equatorial Current (from 5°N latitude to 5°S) and Equatorial Countercurrent (from 5°N to 10°N; Wyrtki, 1967), including the two major convergences of the tropical Pacific, located at the north and south boundaries of the Equatorial Countercurrent. The purpose was to sample prey of birds, however, neuston plastic of width > 1 mm was also noted.

At each location, the net was towed horizontally at the ocean surface off the side of the ship at known speed for 10-30 min. Following Day *et al.* (1990), the time the mouth of the net was not at the surface (which depended on sea conditions) was estimated and subtracted from the sampling period for a given tow. The surface area of water sampled was the net width multiplied by the distance traveled by the ship, minus the distance that the net was estimated to have been submerged (average 12% of the distance for all tows).

RESULTS

Density of neuston plastic

Densities of neuston plastic were extremely low in both the South Equatorial Current and the Equatorial Countercurrent (Table 1). The small sample of particles precluded statistical comparison.

TABLE 1
Densities of Neuston Plastic in Two Current Systems in the Eastern and Central Tropical Pacific, 1988–91. Densities are Given as the Number of Pieces per Square Kilometer

Parameter	*South Equatorial current*	*Equatorial countercurrent*
Number of tows	19	17
Area sampled m^2	43 900	41 600
Number of pieces found:	6	1
(a) pellets	2	0
(b) user fragments	4	1
Number per tow (range)	0–2	0–1
Total density	137	24

Incidence, number, type and width of plastic particles as related to species and distribution/migration patterns

Only three of 11 (27%) species of the Charadriiformes and Pelecaniformes contained plastic, compared to 17 of 24 (71%) of the Procellariiformes (Table 2). Yet, incidence of plastic in Charadriiformes/Pelecaniformes resident in the tropical Pacific ($0.019 + 0.045$, $n = 8$ species) did not vary significantly from that of Procellariiformes also resident in the tropical Pacific ($0.06 + 0.13$, $n = 9$ species, Mann–Whitney U test $= -1.08$, $p = 0.28$). This analysis should, however, be repeated after sample sizes for some of the species have been increased. To ensure standardization in the following analyses we excluded non-Procellariiformes, and also Procellariiformes with samples < 5 birds.

Incidence of plastic was 0.06 ± 0.13 ($n = 9$ species) in year-round residents of the study region, 0.18 ± 0.24 ($n = 9$) in migrants to the tropics from breeding colonies in the South Pacific, 0.20 ($n = 1$) in migrants to the tropics from North Pacific breeding areas, and 0.54 ± 0.35 ($n = 3$) in migrants crossing the tropics between the South Pacific and North Pacific (Kruskal–Wallis $T = 6.80$, $df = 2$, $0.025 < p < 0.05$, migrants from the north Pacific excluded, Table 2). Incidence of plastic was significantly lower among the tropical residents compared to species migrating between the South Pacific and North Pacific (posterior multiple-comparison, $P < 0.05$), but did not vary significantly between other group combinations ($p > 0.10$).

Frequency of industrial pellets versus user fragments (these two plastic 'types' composed $> 99\%$ of the particles found; Table 3) differed significantly between the four distributional species-groups ($G = 120.96$, $df = 3$, $p < 0.001$; comparisons were of the total number of pellets versus

TABLE 2
Incidence of Plastic and Average Number of Particles Found in Stomachs of 1 574 Individuals Representing 36 Species of Seabirds Collected in the Tropical Pacific. Incidence of Plastic for a Given Species is the Number of Birds Containing Plastic Divided by the Total Number Examined

	Incidence	n^a	n^b	*Number of particles*	
				$x \pm SD$	*Range*
Year-round resident in the tropical Pacific:					
Procellariiformes					
Tahiti petrel					
Pterodroma rostrata	0.01	121	1	1	
Phoenix petrel					
Pterodroma alba	0.00	19			
Bulwer's petrel					
Bulweria bulwerii	0.00	39			
Christmas shearwater					
Puffinus nativitatus	0.40	5	2	1	
Wedge-tailed shearwater					
Pu. pacificus (light phase)	0.09	23	2	2.5 ± 2.1	1–4
White-throated storm petrel					
Nesofregetta fuliginosa	0.00	14			
White-bellied storm petrel					
Fregetta grallaria	0.06	18	1	1	
Band-rumped storm petrel					
Oceanodroma castro	0.00	7			
Wedge-rumped storm petrel					
Oceanodroma tethys	< 0.01	296	1	1	
Pelecaniformes					
Red-tailed tropicbird					
Phaethon rubricauda	0.00	6			
Masked boobie					
Sula dactylatra	0.00	6			
Brown boobie					
Sula leucogaster	0.00	5			
Charadriiformes					
Sooty tern					
Sterna fuscata	0.02	64	1	2	
Gray-backed tern					
Sterna lunata	0.00	5			
White tern					
Gygis alba	0.13	8	1	5	
Black noddy					
Anous tenuirostris	0.00	3			
Blue-grey noddy					
Procelsterna cerulea	0.00	3			
Breed in South Pacific; winter in tropical Pacific:					
Procellariiformes					
Juan Fernandez petrel					
Pterodroma externa	< 0.01	183	1	1	
White-necked petrel					
Pterodroma cervicalis	0.08	12	1	5	

TABLE 2 — *contd*

Kermadec petrel *Pterodroma neglecta*	0.00	11			
Herald's petrel *Pterodroma arminjoniana*	0.00	11			
Pycroft's petrel *Pterodroma pycrofti*	0.40	5	2	2.5 ± 0.7	2–3
White-winged petrel *Pterodroma leucoptera*	0.12	110	13	2.2 ± 3.0	1–12
Collared petrel *Pterodroma brevipes*	0.66	3	2	1	
Black-winged petrel *Pterodroma nigripennis*	0.05	66	3	3.0 ± 3.5	1–7
Wedge-tailed shearwater (dark) *Puffinus pacificus* (phase)	0.24	62	15	3.5 ± 2.7	1–9
White-faced storm petrel *Pelagrodroma marina*	0.73	15	11	13.2 ± 9.5	1–33
Breed in North Pacific; winter in tropical Pacific:					
Procellariiformes					
Leach's storm petrel *Oceanodroma leucoroha*	0.20	354	70	3.5 ± 2.6	1–15
Charadriiformes					
Black tern *Childonias niger*	0.00	2			
Pomarine jaeger *Stercorarius pomarinus*	0.00	2			
Long-tailed jaeger *Stercorarius longicaudus*	0.50	2	1	5	
Breed in South Pacific; winter in North Pacific:					
Procellariiformes					
Murphy's petrel *Pterodroma ultima*	0.14	7	1	5	
Mottled petrel *Pterodroma inexpecta*	0.00	2			
Stejneger's petrel *Pterodroma longirostris*	0.74	46	34	6.8 ± 8.6	1–45
Sooty shearwater *Puffinus griseus*	0.75	36	27	11.4 ± 12.2	1–42
Buller's shearwater *Puffinus bulleri*	1.00	3	3	8.7 ± 8.6	1–18

[a]Number of birds examined for presence of plastic.
[b]Number of birds that contained plastic.

fragments summed for all species of each group, see 'overall frequencies'). Residual analysis showed that the difference resulted primarily from the higher proportion of pellets in species that bred in the South Pacific (and wintered in the tropical Pacific), and the higher proportion of user-fragments in Leach's storm-petrel (which breeds in the North Pacific and winters in the tropical Pacific). However, there was variability within species groups. Among species that breed in the South Pacific and migrate

TABLE 3

Type and Size of Plastic Particles Found in Stomachs of 20 Species of Seabirds Collected in the Tropical Pacific. Width, Measured at the Widest Point, of Industrial Pellets was 3–5 mm; Widths Reported are Those of User Fragments. Note that Some Particles Included in the Particle Counts Given in Table 2 Were not Classified to Particle Type. Therefore, Some Values Given in This Table for Total Number of Particles Examined are not Consistent with Those of Table 2. Nylon Line/Chord and Plastic Bag Occurred Infrequently and are not Reported[a]

Species	*Type of plastic (percent of total number of particles examined)*		*Total n*	*Width (mm)*
	User-fragment	*Pellet*		
Year-round residents in the tropical Pacific:				
Tahiti petrel	100	0	1	—
Christmas shearwater	50	50	2	4
Wedge-tailed shearwater (light phase)	100	0	5	—
White-bellied storm petrel	100	0	1	—
Wedge-rumped storm petrel	100	0	1	—
Sooty tern	0	100	2	4
White tern	100	0	5	3–4
Overall frequency	82	18	17	
Breed in South Pacific; winter in tropical Pacific:				
Juan Fernandez petrel	0	100	1	—
White-necked petrel	100	0	5	3–4
Pycroft's petrel	66	33	3	2–5
White-winged petrel	100	0	16	2–5
Collared petrel	0	100	2	—
Black-winged petrel	100	0	3	3–5
Wedge-tailed shearwater (dark phase)	48	52	44	5–14
White faced storm petrel	0	100	45	—
Overall frequency	40	60	119	
Breed in North Pacific; winter in tropical Pacific:				
Leach's storm petrel	94	5	189	2–4
Breed in South Pacific; winter in North Pacific:				
Murphy's petrel	0	40	5	8–12
Stejneger's petrel	86	14	189	2–5
Spring	59	41	41	
Autumn	94	6	148	
Sooty shearwater	47	53	115	3–20
Spring	0	100	1	
Autumn	47	53	114	
Buller's shearwater	44	56	18	2–8
Overall frequency	69	30	324	

[a]Only the Murphy's petrel contained nylon line/chord (3 pieces; 60% of all plastic inspected for that species). Only the Leach's storm-petrel contained pieces of plastic bag (2 pieces; 1% of all plastic inspected for that species).

to the North Pacific, the Stejneger's petrel contained a significantly-higher proportion of user-fragments than other species in that group during the autumn movement out of the North Pacific, and than Stejneger's petrels during the spring movement out of the South Pacific ($G = 89.7$, $df = 3$, $p < 0.001$; and residual analysis). Among species that breed in the South Pacific and winter in the tropical Pacific, the white-faced storm-petrel (*Pelagodroma marina*) contained a significantly higher proportion of pellets compared to other species in the group ($G = 85.0$, $df = 3$, $p < 0.001$; and residual analysis).

Relation between incidence of plastic and species mass, sex, age, season, year and body weight

Incidence of plastic increased significantly with increase in age, year and body weight, and was greater in autumn compared to spring (Table 4). Effects of age and body weight were linear (LRS test for quadratic, $p > 0.4$)), however, there was a tendency for a quadratic effect of year ($p = 0.09$) because of a steady increase in incidence from 1984 to 1990, followed by a decline in 1991 (Fig. 2). The effect of body weight on incidence was 13, 5 and 2 times greater than the effects of age, year, and season, respectively, as indicated by deviances explained (i.e. LRS values). Incidence of plastic varied insignificantly between the sexes, and was not significantly correlated with species mass (numerical values assigned to each species increased with increase in mean body mass of respective species; see Section 2.2).

TABLE 4

Logistic Multiple Regression Model for Presence Versus Absence of Plastic in the Stomachs of Five Species of Procellariiformes. Variables Entered in the Model Included Species, Age, Sex, Season, Year and Body Weight. Interactions between Species and Each of the Other Terms (Denoted with an Asterisk) were also Included. Logistic Regression Statistic Values (LRS) for Single Terms were Calculated after Interaction Terms were Dropped from the Model. Model Terms Having a Significant Effect are Reported. Sample Size was 552

Term	*LRS*	*p-value*	*Regression coefficient (B)*	*SE of B*
Age	2.11	0.043	0.342	0.169
Season	14.18	<0.001	0.844	0.231
Year	5.45	0.020	0.180	0.0774
Body weight	27.54	<0.001	0.00685	0.00149
Species*season	6.42	0.025	—	—
Species*body weight	22.48	<0.001	—	—

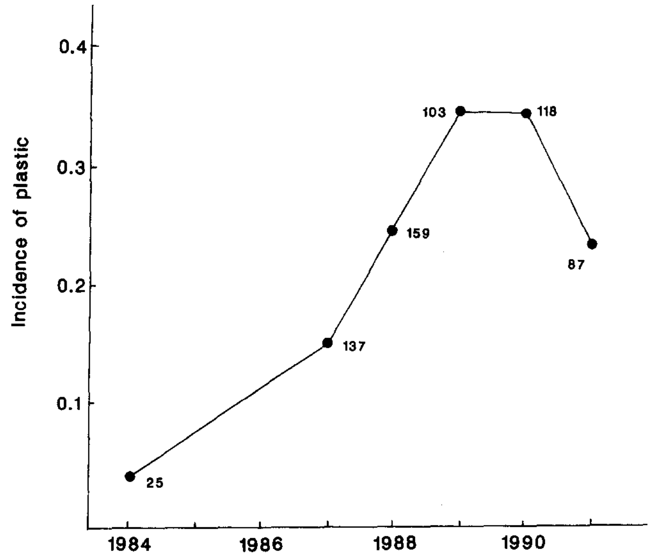

Fig. 2. Incidence of plastic as related to year in five species of Procellariiformes. Numbers are sample sizes.

Significant interactions between season and species, and between body weight and species, indicated that relationships of season and weight with incidence of plastic varied among the five species (Table 4). The interaction with season resulted from a higher incidence in autumn than spring in Leach's storm petrels and the two shearwaters, in contrast to higher incidence in spring than autumn in white-winged petrels, and absence of seasonal variation in Stejneger's petrels (Table 5).

TABLE 5
Mean ± One Standard Deviation for Incidence of Plastic for Five Species of Procellariiformes Collected in the Tropical Pacific (1984–91); Values are Reported with Respect to Season. Sample Sizes are Given in Parentheses. p-Values Give Results of Separate Logistic Regression Analyses on Each Species. Significance was Assumed at $p = 0.01$ to Adjust for Multiple Tests

Species	*Season*		*p-value*
	Spring	*Autumn*	
Leach's storm petrel	0.02 ± 0.13 (108)	0.28 ± 0.45 (246)	< 0.001
Stejneger's petrel	0.72 ± 0.45 (29)	0.76 ± 0.44 (17)	0.8
White-winged petrel	0.26 ± 0.44 (39)	0.04 ± 0.20 (71)	0.005
Wedge-tailed shearwater	0.14 ± 0.35 (43)	0.47 ± 0.51 (19)	0.007
Sooty shearwater	0.18 ± 0.40 (11)	1.00 ± 0.00 (25)	0.005

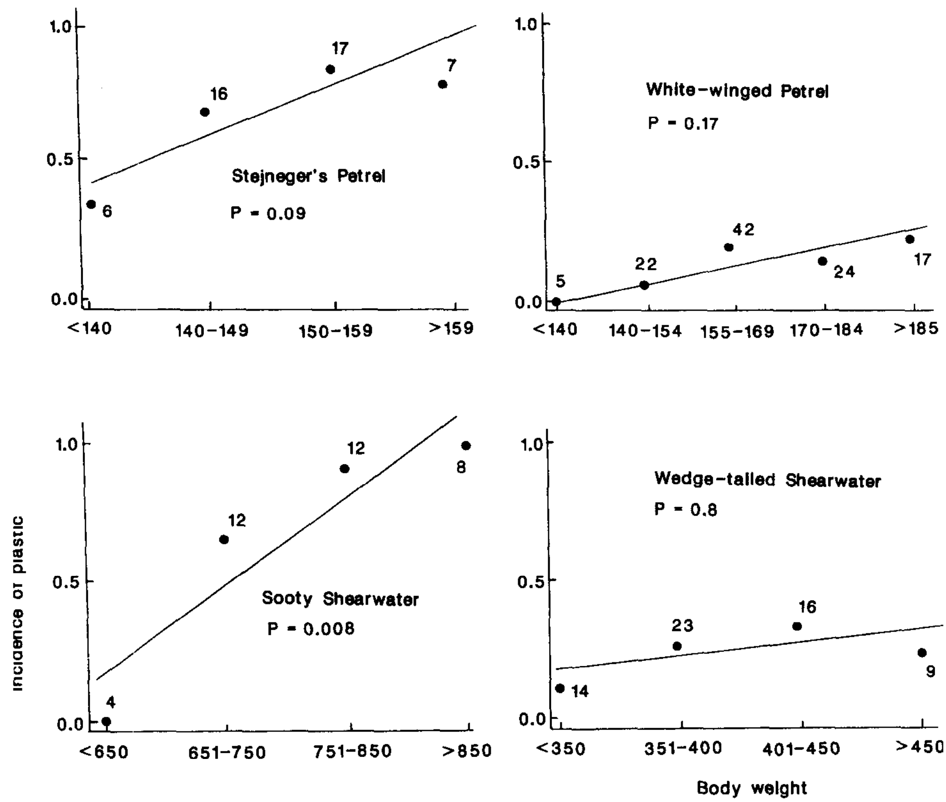

Fig. 3. Incidence of plastic as a function of body weight (grams) in five species of Procellariiformes, including logistic regression lines of best fit. Numbers are sample sizes. Analyses were of the original, ungrouped data. Significance was assumed at $p = 0.01$ to adjust for multiple tests.

The interaction with body weight was mainly due to the steeper increase in incidence with body weight in sooty shearwaters and Stejneger's petrels compared to the other three species (Fig. 3).

Relation between number of plastic particles and species mass, sex, age, season, year and body weight among birds that contained plastic

Number of plastic particles was significantly correlated with body weight (controlling for species analysed as a categorical term, Table 6). The negative coefficient indicated that, for a given species, body weight declined with increase in number of particles among birds that contained plastic. The effect was linear (*F* test for quadratic, $P = 0.6$). Number of particles was greater in autumn than in spring, and varied significantly

TABLE 6

Linear Multiple Regression Model for Number of Plastic Particles (Log-Transformed) in the Stomachs of Five Species of Procellariiformes. Variables Entered Into the Model Include Species, Age, Sex, Season, Year and Body Weight. Interactions between Species and Each of the Other Terms (Denoted with an Asterisk) were also Included. *F*-Values for Single Terms were Calculated after Interaction Terms were Dropped from the Model. Only Terms Having a Significant Effect are Reported. R^2 for Full Model was 0.378; $F[15,137] = 5.56, p - 0.0001$, Including 1 *df* for the Unreported (Nonsignificant) Term Age

Term	*df*	*F-value*	*p-value*	*Regression coefficient (B)*	*SE of B*	*Partial R^2*
Species	4	6.65	< 0.001	—	—	17.2
Season	1	6.03	0.015	0.501	0.204	3.0
Body weight	1	6.72	0.0111	−0.00461	0.00178	3.4
Species*age	4	3.11	0.018	—	—	5.6
Species*season	4	5.09	0.001	—	—	9.2

among species, but was not affected significantly by sex, age or year. Between-species differences was the most important factor affecting number of particles.

Significant interaction between species and season, and between species and age, indicated that the relationships of age and season with number of particles differed between species (Table 6). Seasonal interaction with species resulted from a significantly higher number of particles in autumn than spring in Stejneger's petrels, in contrast to insignificant seasonal difference among the other four species (Table 7).

The interaction with age resulted mainly from species contrast in differences in number of particles between subadult and adult age-classes; fledglings of all species contained fewer (or no) particles (Table 7). In subadult sooty shearwaters and white-winged petrels, respectively, number of particles averaged significantly higher, or tended to be higher, than in adults. In contrast, number of plastic particles varied little between subadult and adult Leach's storm petrels, Stejneger's petrels and wedge-tailed shearwaters.

DISCUSSION

Density of neuston plastic

During 1988–91, the estimated density of neuston plastic in the central and eastern tropical Pacific (24-137 pieces per km^2) was low compared to North Pacific waters (density 13 000 to 300 000 pieces per km^2) sampled

TABLE 7

Means ± One Standard Deviation for Number of Plastic Particles Found in Five Species of Procellariiformes Collected in the Tropical Pacific (1984–91); Values Reported with Respect to Age of Bird and Season When Collected. Samples Pertain Only to Individuals Who Contained at Least One Particle; Sample Sizes are Given in Parentheses. *p*-Values Give Results of Separate Linear Regression Analyses on Each Species. Significance was Assumed at $p = 0.01$ to Adjust for Multiple Tests

Species	*Age*			*p-Value*
	Fledgling	*Subadult*	*Adult*	
Leach's storm petrel	3.0 ± 1.6 (4)	3.4 ± 2.7 (30)	3.6 ± 2.8 (32)	0.7
Stejneger's petrel	1.0 (1)	6.3 ± 4.3 (6)	7.3 ± 9.8 (25)	0.6
White-winged petrel	—	5.0 ± 6.1 (3)	1.3 ± 0.7 (10)	0.059
Wedge-tailed shearwater (dark form)	2.0 (1)	3.8 ± 3.9 (5)	3.6 ± 2.2 (9)	0.8
Sooty shearwater	—	18.0 ± 14.0 (13)	5.4 ± 5.8 (14)	0.005

	Season		*p-Value*
	Spring	*Autumn*	
Leach's storm-petrel	2.5 ± 0.7 (2)	3.5 ± 2.6 (68)	0.6
Stejneger's petrel	3.2 ± 2.3 (21)	12.3 ± 11.7 (13)	0.001
White-winged petrel	2.5 ± 3.4 (10)	1.0 (3)	0.5
Wedge-tailed shearwater	5.0 ± 2.8 (6)	2.6 ± 2.3 (9)	0.085
Sooty shearwater	4.5 ± 4.9 (2)	12.0 ± 12.5 (25)	0.4

during 1985–88, by Day *et al.* (1990). Although the surface area of ocean sampled in the two studies was nearly the same (85 500 m^2 in the present study versus 91 000 m^2 sampled by Day *et al.*, 1990), this study found only seven particles compared to thousands found in the latter study. Densities are not directly comparable between the two studies because the 0.5 mm mesh used in the latter was smaller than the 1.0 mm mesh used in this study, however, 52.6% (by number) of the plastic pieces found in the North Pacific and sorted by size-class were > 1 mm (Table 2 in Day, 1988). Clearly, during the late-1980s, densities of neuston plastic in the eastern and central tropical Pacific were very low compared to densities in the North Pacific. Densities of plastic in the South Pacific are less well known but may be lower, in general, than in the North Pacific (reviewed in Pruter, 1987).

Species differences in incidence of ingesting plastic

Species differences in ingestion incidence (the proportion of individuals containing plastic relative to the number of individuals examined) as related to feeding behavior are discussed in Ainley *et al.* (1990*a*) and Moser & Lee (1992). In contrast to findings of others (Harrison *et al.*, 1983; Day *et al.*, 1985; Sileo *et al.*, 1990; Moser & Lee, 1992), this study found little evidence for a lower incidence of plastic ingestion by non-Procellariiformes (boobies *Sula* spp., tropicbirds *Phaethon* spp. or terns and noodies; Family Laridae), compared to Procellariiformes (shearwaters, petrels and storm-petrels) resident in the tropical Pacific. However, incidence of plastic ingestion in the tropical Pacific was very low, making it difficult to detect possible differences in ingestion incidence, especially with the low sample sizes for some of the non-Procellariiform species.

Ingestion of plastic was influenced by a number of factors in the five Procellariiform species studied extensively. In order of increasing importance, factors were age, year and season (i.e. location of wintering and breeding areas).

Effects of sex and age

Sex was not an important variable affecting ingestion incidence in the five Procellariiform species. Similarly, Day *et al.* (1985) did not find sex-related differences in incidence of plastic ingestion in any of six seabird species studied in Alaskan waters.

In this study, the significant increase in incidence of plastic with increase in age among the five Procellariiformes was in contrast to the results of Day *et al.* (1985), who found a higher incidence of plastic ingestion in subadults compared to adults in two of three species of North Pacific alcids. They suggested that the difference resulted from less efficient foraging by subadults, and thus, avoidance by adults of ingesting plastic. Our findings, on the other hand, including a higher incidence of plastic among heavier birds of a given age group, indicated that the more adept, efficient foragers were more likely to ingest plastic than less efficient foragers.

The present authors believe that a likely explanation for this pattern is that the more adept, experienced birds spent more time in areas where densities of plastic were high. This is probably because plastic is concentrated at fronts and convergences (reviewed in Laist, 1987, see also Day *et al.*, 1990) where prey of seabirds, too, is often concentrated (Murphy & Shomura, 1972; Bradstreet & Brown, 1985; Haney, 1986; Briggs *et al.*, 1987; Hunt & Schnider, 1987; Hunt *et al.*, 1993). Experienced birds, being more efficient foragers (reviewed in Day *et al.*, 1985), are probably better at finding these oceanic features than less-experienced birds. If this scenario is true, age/experience-related avoidance of ingesting plastic was unlikely in the species studied.

Ryan & Jackson (1987) and Ryan (1988) suggested that the off-loading of plastic by parents to young accounted for the lighter plastic load in adults they studied following the breeding season compared to just before it. Although off-loading from adults could explain presence of plastic in fledglings examined, incidence and volume of plastic in fledglings (of which a maximum of one chick is raised annually per pair of adults) offered little evidence to support the hypothesis (although sample sizes of fledglings were small). For example, in sooty shearwaters, none of the fledglings examined contained plastic, whereas plastic was found in all adults who were migrating to breeding colonies (Table 8). There

TABLE 8

Mean ± One Standard Deviation for Incidence of Plastic for Five Species of Procellariiformes Collected in the Tropical Pacific (1984–91). Means are Reported for Fledglings and Adults. Means for Adults are Partitioned into two Seasonal Periods, the Pre-Breeding Period and the Post-Breeding Period. Sample Sizes are Given in Parentheses. p-Values Given Below Means Report Results of Pearson Chi-Square Tests; Comparison of Incidence between Fledglings and Adults Sampled during the Pre-Breeding Period (on the left), and of Fledglings Compared to Adults Sampled during the Post-Breeding Period (on the right). Significance was Assumed at $p = 0.01$ to Adjust for Multiple Tests

Species	*Fledglings*	*Adults*	
		Pre-breeding period	*Post-breeding period*
Leach's storm petrel[a]	0.14 ± 0.36 (28)	0.03 ± 0.16 (39) $p = 0.15$	0.29 ± 0.45 (108) $p = 0.12$
Stejneger's petrel[b]	0.33 ± 0.58 (3)	0.67 ± 0.49 (12) $p = 0.17$	0.89 ± 0.32 (19) $p = 0.019$
White winged petrel[c]	0.00 (6)	0.09 ± 0.28 (35) $p = 0.5$	0.54 ± 0.52 (13) $p = 0.024$
Wedge-tailed shearwater[d] (dark phase)	0.20 ± 0.45 (5)	0.60 ± 0.52 (10) $p = 0.14$	0.12 ± 0.33 (26) $p = 0.6$
Sooty shearwater[e]	0.00 (5)	1.00 (12) $p < 0.001$	0.33 ± 0.52 (6) $p = 0.15$

[a]Incidence of plastic in adults sampled during the pre-breeding season compared to those sampled in the post-breeding season; $X^2 = 11.50$, $df = 1$, $p = 0.001$.
[b]Incidence of plastic in adults sampled during the pre-breeding season compared to those sampled in the post-breeding season; $X^2 = 1.14$, $df = 1$, $p = 0.3$.
[c]Incidence of plastic in adults sampled during the pre-breeding season compared to those sampled in the post-breeding season; $X^2 = 11.78$, $df = 1$, $p = 0.001$.
[d]Incidence of plastic in adults sampled during the pre-breeding season compared to those sampled in the post-breeding season; $X^2 = 9.05$, $df = 1$, $p = 0.003$.
[e]Incidence of plastic in adults sampled during the pre-breeding season compared to those sampled in the post-breeding season; $X^2 = 10.29$, $df = 1$, $p = 0.001$.

was a similar trend in Stejneger's petrels and wedge-tailed shearwaters. Results from adult white-winged petrels and Leach's storm-petrels were also inconsistent with the findings of Ryan & Jackson (1987) and Ryan (1988). In these species, adults showed a significantly higher incidence of plastic after the breeding season, compared to before it. Similarly, the off-loading hypothesis could not explain seasonal variation in species of alcids studied by Day (1980) because these species do not regurgitate stomach contents to their young. Finally, Furness (1985*a*) found little evidence for off-loading in Procellariids breeding in Britain.

As discussed in Ainley *et al.* (1990*a*), seasonal patterns in incidence of plastic in the species studied indicate a degradation time for a plastic particle of less than 1 yr, a result consistent with that of Day *et al.* (1985), but inconsistent with the 1-2 yr degradation period suggested by Ryan & Jackson (1987) and Ryan (1988). A potential problem in the experimental study of Ryan & Jackson (1987) was that one half of the plastic particles they measured for amount of wear had not passed into the gizzard, and the 12 day period that they allowed particles to remain in the petrels may have been too short to allow meaningful extrapolation for rate of degradation. Even if plastic was being off-loaded by adults to chicks (see above), evidence from the present study for a degradation period of less than one year included: (i) the difference in composition of plastic (type) in Stejneger's petrels (age-classes grouped) collected in spring versus autumn; (ii) considerably higher incidence of plastic in adult Leach's storm petrels and white-winged petrels migrating from breeding areas in polluted waters of the North and South Pacific, compared to lower incidence observed after they had wintered in the relatively pristine tropical Pacific (Tablen 8). The data indicate that 90 and 83%, respectively, of the adults had purged themselves of all plastic while on the wintering areas.

As noted by Furness (1985*a*), elimination of plastic by regurgitation may often be difficult in Procellariiformes because, unlike other seabirds, they possess a muscular gizzard separated from the proventriculus by a passage no larger than that leading from the gizzard into the small intestine. The gizzard serves as an organ where cephalopod beaks, fish otoliths, invertebrate exoskeletons and other undigested objects, including plastic, are trapped and degraded. Thus, plastic would probably be retained during regurgitations unless it (i) had been recently ingested and had not yet gone into the gizzard; (ii) was too large to pass into the gizzard; or (iii) the gizzard was too full to accept more items, causing plastic to remain in the proventriculus (but see below). Few of the individuals examined had plastic in their proventriculi.

The three conditions leading to regurgitation of plastic are apparently met more often in other species/localities, however, as indicated by the high incidence of plastic in unfledged Procellariiformes (reviewed in Ryan, 1988). This author also found smaller plastic particles in blue petrel (*Halobaena caerulea*) chicks compared to adults, and concluded that the smaller pellets represented ones that had been partially degraded in the adult's gizzard prior to transfer to the chick. Clearly, lack of consistent results in studies to date identify a need for carefully controlled experiments for assessing factors related to degradation time of plastic in seabirds (see Ryan, 1990).

Effects of year and geographic location

An increase of plastic in seabirds during the 1960s to 1980s was reported from the South and North Pacific and also from the South and North Atlantic (Day *et al.*, 1985; Harper & Fowler, 1987; Ryan, 1988; Slip *et al.*, 1990; Moser & Lee, 1992). The tendency for a curvilinear increase in incidence of plastic with year among the five Procellariiformes in this study offers strong evidence for increase in number of plastic particles in the Pacific from 1984 to 1990, but that a decline may have occurred thereafter. These data provide the first evidence that a decrease in plastic pollution in seabirds may have occurred following enactment of international law (Annex V of MARPOL) in 1989 prohibiting disposal of plastic at sea (Edwards & Rymarz, 1990).

The importance of location was indicated by the significant relationships between season and variables including incidence of plastic, particle number, and type. As noted above, incidence was lowest in species resident in the tropical Pacific where pollution was minimal. Results of this study also indicated that incidence of plastic ingestion and plastic load were higher among birds foraging in the North Pacific than in the South Pacific. This was indicated by: (i) the significantly higher incidence in sooty shearwaters migrating across the tropical Pacific after wintering in the North Pacific, compared to those migrating north after breeding in the South Pacific (origin was New Zealand as indicated by flight direction); and (ii) the greater number of particles in Stejneger's petrels migrating across the tropical Pacific from wintering areas in the western North Pacific, compared to number of particles in birds migrating north after breeding in the South Pacific off the coast of Chile. It is doubted if transfer of plastic from adults to chicks at the breeding colony could explain this difference because of small loads in fledglings. Geographic variation in amount of plastic in seabirds studied elsewhere was suspected to have resulted from varying densities of plastic at sea (Day *et al.*, 1985; Furness, 1985*b*; Ryan, 1988).

The higher proportion of pellets in species breeding in the South Pacific, compared to the species breeding in the North Pacific where user fragments predominated, could have been due to: (i) species selecting different types of particles, or (ii) differing frequencies of particle types in different parts of the Pacific. Predominance of pellets in the South Pacific (Gregory, 1978; Gregory, 1983) and predominance of user fragments in the North Pacific (Shaw, 1977; Day & Shaw, 1987; Day *et al.*, 1990) would suggest the latter. Further support for this idea was the seasonal pattern of particle type observed in the Stejneger's petrel, in which a significantly higher proportion of pellets were found during their northward spring movement from the South Pacific, compared to the return trip from the North Pacific. Other supportive evidence was the dominance of pellets (100%) in the white-faced storm petrel, a planktivorous species that breeds near New Zealand and Australia, compared to the dominance of user fragments (95%) in another planktivorous species, the Leach's storm petrel, which breeds on the rim of the North Pacific.

Effect of ingestion of plastic on body weight

Two results have been presented which demonstrate the first clear relationships between ingestion of plastic and body condition in seabirds (in analyses controlled for potentially confounding factors such as age and season; see review in Ryan, 1990). These included: (i) a significant, positive correlation of body weight with incidence of plastic; and (ii) a significant negative correlation between body weight and number of plastic particles in individuals who contained plastic. Thus, birds who contained no plastic tended to be lighter than those who contained at least one piece, yet among the latter, those who contained more plastic were lighter. Five other studies of seabirds (including one species of phalarope *Phalaropus* spp.; Day, 1980; Connors & Smith, 1982; Furness, 1985*a*,b; Ryan, 1987*a*) indicated weak negative correlations between condition and factors including number, weight and volume of plastic particles in seabirds. It is suggested that these results for number of particles (among birds who contained plastic) are consistent with theirs because incidence of plastic was very high in the species they examined.

Although the two results (i) and (ii) give strong evidence for a relationship between ingestion of plastic and body condition in seabirds, the authors can only speculate as to possible cause and effect. We suspect that the positive correlation between body weight and incidence of plastic is consistent with evidence indicating that plastic is concentrated in the same locations as prey of seabirds, and that more adept foragers are better at finding optimal feeding areas (see Section 4.3). On the other hand, the negative correlation between body weight and number of particles may result from one or a combination of three factors (reviewed in Ryan, 1990): (1) physical damage or blockage of the digestive tract and/or impairment of digestive efficiency; (2) introduction of toxins into the bird's body; and (3) birds already in poor condition could have eaten more plastic than birds in better condition, due to reduced foraging efficiency in the former. Possibility (3), however, is inconsistent with the findings herein that heavier birds (i.e. those presumed to be in better condition than lighter ones) were more likely to have ingested plastic.

Only a few studies have examined the relationship between body weight and fitness components, such as reproductive success and survival rate. Body weight had a significant positive effect on reproductive decision (whether or not to breed in a given season) and reproductive success in blue petrels (*Halobaena caerulea*)(Chastel *et al.*, in press), and adult little penguins (*Eudyptula minor*), who were heaviest during the pre-breeding period, were significantly more likely to survive to the following breeding season than lighter birds (Daan *et al.*, 1992). A similar relationship between post-breeding body weight and annual survival was found in blue tits (*Parus caeruleus*) (Nur, 1984), and only a 5% reduction in body weight significantly reduced the probability an individual kittiwake (*Rissa tridactyla*) would recruit into the breeding colony (i.e. breed for the first time; Porter & Coulson, 1987). Therefore, if the negative relationship between number of particles and body weight observed resulted from either (1) or (2) above, the results reported herein could have serious implications. Higher quality (more 'valuable') members of a population would be most susceptible to plastic ingestion, and thus, the extent of negative impact of plastic pollution on demographic parameters of the populations may be more appreciable than previously thought.

ACKNOWLEDGEMENTS

The authors thank the officers and crew of the National Oceanic and Atmospheric Administration (NOAA) vessels *Discoverer*, *Malcolm Baldrige* and *Oceanographer*. This work was done in conjuction with the Tropical Ocean–Global Atmosphere and Equatorial Pacific Ocean Climate Studies of NOAA. Participation on these cruises was courtesy of the Pacific Marine Environmental Laboratories and Atlantic Marine Oceanographic Laboratories. The authors are especially grateful to the late S. Hayes, as well as M. McPhaden, L. Mangum, and R. Miller for their help and consideration throughout. Comments of B. Heneman, N. Nur and

P.G. Ryan improved the manuscipt. Data collection was funded by NSF grants OCE8515637 and OCE8911125, and National Geographic Society grants 3321-86 and 4106-89. Data analyses and writing were funded by the National Marine Fisheries Service Marine Entanglement Research Program, through J.M. Coe, Sand Point Way NE, Seattle, WA. The work of C.A.R., an employee of the US EPA, was conducted in her own time independent of EPA employment, and was not reviewed by other employees of the Agency. Therefore, conclusions expressed herein do not reflect views of the Agency. This is PRBO contribution 628.

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