THE INCIDENCE AND EFFECTS OF INGESTED PLASTIC IN SEABIRDS

by

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DECLARATION:

I certify that this thesis results from my original investigation, except where acknowledged, and has not been submitted for a degree at any other university.

Signed

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ABSTRACT

This thesis comprises two major sections: an assessment of the incidence of plastic particles at sea and in seabirds (Chapters 1-3), and an investigation of the postulated effects of plastic ingestion on seabirds (Chapters 4-7).

The incidence of plastic at sea was recorded from neuston trawls performed monthly at 120 sampling stations off the southwestern Cape, South Africa, during 1977-78. The types of plastic particles collected are described, and the temporal and spatial distribution patterns of plastic pollution are discussed. Ingested plastic was recorded from 36 of 60 seabird species sampled. The effect of different sampling techniques on the incidence of plastic is discussed. The frequencies of occurrence of plastic colour-types in birds are compared with those of particles collected at sea in neuston trawls. Pale particles were under-represented in all species, but the disparity was less for small than for large species, which may account for the higher incidence of ingested plastic in small than in large species.

Plastic apparently is ingested primarily as a result of confusion with prey items; secondary ingestion is infrequent in most species. The incidence of plastic in seabirds is determined by five factors: foraging technique, the degree of dietary specificity, the density of plastic at sea (which affect the rate of plastic ingestion), the frequency of egestion of indigestible stomach contents and the rate of particle erosion in the stomach (which affect the rate of plastic loss). The incidence of plastic is highest in procellariiform seabirds.

Inter-generation transfer of plastic particles apparently is an important flow pathway for plastic through populations of seabirds which accumulate plastic and feed their chicks by regurgitation. It is hypothesized that this results in annual cycling of plastic loads in successful breeding birds, and large plastic loads in immature and failed breeding birds. The lifespan of polyethylene pellets in seabird stomachs is probably at least one to two years.

Correlations between plastic loads and body condition in Great Shearwaters *Puffinus gravis* and Blue Petrels *Halobaena caerulea* failed to demonstrate an adverse effect resulting from plastic ingestion. Negative correlations may result from differences in the reproductive status of the individuals sampled. Ingested plastic also had no apparent effect on the assimilation efficiency of captive Whitechinned Petrels *Procellaria aequinoctialis*. Intestinal obstruction by plastic particles and fibres was not recorded in more than 400 birds of 25 seabird species, and damage to the stomach lining was infrequent and probably of little significance.

Domestic chickens *Gallus domesticus* were fed polyethylene pellets to test whether plastic impairs feeding activity. Plastic-loaded chicks ate smaller meals and grew more slowly than control birds, apparently as a result of plastic reducing the food storage volume of the stomach. Further experiments on seabirds are needed. Correlations between plastic loads and chlorinated hydrocarbon loads in female Great Shearwaters suggest that ingested plastic is a source of toxic chemicals to seabirds, but further verification is required.

GENERAL INTRODUCTION

Plastic objects are abundant, widespread and persistent marine pollutants which are found floating at the sea-surface (Carpenter et al. 1972, Colton et al. 1974), deposited on the sea-bed (Holmström 1975, Jewett 1976, Carr et al. 1985) and stranded on beaches (Gregory 1978, Merrell 1984). Plastic pollution has three major ecological impacts on marine systems: 1) plastic objects provide shelter and substrata for some marine organisms (Carpenter & Smith 1972, Winston 1982), 2) large numbers of marine organisms are injured or killed by becoming entangled in plastic objects (Wallace 1985), and 3) some marine organisms ingest plastic objects (see below). These impacts of plastic pollution on marine systems have not been studied intensively, and are poorly understood (Shomura & Yoshida 1985).

Plastic objects are ingested by a wide range of marine organisms, including molluscs (Kartar et al. 1976, Araya 1983), chaetognaths (Carpenter et al. 1972), fish (Carpenter el al. 1972, Anon. 1975, Kartar et al. 1976, Anon. 1981), turtles (Balazs 1985), birds (Day et al. 1985, Furness 1985 a,b, van Franecker 1985) and mammals (Wehle & Coleman 1983, Cawthorn 1985). Until recently, this impact of plastic pollution on marine organisms was considered little more than a curiosity, and attracted none of the attention afforded other marine pollutants such as petroleum products, chlorinated hydrocarbons and heavy metals (e.g. Bourne 1976, Ohlendorf et al. 1978). More recently, however, the increasing incidence of plastic ingestion, particularly by birds and turtles, has caused concern about the possible impacts of ingested plastic (Balazs 1985, Day *et al*. 1985, Furness 1985a,b, van Franecker 1985).

Plastic particles and other synthetic objects first were recorded from the stomachs of seabirds from the North Atlantic during the early 1960s (Bennett 1960, Rothstein 1973). Subsequently, plastic has been reported from the stomachs of at least 56 seabird species throughout the world (Day *et al*. 1985, Furness 1985a). Most studies merely have documented the incidence of ingested plastic and speculated about possible adverse effects on birds. Day *et al*. (1985) reviewed studies up to 1984, and the only subsequent published studies of note are those of Furness (1985a,b) and van Franecker (1985). Investigations of the allied problem of shot ingestion by waterfowl have centred on lead toxicity (e.g. White & Stendell 1977), and apparently have not considered the physical effects of shot accumulated in the stomach.

The aims of this thesis are three-fold:

1) to determine the factors affecting the ingestion of plastic by seabirds
2) to investigate the flux of plastic particles through seabird populations
3) to examine the postulated effects of ingested plastic on seabirds.

The factors affecting the ingestion of plastic and the dynamics of plastic particles within seabirds have been investigated by Day (1980), Day *et al*. (1985) and Furness (1985a,b). The effects of ingested plastic on seabirds are poorly understood (e.g. Day *et al*. 1985).

To identify the factors affecting plastic ingestion, it is necessary to compare the incidence of plastic types in seabirds with that in the environment. Chapter 1 considers the distribution of floating plastic particles at sea around the southwestern Cape, South Africa. The ranges of sizes and colours of particles collected at the sea surface form the basis for comparisons with particles found in seabirds in the same area.

Chapter 2 considers inter-specific differences in plastic ingestion among seabirds, collected primarily off southern Africa and in the adjacent Southern Ocean. Factors affecting the ingestion of plastic particles and differences in accumulated plastic loads between species are discussed. Chapter 3 uses intra-specific differences in the incidence of ingested plastic to infer the flux of plastic particles through seabird populations.

The remainder of the thesis investigates the effects of ingested plastic on seabirds. Chapter 4 critically examines the use of multivariate analyses to demonstrate effects of ingested plastic on body condition. Chapter 5 considers the effect of plastic on assimilation efficiency and provides an estimate of the lifespan of plastic particles in seabird stomachs. Chapter 6 examines the effect of ingested plastic on meal size and growth, and Chapter 7 considers the role of plastic particles as sources of polychlorinated biphenyls (PCBs) and other toxic chemicals to seabirds. Appendix 1 presents a potentially non-destructive sampling technique for monitoring the incidence of plastic ingestion in certain seabird species.

Each chapter is written as an independent paper, with its own abstract, introduction, methods, results, discussion, acknowledgements and reference sections. This format facilitates the rapid communication of results, but necessitates some repetition. The synthesis attempts to link the chapters into a cohesive unit.

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CHAPTER 1

THE NATURE AND DISTRIBUTION OF PLASTIC PARTICLES AT THE SEA-SURFACE OFF THE SOUTHWESTERN CAPE, SOUTH AFRICA

ABSTRACT

The nature, abundance and distribution of plastic particles at the sea-surface off the southwestern Cape, South Africa, were described from 1 224 neuston trawls made between August 1977 and August 1978. Mean plastic density was 3 640 particles km^{-2} and 42.4 $\mathrm{g.km}^{-2}$, but variances were great. Foamed plastics were the most abundant items, but industrial pellets and fragments of manufactured articles accounted for most of the mass. The majority of fragments, fibres and foamed plastic particles were small (< 1.0 mg). The dispersion of particles at sea was clustered, presumably at convergence zones, over small areas. Averaging numbers collected over larger areas provided temporal and spatial patterns of distribution which could be explained in terms of the source areas, transport mechanisms and life span of the particles. It is suggested that the Agulhas Current is a major source of plastic pollution to the seas off the southwestern Cape, and that it may introduce plastic into the Southern Ocean across the Subtropical Front.

INTRODUCTION

Plastic particles were first identified as sea-surface pollutants in 1962, when they were found in the stomachs of pelagic seabirds in the northwest Atlantic Ocean (Rothstein 1973). Since then, they have been found to be widespread throughout the Atlantic Ocean (Heyerdahl 1971, Carpenter et al. 1972, Carpenter & Smith 1972, Wellman 1973, Colton et al. 1974, Morris 1980a, van Dolah et al. 1980, Dixon & Dixon 1983), the Mediterranean Sea (Morris 1980b), the Pacific Ocean (Venrick et al. 1973, Wong et al. 1974, Shaw & Mapes 1979, Gregory et al. 1984), the Bering Sea (Shaw 1977) and the Southern Ocean (Gregory et al. 1984). However, most of these studies were based on small numbers of samples (Colton et al. 1974 is the only notable exception), and do not consider the small- to medium-scale temporal and spatial distribution patterns of plastic particles at sea. Our understanding of the dynamics of plastic pollution at sea is still very limited (Gerrodette 1985). Also, there is no published information on the sizes and colours of plastic particles found at sea. This chapter examines the nature and distribution of plastic particles collected during a year of intensive sampling off the southwestern Cape, South Africa.

METHODS

Between August 1977 and August 1978, 120 stations were sampled monthly off the southwestern Cape, South Africa, during the Cape Egg and Larval Programme (CELP) of the Sea Fisheries Research Institute. There were 20 lines of stations, each 20 nautical miles apart, from St Helena Bay to San Sebastian Bay (Fig. 1.1).

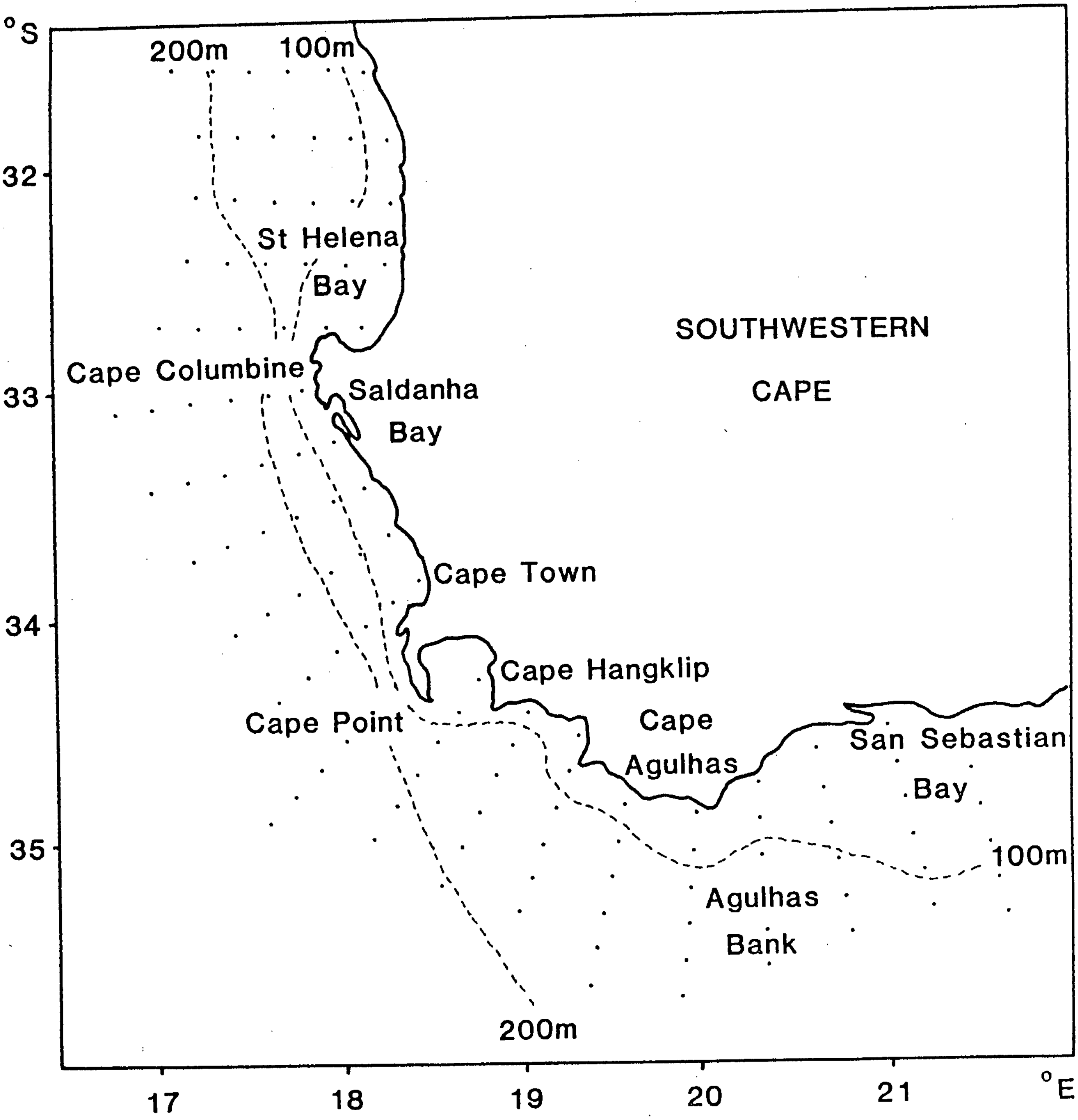

FIGURE 1.1 The study area, showing the sampling grid, the localities mentioned in the text, and 100 m and 200 m isobaths.

Each line consisted of six stations, starting 10 nautical miles offshore, with successive stations separated by intervals of 10 nautical miles. Surface waters were sampled by towing a rectangular neuston net (1.57 X 0.42 m, mesh size 0.9 mm) at 1 $m.s^{-1}$ for 120 s, at each station when weather permitted. Each tow sampled some 190 m^2 of sea surface, assuming efficient net operation (see Colton _et al_. 1974, Morris 1980a).

All plastic particles were identified to one of four types: industrial pellets, pieces of manufactured items (termed user fragments), fibres, and expanded polystyrene and other foamed plastics. The last three types are collectively termed user plastics and derive from manufactured items, as opposed to industrial pellets which form the raw material for the manufacturing industry. Each particle was colour coded while wet into one of nine colour categories: clear-white, grey, tan, dark brown, black, blue, green, red (including pink and orange), and yellow. Lumping of clear and white particles was necessary due to the effect of crazing during weathering on particle colour. Where a particle consisted of two (or more) colours in similar proportions, it was scored under both colours. Buoyancy of all particles collected was tested in both fresh and sea water.

The plastic particles were oven dried at 30 °C and weighed to the nearest 0.1 mg. The state of wear of industrial pellets was scored on a scale from one to three: 1) fresh: edges sharp, surfaces shiny, 2) fairly worn: edges worn, surfaces dull, and 3) very worn: original shape indistinct, surface pitted and crazed (adapted from Day 1980). It was not feasible to estimate the degree of wear for user particles, because their original form could not be inferred with accuracy.

The distribution of plastic particles was analysed in terms of frequency of occurrence, numbers and mass. Due to the great variance in the numbers and mass of plastic particles between stations in both space and time, the data were lumped into two temporal periods, summer (October to April) and winter (May to September). To construct contour plots of plastic density, the numbers of plastic particles were averaged for blocks of four adjacent stations over each season, giving between 20 and 25 trawls per point. Plots of the distribution of plastic by mass were not considered due to the large variability in particle mass. Three possible spatial influences were considered: 1) the effect of distance from land (stations 1 & 2 of all lines compared with stations 3 & 4 and 5 & 6), 2) differences between the west and south coasts (lines 1 - 10 compared with lines 11 - 20), and 3) differences between St Helena Bay (lines 1 - 5) and the Agulhas Bank (lines 16 - 20), both typified by relatively long surface water residence times and broad continental shelves, and the region between Cape Columbine and Cape Agulhas (lines 6 - 15), where the shelf is narrow and currents in the area over the shelf-break are swifter (Shannon 1985).

A count of large plastic and other synthetic objects (visible from 130 m altitude, probably all > 100 mm diameter) at sea was made on 20 August 1985 from a light aircraft when the sea was calm. Two transects were conducted parallel to the coast between Cape Columbine and Cape Point, approximately 10 and 50 km offshore.

All differences were tested using non-parametric statistics (contingency tables).

RESULTS

Abundance and nature of plastic particles

A total of 1 224 neuston trawls was conducted between August 1977 and August 1978, sampling more than 0.23 km^2 of sea surface. Plastic particles were found in 30.6 % of all trawls (Table 1.1). The total number of particles collected was 839, equivalent to 3 640 particles km^{-2}. The total mass of plastic collected was 9.78 g, with a mean particle mass of 11.7 mg. This is equivalent to 42.4 g of plastic km^{-2}. The variances of these mean values were large (Table 1.1).

The frequency of occurrence, abundance and mass of the four plastic types are listed in Table 1.1. Industrial pellets were 99 % polyethylene and other polyolefin pellets, with only two clear polystyrene pellets (for descriptions, see Gregory 1978). Both the polystyrene pellets contained air vacuoles and floated in sea water. The industrial pellets had the largest mean mass and the smallest relative variance in mass (Figs 1.2 & 1.3).

User fragments and fibres both had a similar mean mass to the industrial pellets, but the mean masses of both user fragments and fibres were influenced greatly by a few relatively large pieces. Small particles were the most abundant, with 52.9 % of user fragments and 68.8 % of fibres weighing less than 1.0 mg (Fig. 1.3), which accounts for the great variance in mass (Table 1.1). User fragments were pieces of polyethylene and other polyolefin sheets, polyethylene bags and asymmetrical polyolefin

TABLE 1.1 The frequency of occurrence, abundance and mass of plastic particles collected in neuston trawls off the southwestern Cape, South Africa, 1977-1978. Mean values are given ± one standard deviation, with the range given beneath.

Type of plastic	Frequency of occurrence		Total number		Density	Total mass		Mean mass per	
	n	%	n	%	number.km^{-2}	g	%	particle (mg)	km^2 (g)
Industrial pellets	71	5.8	196	23.4	850 ± 11 800	3.88	39.7	19.8 ± 9.6	16.8 ± 227.5
					0 – 387 500			0.8 – 48.8	0 – 9 500
User fragments	144	11.8	222	26.5	963 ± 3 362	3.55	36.3	16.0 ± 129.7	15.4 ± 297.6
					0 – 53 080			0.1 – 1 917.5	0 – 10 180
Fibres	95	7.8	116	13.8	503 ± 1 940	2.09	21.3	18.0 ± 118.8	9.1 ± 195.4
					0 – 15 920			0.1 – 1 061.0	0 – 5 630
Foamed plastics	168	13.7	305	36.3	1 323 ± 4 143	0.26	2.7	0.9 ± 9.4	1.1 ± 25.0
					0 – 42 460			0.1 – 164.2	0 – 872
Total plastics	374	30.6	839	100.0	3 639 ± 14 633	9.78	100.0	11.7 ± 80.6	42.4 ± 476.8
					0 – 445 860			0.1 – 1 917.5	0 – 10 920

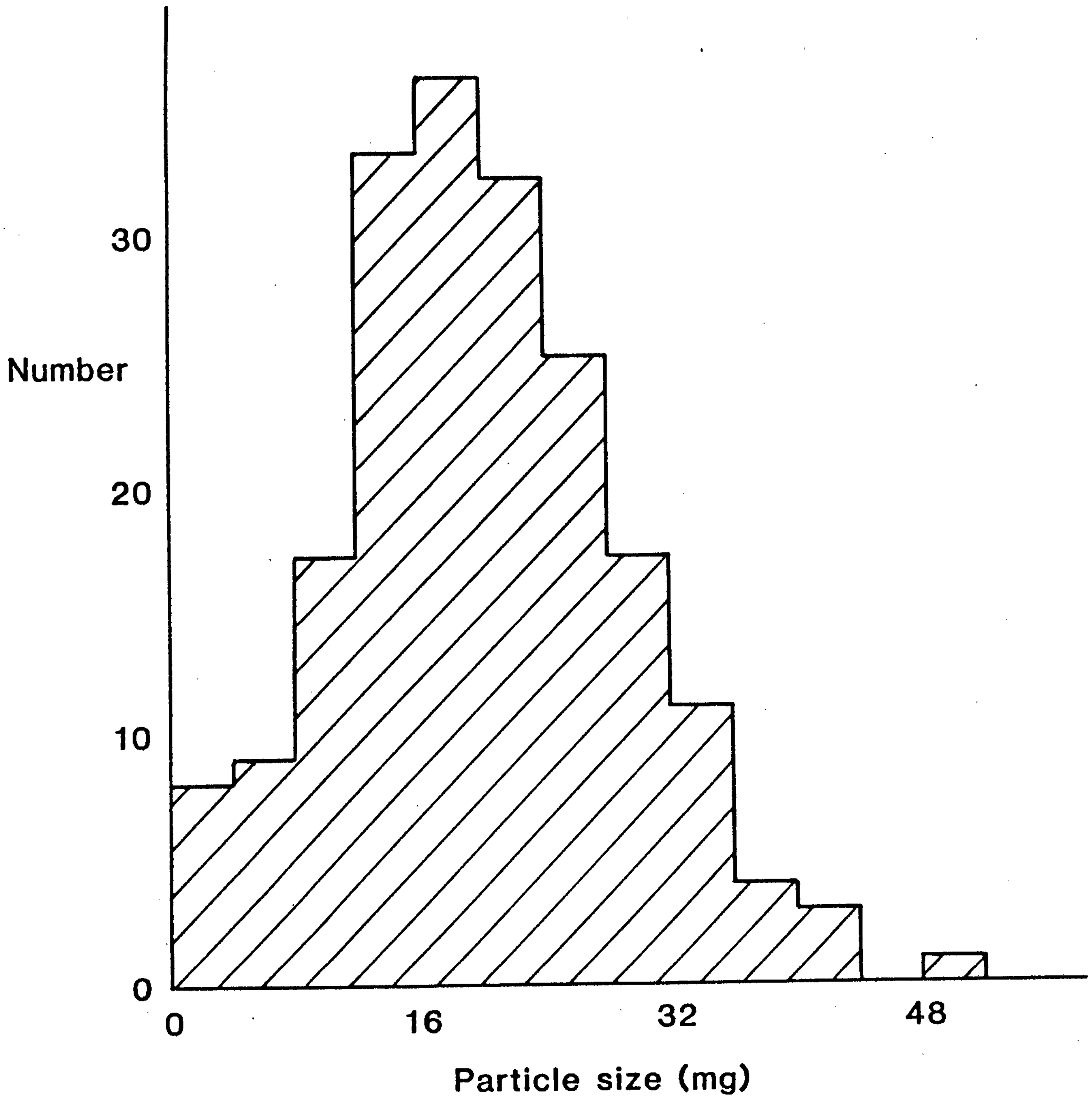

FIGURE 1.2 The masses of industrial pellets collected at sea off the southwestern Cape, South Africa, 1977-1978.

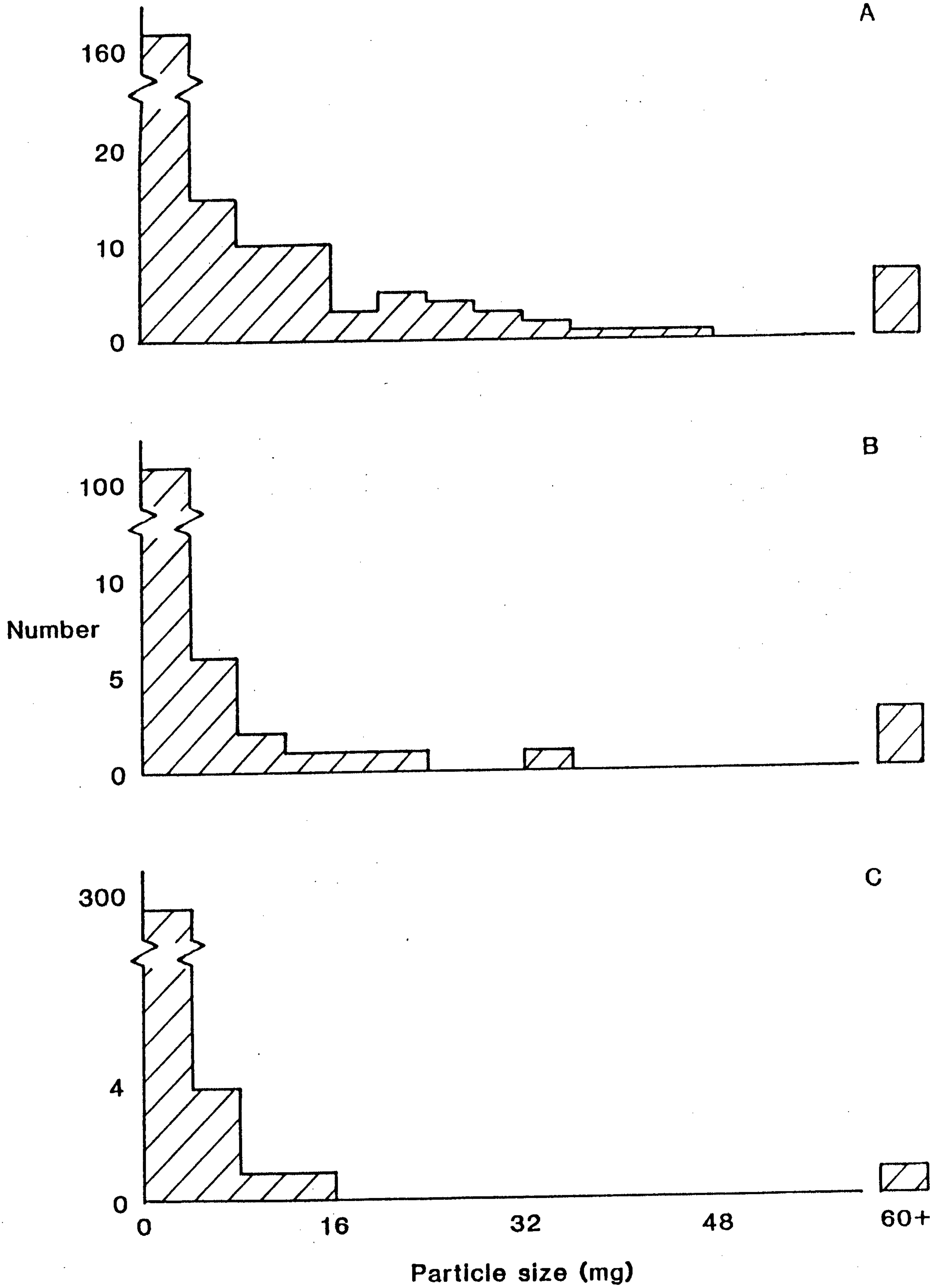

FIGURE 1.3 The masses of user plastics collected at sea off the southwestern Cape, South Africa, 1977-1978. A = user fragments, B = fibres and C = foamed plastics.

chips. Few recognizable user items were found. Fibres were primarily polypropylene, with only two pieces of nylon fishing line. The latter were the only plastics collected which did not float in sea water.

Foamed plastics were the most frequently encountered and abundant type of plastic, but they contributed very little to the total mass of plastic due to their small mean mass (Table 1.1). Nearly all (94.7 %) foamed plastic particles weighed less than 1.0 mg. A single piece of polystyrene cup contributed 62.5 % (164.2 mg) of the total mass of foamed plastics (Fig. 1.3). Expanded polystyrene made up 27.5 % (84) of the foamed plastics, the majority being fragments of foamed resins. Most (78.6 %) of the expanded polystyrene was in the form of single or grouped spheres; the remainder was in sheets similar to those used for food packaging.

Most plastic particles were pale, falling into the clear-white colour category (Table 1.2). This was the main colour category for all the plastic types except fibres, which were predominantly blue and green. Most industrial pellets were fresh (68.4 %), with 20.4 % fairly worn and 11.2 % very worn. The worn pellets were smaller than the fresh ones (Fig. 1.4, $X^2 = 44.21$, d.f. = 4, $\underline{P} < 0.001$, comparing the fresh pellets with those in the combined worn categories). The pattern of industrial pellet wear was similar to that described by Gregory (1978).

Distribution of plastic at sea

The dispersion of plastic at sea was not random at the sampling level of the neuston trawls ($X^2 = 384.2$, d.f. = 4, $\underline{P} < 0.001$,

TABLE 1.2 The proportions of plastic particles assigned to nine colour categories. Particles collected off the southwestern Cape, South Africa, 1977-1978.

Colour	Industrial pellets		User fragments		Fibres		Foamed plastics		Total
	n	%	n	%	n	%	n	%	%
Clear/white	174	88.8	182	82.0	18	15.6	303	99.4	80.7
Grey	1	0.5	5	2.2	1	0.9	1	0.3	1.0
Tan	10	5.1	6	2.7					1.9
Dark brown			2	0.9	1	0.9			0.4
Black	10	5.1	2	0.9	4	3.4			1.9
Blue			9	4.1	54	46.5	1	0.3	7.6
Green	1	0.5	15	6.8	18	15.5			4.0
Red			1	0.4	10	8.6			1.3
Yellow					10	8.6			1.2

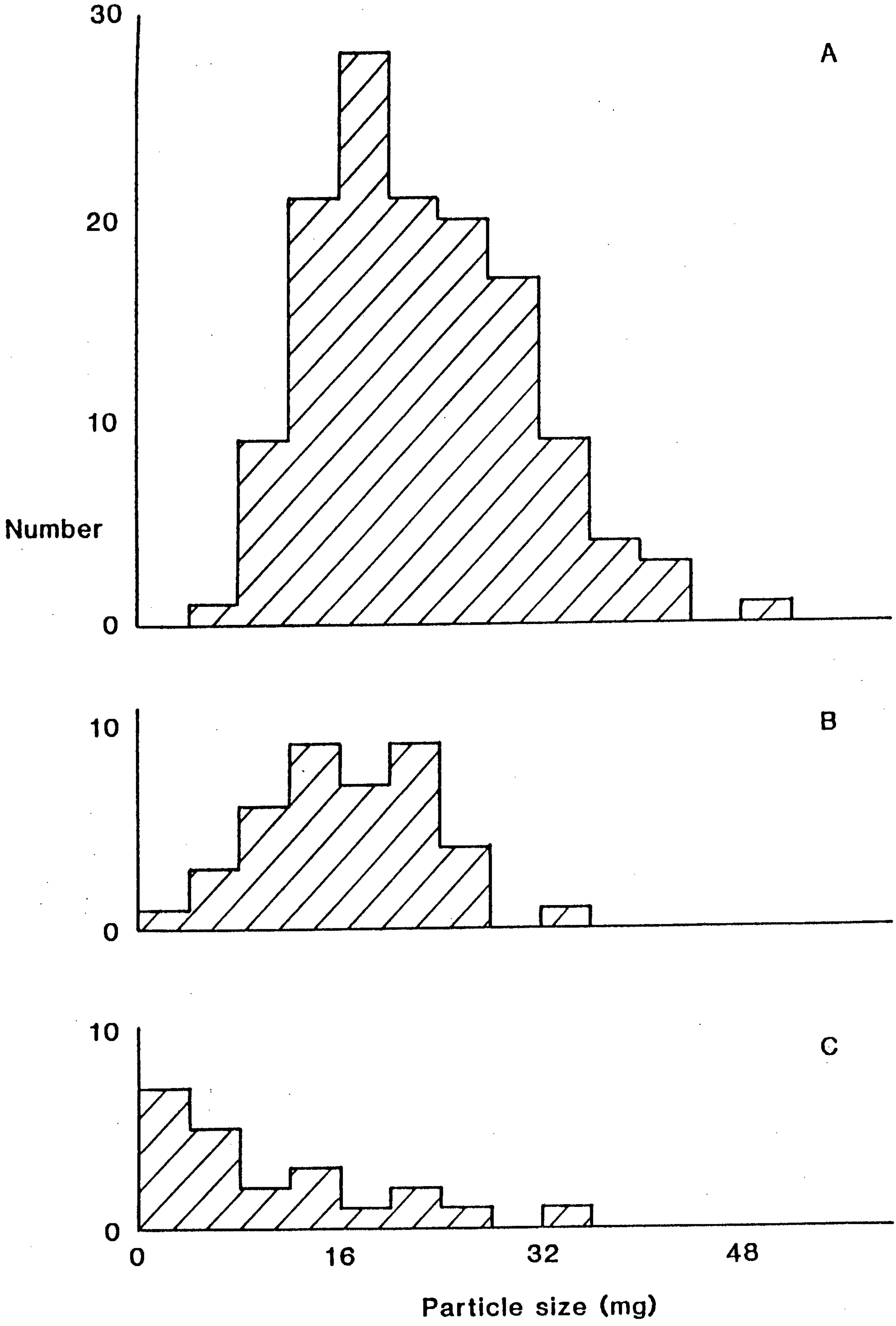

FIGURE 1.4 The masses of industrial pellets assigned to three wear categories: fresh (A), fairly worn (B), and very worn (C).

compared with Poisson distribution); plastics were clustered (variance (7.60) > mean number of items per trawl (0.69)). Almost 10 % of all particles occurred in a single trawl. The frequency with which different numbers of plastic items occurred in trawls is shown in Figure 1.5.

The distribution of plastic particles at sea showed no clear pattern on a monthly basis; variability between months was great. The frequency of occurrence of plastic in trawls and the mean number of particles per trawl were highest in August and September, and lowest in November and December. Lumping the data into summer and winter, gave a higher frequency of occurrence of plastic in winter (38.0 %) than in summer (24.2 %, $X^2 = 18.96$, d.f. = 1, $\underline{P} < 0.001$). Similarly, the total number of particles collected was greater in winter than in summer ($X^2 = 67.87$, d.f. = 1, $\underline{P} < 0.001$), being equivalent to 4 810 km^{-2} and 2 640 km^{-2} respectively. However, there was no difference in the number of particles per trawl containing plastic between summer and winter ($X^2 = 3.14$, d.f. = 1, NS). The mean mass of particles collected in summer and winter were similar (11.0 and 13.0 mg respectively), giving a mean mass of 29.0 g.km^{-2} in summer and 58.2 g.km^{-2} in winter.

The contour plot of plastic density in summer (Fig. 1.6) indicates a uniformly low density over much of the area, with slightly higher densities off the west coast. The very large concentration south of Saldanha Bay was caused by a single trawl containing 84 particles. If this trawl is omitted, the average density for the area is approximately 2 000 particles km^{-2}. The mean density in winter (Fig. 1.7) was higher than that in summer

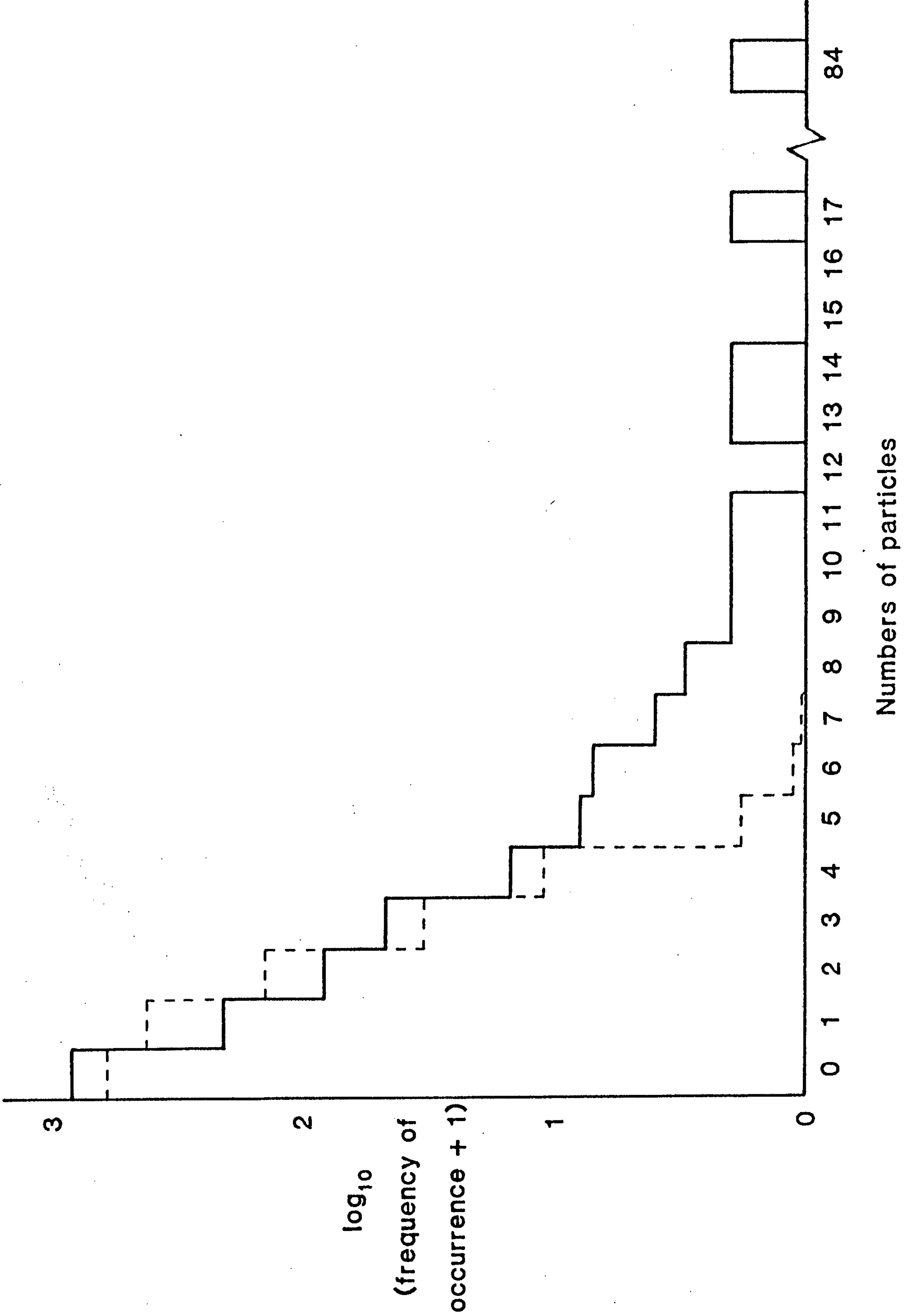

FIGURE 1.5 The frequency of occurrence of different numbers of pastic items in neuston trawls off the southwestern Cape, South Africa, 1977-1978 (solid line), compared with the frequency predicted by random dispersion (dashed line).

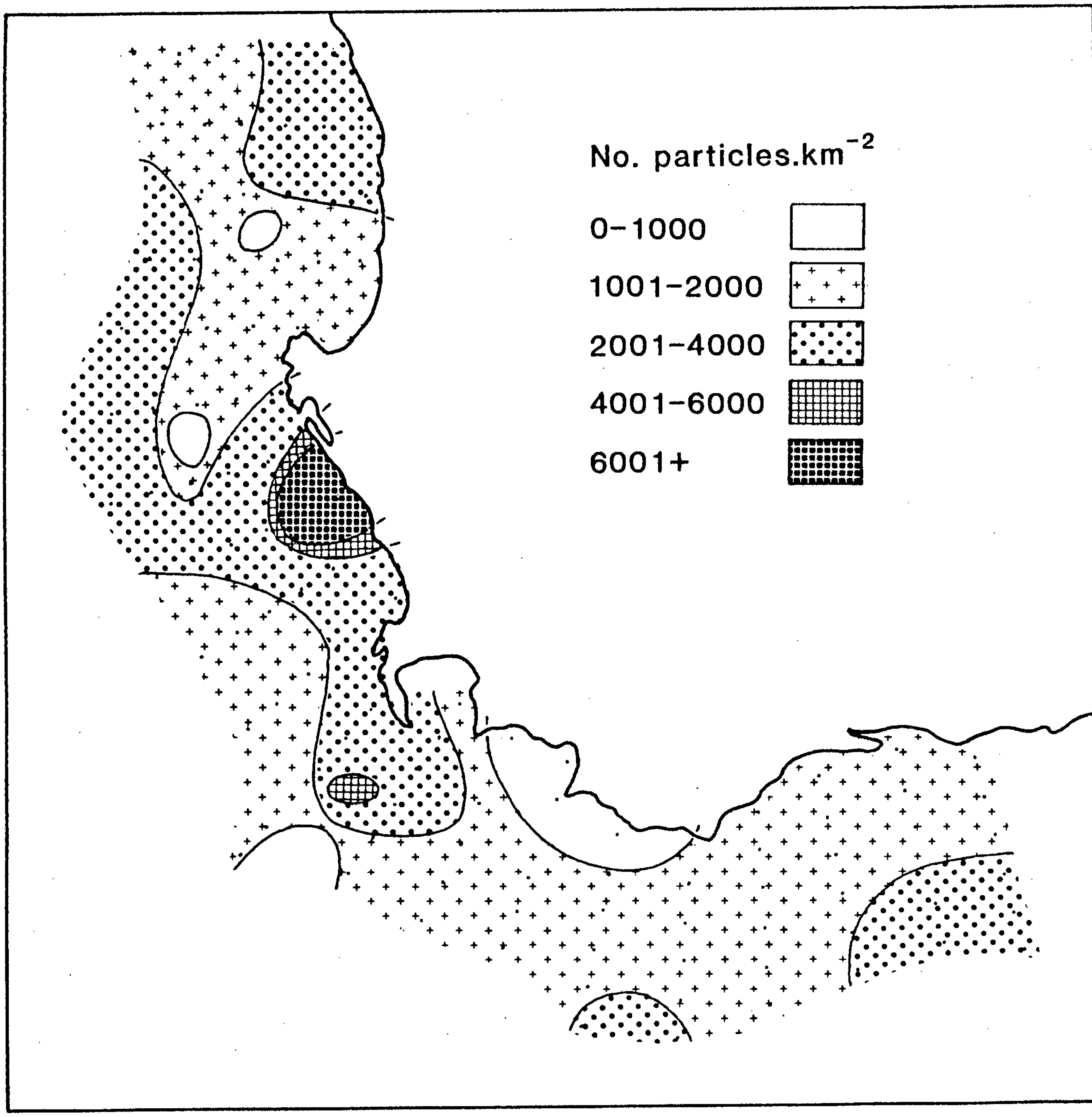

FIGURE 1.6 The surface density (number km^{-2}) of all plastic particles at sea off the south-western Cape in summer.

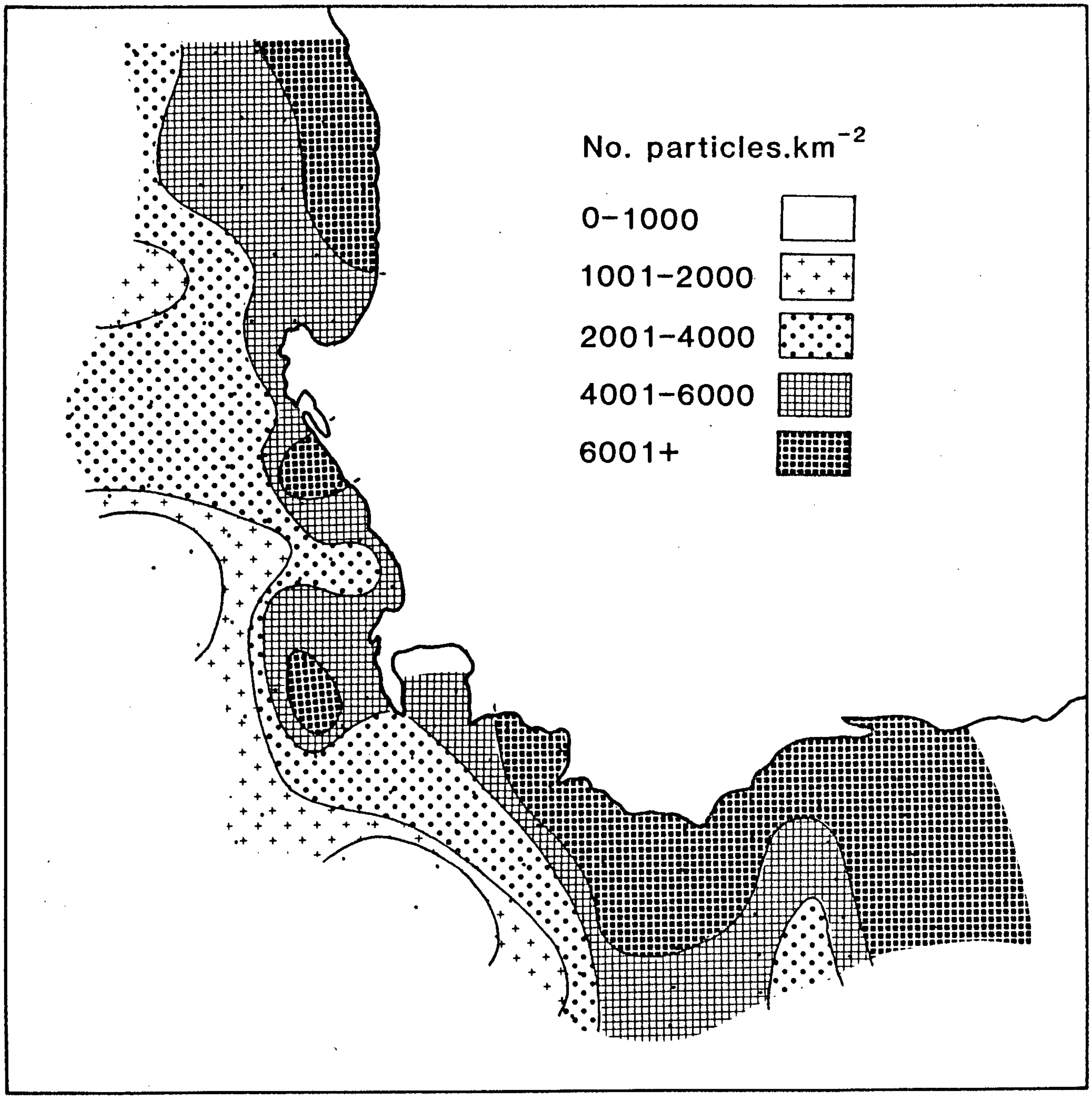

FIGURE 1.7 The surface density (number km^{-2}) of all plastic particles at sea off the south-western Cape in winter.

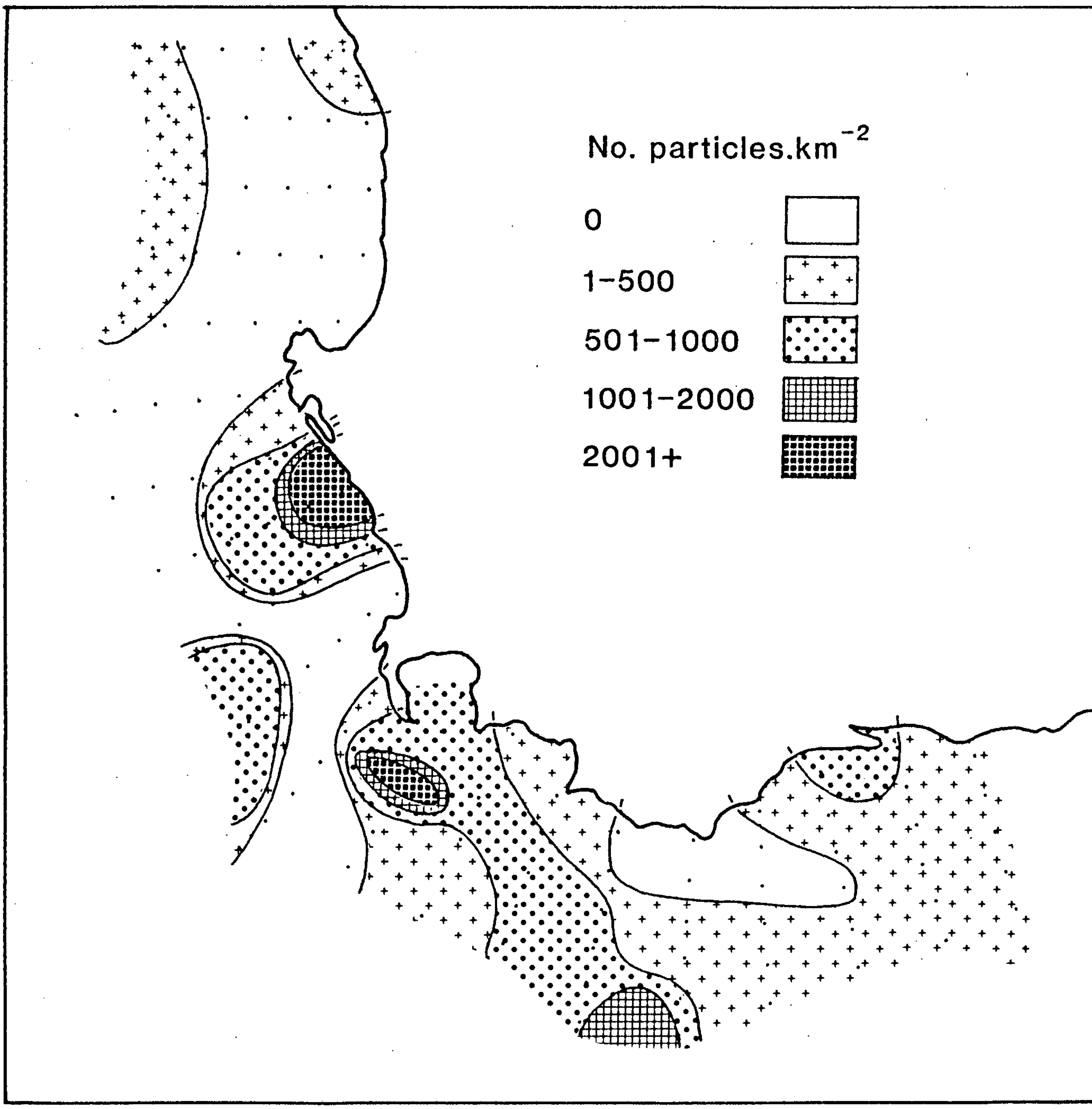

FIGURE 1.8 The surface density (number km^{-2}) of industrial pellets at sea off the south-western Cape in summer.

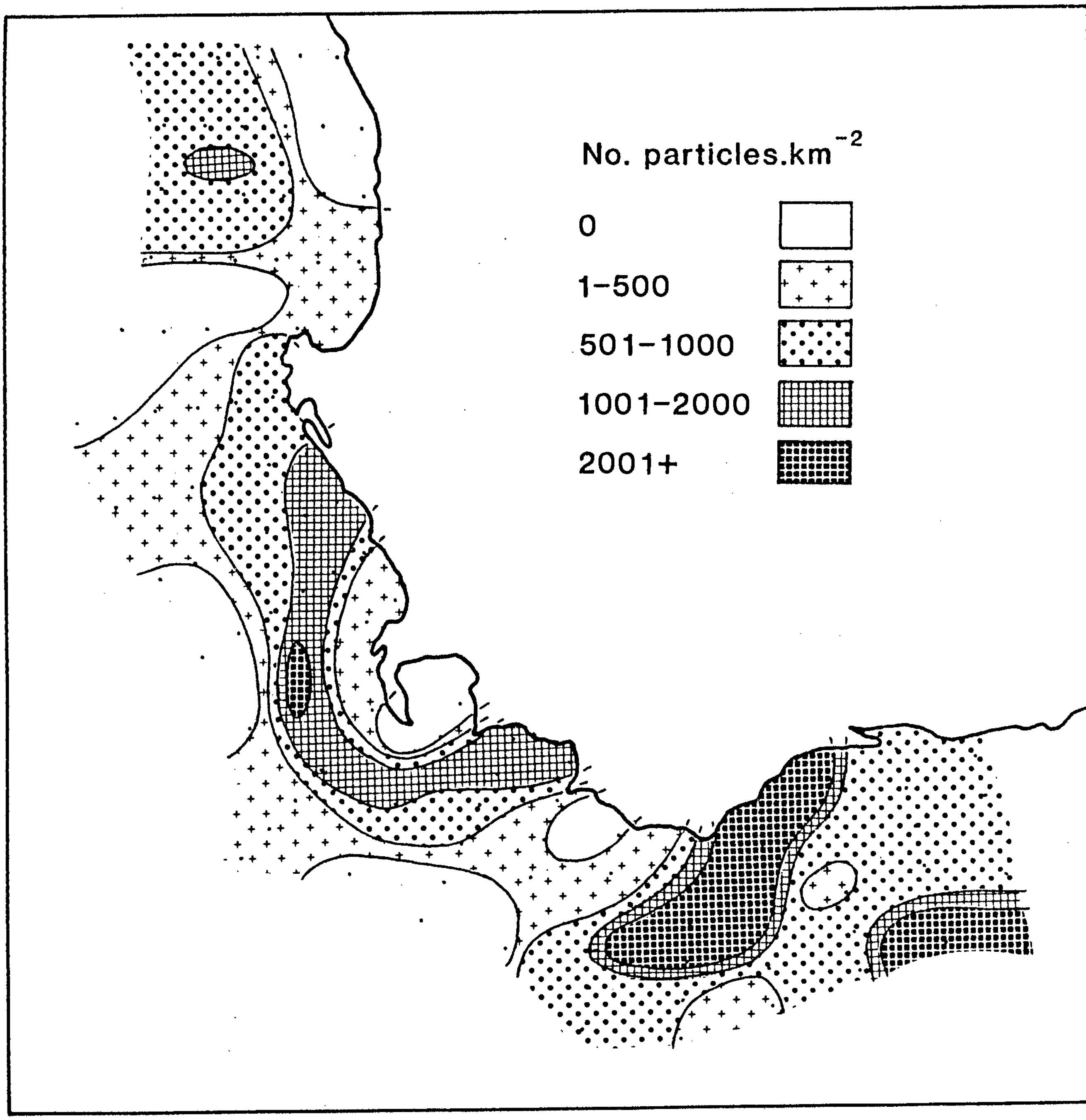

FIGURE 1.9 The surface density (number km^{-2}) of industrial pellets at sea off the south-western Cape in winter.

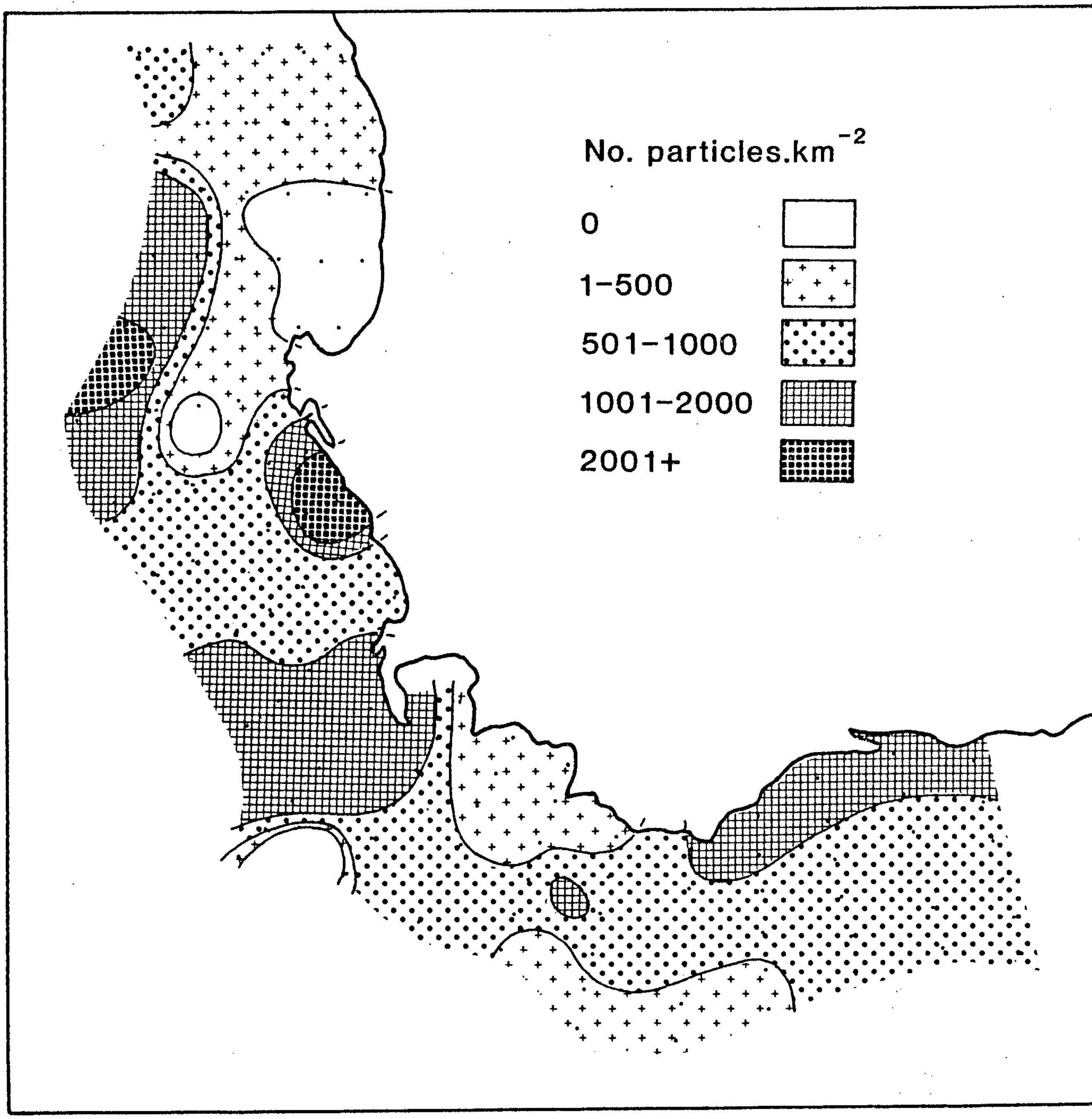

FIGURE 1.10 The surface density (number km^{-2}) of user fragments at sea off the southwestern Cape in summer.

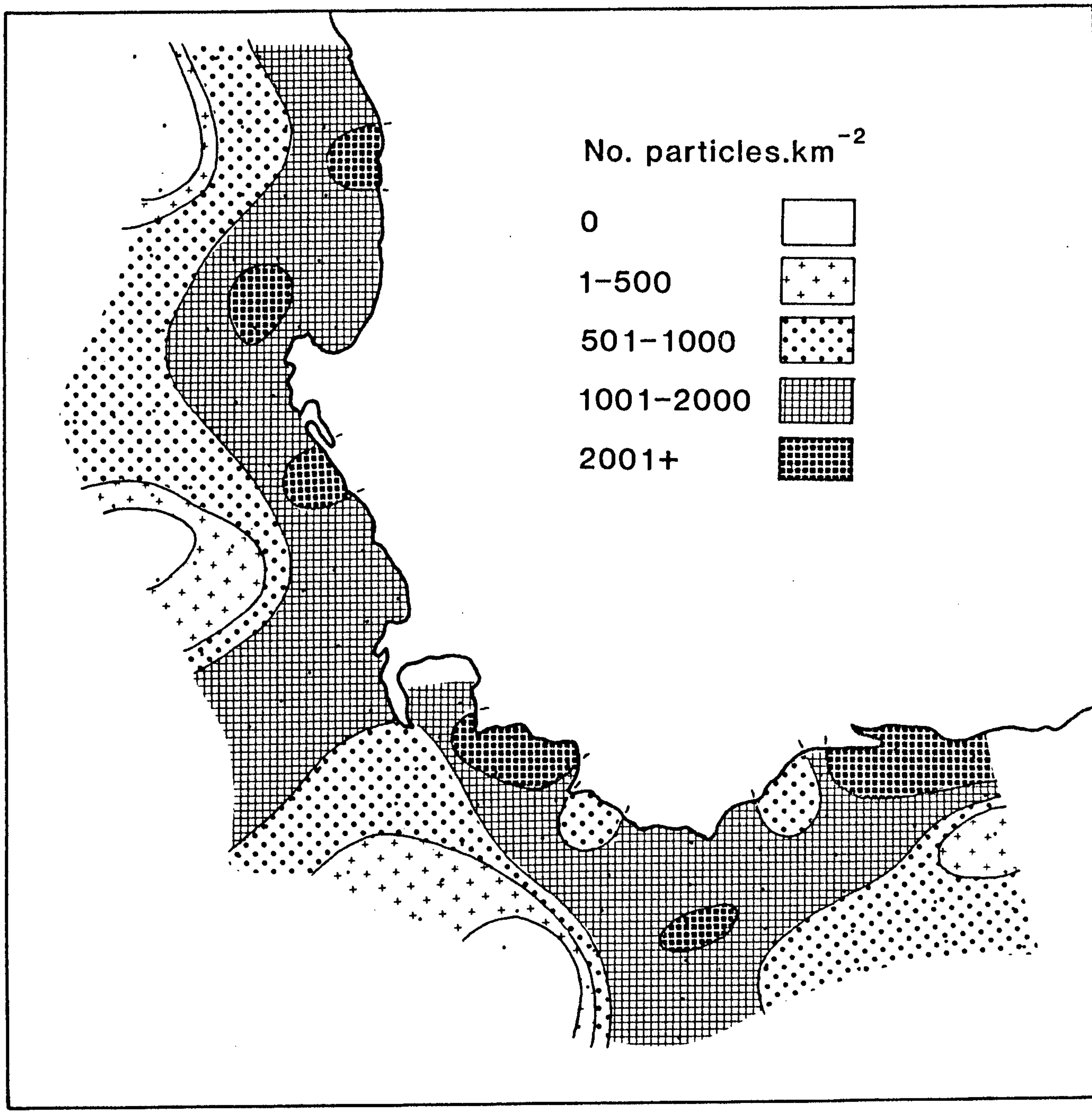

FIGURE 1.11 The surface density (number km^{-2}) of user fragments at sea off the southwestern Cape in winter.

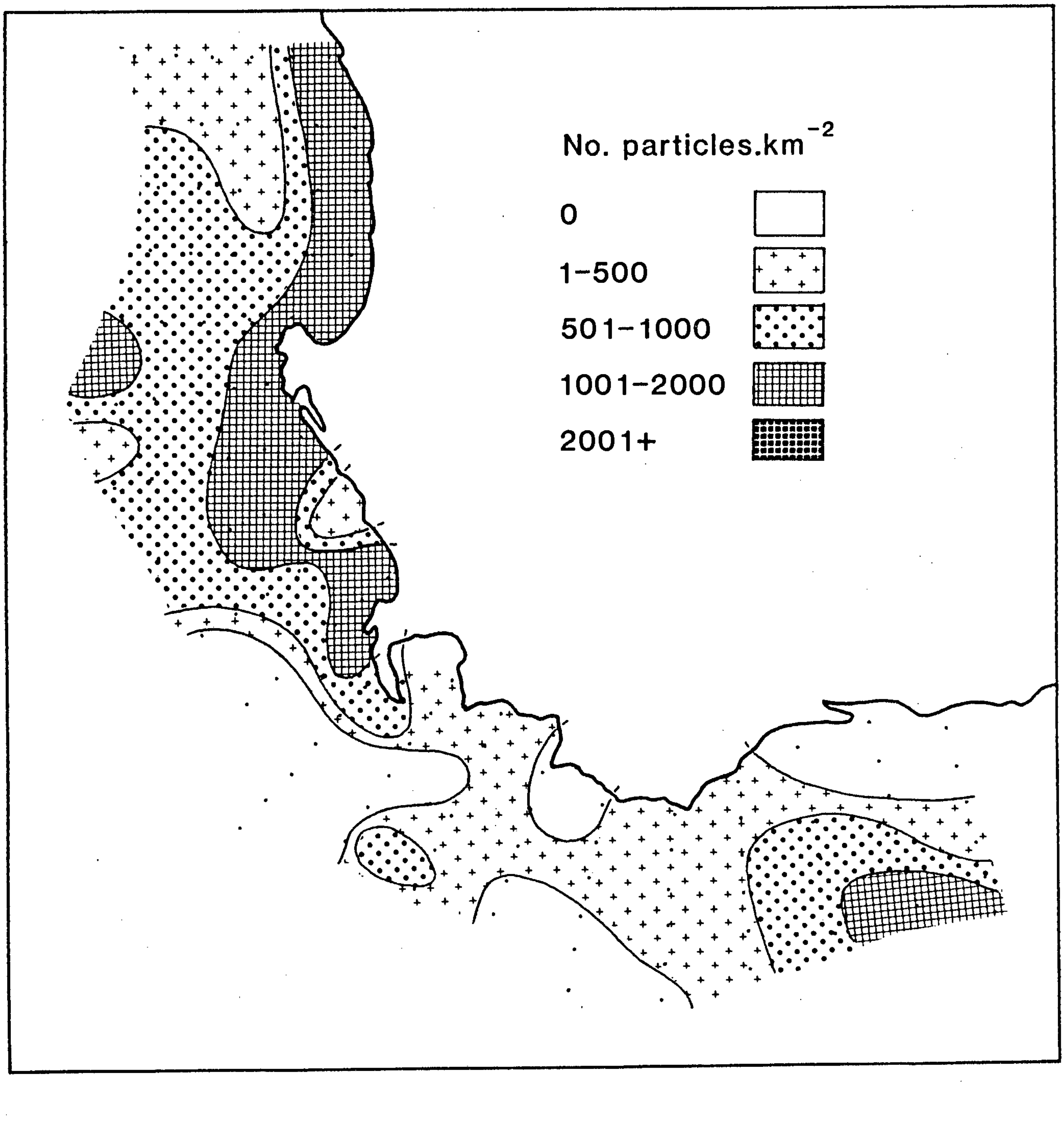

FIGURE 1.12 The surface density (number km^{-2}) of fibres at sea off the southwestern Cape in summer.

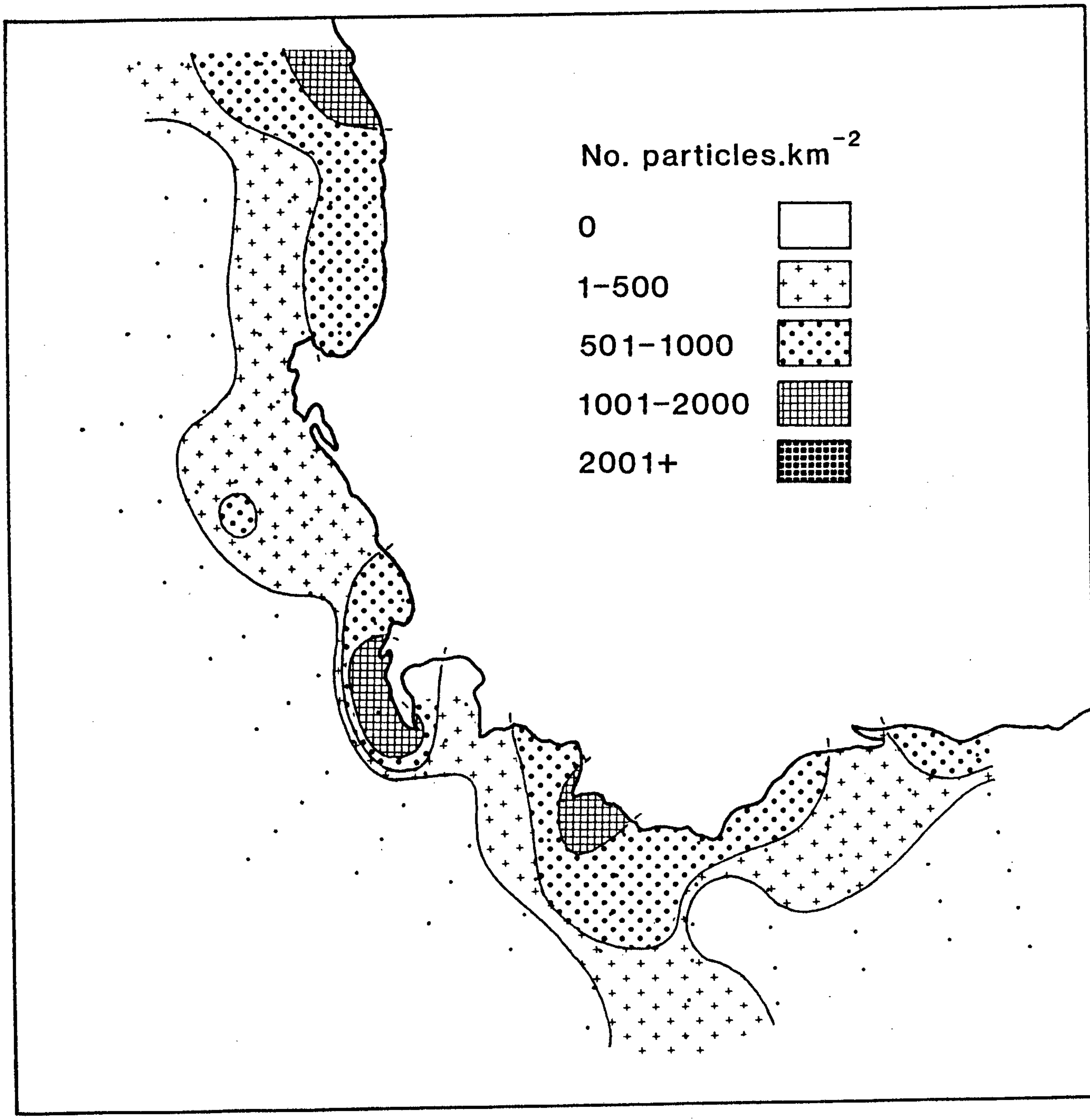

FIGURE 1.13 The surface density (number km^{-2}) of fibres at sea off the southwestern Cape in winter.

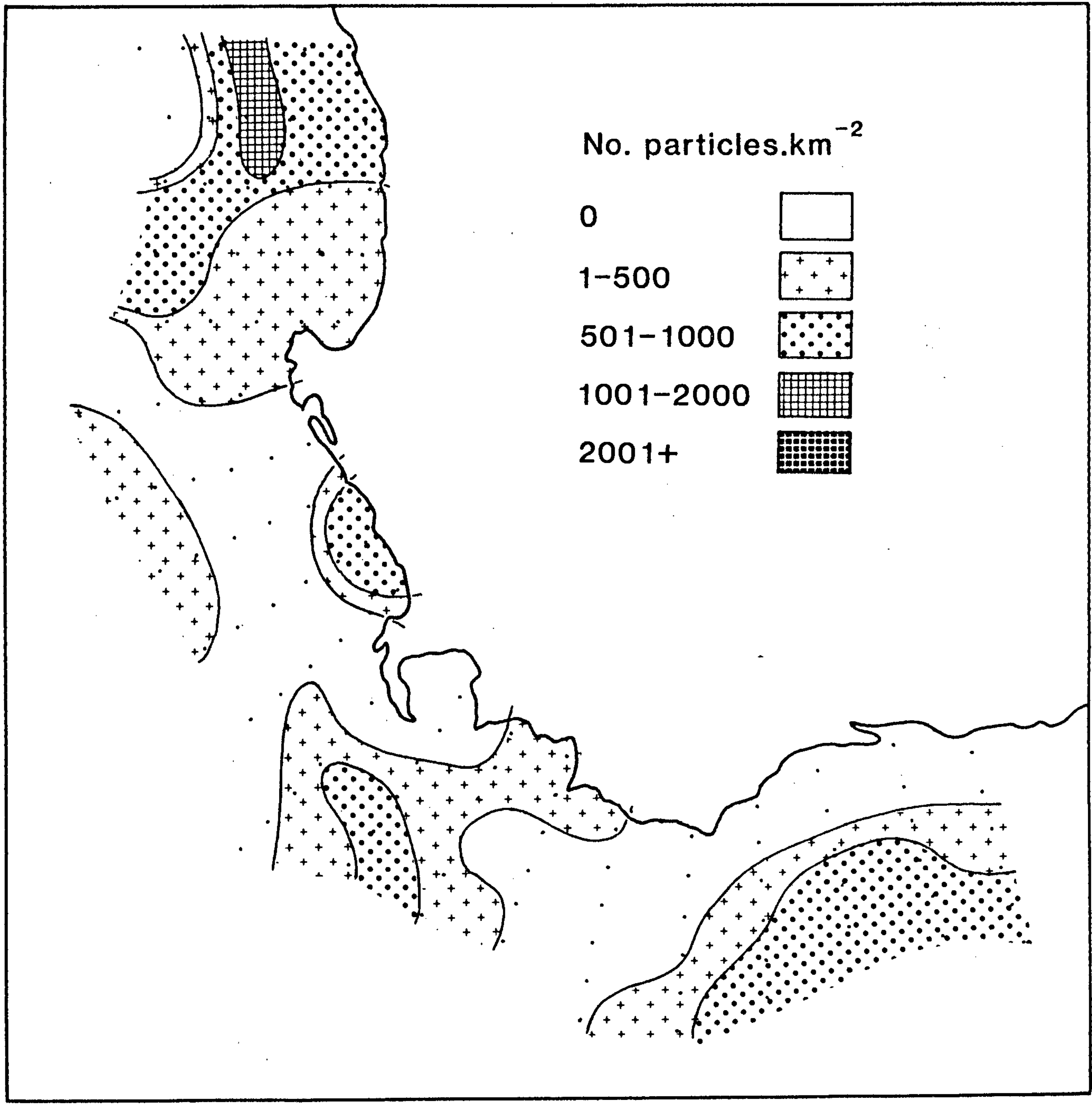

FIGURE 1.14 The surface density (number km^{-2}) of foamed plastics at sea off the southwestern Cape in summer.

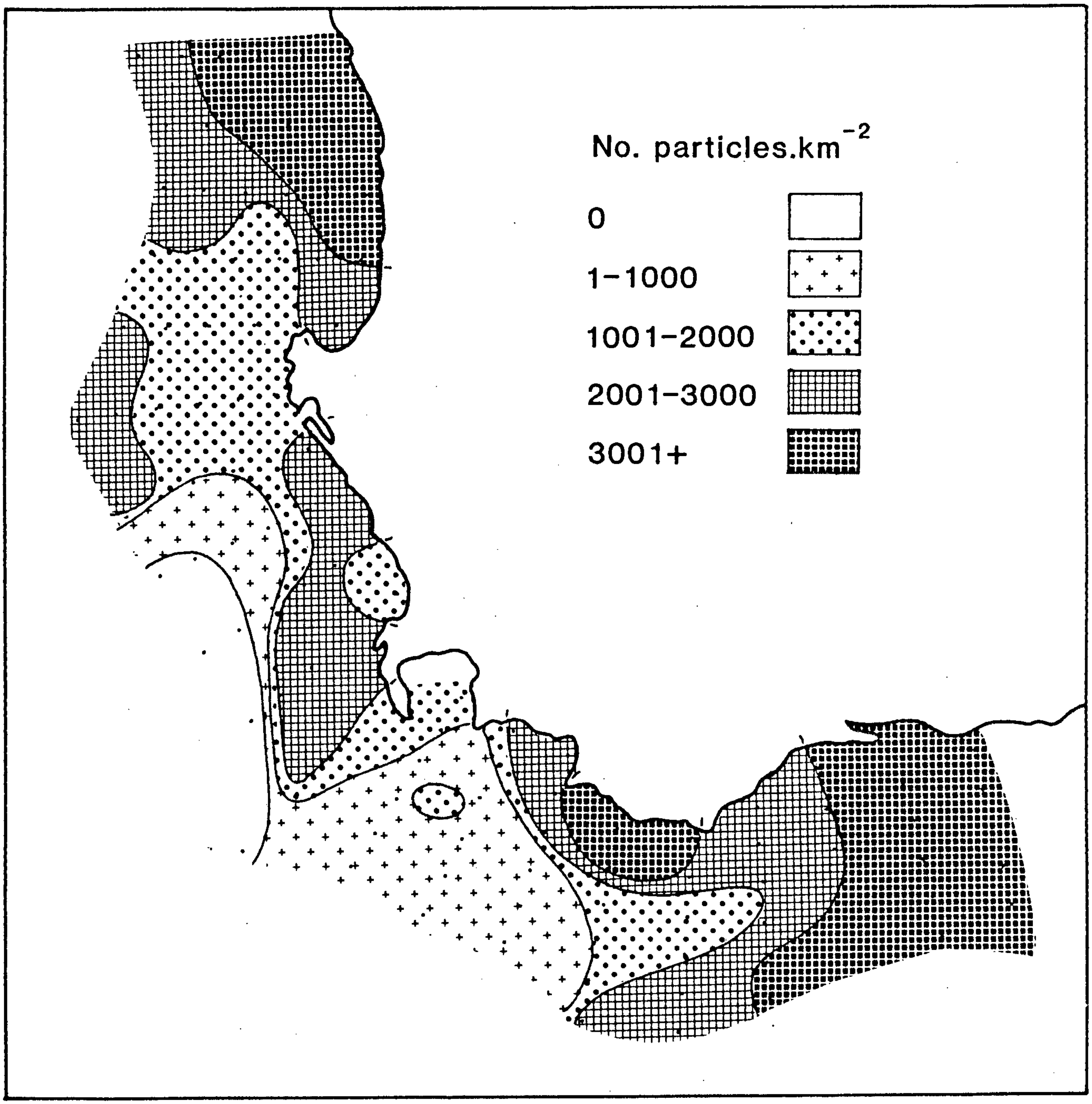

FIGURE 1.15 The surface density (number km^{-2}) of foamed plastics at sea off the southwestern Cape in winter.

over much of the study area. Particularly large concentrations were recorded inshore north of St Helena Bay, off Saldanha Bay, Cape Point and east of Cape Hangklip. Figures 1.8 to 1.15 show the summer and winter distributions of the four types of plastic in terms of particle abundance.

The frequency of occurrence and abundance of plastic decreased with distance from land throughout the year (Table 1.3). Fibres were concentrated inshore in both summer and winter (Figs 1.12 & 1.13), whereas user fragments were concentrated inshore only in winter (Figs 1.10 & 1.11). Industrial pellets were only concentrated inshore if the exceptional trawl containing 84 particles was included in the analysis (Figs 1.8 & 1.9). Foamed plastics showed no significant relationship to distance from land. Aerial counts of large plastic objects at sea also showed that plastic is more abundant near land. The mean density of plastic items on transects 50 km offshore was 1.64 km^{-2}, compared with 19.64 km^{-2} for transects 10 km offshore (X^2 = 57.58, d.f. = 1, $P < 0.001$).

Fibres were collected more frequently off the west coast than off the south coast, whereas industrial pellets were more frequent off the south coast than off the west coast (Table 1.4). Industrial pellets also were more abundant off the south coast, if the trawl containing 84 particles was omitted. Plastics generally were more abundant in St Helena Bay and on the Agulhas Bank than in the rest of the study area (Table 1.5), although the inclusion of the trawl containing 84 particles again disrupts the pattern. Foamed plastics were particularly abundant in the St Helena Bay and Agulhas Bank regions (Figs 1.14 & 1.15). The industrial pellets found in St Helena Bay and

TABLE 1.3 The influence of distance from land on the frequency of occurrence and number of plastic particles collected off the southwestern Cape, South Africa, 1977-1978.

Type of plastic	Season	Inshore - offshore	Significance	(X^2)
Frequency of occurrence				
All types	all year	150 > 114 > 110	$P < 0.05$	6.49
Fibres	all year	46 > 29 > 19	$P < 0.01$	10.94
All types	winter	91 > 76 > 57	$P < 0.05$	7.08
Fibres	winter	21 > 9 > 3	$P < 0.001$	14.86
Numbers of particles				
All types	all year	388 > 247 > 209	$P < 0.001$	62.53
Industrial pellets	all year	108 > 52 > 36	$P < 0.001^{*}$	41.13
User fragments	all year	89 > 64 > 59	$P < 0.01$	10.89
Fibres	all year	64 > 31 > 21	$P < 0.001$	24.62
All types	summer	168 > 81 > 80	$P < 0.001^{*}$	42.49
Industrial pellets	summer	83 > 17 > 15	$P < 0.001^{*}$	74.51
Fibres	summer	35 > 22 > 17	$P < 0.05$	6.17
All types	winter	220 > 166 > 124	$P < 0.001$	25.22
User fragments	winter	60 > 40 > 24	$P < 0.001$	14.97
Fibres	winter	29 > 9 > 4	$P < 0.001$	24.38

* NS if the trawl with 84 particles is omitted.

TABLE 1.4 Differences in the frequency of occurrence and numbers of plastic particles collected off the west and south coasts of the southwestern Cape, South Africa, 1977-1978.

Type of plastic	Season	West - south	Significance	(X^2)
Frequency of occurrence				
Industrial pellets	all year	24 < 47	$P < 0.01$	8.35
Fibres	all year	59 > 35	$P < 0.025$	5.25
Fibres	summer	43 > 18	$P < 0.01$	8.87
All types	winter	87 < 127	$P < 0.01$	6.65
Industrial pellets	winter	13 < 26	$P < 0.05$	4.06
Number of particles				
Industrial pellets	all year	37 < 86	$P < 0.001^{+}$	20.45
Fibres	all year	75 > 41	$P < 0.01$	8.72
All types	summer	218 > 111	$P < 0.001^{*}$	28.94
Industrial pellets	summer	84 > 31	$P < 0.001^{\sim}$	21.49
Fibres	summer	55 > 19	$P < 0.001$	15.52
Industrial pellets	winter	27 < 55	$P < 0.01$	8.98

[*] NS if the trawl with 84 particles is omitted.

[+] Only significant if the above trawl is omitted.

[~] Becomes significant in the other direction if the above trawl is ommitted (11 < 31, $P < 0.01$, $X^2 = 9.25$).

TABLE 1.5 Differences in the frequency of occurrence and numbers of plastic particles between those collected in St Helena Bay (St H) and on the Agulhas Bank (AB), and those collected off the rest of the southwestern Cape, South Africa, 1977-1978.

Type of plastic	Season	St H & AB	–	rest	Significance	(X^2)
Frequency of occurrence						
All types	all year	220	>	154	$P < 0.025$	5.40
Foamed plastics	all year	103	>	63	$P < 0.025$	5.66
All types	winter	131	>	83	$P < 0.01$	10.10
Foamed plastics	winter	84	>	51	$P < 0.01$	7.61
Numbers of particles						
All types	all year	438	>	304	$P < 0.001^{+}$	16.36
Industrial pellets	all year	65	<	131	$P < 0.001^{*}$	30.41
Foamed plastics	all year	206	>	99	$P < 0.001$	26.50
All types	summer	131	<	198	$P < 0.001^{*}$	18.73
Industrial pellets	summer	15	<	100	$P < 0.001^{*}$	68.96
User fragments	summer	40	<	57	$P < 0.05^{*}$	4.29
Foamed plastics	summer	31	>	12	$P < 0.01$	7.13
All types	winter	307	>	192	$P < 0.001$	24.90
Industrial pellets	winter	50	>	31	$P < 0.05$	4.19
Foamed plastics	winter	185	>	87	$P < 0.001$	33.93

[*] NS if the trawl with 84 particles is omitted.

[+] Only significant if the above trawl is omitted.

on the Agulhas Bank generally were more worn (57 % worn) than those found elsewhere (39 % worn, $X^2 = 3.99$, d.f. = 1, $P < 0.05$).

DISCUSSION

Abundance and nature of plastic particles

The density of plastic pollution off the southwestern Cape, South Africa, is typical of moderately polluted areas elsewhere in the world. Similar densities (2 000 - 5 000 particles km^{-2}) have been recorded from oceanic waters in the North Pacific and Atlantic Oceans (Carpenter & Smith 1972, Wong _et al_. 1974, Shaw & Mapes 1979, Morris 1980a) and the Carribean Sea (Colton _et al_. 1974). Much higher densities of plastic particles (up to 200 000 km^{-2}) have been recorded off the heavily industrialized eastern seaboard of the United States and Canada (Colton _et al_. 1974, van Dolah _et al_. 1980), whereas the density in polar waters, far removed from major sources of plastic pollution, is considerably lower (less than 200 km^{-2}) (Shaw 1977, Gregory _et al_. 1984). The mean mass of plastic per unit area recorded off the southwestern Cape is somewhat lower than those recorded elsewhere at similar particle densities, because of the large numerical contribution of small user items (fragments, fibres and foamed plastics).

The types of plastic particles found at sea off the southwestern Cape are similar to those recorded in other studies. The only type not found during the present survey which has been recorded at sea elsewhere was opaque polystyrene spherules, a type of industrial pellet (Carpenter _et al_. 1972, Colton _et al_. 1974).

These pellets are small (mean diameter 0.5 mm) and may not have been sampled using a net mesh of 0.9 mm. However, Colton et al. (1974) collected some using a similar mesh size. Their absence from the waters off the southwestern Cape is probably related to the nature of the spherules. Opaque polystyrene pellets are almost invariably negatively buoyant in sea water and are only at the sea-surface close to source areas, where strong vertical mixing allows them to remain near the surface (Colton et al. 1974).

There is very little published information on the proportions of types of plastic particles at sea. The predominance of polyethylene and other polyolefin pellets among industrial pellets off the southwestern Cape is similar to that reported for oceanic waters (Carpenter & Smith 1972, Wong et al. 1974, Morris 1980a) and coastal waters removed from industrial source areas (Colton et al. 1974, Gregory et al. 1984). The proportions of the various types of manufactured user plastics (fragments, fibres and foamed plastics) have not been quantified previously.

The ranges of sizes and colours of the different plastic types at sea are largely unrecorded. Industrial pellets have a fairly uniform mass and few colour morphs (most are clear-white, tan or black). User plastics are much more variable in both mass and colour than are industrial pellets. Most of the mass of user plastics is found in a few large items which represent a very small numerical proportion of the total population. The majority of particles were small (< 1.0 mg) in all three types of user plastics. These small particles collectively present a much larger surface area than the fewer, large pieces of plastic.

They are thus likely to be more important sources of toxic substances (e.g. polychlorinated biphenyls [PCBs], colourants and plasticizers) into the environment through surface leaching. Presumably the large user items gradually degrade to form the abundant small particles, provided they remain at sea long enough, but the rates involved are unknown. The fate of the small particles at sea, and the role of micro-particles in marine systems, remains unresolved (Gregory 1978).

The form of the industrial pellet mass spectrum differs from those of the other types of plastic in that small particles (< 10 mg) are less abundant than larger particles. This is in part due to the difficulty of recognizing very small fragments of pellets, but this cannot explain the low numbers of pellets found between 6 and 12 mg. The observed mass spectrum for industrial pellets, together with the dominance of fresh pellets, could result from either or both of the following: 1) the southwestern Cape lying close to major source areas of pellets, with high rates of flux carrying away older, more worn pellets, or 2) faster weathering rates in older pellets. The larger proportion of worn industrial pellets in gyres in St Helena Bay and on the Agulhas Bank supports the first hypothesis. However, the extensive fracturing of pellets caused by UV radiation during advanced weathering (Gregory 1978) may indeed cause accelerated pellet disintegration.

The colour of plastic items has been invoked as an important factor in the patterns of plastic ingestion by a number of organisms including fish (Anon. 1981), turtles (Balazs 1985) and seabirds (Day 1980). The colour-frequency data recorded here will allow the first critical tests of these hypotheses, at least for surface-feeding animals. Day et al. (1985) presented colour frequency data for large plastic objects (user plastics) seen from a boat in the North Pacific Ocean, and assumed these to be representative of plastic particles at sea. This is naive, given the widespread addition of colorants to plastics during manufacture and the concomitant differences in colour frequencies between different types of plastic (see Table 1.2).

Distribution of plastics at sea

The small-scale distribution pattern of plastic particles at the sea-surface is clustered, presumably around surface convergence zones. Discrete convergence lines with large concentrations of floating debris frequently are seen during calm weather (e.g. Bourne & Clark 1984, pers. obs). This clustered distribution at the scale at which sampling occurs probably accounts for most of the variance in the frequence of occurrence, numbers and, to a lesser extent, mass of plastic particles recorded in neuston trawls. The biases introduced by inadequate sampling of such a clustered distribution probably are as important as those resulting from the variable efficiency of neuston nets as discussed by Colton et al. (1974) and Morris (1980a).

These local differences average out on a larger scale, and meso- to large-scale distribution patterns can be detected (Colton et al. 1974). Three factors influence the distribution of plastics at sea:

1) Source areas. Plastic density is inversely related to the distance from major source areas (e.g. Colton et al. 1974).
2) Surface currents and winds. These are responsible for the

dispersal of plastic particles away from source areas (Shaw & Mapes 1979, Galt 1985). Low-density foamed plastics probably are influenced more by wind than by currents, whereas plastics with densities approaching that of sea water (e.g. polyolefins) are more influenced by currents than by wind.

3) Life span at sea. Long-lived plastic particles travel at sea until they are eventually trapped in "sinks", such as stable gyres (e.g. the Sargasso Sea - Carpenter & Smith 1972) and beaches where they are stranded (e.g. Gregory 1978). Short-lived plastic particles may degrade before reaching sink areas.

In order to explain the distribution of plastic at sea off the southwestern Cape, it is necessary to examine these factors as they relate to the study area.

The sources of plastics at sea have been discussed at length (e.g. Colton _et_ _al_. 1974, Gregory 1978, Dixon & Dixon 1981, Horsman 1982, Merrell 1984). There is a large contribution of user plastics from ships. The southwestern Cape lies on a major shipping route and there are large demersal and pelagic fisheries. Ashore, plastics are widely employed and some of these, particularly disposable items, end up in the sea. There is an industrial centre at Cape Town, which includes several plastics manufacturers which use industrial pellets as feedstock. Pellets frequently are spilt during handling (Shiber 1979), occasionally in large numbers (Gregory 1978, pers. obs), and they enter the sea via drainage lines. The magnitudes of these sources of plastic are unknown, as is the importance of advection of plastic into the area by currents and winds.

South Africa is bounded by two major current systems, the Benguela Current on the west coast and the Agulhas Current on the south and east coast (Fig. 1.16). The Agulhas Current runs parallel to the coast, following the 200 m isobath, until it reaches the Agulhas Bank, where it swings away from the coast, retroflexes and forms the Return Agulhas Current (Lutjeharms & Walters 1985). Shear eddies along the northern boundary of the current advect water over the Agulhas Bank, where circulation is sluggish and a meso-scale gyre occurs (Shannon _et al_. 1983). Between Cape Agulhas and Cape Point there is a divergence zone between the Agulhas and Benguela Currents, and currents run northwest around Cape Point to join the main northward Benguela Current (Shannon 1985). The Benguela Current is swift where the shelf is narrow, but is much slower in the shallow waters of St Helena Bay, where an inshore counter-current balances the northward flow (Holden 1985).

During summer, strong southerly winds blow over the southwestern Cape, resulting in upwelling off the west coast (Shannon 1985). Plumes of upwelled water move northwest off the upwelling centres of the Cape Peninsula and Cape Columbine (Shannon 1985). During winter, cyclonic depressions move eastwards over the area, bringing initially northwesterly winds, which then back to southerly winds. Net wind vectors for this period are small (Kamstra 1985).

The life spans of different plastics at sea are not known, but are thought to be between three and 30 years, depending on the type of plastic and its additives (Gregory 1978). These time scales presumably are sufficiently long to allow complete

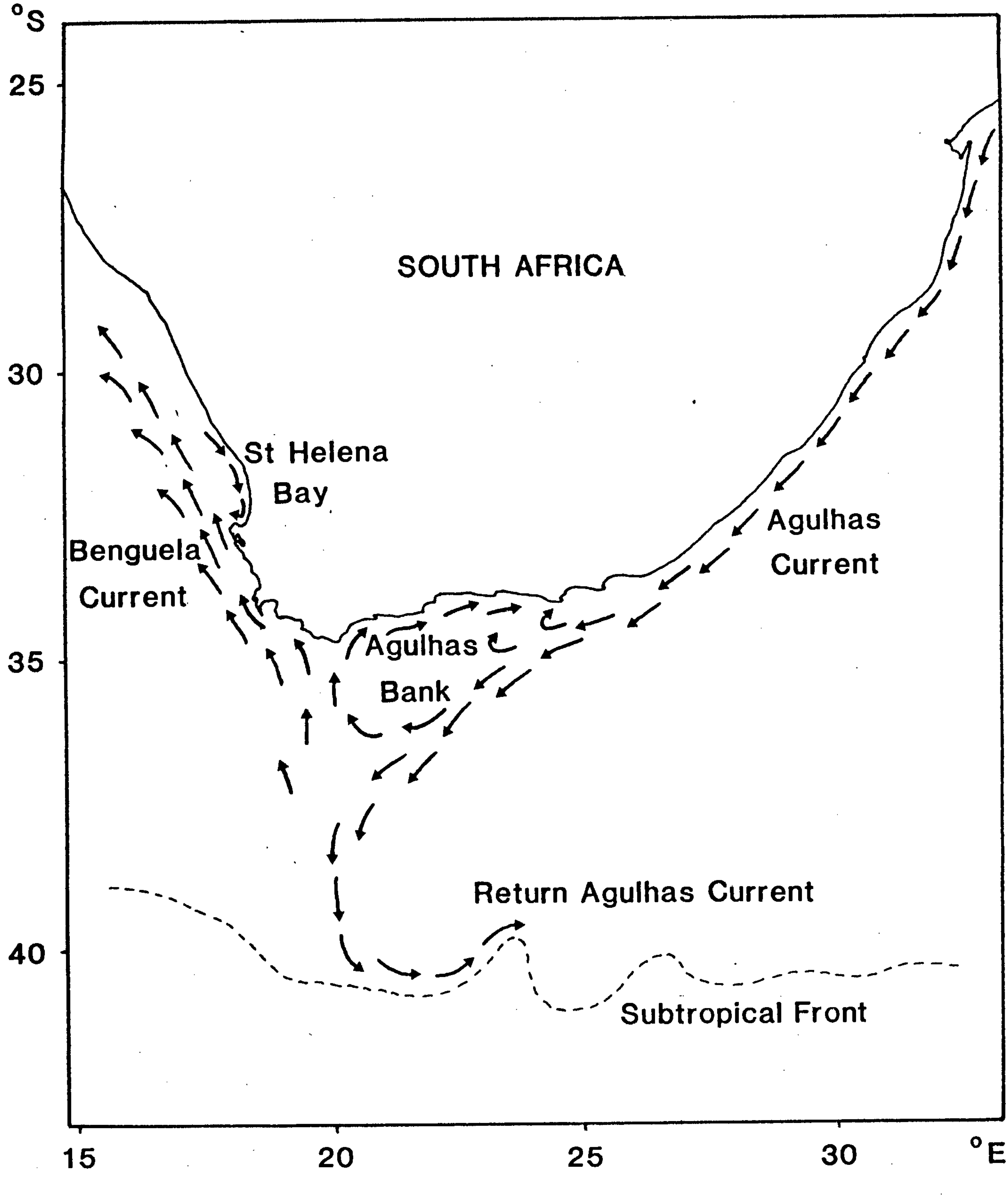

FIGURE 1.16 The major currents off South Africa.

dispersion over an area the size of the study area. It is not known whether different types of plastic are subject to different rates of sedimentation due to colonization by marine organisms (Holmström 1975), but few of the plastic objects found supported marine organisms.

The concentration of plastic in the inshore zone (< 40 km from land) off the southwestern Cape (Table 1.3), suggests that local input, either from ships or the land, is an important source of plastic particles at sea. Fibres are particularly concentrated inshore and along the west coast, where most of the fishing harbours are found. Fisheries are probably the major source of polypropylene fibres, the commonest type of fibre at sea. User fragments showed few clear trends, other than a tendency to be commoner inshore. This probably reflects the varied origins of this heterogenous group of plastic particles.

Industrial pellets were more frequent and abundant off the south coast than off the west coast, suggesting that advection in the Agulhas Current is an important source of these particles into the study area. Effluent from the only potential local sources of industrial pellets discharges into the sea on the west coast, and the particles would have to travel against the current to reach the south coast (although a few drift cards have rounded Cape Point from west to east in winter (Shannon et al. 1983)). This argument also holds for most user plastics, because there are few population centres along the south coast. The Agulhas Current probably is a major plastic vector as is the Gulf Stream (van Dolah et al. 1980), a comparable western boundary current.

The ultimate source of industrial pellets reaching the south coast must lie farther east, either in South Africa (e.g. Port Elizabeth, East London and Durban) or elsewhere in the Indian Ocean. Pellets are very abundant on beaches along the south and east coasts of South Africa (pers. obs). The only local production of pellets occurs at Secunda on the Witwatersrand, at the watershed of rivers entering the Atlantic (Orange River) and Indian (Olifants River, tributary of the Limpopo River) Oceans, but losses from these sources are likely to be small because emphasis is placed on recycling spillages (G. Pickwell, AECI, pers. comm.). Most pellets probably are lost during transport or by manufacturers of user articles in industrial areas throughout South Africa. Some pellets may also enter the area via oceanic circulation from the South Atlantic (Morris 1980a).

Foamed plastics were most frequent and abundant in the sluggishly circulating surface waters of St Helena Bay and the Agulhas Bank. These areas probably act as temporary sinks for plastic particles. This is supported by the larger proportion of worn (and presumably older) pellets in these areas.

Seasonal differences in the amount of plastic at sea off the southwestern Cape can be attributed to the effects of wind. During summer, the consistent southerly trade winds move plastics onto the beaches of the south coast (evidence from drift card returns (Shannon et al. 1983) and the very high plastic densities found on those beaches in summer (pers. obs)), accounting for the low plastic densities at sea off the south coast in summer (Fig. 1.6). On the west coast, the Benguela Current, aided by southerly winds, moves plastic particles offshore and northwards, out of the study area (Shannon et al.

1983). Upwelling enhances this offshore movement and the low plastic densities off the Cape Peninsula and Cape Columbine (Figs 1.6, 1.8, 1.10, 1.12, 1.14) probably result from upwelling plumes.

In winter, northwesterly winds oppose the northward advection of plastic by the Benguela Current (drift card returns in Shannon *et al*. 1983), causing concentrations inshore along the west coast, particularly in St Helena Bay (Fig. 1.7). However, the northwesterly winds are not consistent enough to to trap a large proportion of the particles ashore. On the south coast, plastic accumulated on the beaches during summer apparently is released into the sea by wind and wave action during winter, because the density of plastic on south coast beaches during winter is low (pers. obs). Much of this plastic is trapped in the slowly circulating gyre on the Agulhas Bank (Fig. 1.7), although there is probably some interchange with the Agulhas Current. In winter, both the St Helena Bay and Agulhas Bank regions experience positive wind stress curl (Kamstra 1985) which causes surface convergence. These mechanisms explain the higher density of plastic particles at sea in these areas during winter.

Plastic pollution at sea off the southwestern Cape is thus in a constant state of flux. Particles enter the region either through local inputs (land-based or ships) or through oceanic circulation (primarily the Agulhas Current, but perhaps also from the South Atlantic via the Benguela Current). Local concentrations occur in temporary sinks in St Helena Bay and on the Agulhas Bank. Other sinks are beaches, where plastic particles are stranded, and advection into oceanic circulation systems in both the Atlantic and Indian Oceans. The apparently high levels of plastic pollution entrained in the Agulhas Current may be an important factor in introducing plastic particles to the Southern Ocean through mixing at the Subtropical Front.

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CHAPTER 2

THE INCIDENCE AND CHARACTERISTICS OF PLASTIC PARTICLES INGESTED BY SEABIRDS

ABSTRACT

Plastic ingestion was recorded for 36 of 60 seabird species sampled in the southern hemisphere (mostly off southern Africa). The effects of different sampling techniques were considered. Plastic was most frequent in procellariiform species, notably Blue Petrels *Halobaena caerulea*, Great Shearwaters *Puffinus gravis*, Whitefaced Storm Petrels *Pelagodroma marina* and Pintado Petrels *Daption capense*. The nature of ingested plastic particles was described and compared with that found at sea. Ingested particle size was related to body size, and this affected the proportions of plastic types ingested. Pale particles were under-represented in all species, suggesting selection for darker-coloured particles. Small species were less colour selective than large species and had a higher incidence of plastic ingestion than did large species. The incidence of ingested plastic was directly related to foraging technique (highest in surface feeders) and niche breadth (highest in dietary generalists), and inversely related to the frequency of egestion of indigestible stomach contents (lowest in petrels and perhaps phalaropes). Secondary ingestion of plastic through contaminated prey was important in only one species sampled.

Five factors determine the incidence of plastic pollution in seabirds: foraging technique, the degree of dietary specificity, the density and type of plastic particles in the foraging area (which affect the rate of plastic ingestion), and the frequency of egestion of indigestible stomach contents and the rate of wear of particles in the stomach (which affect the rate of plastic loss).

INTRODUCTION

The ingestion of plastic particles by seabirds has become a widespread and frequent phenomenon during the last 25 years (Day et al. 1985). The factors affecting the incidence and nature of plastic ingestion have been related to foraging behaviour and diet (Day 1980), but these relationships have not been tested on an independent suite of seabirds. Also, Day et al. (1985) failed to consider the potential effect of taxonomic differences on the relationships between foraging techniques and diet and the incidence of plastic ingestion.

This chapter examines the incidence of plastic ingestion by southern hemisphere seabirds, primarily off southern Africa and in the adjacent sector of the Southern Ocean. Only differences between species are considered here. Variation in the incidence of ingested plastic within species is considered elsewhere (Chapter 3). The types, sizes and colours of ingested plastic particles are compared with those found at sea off the southwestern Cape, South Africa (Chapter 1). This represents the first meaningful test of the hypothesis that the colour and shape of plastic particles influence the probability of ingestion by seabirds (cf. Day 1980, Day et al. 1985).

Little has been published to date on the incidence of plastic in seabirds in the southern hemisphere (Crockett & Reed 1976, Day 1980, Prince 1980, Reed 1981, Bourne & Imber 1982, Furness 1983, Randall et al. 1983). Furness (1985a) presented data for 15 seabird species from Gough Island, South Atlantic Ocean, and these are included where relevant.

METHODS

Collection of samples

The incidence of plastic in seabirds was sampled by myself and other members of the FitzPatrick Institute between 1979 and 1985. Two sampling techniques were employed: 1) birds were collected (either found dead or killed) and their stomachs dissected out to examine the contents, and 2) stomach regurgitations (either natural or induced) were collected and examined for plastic particles. The first method was preferred because it ensured that the entire stomach contents could be collected and allowed examination of the rest of the digestive tract as well. However, the destructive nature of this technique prevented the extensive collection of live birds solely to assess the incidence of ingested plastic.

Albatrosses, cormorants, skuas and gulls periodically regurgitate pellets of indigestible material (Kenyon & Kridler 1969, Below 1979, pers. obs), and these were examined for plastic. A wet-offloading stomach pump (Wilson 1984) was used to obtain stomach samples from penguins and giant petrels. The data from natural and induced regurgitations were lumped with those from collected birds. Collected birds were divided into three groups: 1) fully grown birds either collected at sea or at breeding sites, 2) chicks and fledglings, and 3) beached birds (see Table 2.1). Included in the first two categories are adults and fledglings killed at breeding sites by Subantarctic Skuas (the scientific names of all seabirds mentioned in the text are given in Table 2.1) or by misadventure (e.g. night-strikes against buildings).

All birds were sampled off southern Africa and in the African sector of the Southern Ocean, with the exception of Magellanic and Humboldt Penguins and the Magellan Diving Petrel, which were sampled in central and southern Chile. Most birds were either shot at sea off the southwestern Cape, South Africa, or were collected at their breeding grounds at Inaccessible Island (37 15S, 12 30W), Gough Island (40 21S, 9 53W), Bouvet Island (54 26S, 03 24E) and the Prince Edward Islands (46 45S, 37 50E). Snow Petrels, Antarctic Petrels and Arctic Terns were collected in the African sector of the Southern Ocean south of 65S, whereas the Adélie Penguins and Antarctic Fulmar were collected farther east, off eastern Enderby Land, Antarctica. The Pomarine Skua was collected off Walvis Bay (22 55S, 14 25E), Namibia. Beached birds were collected from beaches in South Africa, primarily in the southwestern Cape. All regurgitations were collected at breeding sites.

Analysis of samples

All plastic particles found in seabird stomachs were identified to one of four types: industrial pellets, pieces of manufactured items (termed user fragments), fibres and foamed plastics. The last three are collectively termed user plastics and derive from manufactured articles. Each particle was colour coded while wet into one of nine colour categories: clear-white, grey, tan, dark brown, black, blue, green, red (including pink and orange), and yellow. Lumping of clear and white particles was necessary due to the effect of crazing during weathering on particle colour (c.f. Gregory 1978, Chapter 1). Where a particle consisted of two (or more) colours in similar proportions, the particle was scored under both categories. Buoyancy was tested in sea water. The plastic particles were then oven dried at 30 °C and weighed to the nearest 0.1 mg.

The incidence of ingested plastic in each species was analysed in terms of frequency of occurrence, number and mass per bird. Maximum plastic loads (in terms of mass) were compared with body mass and gizzard (ventriculus) volume (estimated from Furness 1985a). Plastic volume was calculated using the specific density of polyethylene (0.9).

The sizes (by mass) and colours of the major types of plastic particles ingested by each species were compared with those found in the environment (Chapter 1). Dark brown and black industrial pellets were lumped to enable comparison with pellets collected at sea. Where no particle of a given colour was collected at sea (e.g. red industrial pellets), the frequency of occurrence at sea was assumed to be 1/n+1 (where n is the total number of particles of a given type of plastic collected at sea).

Plastic particles found in Subantarctic Skua pellets could be ascribed to the prey species in the pellet (Appendix 1). The colour data from these pellets were included with those from stomachs of collected Broadbilled Prions, Whitebellied and Whitefaced Storm Petrels for the analyses of colour selectivity, because there was no significant difference in colour frequencies between plastic particles in skua pellets and those from collected birds (Appendix 1). The sizes of particles found in skua pellets were, however, larger than those in collected birds (Appendix 1) and therefore were not included in the analyses of particle size selection.

Non-parametric statistics (contingency tables, log-likelihood ratios and binomial tests) were used to test the significance of differences between ingested and environmental plastic particles. Size spectra of industrial pellets were divided into two to five mass classes, and those of user fragments and fibres into two mass classes (</> 4 mg). Spearman Rank Correlations were used to test the significance of relationships between the mean number of particles per bird containing plastic and the frequency of occurrence of plastic, between body mass and mean particle size, between body mass and the degree of colour discrimination, and between body mass and the frequency of occurrence of plastic.

Mann-Whitney U tests and log-likelihood ratios were used to test differences between plastic ingestion in beached birds and those collected at sea and at breeding colonies. Only data from Procellariiformes which were sampled by examining both beached and collected birds, and where the proportion of beached birds exceeded 2 % of the number sampled, were used in these analyses.

The results have been combined with published data to consider patterns of plastic ingestion in taxa above the species level. To examine the influence of foraging behaviour and diet on the incidence of plastic ingestion, each species was assigned to a primary foraging technique and diet category. Five foraging techniques were recognized (after Ashmole 1971, Day 1980, Harper _et_ _al_. 1985): 1) dipping and pattering - the picking of prey items from the surface by a flying bird; 2) surface seizing - the capture of prey at or near the surface by birds sitting on the water; 3) pursuit diving - the active underwater pursuit of prey using either wings or feet for propulsion; 4) plunge diving - the use of momentum gained by falling from the air to penetrate the surface waters; and 5) piracy - the forcing of other birds to drop or regurgitate prey. Four main diet categories were recognized: 1) fish, 2) cephalopods, 3) crustaceans and 4) mixed diet (omnivores), where none of the other three prey types is dominant. Included among the omnivores were scavengers such as giant petrels. The categories to which each species was assigned are listed in Table 2.1. To reduce the effects of geographical variation, these last two analyses were restricted to the data set given here. To ensure that the influences of foraging technique and diet were not the result of taxonomic differences, comparisons based only on Procellariiformes (excluding albatrosses and giant petrels which regurgitate pellets) also were made.

RESULTS

The incidence and amount of ingested plastic

More than 3 500 birds from 60 seabird species were sampled for ingested plastic (Table 2.1). Plastic particles were found in 36 species (60 %), of which 19 species (53 %) had plastic in more than 20 % of birds examined, and 10 species (28 %) had plastic in more than 50 % of birds examined (Table 2.2). In four species, Blue Petrel, Great Shearwater, Whitefaced Storm Petrel and Pintado Petrel, plastic was found in more than 80 % of birds examined.

TABLE 2.1 The number of seabirds examined for plastic, the manner in which they were sampled, and their chief foraging technique (dipping and pattering (D & P), surface seizing (SS), pursuit diving, plunge diving and piracy) and diet class (fish (F), cephalopods (S), crustaceans (C) and mixed (M)). Data on foraging technique and diet are derived from Cramp & Simmons (1977), Prince (1980), Cramp & Simmons (1982), Hunter (1983), Griffiths (1983), Schramm (1984), Croxall (1984), Harper *et al*. (1985) and FitzPatrick Institute unpubl. data.

Species	N	Collected birds			Regurgitates	Feeding Technique	Diet
		Adults	Chicks	Stranded			
King Penguin *Aptenodytes patagonicus*	150				150	Pursuit	S
Gentoo Penguin *Pygoscelis papua*	214				214	Pursuit	C
Adélie Penguin *P. adeliae*	6		6			Pursuit	C
Chinstrap Penguin *P. antarctica*	6	6				Pursuit	C
Rockhopper Penguin *Eudyptes chrysocome*	177	12			165	Pursuit	C
Macaroni Penguin *E. chrysolophus*	46	6			40	Pursuit	C
Jackass Penguin *Spheniscus demersus*	210	10			200	Pursuit	F

Magellanic Penguin *S. magellanicus*	35				35	Pursuit	F
Humboldt Penguin *S. humboldti*	30				30	Pursuit	F
Wandering Albatross *Diomedea exulans*	156	2			154	SS	S
Blackbrowed Albatross *D. melanophris*	18	9		9		SS	M
Greyheaded Albatross *D. chrysostoma*	170				170	SS	S
Whitecapped Albatross *D. cauta*	2	2				SS	F
Yellownosed Albatross *D. chlororhynchos*	87	11	1		75	SS	S
Sooty Albatross *Phoebetria fusca*	73	8			65	SS	S
Northern Giant Petrel *Macronectes halli*	42		1		41	SS	M
Southern Giant Petrel *M. giganteus*	123[a]	2			121	SS	M
Antarctic Fulmar *Fulmarus glacialoides*	27	1		26*		SS	C
Snow Petrel *Pagodroma nivea*	22	22				SS	C
Antarctic Petrel *Thalassoica antarctica*	30	29		1		SS	C
Pintado Petrel *Daption capense*	18	17		1		SS	M
Broadbilled Prion *Pachyptila vittata*	137	133		4		SS	C

Salvin's Prion *P. salvini*	31	4	26	1	SS	C
Antarctic Prion *P. desolata*	88	11		77	SS	C
Thinbilled Prion *P. belcheri*	32			32	SS	C
Blue Petrel *Halobaena caerulea*	74	38	15	21	SS	C
Greatwinged Petrel *Pterodroma macroptera*	13	8	3	2	SS	S
Atlantic Petrel *P. incerta*	20	16	4		SS	S
Kerguelen Petrel *P. brevirostris*	63	23	34	6	SS	S
Softplumaged Petrel *P. mollis*	29	24		5	SS	S
Whitechinned Petrel *Procellaria aequinoctialis*	201	193	7	1	SS	M
Cory's Shearwater *Calonectris diomedea*	7	5		2	SS	F
Great Shearwater *Puffinus gravis*	50	49		1	SS	M
Sooty Shearwater *P. griseus*	63	60		3	Pursuit	F
Little Shearwater *P. assimilis*	15	15			Pursuit	F
Wilson's Storm Petrel *Oceanites oceanicus*	4	1		3	D & P	C
British Storm Petrel *Hydrobates pelagicus*	1			1	D & P	C

Whitebellied Storm Petrel *Fregetta grallaria*	13	13			D & P	C
Whitefaced Storm Petrel *Pelagodroma marina*	24	24			D & P	C
Greybacked Storm Petrel *Garrodia nereis*	12	12			D & P	C
Common Diving Petrel *Pelecanoides urinatrix*	53	53			Pursuit	C
Georgian Diving Petrel *P. georgicus*	2	2			Pursuit	C
Magellan Diving Petrel *P. magellani*	1		1		Pursuit	C
Cape Gannet *Sula capensis*	5	3	2		Plunge	F
Cape Cormorant *Phalacrocorax capensis*	239	33	6	200	Pursuit	F
Bank Cormorant *P. neglectus*	167	11	8	148	Pursuit	F
Crowned Cormorant *P. coronatus*	24		6	18	Pursuit	F
Imperial Cormorant *P. atriceps*	12			12	Pursuit	F
Grey Phalarope *Phalaropus fulicarius*	2		2		SS	C
Wilson's Phalarope *P. tricolor*	1	1			SS	C
Subantarctic Skua *Catharacta antarctica*	494	17		477	Piracy	M
Arctic Skua *Stercorarius parasiticus*	2	1	1		Piracy	M

Pomarine Skua *S. pomarinus*	1	1				Piracy	M
Kelp Gull *Larus dominicanus*	52	47		2	3	SS	M
Hartlaub's Gull *L. hartlaubii*	13	11		2		SS	C
Sabine's Gull *L. sabini*	4	2		2		SS	F
Common Tern *Sterna hirundo*	13			13		Plunge	F
Arctic Tern *S. paradisaea*	21	20		1		Plunge	F
Antarctic Tern *S. vittata*	4	4				Plunge	F
Swift Tern *S. bergii*	12		10	2		Plunge	F

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* Includes data from Crockett & Reed (1976).

The species with the highest frequencies of occurrence of ingested plastic had the largest mean numbers of plastic particles per bird. This was not solely due to the high frequency of occurrence of plastic, because there was a significant correlation between the mean number of particles per bird containing plastic and the frequency of occurrence of plastic (Fig. 2.1, $\underline{r}_{\underline{s}} = 0.91$, d.f. = 17, $\underline{P} < 0.001$). The mean mass of plastic per bird also increased with increasing frequency of occurrence of plastic (Table 2.2), but this pattern was disrupted by the effect of bird size on the size of particles eaten. The number and mass of items varied greatly between individuals in all species found to contain plastic.

The largest plastic load relative to body mass was found in a Whitefaced Storm Petrel (0.7 % body mass). Seven other species had maximum plastic loads exceeding 0.1 % body mass, but none of these was greater than 0.4 % body mass (Table 2.3). A Wandering Albatross contained the greatest plastic load relative to gizzard volume (Table 2.3), but this record came from a chick regurgitation and most of the plastic presumably was stored in the proventriculus (fore-stomach). Individuals from four other species, Great Shearwater, Blue Petrel, Antarctic Prion and Broadbilled Prion, had plastic loads exceeding relaxed gizzard volume (Table 2.3). Of these, all but the Broadbilled Prion had plastic in the proventriculus as well as in the gizzard. The maximum recorded loads for Blue Petrel, Antarctic Prion and Broadbilled Prion all came from beached birds. The largest proportion of relaxed gizzard volume occupied by plastic in individuals of these three species collected at sea or at

TABLE 2.2 The incidence of plastic particles in seabird species found to contain plastic (including data from Crockett & Reed (1976) and Furness (1985a)).

Species	Ratio with plastic	%	No. per bird mean	No. per bird range	Mass per bird (mg) mean	Mass per bird (mg) range
Blue Petrel	68:74	92	9.7	0-41	111.3	0-793
Great Shearwater	45:50	90	13.6	0-79	335.2	0-2078
Whitefaced Storm Petrel	21:24	88	11.2	0-40	38.5	0-347
Pintado Petrel	15:18	83	8.6	0-40	106.3	0-391
Wilson's Storm Petrel	3:4	75	4.0	0-7	4.2	0-8
Thinbilled Prion	22:32	69	2.2	0-11	22.2	0-150
Antarctic Prion	52:88	59	2.7	0-22	50.2	0-615
Whitechinned Petrel	115:201	57	1.7	0-28	46.1	0-579
Salvin's Prion	16:31	52	1.6	0-10	50.9	0-109
Sooty Shearwater	32:63	51	1.3	0-6	20.0	0-189
Grey Phalarope	1:2	50	5.0	0-10	59.0	0-108
Arctic Skua	1:2	50	1.0	0-2	5.0	0-10
Cory's Shearwater	3:7	43	1.9	0-11	12.5	0-51
Whitebellied Storm Petrel	5:13	38	1.2	0-9	6.1	0-42
Greybacked Storm Petrel	4:12	33	0.3	0-1	2.6	0-15

Broadbilled Prion	41:137	30	0.8	0-24	11.8	0-505
Kerguelen Petrel	15:63	24	0.4	0-7	4.0	0-109
Subantarctic Skua	113:494	23	1.3	0-53	25.6	0-980
Softplumaged Petrel	6:29	21	0.3	0-4	1.5	0-50
Kelp Gull	6:52	13	0.1	0-2	9.0	0-230
Blackbrowed Albatross	2:18	11	0.2	0-2	9.4	0-150
Antarctic Fulmar	3:27	11	0.1	0-1	2.0	0-55
Atlantic Petrel	2:20	10	0.2	0-2	1.4	0-23
Greatwinged Petrel	1:13	8	0.1	0-1	0.8	0-10
Southern Giant Petrel	9:123	7	0.1	0-3	28.7	0-1481
Northern Giant Petrel	3:42	7	0.4	0-6	89.0	0-1563
Antarctic Petrel	2:30	7	0.2	0-3	1.5	0-41
Little Shearwater	1:15	7	0.7	0-11	8.0	0-120
Snow Petrel	1:22	5	<0.1	0-3	0.9	0-20
Wandering Albatross	7:156	4	0.4	0-33	310.9	0-18404
Yellownosed Albatross	2:87	2	<0.1	0-1	16.5	0-1197
Common Diving Petrel	1:53	2	<0.1	0-1	<0.1	0-2
Rockhopper Penguin	2:177	1	<0.1	0-1	0.1	0-10
Greyheaded Albatross	1:170	1	<0.1	0-2	3.7	0-1407
Sooty Albatross	1:73	1	<0.1	0-1	0.5	0-40
Bank Cormorant*	1:167	1	<0.1	0-1	?	?

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* J. Cooper pers. comm., a single green fibre, not collected

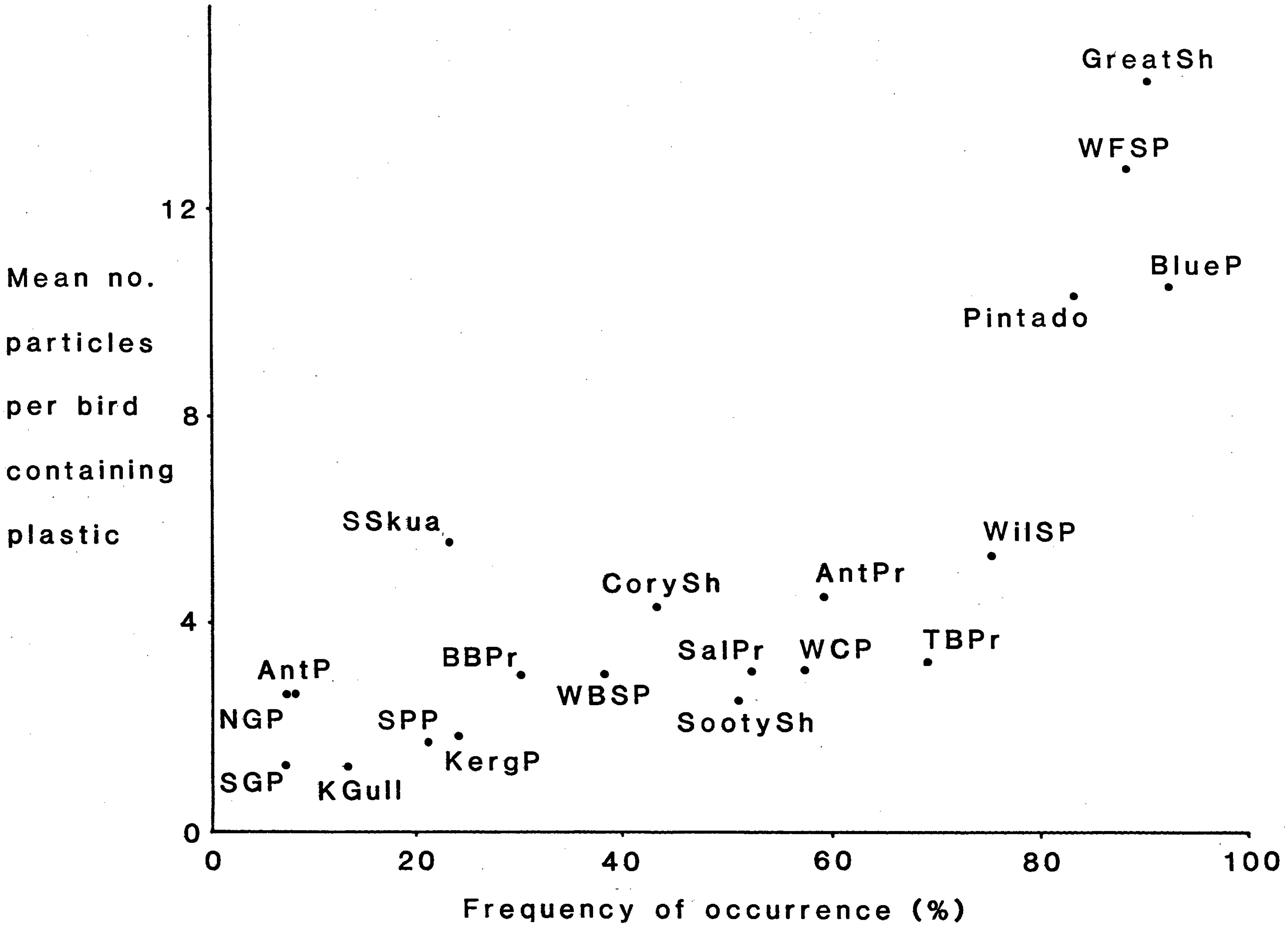

Mean no. particles per bird containing plastic
0
4
8
12
0
20
40
60
80
100
Frequency of occurrence (%)
GreatSh
WFSP
BlueP
Pintado
SSkua
WilSP
CorySh
AntPr
TBPr
SalPr
WCP
AntP
BBPr
WBSP
SootySh
NGP
SPP
KergP
SGP
KGull

TABLE 2.3 The proportion of body mass and gizzard volume made up by plastic particles in the most heavily loaded individuals of each species found to contain plastic. Gizzard volumes were estimated from Furness (1985a). Bird masses were derived from sources listed in Table 2.1.

Species	Body mass (g)	Max. prop. body mass ($X10^3$)	Estimated gizzard volume (cm^3)		Max. % gizzard vol. occupied by plastic	
			Distended	Relaxed	Distended	Relaxed
Blue Petrel	204	3.89	2.50	0.63	35.2	140.0
Great Shearwater	930	2.23	6.15	1.54	37.5	149.9
Whitefaced Storm Petrel	49	7.08	1.59	0.40	24.3	96.4
Pintado Petrel	380	1.03	3.10	0.78	14.0	55.7
Wilson's Storm Petrel	36	0.22	1.00	0.25	0.8	3.6
Thinbilled Prion	132	1.14	2.00	0.50	8.3	33.3
Antarctic Prion	162	3.80	2.04	0.51	33.5	134.0
Whitechinned Petrel	1280	0.45	5.80	1.45	11.1	44.4
Salvin's Prion	166	0.66	2.08	0.52	5.8	23.3
Sooty Shearwater	823	0.23	4.40	1.10	4.8	19.1
Grey Phalarope	56	1.93	2.10	0.53	5.7	22.6
Arctic Skua	460	0.02	11.00	2.75	0.1	0.4
Cory's Shearwater	935	0.06	4.60	1.15	1.2	4.9

Whitebellied Storm Petrel	52	0.81	1.46	0.36	3.2	12.9
Greybacked Storm Petrel	35	0.43	1.35	0.34	1.2	4.9
Broadbilled Prion	184	2.75	2.12	0.53	26.5	105.9
Kerguelen Petrel	357	0.31	2.35	0.59	5.2	20.5
Subantarctic Skua	1524	0.64	38.00	9.50	2.9	11.5
Softplumaged Petrel	312	0.16	2.92	0.73	1.9	7.6
Greatwinged Petrel	587	0.02	4.25	1.06	0.3	1.0
Kelp Gull	920	0.25	14.00	3.50	1.8	7.3
Blackbrowed Albatross	3788	0.04	7.00	1.75	2.4	9.5
Antarctic Fulmar	775	0.07	5.60	1.40	1.1	4.4
Atlantic Petrel	566	0.04	4.21	1.05	0.6	2.4
Southern Giant Petrel	4417	0.34	8.00	2.00	20.6	82.3
Northern Giant Petrel	4313	0.36	8.00	2.00	21.7	86.8
Antarctic Petrel	680	0.06	4.00	1.00	1.1	4.6
Little Shearwater	241	0.50	2.28	0.57	5.8	23.4
Snow Petrel	270	0.07	2.50	0.62	0.9	3.6
Wandering Albatross	8727	2.11	10.00	2.50	204.5	818.0
Yellownosed Albatross	2218	0.54	5.94	1.48	22.4	89.9
Common Diving Petrel	120	0.02	2.67	0.67	0.1	0.3
Rockhopper Penguin	2482	0.01	22.11	5.53	0.1	0.2
Greyheaded Albatross	3788	0.37	7.00	1.75	22.3	89.3
Sooty Albatross	2512	0.02	7.62	1.90	0.6	2.3

breeding islands was 67 %, 21 % and 22 % respectively.

The majority of plastic particles was found in the gizzards of seabirds, with some in the proventriculus. None was found in the intestinal tract. Hard parts of prey items > 0.1 mm diameter were found only in the intestine and faeces of gulls.

The nature of plastic particles ingested by seabirds

More than 3 000 plastic particles were examined from the 36 seabird species found to contain plastic. Industrial pellets and user fragments were most frequently ingested, whereas relatively few fibres and foamed plastics were ingested (Table 2.4). The proportions of fibres and foamed plastics were lower in most species than in the environment (Chapter 1). Among species for which 20 or more pieces of plastic were examined, only Whitechinned Petrels and Sooty Shearwaters contained a large proportion of fibres, and Kerguelen Petrels contained a large proportion of foamed plastics (Table 2.4).

The relative importance of industrial pellets and user plastics was related to the size of the plastic particles ingested. The proportion of industrial pellets increased with median particle size ingested, up to the upper size limit of industrial pellets (approximately 50 mg), whereupon only user plastics were recorded (Fig. 2.2).

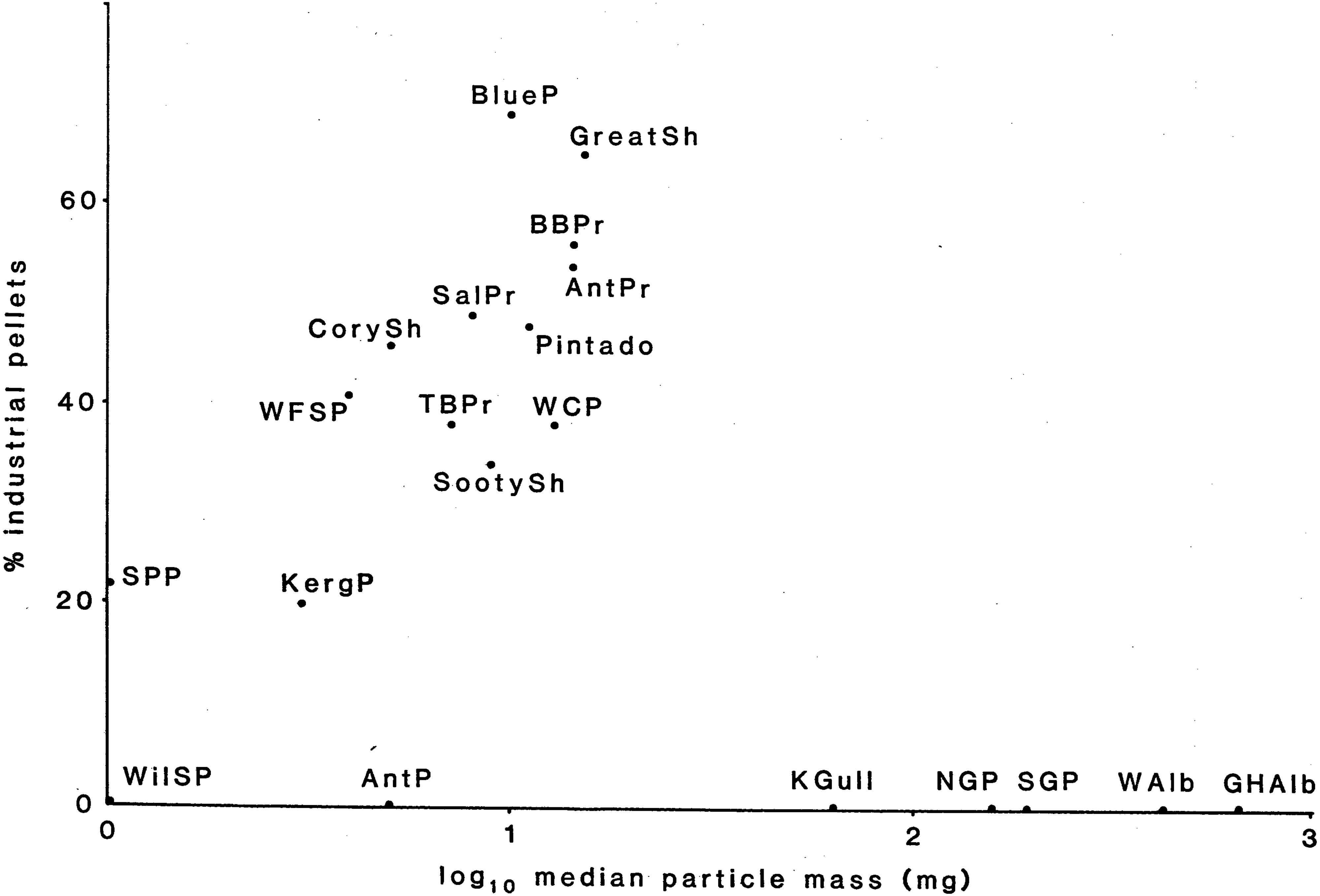
The mean size of plastic particles ingested by seabirds was directly related to the species' body mass (Fig. 2.3, $r_s = 0.78$, d.f. = 21, *P* < 0.001). The same was true for median particle mass ($r_s = 0.65$, d.f. = 21, *P* < 0.01). Figure 2.4 shows the

TABLE 2.4 The frequency of occurrence and contribution by number and mass of the four types of plastic particles (industrial pellets (IP), user fragments (UF), fibres (Fib) and foamed plastics (FP)) in seabirds, and at sea off the southwestern Cape (Chapter 1).

Species	No. with plastic	Frequency of occurrence (%)				No. items	% contribution by number				mean item mass (mg)	% contribution by mass			
		IP	UF	Fib	FP		IP	UF	Fib	FP		IP	UF	Fib	FP
Environmental plastic (at sea off SW Cape)						839	23	27	14	36	12	40	36	21	3
Blue Petrel	63	95	84	2	2	662	69	31	<1	<1	13	76	24	<1	<1
Great Shearwater	32	84	75	9	3	536	64	34	1	1	21	54	46	<1	<1
Whitefaced Storm Petrel	5	80	80		20	46	41	57		2	4	64	35		1
Pintado Petrel	15	73	87	13	20	155	48	44	2	6	12	59	29	6	6
Wilson's Storm Petrel	3		100			16		100			1		100		
Thinbilled Prion	22	64	82			71	38	62			10	59	41		
Antarctic Prion	42	83	62	5	2	193	53	44	2	1	18	60	40	<1	<1
Whitechinned Petrel	110	46	50	52	1	326	38	39	21	2	27	22	29	49	<1
Salvin's Prion	16	50	67			68	49	51			11	74	26		
Sooty Shearwater	31	39	68	45		71	34	43	23		17	37	28	35	
Grey Phalarope	1	100				10	100				5	100			

Arctic Skua	1	100		100		2	50		50		5	70		30	
Cory's Shearwater	3	100	33			13	46	54			7	73	27		
Greybacked Storm Petrel	1	100				1	100				15	100			
Broadbilled Prion	28	68	50		4	85	56	42		1	14	78	22		<1
Kerguelen Petrel	14	29	50	14	21	25	20	36	8	36	10	35	57	2	6
Subantarctic Skua	112	88	48	2		627	67	33	<1		20	69	31	<1	
Softplumaged Petrel	6	33	33	33		9	22	33	45		8	23	71	6	
Greatwinged Petrel	1	100				1	100				10	100			
Kelp Gull	6		83	33		7		71	29		63		62	38	
Blackbrowed Albatross	2		50	50		2		50	50		81		93	7	
Antarctic Fulmar	3		100			3		100			55		100		
Atlantic Petrel	1	100				2	100				12	100			
Southern Giant Petrel	9		89		11	11		91		9	321		97		3
Northern Giant Petrel	6		67		33	15		87		13	249		93		6
Antarctic Petrel	2		50	50	50	5		40	20	40	9		22	67	11
Snow Petrel	1		100			3		100			7		100		
Wandering Albatross	9		100			65		100			746		100		
Yellownosed Albatross	2		100			2		100			719		100		
Common Diving Petrel	1		100			1		100			2		100		
Rockhopper Penguin	2		50	50		2		50	50		8		38	62	
Greyheaded Albatross	4		100			5		100			598		100		
Sooty Albatross	1		100			1		100			1		100		

FIGURE 2.2 The proportion of industrial pellets among plastic particles ingested by seabirds as a function of median particle size (mass) ingested. Species codes: Antarctic Petrel (AntP), Antarctic Prion (AntPr), Blue Petrel (BlueP), Broadbilled Prion (BBPr), Cory's Shearwater (CorySh), Greyheaded Albatross (GHalb), Great Shearwater (GreatSh), Kelp Gull (KGull), Kerguelen Petrel (KergP), Northern Giant Petrel (NGP), Pintado Petrel (Pintado), Salvin's Prion (SalPr), Southern Giant Petrel (SGP), Softplumaged Petrel (SPP), Sooty Shearwater (SootySh), Thinbilled Prion (TBPr), Wandering Albatross (WAlb), Whitefaced Storm Petrel (WFSP) and Wilson's Storm Petrel (WilSP).


% industrial pellets
60
40
20
0
0
1
2
3
log$_{10}$ median particle mass (mg)
BlueP
GreatSh
BBPr
AntPr
SalPr
CorySh
Pintado
WFSP
TBPr
WCP
SootySh
SPP
KergP
WilSP
AntP
KGull
NGP
SGP
WAlb
GHAlb

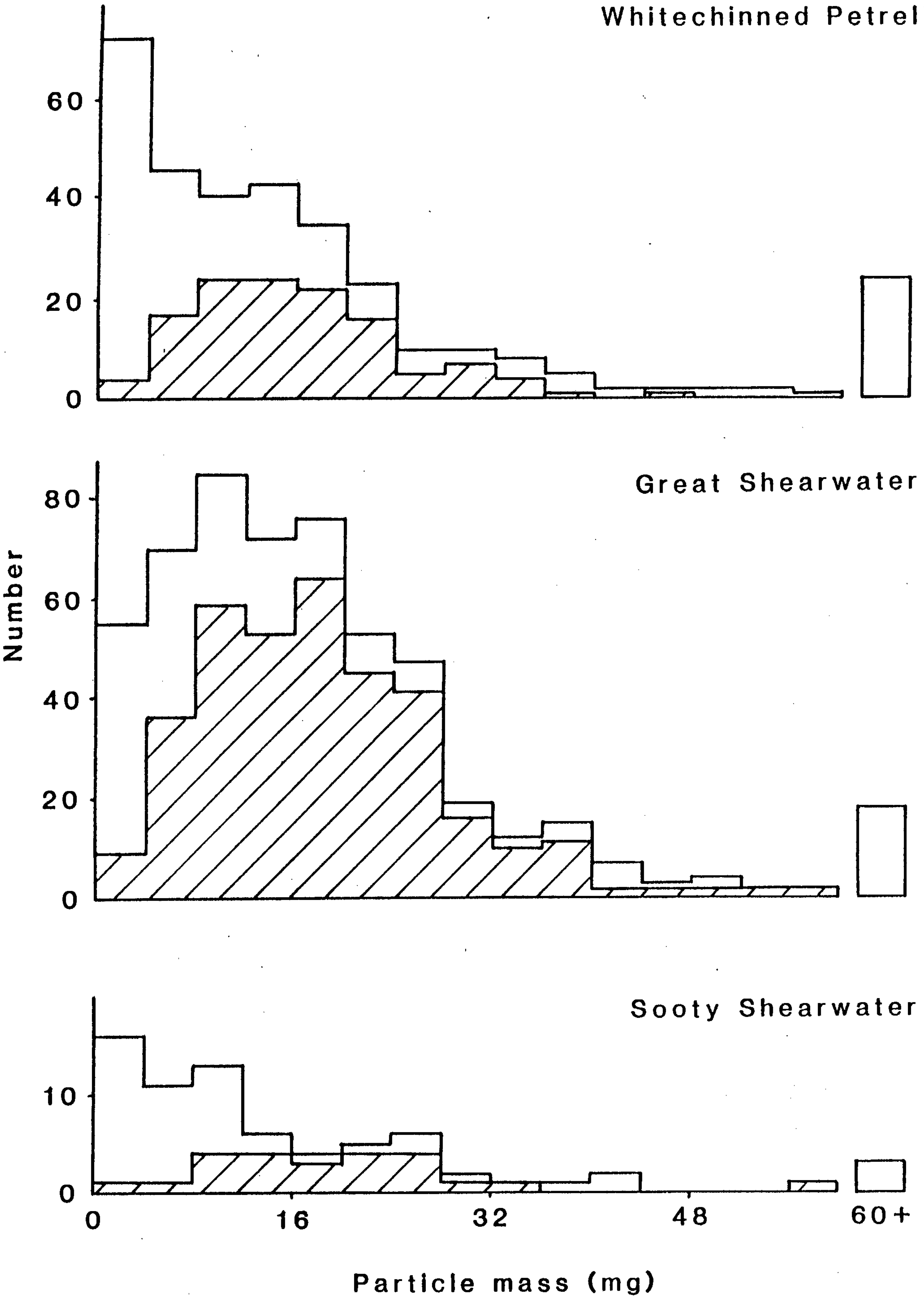


FIGURE 2.4 (b) The masses of plastic particles ingested by seabirds. Industrial pellets are depicted by hatching, user plastics are left blank.

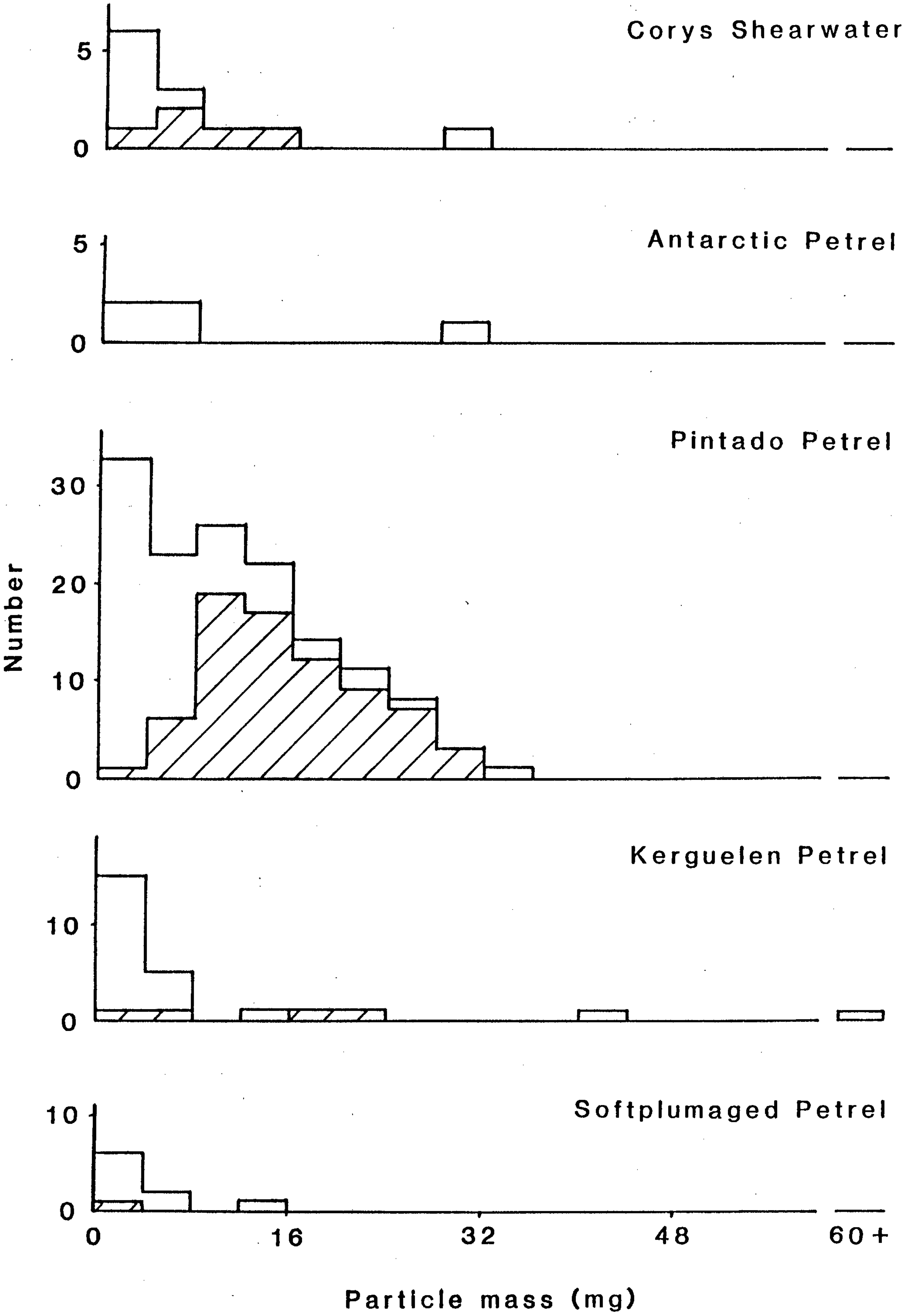


FIGURE 2.4 (c) The masses of plastic particles ingested by seabirds. Industrial pellets are depicted by hatching, user plastics are left blank.

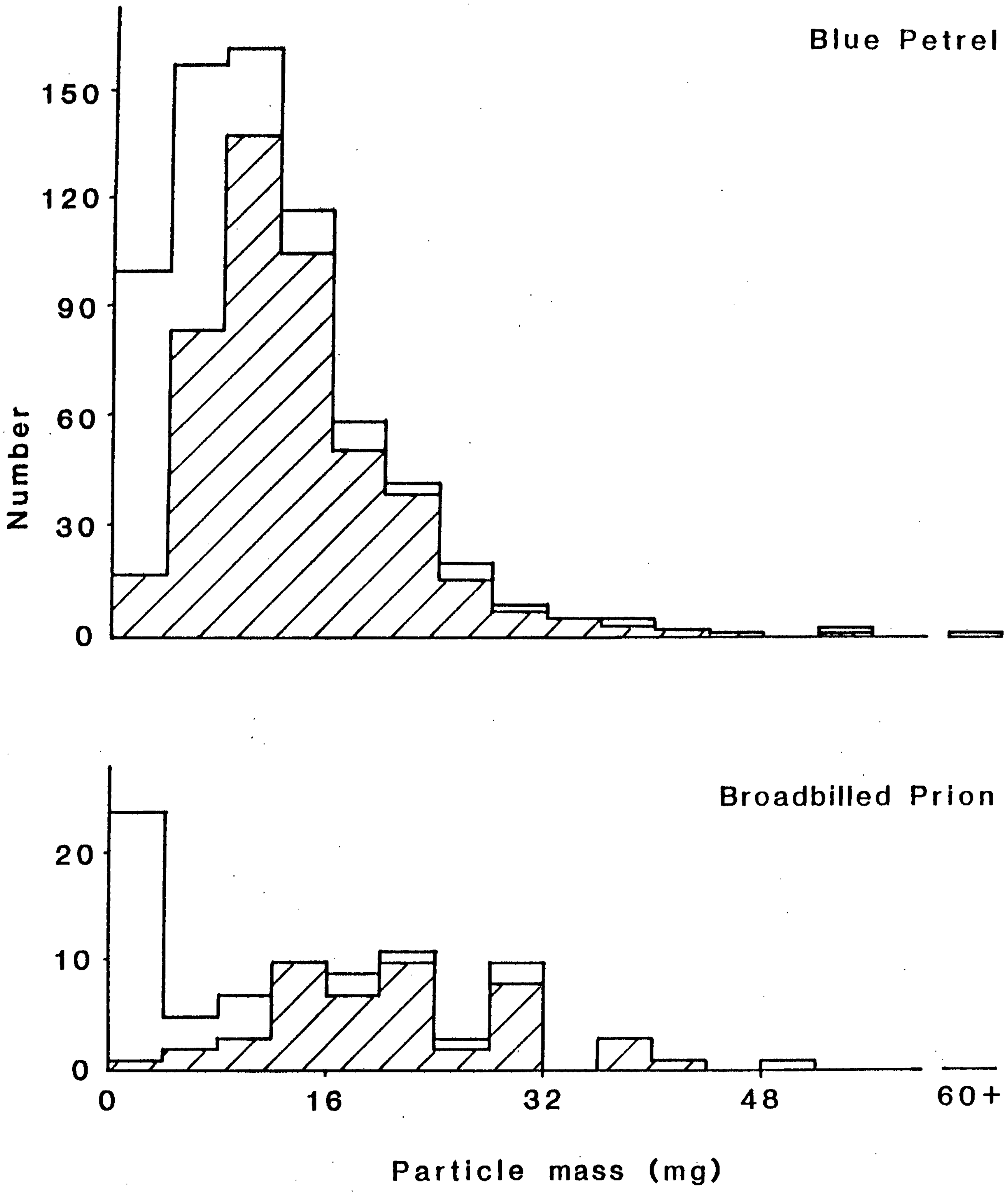


FIGURE 2.4 (d) The masses of plastic particles ingested by seabirds. Industrial pellets are depicted by hatching, user plastics are left blank.

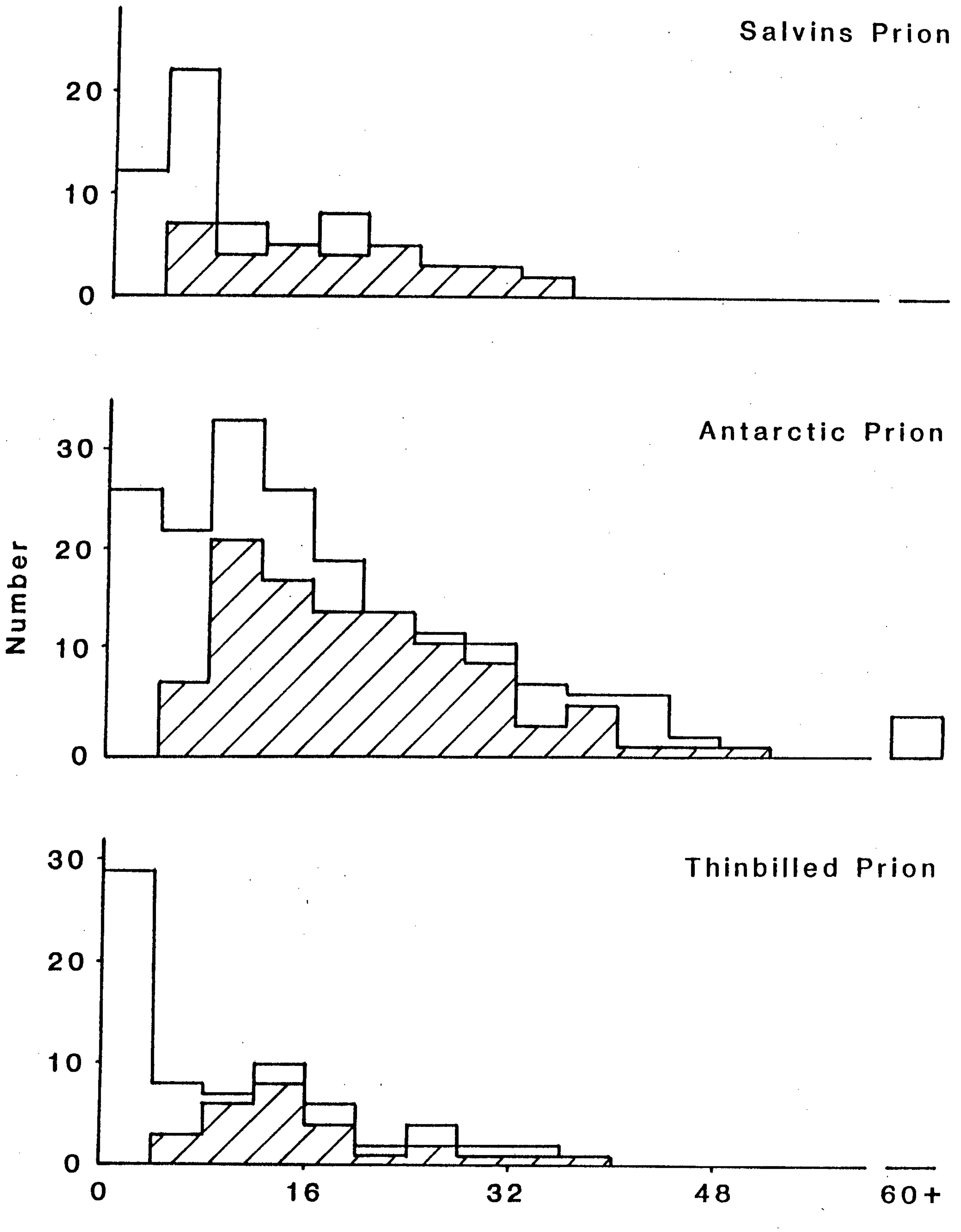


FIGURE 2.4 (e) The masses of plastic particles ingested by seabirds. Industrial pellets are depicted by hatching, user plastics are left blank.

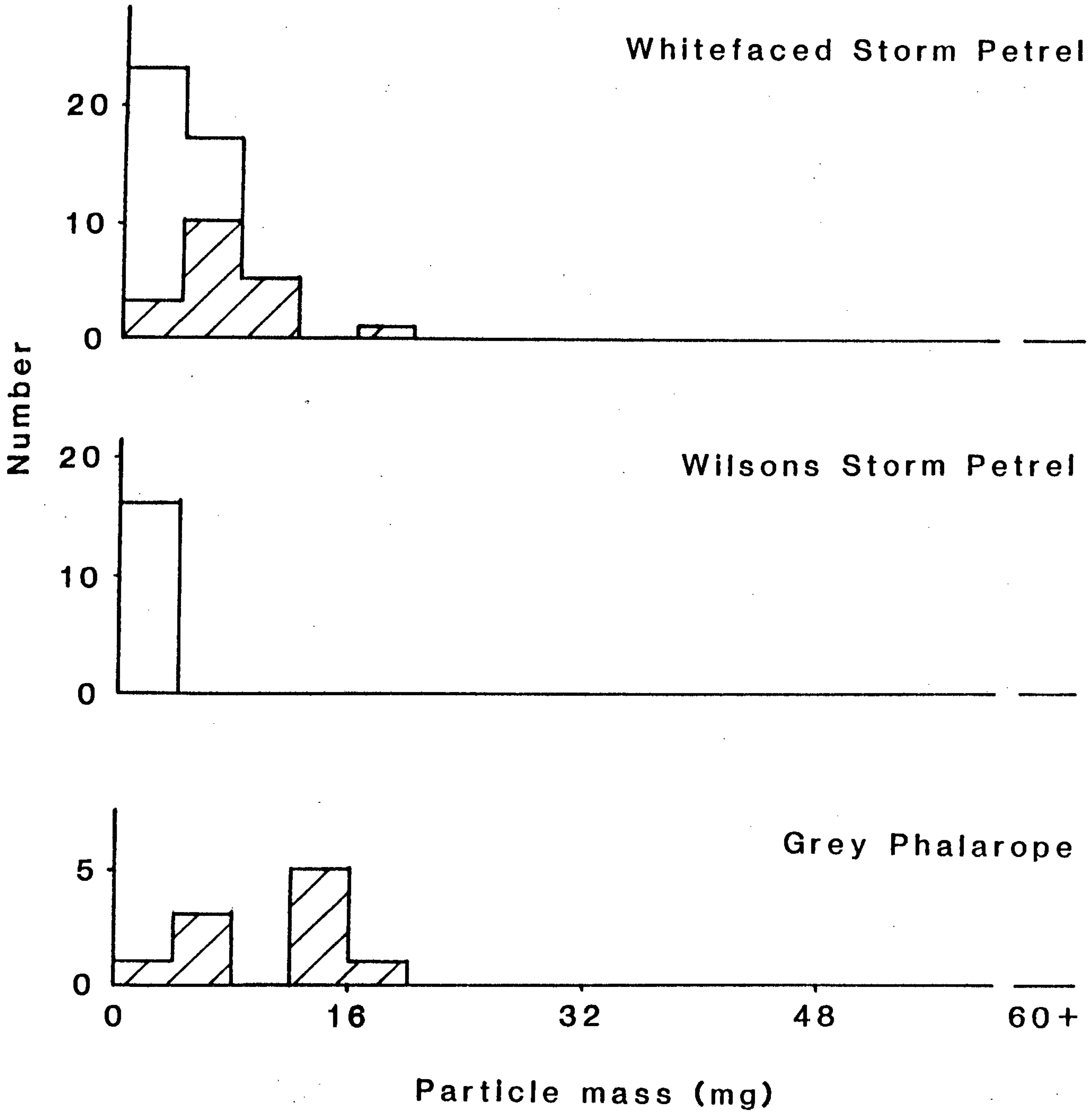


FIGURE 2.4 (f) The masses of plastic particles ingested by seabirds. Industrial pellets are depicted by hatching, user plastics are left blank.

particle size spectra of ingested particles for all species for which five or more particles were examined. Comparing these with the size spectrum of plastic particles found at sea (Chapter 1), all species selected industrial pellets the same size or smaller than the mean size pellets found in the environment (Table 2.5). User plastics (fragments and fibres) ingested by seabirds were either the same size or larger than particles found at sea, with the exception of user fragments taken by Wilson's Storm Petrels which were smaller than particles in the environment (Table 2.5).

All plastic particles ingested by seabirds floated in sea water, with the exception of two sections of PVC tubing collected from Southern Giant Petrels breeding at the Prince Edward Islands.

The proportions of different colours of plastic particles found in seabirds are given in Table 2.6. Comparing these with the colour frequencies found in the environment (Chapter 1), all species ingested fewer clear-white industrial pellets and user fragments than expected, and ingested more tan, brown, black, blue, green and red particles than expected (Table 2.7). Brown and black fibres also were more frequent than expected, whereas blue, green, yellow, clear and white fibres were less frequent than expected (Table 2.7). There was a tendency for smaller birds to be less colour-selective than larger birds for both industrial pellets ($\underline{r}_{\underline{s}} = 0.87$, d.f. = 8, $\underline{P} < 0.01$) and user fragments ($\underline{r}_{\underline{s}} = 0.87$, d.f. = 12, $\underline{P} < 0.001$, Fig. 2.5). Smaller birds also tended to have a higher frequency of occurrence of plastic ($\underline{r}_{\underline{s}} = 0.59$, d.f. = 22, $\underline{P} < 0.01$ for Procellariiformes).

TABLE 2.5 Comparison of the mass frequencies of plastic particles ingested by seabirds with those found at sea off the southwestern Cape, South Africa (Chapter 1). +/- signifies masses larger/smaller than particles found at sea. Significance level is denoted by the number of symbols, 1-3 equivalent to $P < 0.05$, 0.01 and 0.001 respectively.

Species	Industrial pellets	User fragments	Fibres
Wandering Albatross		+++	
Southern Giant Petrel		+++	
Northern Giant Petrel		+++	
Other albatrosses		+++	
Whitechinned Petrel	---	+++	+++
Great Shearwater	---	+++	
Sooty Shearwater	NS	+++	+++
Pintado Petrel	---	+++	
Blue Petrel	---	+++	
Broadbilled Prion	NS	NS	
Salvin's Prion	NS	+++	
Antarctic Prion	NS	+++	
Thinbilled Prion	--	NS	
Grey Phalarope	---		
Whitefaced Storm Petrel	---	NS	
Wilson's Storm Petrel		--	

TABLE 2.6 The proportions (%) of colours of plastic particles ingested by seabirds, with those collected at sea off the southwestern Cape, South Africa (Chapter 1), for comparison. Black and brown industrial pellets were lumped.

Type	Species	Clear-white	Grey	Tan	Brown	Black	Blue	Green	Red	Yellow	N
Industrial Pellets											
	Environmental (at sea off the SW Cape)	88.8	0.5	5.1	5.1			0.5			196
	Whitechinned Petrel	63.6	1.7	17.4	16.5			0.8			121
	Great Shearwater	40.9	0.9	30.4	27.2			0.3	0.3		342
	Sooty Shearwater	41.7		4.1	54.2						24
	Pintado Petrel	56.8		29.7	13.5						74
	Blue Petrel	41.9	0.7	36.4	20.4			0.2	0.4		454
	Broadbilled Prion	63.5	0.6	19.7	14.0			1.7	0.6		178
	Salvin's Prion	66.7		27.3	6.0						33
	Antarctic Prion	77.6	1.0	17.5	3.9						103
	Thinbilled Prion	81.5		11.1	7.4						27
	Whitebellied Storm Petrel	78.2		15.7	3.1				3.1		64
	Whitefaced Storm Petrel	81.8		11.5	5.5			0.6	0.6		165

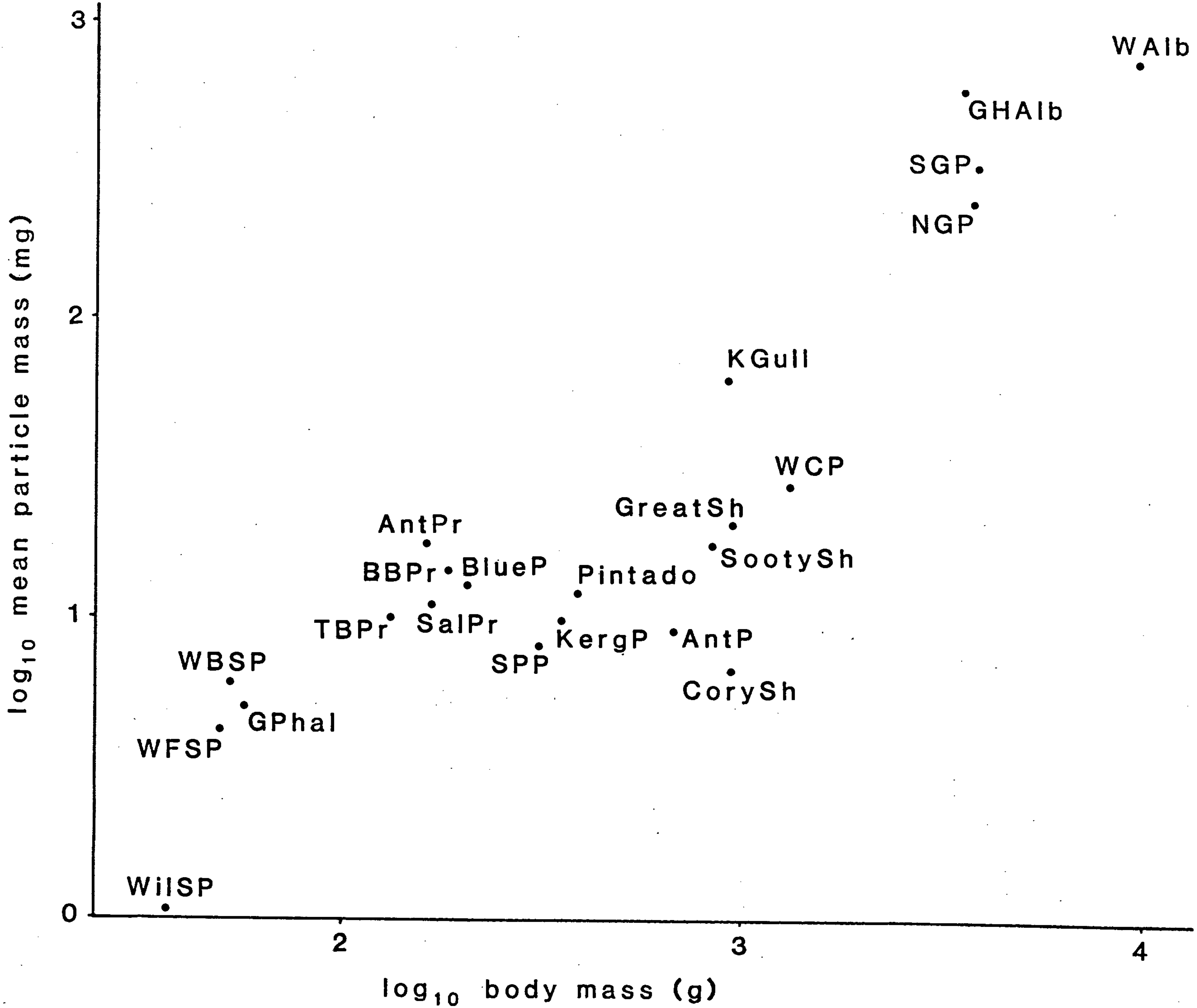
User Fragments										
Environmental (at sea off the SW Cape)	82.0	2.2	2.7	0.9	0.9	4.1	6.8	0.4		222
Wandering Albatross	10.9		1.6			34.4	43.7	9.4		65
Giant petrels	26.1		4.3	8.7	8.7	17.4		34.8		26
Other albatrosses	10.0				10.0	10.0	10.0	60.0		10
Whitechinned Petrel	43.6	3.2	11.1	4.8	13.4	4.0	15.1	4.8		126
Great Shearwater	37.0	3.8	5.8	17.8	1.0	6.7	24.1	3.8		208
Sooty Shearwater	33.0	3.3	6.7	16.7	30.0		6.7	3.3		30
Pintado Petrel	58.0	4.3	11.6	14.5	1.4	2.9	7.3			69
Blue Petrel	52.6	4.4	9.8	4.9		7.3	9.8	11.3		205
Broadbilled Prion	43.9	1.4	15.5	6.1	3.4	6.8	20.9	2.0		148
Salvin's Prion	45.7		2.9	2.9		5.7	37.1	5.7		35
Antarctic Prion	62.3	2.2	4.4	2.2	1.1	20.0	5.6	2.2		90
Thinbilled Prion	61.4	6.8	9.1	6.8	6.8		6.8	2.3		44
Whitebellied Storm Petrel	56.0	4.0	20.0	12.0			8.0			25
Whitefaced Storm Petrel	61.5	1.3	6.4		2.6	6.4	19.2	1.3	1.3	78
Fibres										
Environmental (at sea off the SW Cape)	15.6	0.9		0.9	3.4	46.5	15.5	8.6	8.6	116
Whitechinned Petrel	4.4			40.0	28.9	8.9	5.6	12.2		90
Sooty Shearwater				35.0	65.0					20

TABLE 2.7 Comparison of the colour frequencies of plastic particles ingested by seabirds with those found at sea off the southwestern Cape, South Africa (Chapter 1). +/- denotes colours significantly more/less frequent in seabirds than at sea. Significance level is denoted by the number of symbols, 1-3 equivalent to $P < 0.05$, 0.01 and 0.001 respectively.

Type	Species	Clear-white	Grey	Tan	Brown	Black	Blue	Green	Red	Yellow
Industrial Pellets										
	Whitechinned Petrel	---		+++	+++					
	Great Shearwater	---		+++	+++					
	Sooty Shearwater	---			+++					
	Pintado Petrel	---		+++	++					
	Blue Petrel	---		+++	+++					
	Broadbilled Prion	---		+++	+++					
	Salvin's Prion	---		+++						
	Antarctic Prion	---		+++						
	Thinbilled Prion									
	Whitebellied Storm Petrel	-		++					+	
	Whitefaced Storm Petrel	--		+++						

User Fragments									
Wandering Albatross	---					+++	+++	+++	
Giant petrels	---			+	+	+		+++	
Other albatrosses	---							+++	
Whitechinned Petrels	---		+++	++	+++		+++	+++	
Great Shearwater	---		++	+++		+	+++	+++	
Sooty Shearwater	---			+++	+++				
Pintado Petrel	---		+++	+++					
Blue Petrel	---	+	+++	+++		+		+++	
Broadbilled Prion	---		+++	+++	+		+++	+	
Salvin's Prion	---						+++	+	
Antarctic Prion	---					+++			
Thinbilled Prion	--		+	++	++				
Whitebellied Storm Petrel	--		+++	++					
Whitefaced Storm Petrel	---						+++		
Fibres									
Whitechinned Petrel	--			+++	+++	---	--		---
Sooty Shearwater	-			+++	+++	---	-		

FIGURE 2.3 The relationship between mean plastic particle mass and body mass in 24 seabird species. Species codes: Antarctic Petrel (AntP), Antarctic Prion (AntPr), Blue Petrel (BlueP), Broadbilled Prion (BBPr), Cory's Shearwater (CorySh), Greyheaded Albatross (GHAlb), Grey Phalarope (GPhal), Great Shearwater (GreatSh), Kelp Gull (KGull), Kerguelen Petrel (KergP), Northern Giant Petrel (NGP), Pintado Petrel (Pintado), Salvin's Prion (SalPr), Southern Giant Petrel (SGP), Softplumaged Petrel (SPP), Sooty Shearwater (SootySh), Thinbilled Prion (TBPr), Wandering Albatross (WAlb), Whitebellied Storm Petrel (WBSP, from Furness 1985b), Whitefaced Storm Petrel (WFSP) and Wilson's Storm Petrel (WilSP).



WAlb
GHAlb
SGP
NGP
KGull
WCP
GreatSh
SootySh
AntPr
BBPr
BlueP
Pintado
TBPr
SalPr
KergP
AntP
SPP
CorySh
WBSP
GPhal
WFSP
WilSP
3
2
1
0
2
3
4
$\log_{10}$ mean particle mass (mg)
$\log_{10}$ body mass (g)

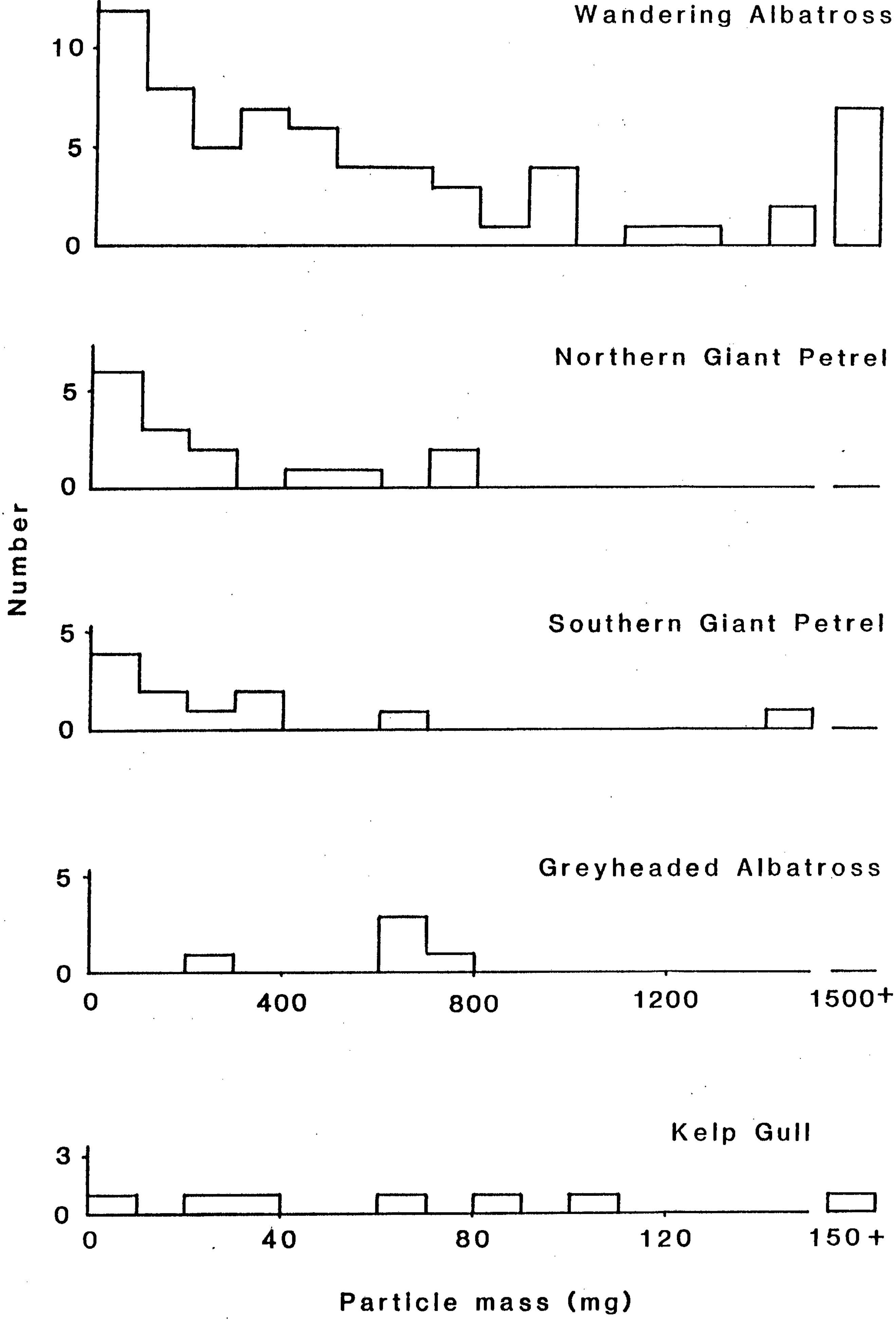
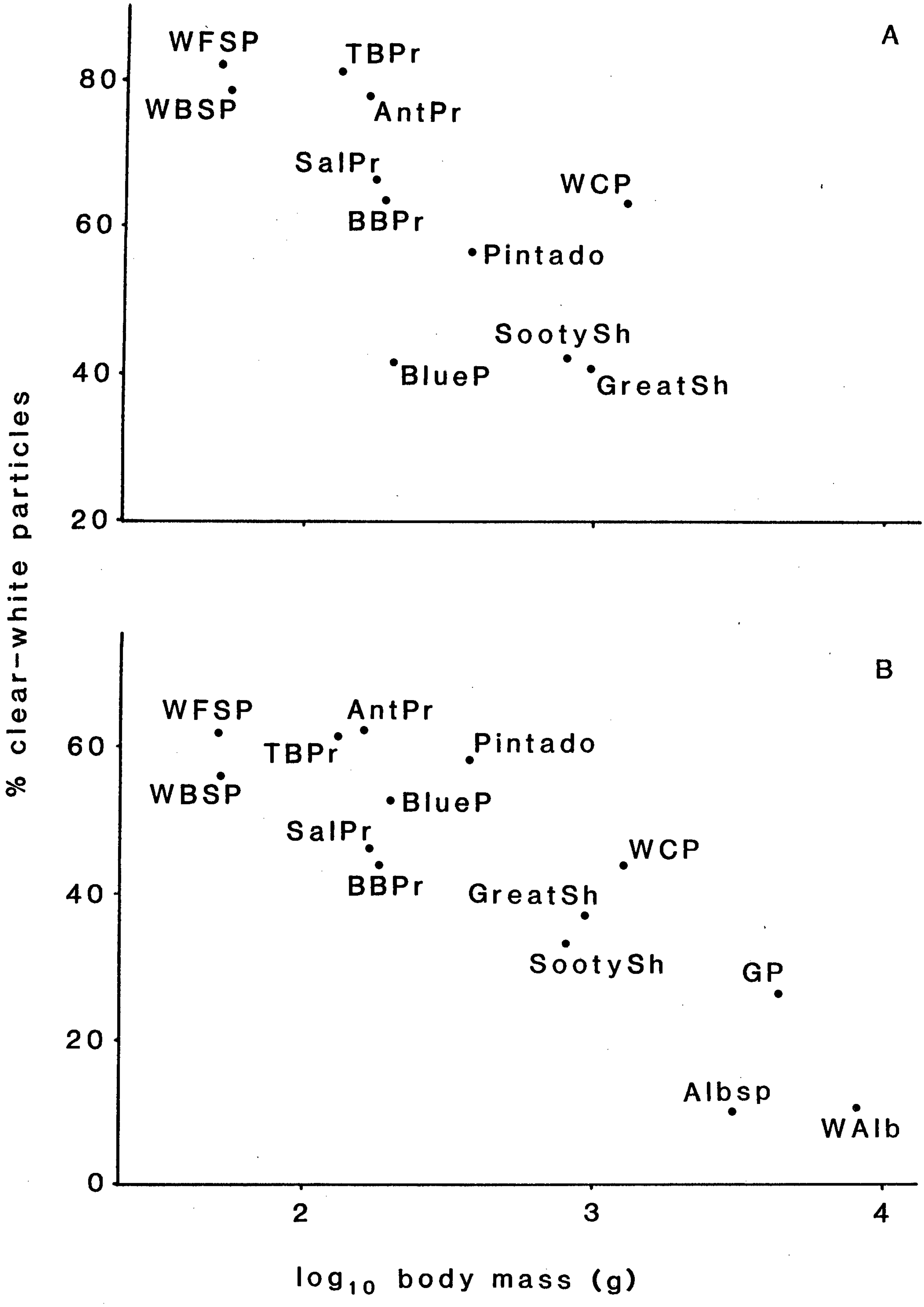


FIGURE 2.4 (a) The masses of plastic particles ingested by seabirds. Industrial pellets are depicted by hatching, user plastics are left blank.

FIGURE 2.5 The relationship between the proportion of clear-white plastic particles ingested by seabirds and their body mass, for both industrial pellets (A) and user plastics (B). Species codes: albatross species (excluding Wandering, Albsp), Antarctic Prion (AntPr), Blue Petrel (BlueP), Broadbilled Prion (BBPr), giant petrels (GP), Great Shearwater (GreatSh), Pintado Petrel (Pintado), Salvin's Prion (SalPr), Thinbilled Prion (TBPr), Whitebellied Storm Petrel (WBSP) and Whitefaced Storm Petrel (WFSP).


A
WFSP
TBPr
80
WBSP
AntPr
SalPr
WCP
BBPr
60
Pintado
SootySh
40
BlueP
GreatSh
20
% clear-white particles
B
WFSP
AntPr
60
TBPr
Pintado
WBSP
BlueP
SalPr
WCP
40
BBPr
GreatSh
SootySh
GP
20
Albsp
WAlb
0
2
3
4
log10 body mass (g)

Incidence by taxa, foraging behaviour and diet

Plastic particles were most frequent in Procellariiformes, being present in 30 (88 %) of the 34 species sampled. Of those that did not contain plastic, one, the British Storm Petrel, has been found to contain plastic elsewhere (Zonfrillo 1985). Combining the published records of plastic ingestion with the data presented here, the highest incidence of plastic ingestion among species and the highest mean frequency of occurrence within species occurred in Procellariiformes (Table 2.8). Plastic ingestion was rare among Pelecaniformes and Sphenisciformes. The incidence within Charadriiformes was varied. There was a high incidence among phalaropes, skuas, gulls and auks, but with generally lower mean frequencies of occurrence within species than in Procellariiformes (Table 2.8). Plastic particles have not been found in the stomachs of terns, but polystyrene spherules have been recorded from pellets regurgitated by terns (Hays & Cormons 1974). Plastic ingestion has been recorded for 69 (55 %) of the 125 seabird species so far examined (Table 2.8).

Among Procellariiformes the incidence of ingested plastic was not uniformly high (Table 2.8). Diving petrels had both a low incidence among species and a low mean frequency of occurrence within species. Albatrosses, giant petrels and, to a lesser extent, gadfly petrels (Pterodroma spp.) had a high incidence among species but a low mean frequency of occurrence within species (Table 2.8).

The incidence of plastic ingestion was influenced by foraging behaviour (Table 2.9). A higher mean frequency of occurrence of

TABLE 2.8 The incidence and mean frequency of occurrence of ingested plastic in seabird taxa examined. Records from regurgitations by Procellariiformes are omitted because they seldom include gizzard contents.

Taxon	Spp. with plastic ratio	%	Mean freq. occur. within spp. (%)	Source
Sphenisciformes				
Penguins	1:10	10	<1	This study, Day *et al*. 1985, Furness 1985a
Procellariiformes				
Albatrosses	8:9	88	4*	This study, Kenyon & Kridler 1969, Prince 1980, Pettit *et al*. 1981, Conant 1984, Day *et al*. 1985, Furness 1985a
Giant petrels	2:2	100	7	This study
Gadfly petrels	5:5	100	16	This study, Reed 1981, Day *et al*. 1985, Furness 1985a
Other petrels & fulmars	9:9	100	48	This study, Baltz & Morejohn 1976, Crockett & Reed 1976, Day 1980, Reed 1981, Furness 1983, Harrison *et al*. 1983, Day *et al*. 1985, Furness 1985b, van Franecker 1985

Shearwaters	7:7	100	42	This study, Baltz & Morejohn 1976, Day 1980, Brown *et al.* 1981, Zonfrillo 1982, Furness 1983, Randall *et al.* 1983, Day *et al.* 1985, Furness 1985a,b
Prions	5:5	100	53	This study, Bourne & Imber 1982, Day *et al.* 1985, Furness 1985a
Storm petrels	8:8	100	62	This study, Rothstein 1973, Day 1980, Day *et al.* 1985, Furness 1985a,b, Zonfrillo 1985
Diving petrels	1:3	33	1	This study, Furness 1985a
Pelecaniformes				
Tropicbirds	0:1	0	0	Harrison *et al.* 1983
Frigatebirds	0:1	0	0	Harrison *et al.* 1983
Gannets & boobies	1:6	17	? (low)	This study, Bourne 1976, Anon. 1981, Harrison *et al.* 1983
Cormorants	1:8	13	<1	This study, Bourne 1976, Day 1980
Anseriformes				
Marine ducks	0:6	0	0	Day *et al.* 1985

Charadriiformes				
Phalaropes	2:3	67	34	This study, Bond 1971, Day 1980, Briggs *et al*. 1982, Connors & Smith 1982
Skuas	2:3	67	16	This study, Day 1980, Furness 1985a
Gulls	8:13	62	5	This study, Baltz & Morejohn 1976, Bourne 1976, Below 1979, Day 1980
Terns	0:10[+]	0	0	This study, Day 1980, Harrison *et al*. 1983
Auks	9:16	56	12	Baltz & Morejohn 1976, Ohlendorf *et al*. 1978, Day 1980, Pettit *et al*. 1981, Bourne 1982, Wehle 1982, Harris 1984, Day *et al*. 1985

---

[*] excludes dead chicks (Kenyon & Kridler 1969, Pettit *et al*. 1981, Conant 1984) which may contain much higher plastic loads than average (Chapter 3)

[+] plastic particles recorded from "tern" pellets (Hays & Cormons 1974) not identified to species ingested plastic was recorded among species feeding by dipping and pattering than among species using other foraging techniques. Species feeding by surface seizing and piracy contained plastic more frequently than those feeding by pursuit and plunge diving. This trend remained the same if only Procellariiformes (excluding albatrosses and giant petrels) were considered, but the difference in the frequency of occurrence of plastic ingestion between dipping and pattering and surface-seizing species was reduced (Table 2.9).

A similar analysis of the effect of diet on the incidence of ingested plastic showed a higher mean frequency of occurrence of plastic in omnivores than in other dietary groups (Table 2.10). Species feeding primarily on crustaceans contained plastic more frequently than did species feeding primarily on cephalopods and fish. Among Procellariiformes (excluding albatrosses and giant petrels), omnivores also had the highest frequency of occurrence of ingested plastic, double that of species feeding on crustaceans and fish, and almost four times that of species which feed on cephalopods (Table 2.10).

DISCUSSION

Influence of sampling techniques

The incidence of ingested plastic in seabirds is inferred from birds sampled in several different ways (see Day et al. 1985, this study), but little consideration has been given to the degree of similarity between different sampling techniques. Lumping data collected in different ways assumes the sampling techniques to be compatible. Dissection allows examination of

TABLE 2.9 The incidence of ingested plastic particles in seabirds in relation to foraging behaviour. Each species' main foraging technique is listed in Table 2.1.

Foraging technique	Spp. with plastic ratio	 %	Mean freq. occur. within spp. (%)
All species			
Dipping & pattering	4:5	80	47
Surface seizing	25:29	86	26
Piracy	2:3	67	24
Pursuit diving	5:18	28	3
Plunge diving	0:5	0	0
Procellariiformes (excluding albatrosses & giant petrels)			
Dipping & pattering	4:5	80	47
Surface seizing	16:16	100	40
Pursuit diving	3:5	60	12

TABLE 2.10 The incidence of ingested plastic particles in seabirds in relation to prey type. Each species' main diet class is listed in Table 2.1.

Diet class	Spp. with plastic ratio	Spp. with plastic %	Mean freq. occur. within spp. (%)
All species			
Mixed (omnivores)	9:10	90	34
Crustaceans	15:24	63	25
Cephalopods	8:9	89	8
Fish	4:17	24	6
Procellariiformes (excluding albatrosses & giant petrels)			
Mixed (omnivores)	3:3	100	77
Crustaceans	13:16	81	35
Fish	3:3	100	33
Cephalopods	4:4	100	16

the entire stomach contents, whereas regurgitations may or may not represent the entire stomach contents. The stomach pump employed to induce regurgitation is approximately 100 % effective (Wilson 1984), at least for seabird species with simple stomach morphologies (Ryan & Jackson 1986). In the majority of Procellariiformes (all except albatrosses and giant petrels) the angled constriction between the proventriculus and gizzard prevents the sampling of gizzard contents using a stomach pump (Ryan & Jackson 1986). Destructive sampling is necessary in these species because most plastic particles are found in the gizzard (Day 1980, Furness 1985a, pers. obs). It is not known whether naturally regurgitated pellets contain all the hard parts in the stomach, and this may have resulted in underestimates of the incidence of plastic in albatrosses.

The incidence and amount of plastic in a bird is affected by its age, the time of year and the place and year of collection (Chapter 3). For example, chicks and fledglings tend to contain larger plastic loads than do adults. Such differences could affect inter-specific comparisons of the incidence of ingested plastic if the species in question are sampled in different ways. The large proportion of chicks in the samples of Salvin's Prions and Kerguelen Petrels (Table 2.1) may result in overestimates of the incidence of plastic in these species. Such biases have to be considered, but are likely to be small compared to the large intra-specific variance in plastic ingestion.

A potentially more important bias may result from beached birds containing larger plastic loads than average, either as a result of reduced discrimination against plastic particles as non-food items by starving birds immediately prior to stranding, or as a result of greater mortality in birds with larger plastic loads (Bond 1971, Bourne & Imber 1982). This hypothesis has not been tested, although Furness (1985a) suggested that the lack of a negative correlation between the numbers of plastic particles and numbers of hard prey remains indicates that there is no tendency to ingest more plastic particles when food is scarce.

Comparison of the incidence of plastic in 21 Blue Petrels stranded on the beaches of the southwestern Cape, South Africa, and 17 adults collected at the same time at sea off the southwestern Cape (n = 2) and at breeding colonies at the Prince Edward Islands (n = 15), showed no significant difference in the frequency of occurrence (*G* = 1.64, d.f. = 1, NS), number ($U_{17,21}$ = 181.5, NS) or mass ($U_{17,21}$ = 184.5, NS) of ingested plastic particles. However, large variances reduce the likelihood of obtaining significant differences. Of the 12 procellariiform species sampled by examining both beached and collected birds, beached birds made up only 27 % (134 out of 500) of the birds sampled, yet maximum plastic loads were recorded in beached birds in eight (67 %) of these species. This is significantly greater than the proportion expected by random assortment (G = 8.29, d.f. = 1, *P* < 0.01). Also, the frequency of occurrence of plastic in beached Kerguelen Petrels (83 %, n = 6) was significantly greater than that in adults killed at breeding colonies (9 %, n = 22) prior to egg hatching (G = 12.68, d.f. = 1, *P* < 0.001), but there was no significant difference in the frequency of occurrence of plastic in beached (36 %, n = 77) and collected (73 %, n = 11) Antarctic Prions. These somewhat contradictory results suggest that beached birds may contain greater plastic loads than free-ranging birds.

The incidence and amount of ingested plastic

The incidence of ingested plastic in seabirds off southern Africa is similar to that recorded in seabirds elsewhere in the world (Day et al. 1985). The large proportion of procellariiform species sampled off southern Africa results in a high mean frequency of occurrence of plastic. The very high plastic incidence in Blue Petrels, which seldom range north of the Subtropical Front (Watson 1975), indicates that plastic particles are widespread in the Southern Ocean. However, the low frequency of occurrence of plastic in petrels collected south of the Antarctic Polar Front suggests that plastic particles are not yet abundant in continental Antarctic waters (cf. Gregory et al. 1984).

The maximum proportions of gizzard volume occupied by plastic exceeded relaxed gizzard volume, and were larger than those recorded by Furness (1985a,b). This is partly a consequence of the larger sample sizes dealt with here, given the large individual variance in plastic loads. The record from the Great Shearwater shows that apparently healthy, free-ranging birds can survive plastic loads which occupy more than relaxed gizzard volume.

The nature of plastic particles ingested by seabirds

The predominance of industrial pellets and user fragments among plastic particles ingested by seabirds is similar to that reported in other studies (Baltz & Morejohn 1976, Day 1980, Randall et al. 1983, Day et al. 1985, van Franecker 1985). The absence of industrial pellets from seabirds largely confined to Antarctic waters (Antarctic and Snow Petrels and Antarctic Fulmars - Watson 1975), suggests that this type of plastic is scarce in these waters. This implies that most plastic pollution at sea off continental Antarctica derives from ships operating in the area.

All industrial pellets and nearly all user fragments found in seabirds were polyethylene or other polyolefins which float in sea water. Furness (1983) reported a high incidence of expanded polystyrene spheres from birds collected off South Africa, but this was a mis-identification of polyethylene pellets. The only non-floating particles collected were from Southern Giant Petrels breeding at Marion Island, in the Prince Edward Islands, and probably were swallowed by birds scavenging in the vicinity of the meteorological station. At this locality, plastic wastes are incinerated routinely, but occasionally are mixed with food wastes which are dumped into the sea (pers. obs).

The ranges of particle sizes (mass) ingested by seabird species were large, but there were linear relationships between mean and median particle sizes and body mass. Most species ingested very small particles relative to body mass. The masses of particles given in Furness (1985a,b) are all an order of magnitude too large, due to the omission of decimal points on the figure axes.

Plastic selectivity by seabirds

The inference of selection for and against different types of plastic particles by seabirds requires comparison with the suite of particles available in the environment. Comparing the range of particles ingested by a species with the total range ingested by a number of seabird species (Day 1980, Day et al. 1985) is fraught with biases. To assume that the colour frequency of large manufactured items at sea is representative of the different types of plastic particles at sea (Day et al. 1985) is naive (Chapter 1).

The inference of selectivity from a comparison of plastic particles ingested by seabirds with those found at sea makes two assumptions: that the nature of plastic particles collected at sea are typical of those encountered by birds, and that residence in seabirds' stomachs does not modify plastic particles. There is no test of the first assumption, because there are no comparable data sets (Chapter 1). The absence of industrial pellets from Antarctic Fulmars, Snow Petrels and Antarctic Petrels suggests that there are differences in the proportions of types of plastic between Antarctic waters and the seas off the southwestern Cape. However, all the species used in these analyses occur off the southwestern Cape for at least part of the year (Maclean 1985).

The second assumption, that plastic particles are not modified by residence in birds' stomachs, can be examined more critically. Plastic particles gradually are eroded away in the stomachs of seabirds (Day 1980, Bourne & Imber 1982, Chapter 3), but the rate of wear is unknown and probably differs between types of plastic and is different from that of particles at sea (Chapter 3). This necessitates caution when interpreting apparent selection for types and sizes of plastic particles by seabirds (see below). Superficial staining of plastic particles can occur within the stomachs of seabirds, but this was overcome by scraping off the surface layer of stained particles.

Bearing these limitations in mind, it is difficult to infer selection for different types of plastic particles. Foamed plastics may be avoided because, being much less dense than other types, they bear little resemblance to prey items. However, foamed plastics generally are soft and probably are eroded rapidly within seabird stomachs compared to other plastic types. The relative proportions of industrial pellets and user fragments varies between species largely as a function of body mass, which influences particle size selection (cf. Day 1980, Day *et al*. 1985).

Most species ingested user fragments and fibres larger than those collected at sea. This results from the very small size of most fragments and fibres collected at sea (Chapter 1). Only the smaller seabirds contained a large proportion of very small particles. The range of industrial pellet sizes found at sea includes the mean particle size of ingested particles for most seabirds examined. The expected pattern of large birds selecting large pellets and small birds selecting small pellets was not observed. All species took pellets which were either the same size or smaller than those sampled in the environment. There are two possible reasons for this disparity. The pellets collected off the southwestern Cape may be larger than the average size found throughout most species' foraging ranges. There is some evidence that this may be true; due to local sources of industrial pellets in the southwestern Cape (Chapter 1), pellets off the southwestern Cape may be less worn and hence larger than those found in oceanic waters. Equally important is the possibility that there are different rates of pellet wear between those at sea and those in seabird stomachs. Industrial pellets in bird stomachs are not subject to degradation from UV radiation and do not show the extensive crazing and fracturing characteristic of this type of weathering (Gregory 1978, Chapter 1). If the rate of pellet degradation is more uniform (i.e. not accelerated in small pellets as a result of surface crazing) within bird stomachs than at sea, a larger proportion of small particles in seabird stomachs than at sea would result.

The apparent selection of different colours of plastic particles by seabirds has been related to the degree of similarity with potential prey items (Day 1980, Prince 1980, Day _et_ _al_. 1985). It is also possible that differences in ratios between ingested and environmental plastic particle colours result from differences in conspicuousness of particles at sea. The avoidance of clear-white particles by all species and selection of tan and brown particles (in most species) agrees with the findings of Day _et_ _al_. (1985), but contrasts with the earlier suggestion of selection of pale particles (Day 1980). Clear particles presumably are less conspicuous than coloured ones, but opaque white particles are highly conspicuous at sea (at least to human vision). Thus the relatively low proportion of clear-white particles in seabirds probably results from foraging decisions rather than from differences in the conspicuousness of particles.

Red, green and blue particles also were selected by several species (cf. Day _et_ _al_. 1985). Red is the colour most attractive to foraging Procellariiformes (Harper 1979) and it has been assumed that the predominance of red particles taken by albatrosses is due to confusion with red-pigmented crustaceans (Prince 1980). Some planktivorous species selected red particles, but few red particles were found in the predominantly planktivorous prions and storm petrels. This discrepancy is puzzling. There is no evidence to suggest a relationship between particle size and colour at sea.

The tendency for small birds to contain plastic more frequently than do large birds has been reported previously (Bourne & Imber 1982, Furness 1985a). The higher degree of colour selectivity shown by large birds than by small birds (Fig. 2.5) suggests that this difference is at least in part due to more specific prey-identification criteria in large birds.

Patterns of plastic ingestion by seabirds

Plastic ingestion by birds largely is restricted to seabirds; few terrestrial birds have been recorded to eat plastic (e.g. Brooke & Grobler 1973, Radford 1977). Worldwide, a total of 69 seabird species has so far been found to contain plastic particles. Among seabirds there is considerable variation in the incidence of plastic both between species and between individuals within species. It is not possible to explain in detail specific differences in the incidence of plastic ingestion. It is more profitable to consider the patterns of plastic incidence in seabirds above the species level, to test the hypotheses erected by Day (1980) to explain the incidence of ingested plastic in Alaskan seabirds.

At the simplest level, the incidence of plastic in the digestive tracts of seabirds is a function of the rate of plastic ingestion and the rate of plastic loss. Plastic ingestion is believed to be caused primarily by plastic particles being confused with food items, eliciting a feeding response (Day 1980, Day et al. 1985). Inter-specific differences in ingestion rate are thus likely to be related to differences in search images and foraging techniques, and variations in the abundance of plastic in the environment, which affects the rate of encounter with plastic particles. Plastic loss, either through egestion or through wear within the stomach, counters ingestion.

In species groups where egestion of indigestible stomach contents is frequent (giant petrels, cormorants, skuas, gulls and terns), plastic particles will not accumulate in the stomach and plastic loads will be low. In these groups the incidence of plastic ingestion is best reflected by the proportion of species found to contain plastic. This is high for giant petrels, skuas and gulls, and low for cormorants and terns; differences which result from foraging and dietary differences (see below). Albatrosses regurgitate pellets, at least while on the nest (Clarke et al. 1981, pers. obs), and this probably accounts for the low frequencies of occurrence of plastic in this group.

All Procellariiformes, except albatrosses and giant petrels, seldom, if ever, regurgitate indigestible stomach contents (Furness 1985a,b, pers. obs), which limits the processes of plastic loss either to wear within the stomach or regurgitation to chicks (Chapter 3). The lack of large particles in the faeces of all seabirds examined other than gulls, suggests that little plastic is lost through excretion. These limitations result in the accumulation of plastic particles with concomitant large plastic loads and increased risk of adverse effects from plastic ingestion in Procellariiformes. Whether phalaropes, auks and Pelecaniformes other than cormorants regurgitate indigestible stomach contents is not reported, but the high frequency of occurrence of plastic in phalaropes (Bond 1971, Briggs et al. 1982) and some auks (Day 1980) suggests that regurgitation of pellets is infrequent.

The factors affecting the rate of plastic ingestion can be examined only after controlling for the effects of different rates of plastic loss (cf. Day 1980, Day et al. 1985), because foraging techniques in particular are non-randomly distributed among taxa. Thus, among Procellariiformes (excluding albatrosses and giant petrels) surface feeders (feeding either by dipping and pattering or surface seizing) have a greater frequency of occurrence of plastic than species which feed below the surface (pursuit divers). This is to be expected because almost all ingested plastic particles float in sea water. Also, surface-feeding seabirds have a smaller diversity of potentially available prey than do diving species (Duffy 1982), which may favour broader prey identification criteria. Such generalized feeding behaviour is more likely to lead to confusion of plastic particles with prey items.

Day (1980) considered diet an important influence on the incidence of plastic ingestion in Alaskan seabirds, with plastic more frequent in cephalopod and crustacean feeders than piscivores. Day's (1980) contention that the greater similarity of plastic particles to crustaceans than to other prey groups accounts for the higher incidence of plastic in species feeding on crustaceans may be correct. However, I consider it only a facet of the true picture, where the broadness of criteria used to identify prey items determines the probability of confusion of plastic particles with prey. This hypothesis predicts that omnivores, characterized by the broadest criteria, are most likely to confuse plastic particles for prey items and thus have the highest ingestion rate. This was the case for seabirds off southern Africa. Dietary specialists are less likely to misidentify plastic particles for prey, unless a particular plastic type closely resembles their prey.

This argument assumes that plastic is ingested as a result of foraging decisions by seabirds, and is not consumed either along with food items or is already within food items (secondary ingestion). The extent to which plastic is ingested accidently along with prey items is not known. Pettit _et_ _al_. (1981) suggested plastic may be consumed by albatrosses when it is associated with flying fish egg-masses. The simultaneous dumping of plastic and food refuse from ships may also cause accidental rather than directed plastic ingestion.

Secondary ingestion of plastic through eating prey containing plastic particles is uncommon (Hays & Cormons 1974, Anon. 1981, Bourne & Imber 1982, Day _et_ _al_. 1985). The only species in which it frequently occurs is the Subantarctic Skua, which often preys on small petrels containing plastic particles (Appendix 1). The regular regurgitation of bones and other indigestible matter prevents plastic accumulation in this species.

Three factors thus determine the rate of plastic ingestion by seabird species:- 1) the foraging technique, particularly as regards foraging depth, 2) the range of criteria used to identify prey items (degree of dietary specificity), 3) the density and nature of plastic pollution at sea in the foraging area. These factors interact with the rate of plastic loss (determined by the frequency of egestion of indigestible stomach contents and the rate of wear of plastic particles in the stomachs of seabirds) to produce the observed patterns of plastic incidence in seabirds. Procellariiformes have the largest plastic loads because they frequently forage at or near the sea-surface, taking a wide range of prey types (c.f. Rothstein 1973), and seldom regurgitate indigestible stomach contents. It is this group of seabirds which is most likely to be affected by ingested plastic pollution.

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CHAPTER 3

INTRASPECIFIC VARIATION IN PLASTIC INGESTION BY SEABIRDS: TOWARDS AN UNDERSTANDING OF PLASTIC FLUX THROUGH POPULATIONS

ABSTRACT

Patterns of intraspecific variability of ingested plastic loads in seabirds were examined for species collected off southern Africa. The incidence of plastic pollution was shown to be increasing during the 1980s. Both large and small-scale geographic variation in plastic loads occurred as a function of variable plastic density in the environment. Inter-generation transfer of plastic particles was identified as an important pathway of plastic flow in species which accumulate plastic particles and which feed their chicks by regurgitation. This can account for larger plastic loads in non-breeding and failed breeding birds than in successful breeding birds, and such results need not indicate adverse effects from plastic ingestion. Inter-generation transfer resulted in annual cycling of plastic loads in successful breeding birds. In species which do not regurgitate indigestible stomach contents, immature birds tend to have the largest plastic loads and are thus most likely to exhibit adverse effects from plastic ingestion.

INTRODUCTION

The effects of plastic ingestion on seabirds are unknown (Day et al. 1985, Furness 1985a, van Franecker 1985) and studies to determine the residence time and fate of ingested plastic particles are a priority (Furness 1985b). The only evaluation of plastic flux through seabird populations to date is that of Day (1980) and Day et al. (1985), based on changes in the numbers and state of wear of plastic particles in seabirds collected throughout the year. These studies considered the observed fluctuations solely in terms of changes in the rate of ingestion, balanced by erosion of particles in the stomach. This approach is simplistic and has been questioned (Furness 1985b). I propose an alternative explanation for Day's data, drawing supportive evidence from intraspecific variation in the incidence of plastic in seabirds collected off southern Africa.

The large intraspecific variability in the incidence of ingested plastic in seabirds is a feature of this type of pollution (Day et al. 1985, Furness 1985a,b, Chapter 2). Most studies are based on small sample sizes and ignore this variability. Day (1980) and Day et al. (1985) considered the effect of five possible influences on intraspecific variation: geographic differences, bird age and sex, and changes on a long (inter-annual) and short (intra-annual) time-scale. I examine each of these factors, with special emphasis on age-related and short time-scale variation.

METHODS

The incidence of plastic in seabirds was sampled by myself and other members of the FitzPatrick Institute between 1979 and 1985 (Chapter 2). The incidence of plastic in most species was determined by dissecting out the stomach contents of collected birds, or birds found dead. For Wandering Albatrosses *Diomedea exulans* and giant petrels *Macronectes* spp., the incidence of plastic was determined from regurgitations (Chapter 2). Most sampling took place at sea off the southwestern Cape, South Africa, and at Inaccessible Island (37 50S, 12 30W), Gough Island (40 21S, 9 53W) and the Prince Edward Islands (46 45S, 37 50E).

All plastic particles found in seabirds were oven dried at 30 °C and weighed to the nearest 0.1 mg. No attempt was made to score the degree of wear of individual particles (c.f. Day 1980), because the original shape and state of wear of particles at the time of ingestion cannot be inferred with accuracy. Industrial pellets from seabird stomachs seldom showed the surface crazing induced by UV degradation typical of pellets at sea (Gregory 1978, Chapter 1); pellet wear in seabird stomachs was uniform, resulting in smooth pellets, the original shapes of which were obscure.

Non-parametric statistics (contingency tables, log-likelihood ratios, Spearman Rank Correlations, Fisher Exact Tests and Mann-Whitney U-tests) were used to test the significance of all comparisons made.

RESULTS AND DISCUSSION

Long time-scale (inter-annual) variation

Plastic and other synthetic products were first recorded in seabird stomachs in the early 1960s (Bennett 1960, Rothstein 1973), following the rapid growth of the plastics industry in the 1950s (Colton 1974). Since then the incidence of plastic in seabirds has increased to its present ubiquitous level (Day *et al*. 1985, Chapter 2). Day (1980) and Day *et al*. (1985) showed a general increase in the incidence of plastic in Shorttailed Shearwaters *Puffinus tenuirostris* up to 1977. This trend has continued into the 1980s in at least one species of seabird off southern Africa. Comparing the incidence of plastic in Antarctic Prions *Pachyptila desolata* collected during 1979-80 with those collected during 1983-85, there was an increase in the frequency of occurrence of plastic (4:12 and 42:60 respectively, $G = 5.64$, d.f. = 1, $P < 0.05$), and the number and total mass of plastic particles per bird also increased ($U_{12,60} = 475.5$, 472.5 respectively, 1-tailed $P < 0.05$).

Local decreases in plastic pollution and plastic ingestion by organisms have occurred as a result of improved handling and processing systems in specific industries (Kartar *et al*. 1973, 1976). However, seabirds ingest plastic from widespread and diverse origins (Chapter 1). International legislation may reduce the amount of plastic at sea (Horsman 1982, Dixon & Dixon 1983, van Franecker 1985), but there are many problems associated with the implementation and enforcement of dumping restrictions (Carvell 1985). Also, growth of the plastic industry in the Third World is likely to maintain the increase in the amount of plastic pollution at sea for some time, and the levels in seabirds presumably will continue to rise.

Geographic variation

Day (1980) and Day et al. (1985) demonstrated differences in plastic loads in seabirds collected in different regions, and attributed them to varying densities of plastic pollution at sea. Similar geographic differences in plastic loads have been recorded by Furness (1985b) and van Franecker (1985). However, any demonstration of geographic variation in plastic loads must be based on comparisons of plastic loads in similarly aged birds at the same time of year (see below).

In the African sector of the Southern Ocean there is a trend for greater incidences of plastic pollution in more northerly seabird populations. The incidence of plastic in Wandering Albatross chick regurgitations is higher at the more northerly Gough Island (6:100) than at the Prince Edward Islands (1:54), although the difference is not significant (G = 1.60, d.f = 1). Similarly, Broadbilled Prions Pachyptila vittata breeding at Inaccessible Island, north of the Subtropical Front, apparently contain larger plastic loads than those at Gough Island, which lies to the south of the front (Appendix 1). The trend for larger plastic loads at more northerly sites is supported by the very low incidence of plastic in petrels confined to Antarctic waters (Chapter 2), and suggests that the frequency of plastic ingestion is directly related to the density of plastic particles at sea. However, geographic variation may be masked by other sources of variation in plastic loads, including bird age and the time of year relative to the breeding season (see below).

On a much smaller scale, local differences in foraging area may also influence the incidence of ingested plastic in seabirds. Kelp Gulls _Larus dominicanus_ feeding at refuse tips in South Africa have a higher frequency of occurrence of plastic (7:33) than those feeding elsewhere (1:29, G = 4.88, d.f. = 1, $\underline{P} < 0.05$). Such differences are less likely to be observed in species which do not regularly regurgitate indigestible stomach contents.

Sex-related variation

No sex-related variation in the incidence of plastic in seabirds has been recorded (Day 1980, Day _et al_. 1985). Such a sexual difference is unlikely in birds lacking any marked sexual dimorphism. Giant petrels have the greatest sexual dimorphism of any seabird species, and a higher incidence of plastic might be expected in the smaller, more marine-foraging females (Hunter 1983). No such trend was observed (Table 3.1), although sample sizes were small.

Age-related variation

Day (1980) and Day _et al_. (1985) reported larger plastic loads for immatures than for adults of Parakeet Auklets _Cyclorrhynchus psittacula_ and Tufted Puffins _Lunda cirrhata_. These differences were attributed to theoretically broader foraging niches and perhaps greater dietary experimentation by young, inexperienced birds (e.g. Porter & Sealy 1982). This apparently is the case for Kelp Gulls foraging at refuse tips in southern Africa; the frequency of occurrence of ingested plastic in immature birds (identified by at least some brown, immature plumage, 4:12) is significantly greater than that in adults (1:18, G = 4.03, d.f. = 1, $\underline{P} < 0.05$). Kelp Gulls regularly regurgitate indigestible

TABLE 3.1 The incidence of plastic in regurgitations from male and female Southern and Northern Giant Petrels *Macronectes giganteus* and *M. halli*.

Species	Ratio with plastic		Significance
	Male	Female	
Southern Giant Petrel	6:70	3:53	$P > 0.5$
Northern Giant Petrel	0:25	2:16	$P > 0.1$

stomach contents as pellets (Chapter 2), thus there is no plastic accumulation, and particles found in the stomach have been ingested recently. However, most Procellariiformes (and some auks - Harris 1984) seldom or never regurgitate pellets, resulting in plastic particles accumulating in the stomach (Furness 1985a,b, Chapter 2). This, coupled with the inter-generation transfer of plastic from adults to chicks, presents an alternative explanation for the age-related variation in the incidence of plastic reported by Day (1980) and Day *et al.* (1985).

Plastic particles frequently are found in the stomachs of seabird chicks (Kenyon & Kridler 1969, Rothstein 1973, Pettit *et al.* 1981) and, occasionally, in meals fed to chicks (Day 1980, pers. obs). I suggest that the larger plastic loads found in immatures than in adults can be explained by this inter-generation transfer of plastic particles, at least in species which regurgitate food to their chicks. All 15 Blue Petrel *Halobaena caerulea* chicks collected at the Prince Edward Islands contained plastic particles, and both the number and total mass of particles was significantly larger in chicks than in adults (Table 3.2, $U_{15,53} = 605.5, 537$, $P < 0.001, 0.02$ respectively). Plastic was also more frequent in Whitechinned Petrel *Procellaria aequinoctialis* and Kerguelen Petrel *Pterodroma brevirostris* fledgings (7:7 and 8:26 respectively) than in adults (108:193 and 2:23, excluding beached birds, $G = 7.93, 3.90$ respectively, d.f. = 1, $P < 0.05, 0.01$).

The plastic in seabird chicks comes from their parents; this has a major bearing on the flux of plastic particles through seabird populations. If the plastic fed to seabird chicks is solely that which is ingested by adults on foraging trips during chick rearing, then the rate of accumulation in chicks gives a minimum estimate of the natural ingestion rate. Coupled with the known incidence of ingested plastic, this would allow calculation of the rate of wear of plastic particles in seabird stomachs. Alternatively, if the particles fed to chicks derive from the plastics stored in the parents' gizzards, as well as those ingested during the chick-rearing period, loss to chicks would form an additional mechanism for the removal of accumulated plastic particles in species which apparently do not regurgitate indigestible stomach contents (except when feeding chicks).

Evidence from Blue Petrels suggests that the latter explanation is correct; plastic particles in chicks were significantly smaller than those in adults (Fig. 3.1, $X^2 = 42.35$, d.f. = 5, $\underline{P} < 0.001$). This is consistent with the hypothesis that chicks are fed particles which have been stored in the parents' gizzards for some time, and are smaller as a result of wear within the parents' stomachs. If chick plastic loads represented plastic ingested during the chick-rearing period only, adult Blue Petrels would have to ingest a plastic particle approximately once every two days, giving a particle turnover time through wear (out of the breeding season) also measured in days. Albatrosses are known to retain indigestible objects in the stomach for up to six weeks (Pettit et al. 1981, Furness et al. 1984) and plastic particles fed to Whitechinned Petrels were little changed after 12 days in their stomachs (Chapter 5).

However, inter-generation transfer of plastic particles cannot explain the larger plastic loads reported from immature Tufted

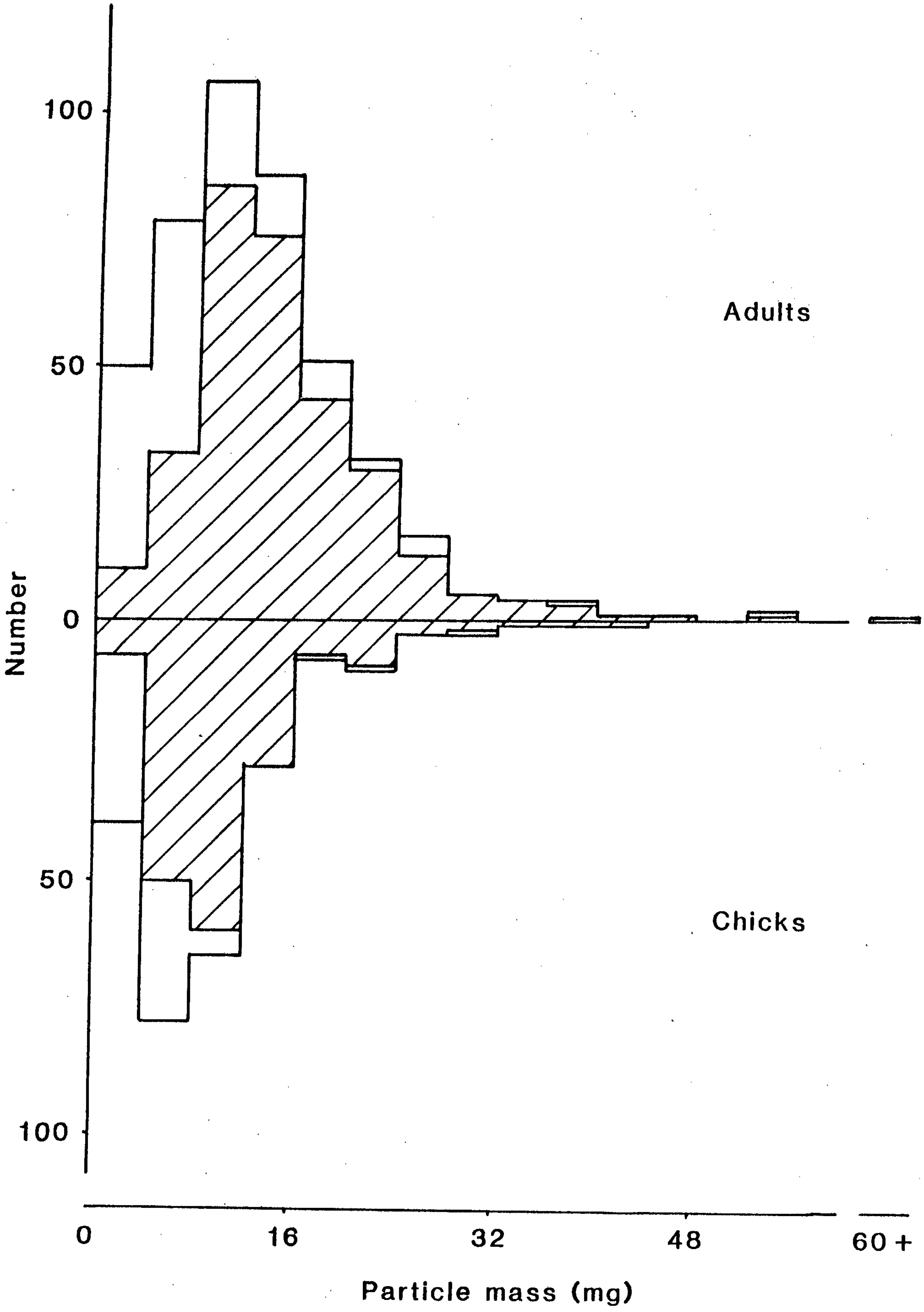

FIGURE 3.1 The masses of plastic particles collected from Blue Petrel adults and chicks. Industrial pellets are depicted by hatching, user plastics are left blank.

Puffins than from adults (Day 1980, Day et al. 1985), because puffins feed their chicks whole prey carried in the bill, and apparently do not regurgitate stored food (Bedard 1969). This could be verified by examining the stomachs of puffin chicks for plastic particles. The age-related difference in plastic loads of Tufted Puffins probably is related to feeding niche differences between age-groups, as suggested by Day (1980) and Day et al. (1985).

A consequence of the inter-generation transfer of accumulated plastic particles from adults to chicks is that it should produce smaller plastic loads in successful breeding birds than those found in non-breeding or unsuccessful breeding birds (pairs which failed before their clutch hatched). Among Broadbilled Prions collected at Gough Island during the chick-rearing period (October/November), those with well developed brood patches contained plastic significantly less frequently (6:38) than those lacking a brood patch (5:10, G = 4.66, d.f. = 1, $P < 0.05$). Day (1980) and Day et al. (1985) also demonstrated larger plastic loads in non-breeding than in breeding Parakeet Auklets, but attributed the failure of birds with large plastic loads to reproduce successfully to adverse effects of plastic ingestion. The inference that plastic ingestion causes reduced breeding success from observations of larger plastic loads in non-breeding birds must be viewed with extreme caution.

Short time-scale (intra-annual) variation

The inter-generation transfer of plastic particles from breeding adults to their chicks has a major impact on short time-scale variation in plastic loads in seabirds. Adults of species which accumulate plastic particles and which feed their chicks by regurgitating stored food, presumably will show an annual cycle in the incidence of plastic; plastic loads gradually increasing from their lowest levels immediately after the breeding season, throughout the non-breeding season, to peak before the eggs hatch in the following breeding season. Losses of accumulated particles to chicks reduce adult plastic loads to the post-breeding minimum. This provides an alternative explanation to the seasonal variation in plastic loads reported by Day (1980) and Day _et al_. (1985), which was attributed to changes in the ingestion rate of plastic particles.

Day (1980) and Day _et al_. (1985) considered seasonal changes in plastic loads of Shorttailed Shearwaters and Tufted Puffins. Shorttailed Shearwaters showed a gradual increase in the number of ingested plastic particles off Alaska during the austral winter, with levels much higher than those found in breeding birds in Australia during the austral summer. This is consistent with the annual cycle hypothesis outlined above. The smaller average plastic loads in breeding birds is reinforced by the absence of non-breeding individuals of this species in the vicinity of the breeding grounds, many remaining in the Northern Hemisphere (Harrison 1983). The only trend in the incidence of plastic in Shorttailed Shearwaters observed by Day (1980) and Day _et al_. (1985) which is not predicted by the annual cycle hypothesis, is the decrease in plastic loads in September, just before the breeding season. However, this is based on a small sample of birds (12), and none of the monthly changes in the number of particles per bird departs significantly from the overall frequency for birds collected off Alaska (G = 5.69, 1.31, 3.51, 4.11, 4.56, d.f. = 3, $P > 0.1$ for May, June, July, August and September respectively).

Day (1980) and Day *et al.* (1985) supported the explanation of seasonal variation in plastic loads based on seasonal changes in plastic ingestion rate with data for the state of wear of particles in Shorttailed Shearwaters. I have reservations about the accuracy of wear data (see Methods), especially because particles at sea exhibit a range of wear states (Chapter 1). In fact, none of the monthly wear frequencies reported by Day (1980) and Day *et al.* (1985) departs significantly from the summed data for birds collected off Alaska (G = 3.19, 4.72, 0.77, 2.04, 2.52, d.f. = 3, $P > 0.1$ for May, June, July, August and September respectively).

The data for seasonal changes in Tufted Puffin plastic loads (Day 1980, Day *et al.* 1985) cannot be explained by the annual cycle hypothesis, because puffins do not feed chicks with regurgitated food (Bedard 1969). However, the trends reported by Day (1980) and Day *et al.* (1985) are not significant (G = 3.00, comparing June/July, the months with the highest frequency of occurrence of plastic in Tufted Puffins, with May/August, the months with the lowest frequency of occurrence).

The seasonal variations in plastic loads in seabirds collected off southern Africa and at islands in the adjacent Southern Ocean support the annual cycle hypothesis. The post-breeding plastic levels in Blue Petrels collected in April were significantly lower than those in birds collected during August-September, just prior to the breeding season (Table 3.2, $U_{15,38} = 389, 367.5$, $P < 0.05, 0.1$ for number and mass of plastic

TABLE 3.2 Seasonal changes in plastic and pumice loads in Blue Petrels collected at the Prince Edward Islands and off the southwestern Cape, South Africa, with those in chicks for comparison.

Period	Frequency of occurrence Ratio	%	Mean no. particles per bird	Mean mass per bird (mg)
Plastic:				
Post-breeding (April)	11:15	73	4.87	65.1
Pre-breeding (August-September)	37:38	97	9.16	115.9
Chicks (December-January)	15:15	100	16.07	146.0
Pumice:				
Post-breeding (April)	8:15	53	0.53	4.4
Pre-breeding (September)	14:15	93	3.00	40.3
Chicks (December-January)	15:15	100	9.26	30.4

particles respectively). There was also significantly more pumice in adult Blue Petrels collected prior to the breeding season than in birds collected after the breeding season (Table 3.2, $U_{15,15} = 321.5, 322$, $\underline{P} < 0.001$ for number and mass of pumice respectively).

Similarly, the frequency of occurrence of plastic in Whitechinned Petrels and Sooty Shearwaters Puffinus griseus was higher during the pre-breeding period than during the post-breeding period (Table 3.3), although the difference was significant only for Sooty Shearwaters ($\underline{P} = 0.03$, Fisher Exact Test). The highest frequencies of occurrence of plastic in these two species off the southwestern Cape coast, South Africa, occurred during the breeding season (Table 3.3), when only non-breeding birds were present. The annual cyclical fluctuations presumably are damped in these data sets due to the inclusion of immature birds, which cannot readily be distinguished from adult birds during the non-breeding season.

Plastic flux through seabird populations

The annual cycle hypothesis assumes that inter-generation transfer of plastic is an important pathway for plastic in species of seabird which feed their chicks regurgitated meals, in addition to loss through erosion in the stomach. The simplistic model of Day (1980) and Day et al. (1985), where variable ingestion rates, balanced by fairly constant erosion, determine plastic loads, can be replaced by a new model where a more constant ingestion rate is countered by fairly constant erosion plus a regular dumping of accumulated particles into chicks by successful breeding birds (and birds which at least

TABLE 3.3 Seasonal fluctuations in the frequency of occurrence of plastic particles in Whitechinned Petrels and Sooty Shearwaters collected at sea off the southwestern Cape, South Africa. Post-breeding is taken as March-June, pre-breeding as July-October and breeding as November-February.

Season	Whitechinned Petrel		Sooty Shearwater	
	Ratio	%	Ratio	%
Post-breeding	19:39	49	1:11	9
Pre-breeding	49:94	52	7:13	54
Breeding	40:60	67	23:38	61

reach the chick-rearing stage).

Unfortunately, the addition of another variable to the model does not improve understanding of the magnitude of the pathways involved. Assuming that all accumulated plastic is passed onto chicks during breeding (I have no data to the contrary), and that the ingestion and erosion rates are constant, the amount of plastic in fledglings represents the difference between ingestion and erosion in the parents since the last successful breeding season. The magnitudes of the rates of ingestion and erosion are unknown. Only when the rate of particle wear is experimentally determined from captive birds, can this equation be resolved. The conservative estimate of a half life for polyethylene pellets of approximately a year (Chapter 5) suggests that the lifespan of plastic particles in seabird stomachs is considerably longer than the six months estimated from Day's model (Day *et al*. 1985). However, as Day *et al*. (1985) observed, the rate of particle wear is likely to vary greatly in relation to the size, number and types of plastic particles, as well as the amount and nature of other retained items (cephalopod beaks, pumice, etc.).

There is one further flow pathway for plastic particles through seabirds: egestion of plastic along with other indigestible stomach contents in pellets (Fig. 3.2). In species where this occurs frequently, the other pathways are presumably of little importance and plastic accumulation is limited. Plastic egestion is tacitly omitted from the model above because it is unknown in Procellariiformes (excluding albatrosses and giant petrels, Furness 1985a,b, pers. obs), the group with the highest levels

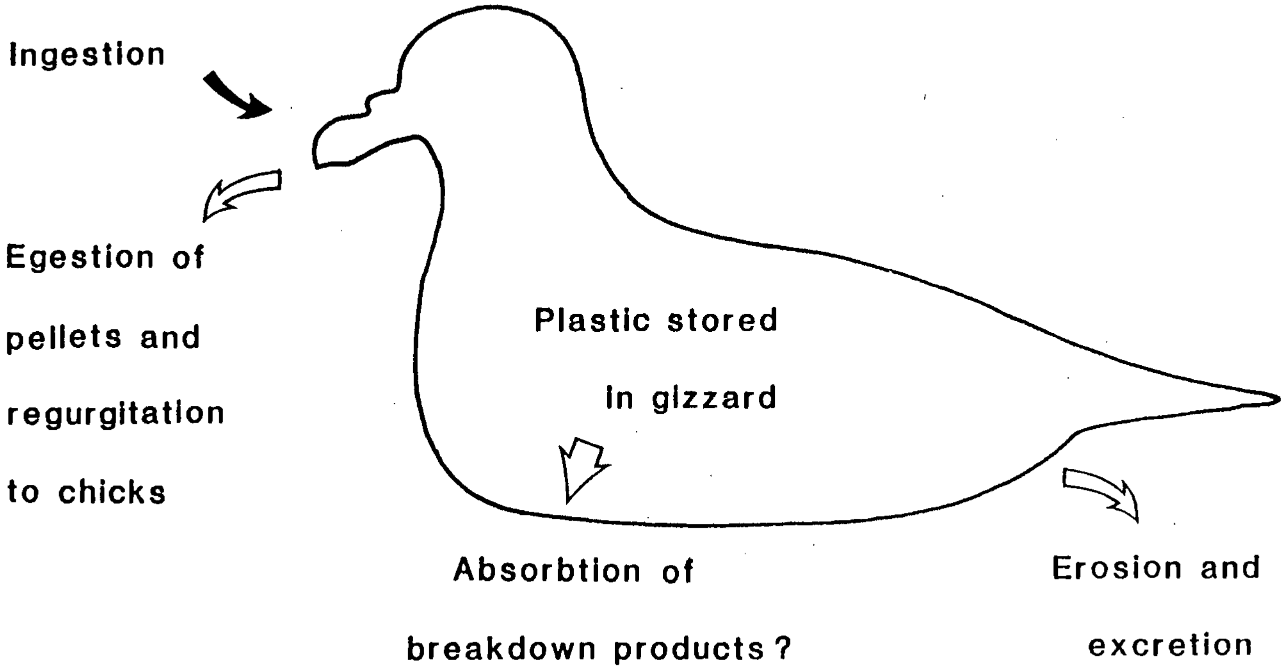

FIGURE 3.2 A conceptual model of plastic pathways through seabirds. The magnitudes of these pathways in each species determine the rate of plastic accumulation.

of accumulated plastic pollution (Day *et al*. 1985, Chapter 2). The fact that petrels apparently can regurgitate accumulated plastic particles along with chick meals suggests that infrequent egestion of pellets may occur. The behaviour of Procellariiformes at sea is still largely unknown (Brown 1980). However, it is unlikely that egestion does occur in Procellariiformes at sea, because there is no correlation between the amount of plastic and other indigestible remains in the gizzards of non-pellet producing seabirds (Furness 1985a), or between the amount of plastic and pumice in pre-breeding Blue Petrels (r_s = 0.23, 0.11, d.f. = 13, for number and mass respectively). Correlations between the numbers and total mass of plastic and other indigestible items should occur if egestion was an important pathway for the loss of indigestible stomach contents. However, there is a significant correlation between plastic and pumice in post-breeding Blue Petrels, (r_s = 0.55, 0.38, d.f. = 13, $P < 0.05$, 0.1 for number and mass respectively), presumably due to the influence of inter-generation transfer of indigestible stomach contents.

The annual cycle hypothesis fundamentally alters our understanding of plastic flux through seabird populations. In species which do not regurgitate indigestible stomach contents and which are fed regurgitated plastic along with their meals as chicks, immature birds up to their first successful breeding attempt will have the largest plastic loads. They are thus more prone to suffer adverse effects from the physical presence of plastic particles in the stomach than are breeding adults. Also, the annual cycle hypothesis does not require the rapid erosion of plastic particles within seabird stomachs (cf. Day 1980, Day *et al*. 1985), which concurs with the considerably longer estimates of the lifespan of plastic particles reported elsewhere (Chapter 5).

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CHAPTER 4

THE EFFECTS OF INGESTED PLASTIC ON SEABIRDS: CORRELATIONS BETWEEN PLASTIC LOAD AND BODY CONDITION

ABSTRACT

Multivariate analyses were used to assess the independent influences of body size, ingested plastic load and parasite load on bird mass and an index of fat reserves in Great Shearwaters *Puffinus gravis* and Blue Petrels *Halobaena caerulea*. Plastic load was negatively correlated with body condition in the sample of Blue Petrels collected after the post-nuptial moult, but differences in reproductive status may account for this negative correlation. Ingested plastic loads had no apparent effect on Blue Petrels and Great Shearwaters collected at the same stage of reproduction, despite large plastic loads in some individuals. The limitations of using correlations to demonstrate the effects of plastic ingestion are discussed.

INTRODUCTION

Much has been speculated about the possible effects of ingested plastic particles on seabirds, but few adverse effects have been demonstrated (Day et al. 1985, Furness 1985a,b). The possible effects of ingested plastic can be divided into three categories: physical damage to the digestive system (Parslow & Jefferies 1972, Bourne 1976, Pettit et al. 1981, Zonfrillo 1985), impairment of digestive and foraging efficiency (Day et al. 1985) and the release of toxic chemicals (Baltz & Morejohn 1976, Pettit et al. 1981, van Franecker 1985). Physical damage caused by ingested plastic particles is the best documented of these three categories, because of the overt impact on affected birds (stomach ulcerations and, in severe cases, intestinal obstruction). Neither the effect of ingested plastic on digestive or foraging efficiency, nor the importance of plastics as sources of toxic chemicals have been quantified (Day et al. 1985); these effects are considered elsewhere (Chapters 5-7).

Most attempts to demonstrate the effects of plastic ingestion on seabirds have been based on correlations between plastic load and indicators of bird condition (Day 1980, Connors & Smith 1982, Furness 1985a,b). This study presents correlations for three additional groups of seabirds characterized by high levels of ingested plastic pollution, and collected at the same locality over a short period of time. The value of this approach is discussed.

METHODS

Twenty female Great Shearwaters Puffinus gravis were collected within two days of laying eggs at Gough Island (40 21S, 9 53W), South Atlantic Ocean, between 9 and 12 November 1984. For each bird the following parameters were measured: culmen length (to the start of feathers), culmen depth at base, maximum culmen width, total head length, tarsus length, length of the middle toe plus claw (all to the nearest 0.1 mm), wing (maximum chord) and tail lengths (to the nearest 1 mm), bird mass less the mass of stomach contents (to the nearest 1 g), mass of abdominal fat reserves (to the nearest 0.1 g), total mass of ingested plastic (to the nearest 1 mg) and number of parasites (almost all cestodes Tetrabothrius spp.). The mass of abdominal fat was assumed to be indicative of total fat reserves (Thomas & Mainguy 1983).

Fifteen Blue Petrels Halobaena caerulea were collected at the Prince Edward Islands (46 45S, 37 50E), southern Indian Ocean, between 4 and 14 September 1984, and a further 15 were collected at the same locality between 18 and 23 April 1985. Those collected in September were all prebreeding males with enlarged testes, occupying nest burrows. The birds collected in April, after the breeding season and the post-nuptial moult, consisted of both males (9) and females (6), and probably included both successful breeding and failed/non-breeding birds. Parameters measured for Blue Petrels were the same as those for Great Shearwaters, except for the omission of parasite load.

Stepwise multiple correlation analyses were performed using Statpro (Imhoff & Hewett 1983) in order to assess the independent influences of body size, plastic load and, in Great Shearwaters, parasite load, on bird mass and the mass of abdominal fat reserves. Analysis was terminated when no additional variable was correlated at below the 0.05 significance level.

RESULTS

Plastic was present in 19 (95 %) Great Shearwaters, 14 (93 %) Blue Petrels collected in September, and 11 (73 %) Blue Petrels collected in April. There was large variation in both plastic loads and the indicators of body condition, bird mass and fat index, in all three data sets (Table 4.1). No significant simple linear correlations were found between plastic mass and either indicator of condition (Table 4.2). The set of Blue Petrels collected in April had the only negative correlations (non-significant) between plastic mass and indicators of bird condition.

The mass of abdominal fat reserves was the major determinant of bird mass in all three data sets (Table 4.3). Various morphometric parameters also were correlated with bird mass, but the mass of ingested plastic was significantly negatively correlated with bird mass only in the sample of Blue Petrels collected in April. Bird mass and morphometric parameters were correlated with the mass of abdominal fat reserves; there were no significant correlations between plastic mass and the mass of fat reserves (Table 4.3). Excluding bird mass from multivariate analyses of the determinants of abdominal fat reserves, and *vice versa*, added no new parameters to the results. Parasite load was

TABLE 4.1 Ranges of the principle parameters for each of the three groups of seabirds sampled.

Parameter	Great Shearwater	Blue Petrel (September)	Blue Petrel (April)
Bird mass (g)	725 - 920	171 - 234	182 - 235
Abdominal fat mass (g)	1.0 - 9.5	3.2 - 6.9	2.4 - 7.4
Number of parasites	130 - 4016	No data	No data
Plastic mass (mg)	0.0 - 1441	0.0 - 211	0.0 - 235

TABLE 4.2 Simple linear correlation coefficients (*r*) between the mass of ingested plastic and two indicators of condition: bird mass and the mass of abdominal fat reserves.

Species	Bird mass		Abdominal fat mass	
	r	significance	*r*	significance
Great Shearwater	0.123	*P*>0.5	0.307	*P*>0.1
Blue Petrel (September)	0.036	*P*>0.5	-0.010	*P*>0.5
Blue Petrel (April)	-0.286	*P*>0.2	-0.167	*P*>0.5

TABLE 4.3 The independent parameters influencing bird mass and the mass of abdominal fat reserves in the three groups of seabirds sampled, as determined by stepwise multiple correlation analyses.

Dependent variable	Independent variable	Sign	Cumulative r^2
Great Shearwater			
Bird mass	Abdominal fat mass	+	0.628
	Tarsus length	+	0.698
	Wing length	+	0.752
Abdominal fat mass	Bird mass	+	0.628
	Culmen length	+	0.716
Blue Petrel (September)			
Bird mass	Abdominal fat mass	+	0.447
	Culmen width	+	0.643
Abdominal fat mass	Bird mass	+	0.447
	Culmen width	-	0.654
Blue Petrel (April)			
Bird mass	Abdominal fat mass	+	0.461
	Culmen width	+	0.658
	Plastic mass	-	0.773
Abdominal fat mass	Bird mass	+	0.461
	Tarsus length	-	0.604

not correlated significantly with body condition in the sample of Great Shearwaters.

DISCUSSION

The use of correlation analyses to demonstrate the effects of ingested plastic on seabirds is attractive, because data are collected easily and, to some extent, indicators of body condition integrate the diverse putative effects of ingested plastic particles. However, there is no means of separating cause from effect. Thus a negative correlation between plastic load and condition may result from adverse effects of ingested plastic, from an increased plastic ingestion rate by birds in poor condition, or from both (Connors & Smith 1982). The second possibility is plausible if birds in poor condition are less discerning as regards prey identification criteria than are birds in better condition (see Chapter 2). An additional problem is that a number of variables including age, reproductive status, and the time of year and place of collection all can influence the amount of ingested plastic and bird condition independently. For example, immature birds are characterized by large plastic loads relative to adults as a result of adults passing stored plastic to their chicks (Chapter 3), but immature seabirds tend to be less efficient at foraging than are adults (e.g. Buckley & Buckley 1974, Searcy 1978, Porter & Sealy 1982, Ainley _et al_. 1983), which could lead to immatures being in poorer condition than adults (Kendeigh _et al_. 1977). This drawback to the use of correlation analyses to show the effect of ingested plastic on seabirds has been ignored in previous studies (Day 1980, Connors & Smith 1982, Furness 1985a,b).

The only solution to the cause-effect dilemma is the use of controlled experiments. However, the influence of individual differences can be overcome by comparing birds of the same sex at the same stage of reproduction and the same time and place. The lack of correlation between plastic load and indicators of bird condition in both female Great Shearwaters immediately after egg laying and male Blue Petrels occupying nest burrows prior to the breeding season suggests that ingested plastic has little overt effect on these species at plastic loads of up to 1500 mg and 200 mg respectively. This is despite the fact that Great Shearwaters and Blue Petrels have the highest known levels of accumulated plastic pollution in seabirds found off southern Africa and in the adjacent Southern Ocean (Chapter 2).

The Blue Petrels collected in April, after the post-nuptial moult, probably included both successful breeding birds and non-breeding/failed breeding birds. Birds which breed successfully subsequently have reduced plastic loads as a result of inter-generation transfer of plastic to chicks, whereas plastic loads in non-breeding/failed breeding birds are relatively large (Chapter 3). The observed negative correlation between plastic mass and bird mass in post-breeding Blue Petrels may well result from the differences in reproductive status of the birds involved. Unfortunately, there is no direct method of distinguishing the two classes of birds.

Previous studies have shown statistically weak, negative correlations between plastic load and bird mass (Day 1980, Furness 1985a,b), and between plastic load and fat indices (Connors & Smith 1982). These studies were based on randomly selected groups of birds, or on birds collected over a period of time. With the exception of the small groups of breeding Northern Fulmars *Fulmarus glacialis* collected by Furness (1985b), the possibility cannot be ruled out that the negative correlations resulted from the independent effects of differences in age, reproductive status, or the time of year of collection on plastic loads and indicators of body condition. Such individual variation within samples must be eliminated if meaningful results are to be obtained.

The problem of separating cause from effect limits the usefulness of correlation analyses for indicating the effects of plastic ingestion; indeed, such analyses cannot provide any evidence for adverse effects. Future attempts to demonstrate adverse effects resulting from plastic ingestion in seabirds should be by controlled experiments, specifically designed for the task.

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CHAPTER 5

THE LIFESPAN OF INGESTED PLASTIC PARTICLES IN SEABIRDS AND THEIR EFFECT ON DIGESTIVE EFFICIENCY

ABSTRACT

The assimilation efficiencies of fledgling Whitechinned Petrels Procellaria aequinoctialis artificially fed large quantities of plastic particles were assessed. No significant differences were detected in either assimilation efficiency or the rate of mass loss between experimental and control birds. Polyethylene pellets lost 1 % of their mass after 12 days in the experimental birds' stomachs, suggesting a half-life of at least one year. No instances of plastic causing intestinal obstruction, and few cases of physical damage to the stomach lining, were found in over 400 individuals of 25 species of seabirds containing ingested plastic. These results suggest ingested plastic seldom impairs digestive efficiency in seabirds.

INTRODUCTION

Plastic particles frequently are ingested by many seabirds, and accumulate in the stomachs (proventriculus plus gizzard) of some species, notably those of the family Procellariiformes (Day *et al.* 1985, Chapter 2). The lifespan of particles in the stomachs of species which accumulate plastic is not known, but has been suggested to be between 3 and 15 months (Day 1980, Day *et al.* 1985). Plastic may occupy a large proportion of the relaxed gizzard (ventriculus) volume, and occasionally plastic fills the gizzard and overflows into the proventriculus (Chapter 2). It has been suggested that plastic particles might impair digestive efficiency by impeding the flow of food into the intestine, in severe cases leading to starvation (Parslow & Jefferies 1972, Bourne 1976, Pettit *et al.* 1981, Zonfrillo 1985), but evidence is lacking (Day *et al.* 1985). Sharp plastic particles might also damage the stomach lining and cause localized ulceration (Bourne 1976, Zonfrillo 1985). Alternatively, plastic particles might improve digestive efficiency by assisting the grinding of food items in the stomach (Day 1980).

This chapter compares the assimilation efficiencies of Whitechinned Petrel *Procellaria aequinoctialis* fledglings artificially loaded with plastic particles, with those of a control group. The rate of particle wear during the experiment is used to estimate the lifespan of plastic particles in seabird stomachs. The incidences of internal injury and intestinal obstruction by plastic particles in several species of seabird collected off southern Africa and in the adjacent Southern Ocean are discussed.

METHODS

Seven fledgling Whitechinned Petrels were collected from their burrows between 11 and 18 April 1985 at Subantarctic Marion Island (46 52S, 37 51E) in the Prince Edward Island group, southern Indian Ocean. They were housed in wire mesh cages (60 X 40 X 40 cm), sheltered from the rain, but subject to the island's temperature and light regimes. Birds were fed after capture, then left until only urine and bile were excreted. Total elimination occurred within 48 h, therefore 48 h was used as the fasting interval between trials.

Five control birds, each used for a single trial, were fed water-soluble placebos equal in volume to the plastic loads fed the experimental birds prior to the feeding trials. Two experimental birds were fed 40 clear, virgin polyethylene pellets each (total mass 1403.7 and 1384.2 mg) along with their first meal. Feeding trials commenced three days after loading with plastic. One experimental bird was used for three trials, the other for two trials. All birds were weighed daily to the nearest 20 g using a Pesola spring balance.

Each trial commenced when the birds were fed meals of a squid <u>Loligo vulgaris</u> (mean meal wet mass 130.3 ± 11.9 g) in the evening after a 48 h fast. The birds were fed again the following evening, then fasted for 48 h. Pre-weighed aluminium foil sheets were placed in trays under the cages before the first meal and removed after the 48 h fast (Cooper 1977). The foil sheets with the collected faeces and urine were dried at between 40 and 50 °C for five days, then weighed, and as large a sample of the combined faeces and urine (hereafter referred to as faeces) as possible scraped off each sheet for later analysis. Squid samples (11 individuals, 478 g wet mass) were dried under the same conditions as the faeces, then weighed. Energy values (in kJ) of duplicates of sub-samples of food and faeces were determined using a Gallenkamp adiabatic macro-bomb calorimeter.

Assimilation efficiency (AE) was calculated as follows:

$$AE = (GE_{in} - GE_{out}) / GE_{in}$$

where GE_{in} and GE_{out} are the gross energy intake and the gross energy eliminated respectively. The nitrogen content (organic and inorganic) of sub-samples of the food and faeces was determined using the Kjeldahl method (Dowgiallo 1975). Values of assimilation efficiency were corrected for nitrogen retention using the formula:

$$AE_n = (GE_{in} - GE_{out} - N) / GE_{in}$$

where N is a nitrogen correction factor derived as follows:

$$N = (N_{in} - N_{out}) \times 36.5\ kJ.g^{-1}$$

where N_{in} and N_{out} are the mass of nitrogen (g) in the food and faeces respectively. The energetic value for urinary nitrogen in birds is 36.5 $kJ.g^{-1}$ (Sibbald 1982). Non-parametric statistics (Mann-Whitney U-tests) were used to compare AE and AE_n of the experimental and control birds.

After the experiment, all birds were sacrificed with Euthenaze to examine the plastic particles fed to the experimental birds. Plastic particles recovered from the birds were washed, dried and then weighed to the nearest 0.1 mg.

More than 400 individuals from 25 species of seabirds, collected off southern Africa and in the adjacent Southern Ocean between 1979 and 1985 (Chapter 2), found to contain plastic were examined for signs of damage to the stomach lining or for intestinal obstruction.

RESULTS

All seven birds contained between 1 and 16 plastic particles, in addition to those fed to the experimental birds, presumably ingested along with meals fed to them by their parents (cf. Chapter 3). None of these "natural" plastic loads exceeded 10 % of the mass of plastic fed to the experimental birds. Neither experimental bird's natural load contained clear polyethylene pellets, a colour type seldom ingested by Whitechinned Petrels (Chapter 2).

All plastic particles fed to the two experimental birds were recovered from their stomachs after feeding trials were completed. Roughly equal proportions of the particles were located in the gizzard (21 and 18) and proventriculus (19 and 22). No changes were observed in the colour or surface texture of the polyethylene pellets after 12 days in the experimental birds' stomachs. The total mass of particles fed to the two experimental birds had decreased by 1.2 % (16.6 mg) and 0.9 % (13.0 mg) respectively after 12 days.

No significant differences in AE or AE$_n$ were detected between the experimental and control groups ($U_{5,5}$ = 17,16 respectively, $P > 0.2$), although the mean values of the experimental group

TABLE 5.1 Mean AE and AE_n of Whitechinned Petrels artificially loaded with plastic particles, compared with those of control birds (see Jackson in press).

Treatment	n	AE (%)			AE_n (%)		
		mean	S.D.	range	mean	S.D.	range
Experimental	5	75.1	1.77	72.9–79.5	68.6	3.45	63.6–73.5
Control	5	74.4	1.25	72.6–76.5	68.0	1.80	64.4–69.2

were slightly higher than those of the control group (Table 5.1, Jackson in press). Mean mass loss per bird over each three-day feeding trial was 1.03 ± 2.74 % body mass for the experimental group and 1.22 ± 1.36 % body mass for the control group. There was no significant difference in the absolute amount of mass loss per trial between the experimental and control groups ($U_{5,5} = 13.5$, $P > 0.2$).

No cases of intestinal obstruction were found in more than 400 individuals of 25 species of seabirds examined which contained plastic particles. This included large numbers found dead on beaches. Local ulcerations (<1 cm^2) of the proventriculous lining were found around particularly large pieces of plastic (all user plastic sheets, including part of a yoghurt carton and several asymmetrical fragments) in Great Shearwaters *Puffinus gravis* (3/36), Pintado Petrels *Daption capense* (1/17) and Blue Petrels *Halobaena caerulea* (1/38). In all cases the plastic particles involved were too large to fit into the gizzard. No damage to the gizzard wall was observed.

DISCUSSION

Lifespan of particles

The most recent estimate of the lifespan of plastic particles in seabirds, based on somewhat dubious reasoning (Furness 1985, Chapter 3), is six months (Day *et al*. 1985). The rate of mass loss of the polyethylene pellets fed to the experimental birds allows the first direct estimate of particle life in seabird stomachs. Given a wear rate of 0.7 % by mass per week (the higher of the two values obtained here), the half-life of polyethylene pellets would be almost two years (98 weeks). This assumes that wear is mass dependent, and not a function of surface area, but even assuming a constant mass decay rate, the half-life would be greater than a year (71 weeks). The fact that half the plastic particles were in the proventriculus, where mechanical grinding is presumably less intense than in the gizzard, probably caused an underestimate of the rate of wear. However, assuming a wear rate twice that recorded here (1.4 % by mass per week), still indicates a half-life of almost a year (49 weeks).

These estimates are gross extrapolations, and do not consider the influence of the amount of plastic and other hard items in the gizzard on the rate of wear (Day _et al_. 1985, Chapter 3). However, given the uniform pattern of wear observed for polyethylene pellets in seabird stomachs (Chapter 3) and the lack of other direct measures of wear rates, I feel that the extrapolation is justified. I suggest that the lifespan of polyethylene pellets in seabird stomachs is in excess of one year, and two years is probably a conservative working figure. This suggests that most plastic particles (at least polyethylene pellets) are not eroded away completely in species which accumulate plastic, but are passed onto chicks (cf. Chapter 3). In annual breeding species, only immature birds and breeding birds which fail to reach the chick-rearing stage are likely to completely erode away plastic particles in their stomachs.

Effect on digestive efficiency

The plastic loads fed to the experimental birds were almost three times the mass of the largest "natural" plastic load (579 mg) recorded from 201 Whitechinned Petrels examined (Chapter 2). The presence of half the plastic pellets in the proventriculi of the experimental birds indicates that the birds' gizzards were overloaded with plastic (cf. Chapter 2). However, the plastic loads were less than the largest load recorded from the slightly smaller Great Shearwater (2078 mg, Chapter 2), therefore the artificial loads approximated some of the larger plastic loads expected for a bird the size of a Whitechinned Petrel. The results suggest that large quantities of ingested plastic (at least in the form of industrial pellets) have little effect on the assimilation efficiency of seabirds.

The incidence of ingested plastic particles and similar synthetic objects causing intestinal obstruction is very low; single records have been reported for Puffins *Fratercula arctica* (Parslow & Jefferies 1972), Laysan Albatrosses *Diomedea immutabilis* (Pettit *et al*. 1981) and British Storm Petrels *Hydrobates pelagicus* (Zonfrillo 1985). No instances were recorded among the large number of seabirds examined by myself or by Day (1980) and Day *et al*. (1985). It has been suggested that threads and fibres are more frequently responsible for intestinal obstruction than plastic pellets or fragments, because they can form knotted balls in the gizzard, where they can obstruct the entrance to the intestine (Parslow & Jefferies 1972, Day *et al*. 1985). Whitechinned Petrels contain the largest numbers of threads and fibres of any species sampled off southern Africa, more frequently containing fibre balls than other types of plastic in their gizzards (Chapter 2). Whitechinned Petrels are abundant off southern Africa (Summerhayes *et al*. 1974), yet none has been found stranded with a large fibre ball partially or completely obstructing the entrance to the intestine. It appears that intestinal obstruction by ingested plastic particles is so infrequent in most species as to be an unimportant cause of mortality.

Cuts and ulcerations of the stomach wall caused by ingesting sharp plastic fragments are more frequent than intestinal obstruction (Bourne 1976, Day *et al*. 1985, Zonfrillo 1985, this study). However, it is likely that these injuries are seldom serious, because seabirds frequently ingest hard, sharp prey items which also cause cuts and infections in the stomach wall (Baltz & Morejohn 1976, Bourne & Imber 1982, Fry & Lowenstine 1982).

These results suggest that ingested plastic particles seldom impair the digestive efficiency of seabirds. However, studies of the effect of ingested plastic on foraging efficiency (Day *et al*. 1985) and the role of plastic as a source of toxic chemicals (van Franecker 1985) are urgently required. Further experiments to determine the lifespan of different types of plastic particles in seabird stomachs are warranted.

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CHAPTER 6

THE EFFECTS OF INGESTED PLASTIC PARTICLES ON MEAL SIZE AND GROWTH OF THE DOMESTIC CHICKEN

ABSTRACT

Domestic chickens _Gallus domesticus_ were fed polyethylene pellets to test whether ingested plastic impairs feeding activity. When food was temporally limited, plastic-loaded birds ate less than control birds, apparently as a result of reduced gizzard volume. When given food _ad libitum_, plastic-loaded birds also ate less and grew slower than did control birds. It is concluded that ingested plastic reduces meal size and thus food consumption when plastic reduces the storage volume of the stomach. This may limit the ability of seabirds with large plastic loads to lay down fat deposits, and thus reduce fitness.

INTRODUCTION

Plastic ingestion by seabirds is a widespread phenomenon, with many species accumulating large numbers of plastic particles in their stomachs (Day et al. 1985, Chapter 2). It has been suggested that large plastic loads in seabird stomachs might impair feeding activity by distending the stomach and preventing stomach contraction, thus simulating satiation (Day 1980, Day et al. 1985). This hypothetical mechanism has been invoked to explain lower reproductive success in individuals with large plastic loads than in individuals with small plastic loads (Day 1980, Day et al. 1985, but see Chapter 3), and may account for the negative correlations recorded between plastic load and indicators of body condition (Day 1980, Connors & Smith 1982, Furness 1985a,b, but see Chapter 4). However, there are no tests of the hypothesis.

In order to test whether plastic particles accumulated in a bird's stomach impair feeding, the choice of an appropriate study animal was important. The following attributes were essential: 1) ingested plastic had to be retained in the stomach at least for the duration of the experiment, 2) the animals had to feed themselves, and 3) they had to be tractable in captivity and easy to keep in large numbers. These criteria excluded seabirds which ingest plastic particles. Only gulls are relatively easy to keep and will feed themselves, but gulls regurgitate ingested plastic (Chapter 2). Domestic chickens *Gallus domesticus* were used because they were found to retain plastic particles in their gizzards. Chickens fulfil the other experimental requirements, and the structure and function of the chicken's alimentary tract have been well documented (e.g. Hill 1971a,b). The use of chicks allowed the comparison of growth rate as well as meal size in control and plastic-loaded experimental groups of birds.

METHODS

Two experiments were conducted on male chicks hatched and reared in a heated battery unit designed for nutritional experiments. All birds were individually marked with patagial tags. Birds were given access to water and dry growth meal, but were prevented by wire grids from climbing into the detachable food troughs and scattering food.

Plastic particles fed to experimental birds were disc-shaped virgin polyethylene pellets with a mean mass of 30.11 ± 2.78 mg. Experimental birds were force fed plastic pellets by opening their beaks and dropping the pellets onto the back of their tongues, whereupon the pellets were swallowed.

All masses of birds and food were measured on a top-loading electronic balance to the nearest 0.1 g.

Experiment 1: effect on feeding behaviour

Ten 14-day old chicks ranging in mass between 101.5 and 112.2 g were selected, ranked in order of mass, and then each alternate bird was fed ten plastic pellets. Control and experimental birds were placed in separate cages and were deprived of food for five hours. All birds were reweighed prior to supplying 200 g of food to each cage. Immediately after feeding, instantaneous scans of behaviour (Altmann 1974) were made each minute, recording the number of birds engaged in each of the following activities: feeding, drinking, resting (lying down), and other activities such as comfort behaviour and standing. Observations were continued until all birds were resting. The remaining food was than removed and weighed, and all birds were reweighed. Two birds, one from each group, were sacrificed and dissected to examine stomach contents.

The numbers of birds involved in each activity were summed over five-minute intervals for both experiments. Non-parametric statistics (contingency tables) were used to test for significant differences in the behaviour of experimental and control groups of birds.

Experiment 2: effect on growth rate

Sixty four-day old chicks were divided into six groups of ten birds each and were placed in separate cages. Three groups were experimental birds, and were fed five plastic pellets each on Day 0, then an additional five pellets over the next four days, to give a total load of 10 pellets. The other three groups were controls, and were not fed any plastic pellets. All birds were weighed prior to the experiment, and were reweighed daily during the experiment (except on weekends). Each group of birds was given a preweighed mass of food each day (initially 200 g, increased to 300 g after Day 10), which was removed at the same time the following day and the mass of food remaining was measured. However, on Day 0 food was left in the cages for only six hours.

The experiment terminated on Day 18, when all birds were sacrificed. The lengths of the culmen (to the nearest 0.1 mm), wing (maximum chord) and tarsus (both to the nearest 0.5 mm) were measured. The number of plastic pellets remaining in the experimental birds' gizzards was determined by dissection. Attempts to measure gizzard volumes using the water injection technique of Furness (1985a) failed due to problems with flushing out the gizzard contents. Maximum internal gizzard measurements (circumference and height) of the opened, flattened gizzard were made to the nearest 1 mm (cf. Connors & Smith 1982).

Comparisons of the mean mass, the mean change in mass, and mean measures of body size between experimental and control groups were made using Student's t-tests. The mass of food eaten daily by experimental and control groups was expressed in terms of mean food consumption per bird. A mass-specific measure of food consumption was calculated by dividing the mean food consumption per bird by the interpolated mean mass of birds (i.e. [mean mass on Day (i) + mean mass on Day (i + 1)] / 2). Production was calculated as the mean change in mass divided by the mean amount of food consumed per bird. Contingency tables were used to test whether food consumption and production by control groups was greater than that by experimental groups, or *vice versa*, significantly more frequently than expected by random chance.

RESULTS

Experiment 1

Both experimental and control birds fed continually for the first 25 minutes after food was supplied, following the five-hour fast (Fig. 6.1). The plastic-loaded experimental birds then broke off to drink and some rested, before a second peak in feeding activity occurred 40 minutes after the introduction of food. Few experimental birds fed after 50 minutes, when most birds settled down to rest (Fig. 6.1). Control birds followed the same activity pattern, but continued to feed for ten minutes after experimental birds started drinking, and only ceased feeding after 60 minutes had elapsed (Fig. 6.1).

Feeding activity of experimental birds was 11.8 % less than that of control birds ($X^2 = 16.06$, d.f. = 1, $\underline{P} < 0.001$), and experimental birds ate 14.5 % less food (mean 4.72 g per bird) than did control birds (mean 5.52 g per bird). Mean mass gain during the experiment was less for experimental birds (6.88 ± 1.74 g) than for control birds (7.68 ± 2.26 g), although the difference was not significant (t = 0.63, d.f. = 8). The difference in mean mass gain between experimental and control birds was the same as the difference in mean food consumption (0.8 g). Both birds dissected had crops and gizzards full of food.

Experiment 2

There was no significant difference between the mean mass of experimental and control birds at the start of the experiment (Fig. 6.2, t = 0.13, d.f. = 58). The mean mass of birds in both groups decreased between Day 0 and Day 1, when food was temporally limited. Mean growth increments on all subsequent days were positive (Fig. 6.2), although one experimental bird died on Day 2 of unknown causes. All other birds survived until

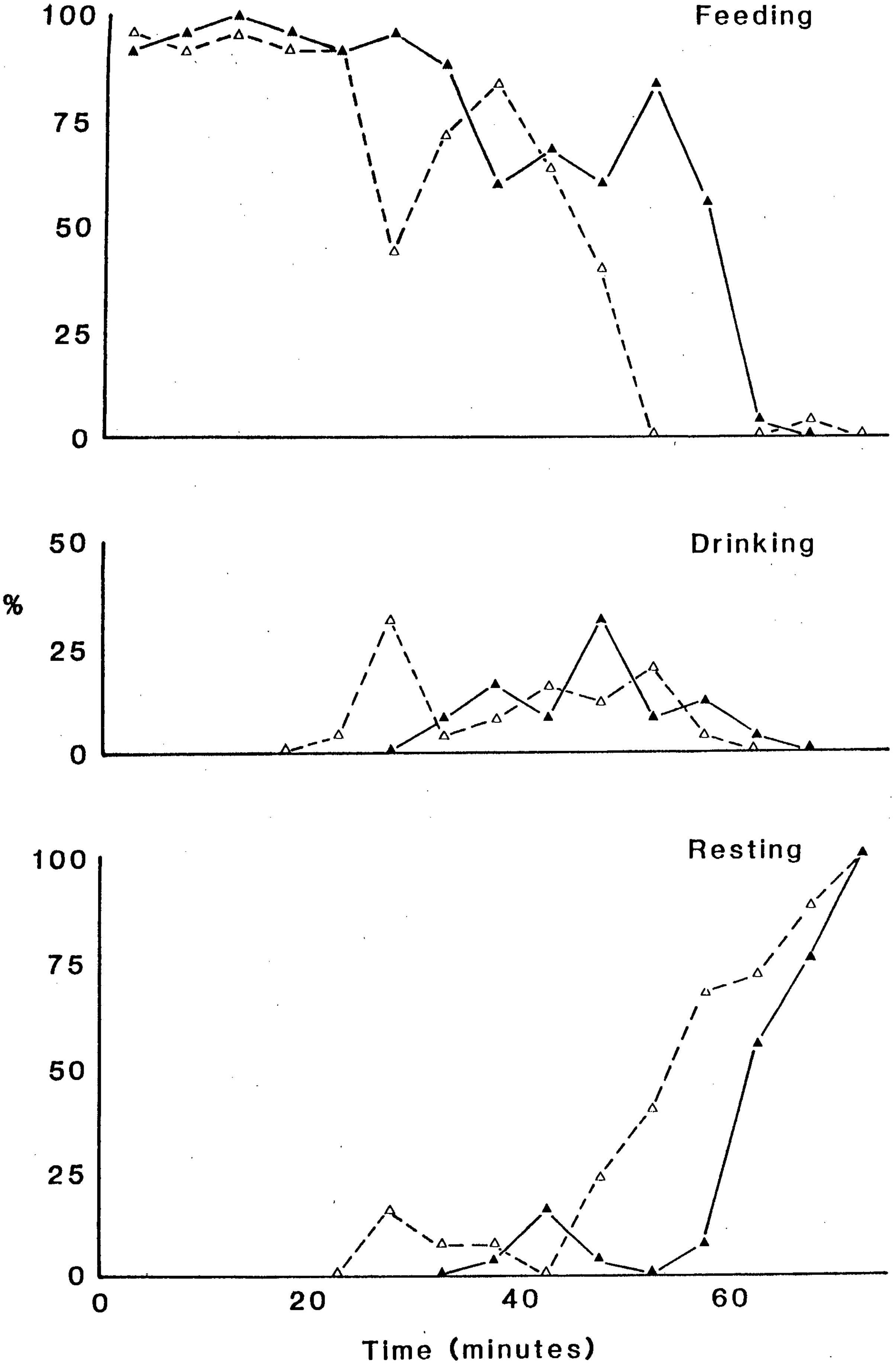

FIGURE 6.1 The proportions of 14-day old chicks feeding, drinking and resting at five-minute intervals after a five-hour fast (see Experiment 1). Open triangles depict experimental birds, closed triangles control birds.

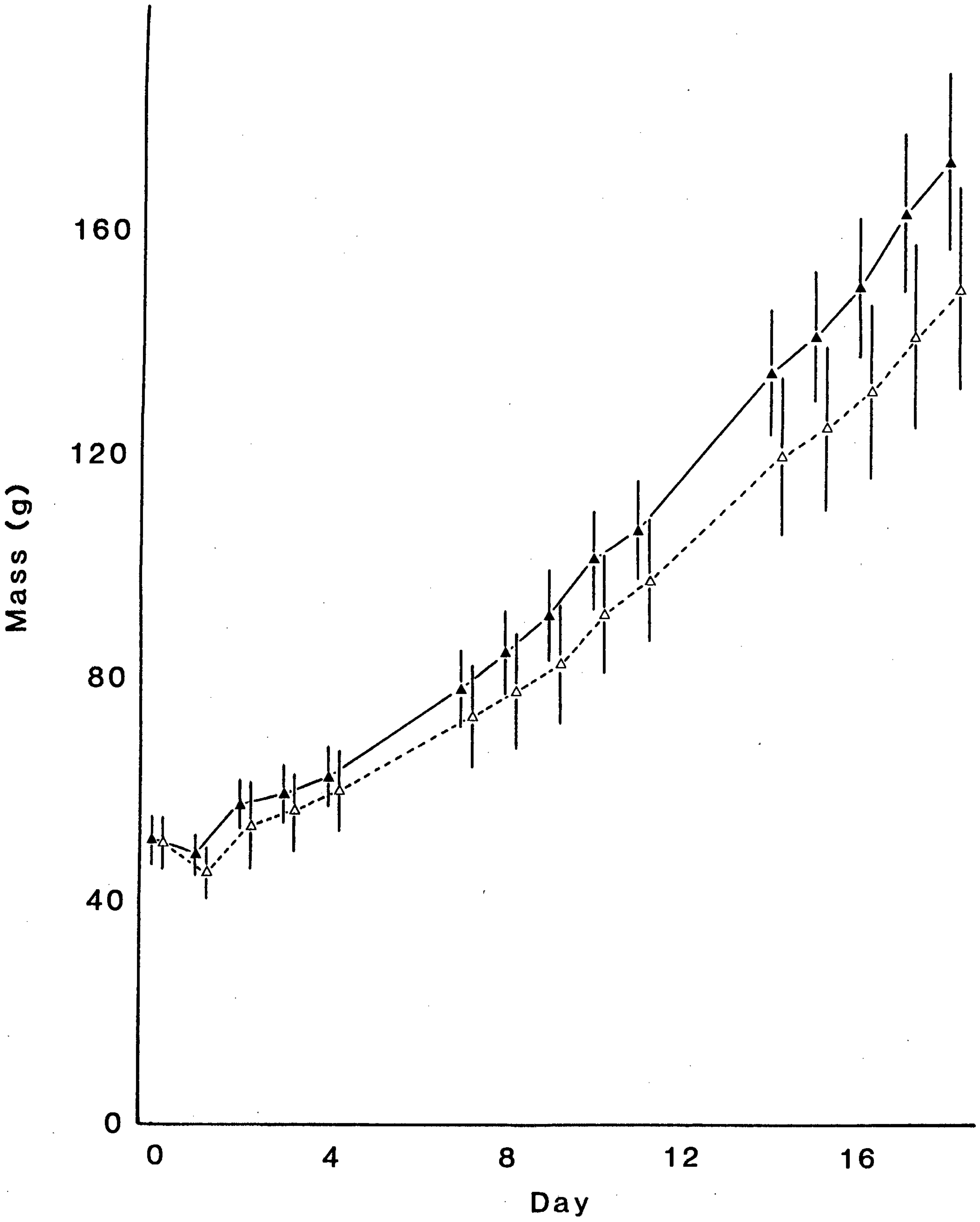

FIGURE 6.2 Growth curves for experimental (open triangles) and control (closed triangles) chicks (see Experiment 2). Mean masses are given ± one standard deviation. Values for experimental birds are shifted slightly to the right.

the end of the experiment.

The mean mass gain of experimental birds during the experiment (100.61 ± 15.27 g) was significantly less than that of control birds (120.95 ± 14.20 g, $t = 5.30$, $\underline{P} < 0.001$). Mean daily mass increments (or three-day increments over weekends) were less for experimental birds than for control birds on 12 out of 14 occasions. The exceptions were on Day 2-3 and Day 3-4. Significant differences in mean growth rate were recorded on eight occasions, all when control birds grew faster than did experimental birds.

Mean food consumption by experimental birds was less than that by control birds on all days except Day 3-4, when experimental birds ate slightly more than did control birds (Fig. 6.3). Mass-specific food consumption by experimental birds was less than that by control birds on 11 out of 14 occasions, significantly more frequently than expected ($X^2 = 4.57$, $\underline{P} < 0.05$). There was no apparent difference between the productivity of the experimental and control groups; mean productivity of control birds was greater than that of experimental birds on eight out of 14 occasions.

On Day 18, when the experiment ended, the mean mass of experimental birds was significantly less than that of control birds (Table 6.1). Experimental birds also were characterized by significantly shorter culmens and tarsi, and smaller internal gizzard dimensions than were control birds (Table 6.1). However, there was no significant difference between the mean wing lengths of birds in the two groups.

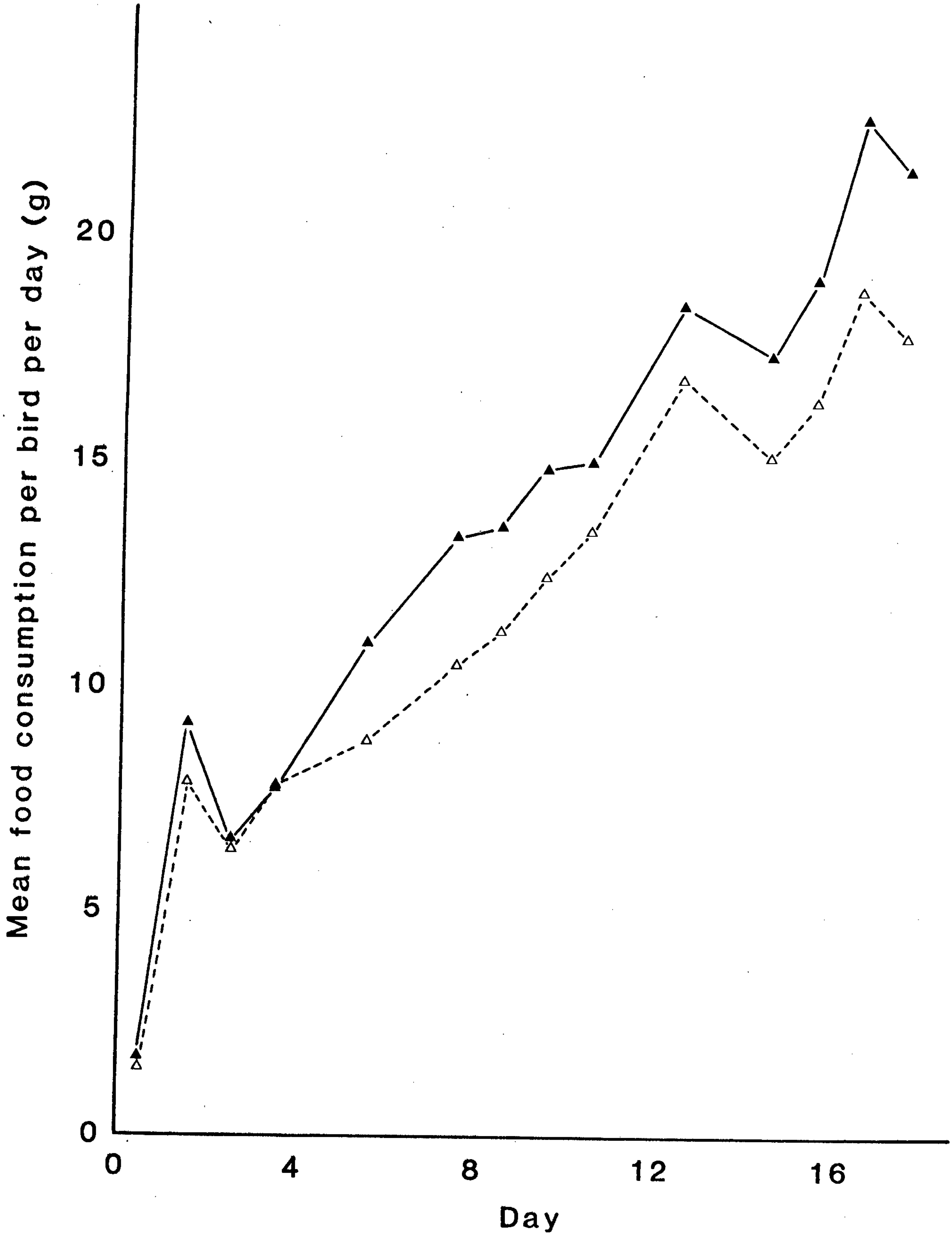

FIGURE 6.3 Mean food consumption of experimental (open triangles) and control (closed triangles) chicks with time (see Experiment 2).

TABLE 6.1 Mean (± 1 SD) masses and linear measurements of experimental and control chickens on Day 18. Significant differences are tested for using Student's t-tests.

Parameter	Experimental (n = 29)	Control (n = 30)	Significance t	 *P* (1-tail)
Mass (g)	149.80 ± 18.27	172.29 ± 15.94	5.05	0.001
Culmen (mm)	12.30 ± 0.47	12.52 ± 0.40	1.94	0.05
Tarsus (mm)	38.84 ± 1.62	40.68 ± 1.15	5.04	0.001
Wing (mm)	106.03 ± 6.68	107.87 ± 7.15	1.02	NS
Gizzard (mm):				
circumference	50.86 ± 2.39	52.33 ± 2.73	2.20	0.05
height	32.97 ± 1.97	34.20 ± 2.26	2.25	0.05

Plastic pellets were recovered from the gizzards of all experimental birds. None was recorded from elsewhere in the birds' digestive tracts. Five birds had lost a single pellet each, giving an overall pellet retention of 98.3 %. The mean mass of pellets was 28.04 ± 3.89 mg, significantly less than that of pellets originally fed to the birds ($t = 7.48$, d.f. = 593, $\underline{P} < 0.001$). This represents a mean mass loss of 2.7 % per week, giving a half-life of 25.3 weeks. Assuming a constant mass decay rate, the lifespan of polyethylene pellets in chicken gizzards would be 37.4 weeks.

DISCUSSION

The mass of plastic fed to experimental birds (approximately 300 mg) is equivalent to large plastic loads in similarly sized seabirds (Chapter 2). The wear rate of polyethylene pellets in chickens was greater than that recorded in Whitechinned Petrels *Procellaria aequinoctialis* (Chapter 5). This probably is related to the more muscular structure of the chicken gizzard compared with that of petrels (Ziswiler & Farner 1972, McLelland 1979).

The passage of food through the anterior section of the chicken's digestive tract is controlled largely by the gizzard (Hill 1971b). After deprivation from food, food boli pass directly to the gizzard until the gizzard is full, whereupon food is diverted into the crop (Hill 1971b). In Experiment 1, the birds' crops and gizzards were filled with food when feeding activity ceased, indicating satiation. The reduction in the experimental birds' gizzard volume caused by plastic particles presumably accounts for the shorter foraging period and smaller meal size of experimental birds compared with those of control birds.

Experiment 1 indicates the disadvantage of ingested plastic particles in temporally limited foraging situations. This disadvantage may be minimal in conditions of continuous food availability. However, experimental birds ate less and grew more slowly than did control birds when given food _ad libitum_ (Experiment 2). This suggests that even under ideal feeding conditions, plastic-loaded birds cannot forage as efficiently as birds free of ingested plastic. Reduced food consumption presumably is responsible for the difference between the growth rates of experimental and control birds in Experiment 2, because productivity did not differ between experimental and control birds. The assimilation efficiency of at least one species of seabird is not affected by ingested plastic particles (Chapter 5).

The results suggest that ingested plastic is likely to impair feeding activity where plastic reduces the food storage volume of the stomach. This assumes that stomach volume does not increase to accommodate a plastic load. This did not occur in the muscular chicken gizzard (Experiment 2), but may be possible in thinner-walled seabird stomachs (Ziswiler & Farner 1972, McLelland 1979). However, most seabirds feed on patchy prey (Brown 1980) which presumably selects for the largest possible stomach volume.

The structure of bird stomachs varies considerably, largely as a function of diet. All seabirds which ingest plastic are primarily carnivorous, and are characterized by smaller, less muscular gizzards than granivores (Ziswiler & Farner 1972, McLelland 1979). Within seabirds, there are two types of stomach morphology: 1) the type found in sphenisciform, pelecaniform and charadriiform seabirds, where the gizzard and the proventriculus together form a single, sac-like organ, and 2) the type restricted to procellariiform seabirds, where the gizzard is a distinct organ separated from the proventriculus by a narrow, angled isthmus (Matthews 1949, Mclelland 1979, Furness 1985a). The stomach structure of albatrosses _Diomedea_ spp. and giant petrels _Macronectes_ spp. is intermediate between these two types (pers. obs).

The food storage volume of the stomach is reduced by ingested plastic in seabirds with the sac-like, single-chambered stomach morphology. However, many of these species regularly regurgitate plastic along with other indigestible prey remains (Chapters 2 & 3). Certain auks and phalaropes are the only species with this stomach type which apparently do not regurgitate indigestible stomach contents and are characterized by high levels of plastic ingestion (Day _et_ _al_. 1985, Chapters 2 & 3). The feeding activity of these species probably is impaired by large loads of ingested plastic.

In procellariiform seabirds, the group with the highest incidence of ingested plastic (Day _et_ _al_. 1985, Chapter 2), most plastic is stored in the gizzard (Chapter 2). The procellariiform gizzard is small and apparently does not store food (Ziswiler & Farner 1972). It is not clear whether plastic in the gizzards of procellariiform seabirds impairs feeding activity. However, in individuals with large plastic loads, plastic also occurs in the proventriculus (Chapter 2), the major food storage organ (Matthews 1949, McLelland 1979).

Until direct tests of the effect of ingested plastic on the feeding behaviour of seabirds are made, it must be assumed that large loads of ingested plastic impair feeding by reducing meal size. This may limit the accumulation of fat reserves essential for reproduction, migration and moulting (Connors & Smith 1982). Small fat reserves in seabirds with large plastic loads may also cause increased mortality during periods of adverse weather when foraging is curtailed.

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CHAPTER 7

PLASTIC INGESTION AND POLYCHLORINATED BIPHENYLS IN SEABIRDS: IS THERE A RELATIONSHIP?

ABSTRACT

Multivariate analyses were used to assess the independent determinants of chlorinated hydrocarbon loads in the fat and eggs of breeding female Great Shearwaters *Puffinus gravis*. The amounts of several different chlorinated hydrocarbons, including polychlorinated biphenyls (PCBs), DDE, DDT and dieldrin, were positively intercorrelated in adult fat tissue and in eggs. This suggests that individual differences in non-breeding range, diet and age are major determinants of pollutant levels within a species. The mass of ingested plastic was positively correlated only with PCBs, a group of chemicals commonly found in plastics. It is probable that seabirds assimilate PCBs and other toxic chemicals from ingested plastic particles.

INTRODUCTION

Polychlorinated biphenyls (PCBs) have become ubiquitous pollutants of marine food webs over the last twenty years, and are particularly prevalent in seabirds (see Bourne 1976, Ohlendorf *et al*. 1978 for reviews). Although adverse effects from PCBs are not always apparent (Harris & Osborn 1981), PCBs have been demonstrated to have many deleterious effects on birds, including reduced breeding success, increased risk of disease, and altered hormone levels, as well as direct mortality (e.g. Friend & Trainer 1970, Peakall & Peakall 1973, Peakall 1975, Bourne 1976, Jefferies & Parslow 1976, Gilbertson & Fox 1977, Ohlendorf *et al*. 1978, Tori & Peterle 1983).

It generally is assumed that PCBs enter birds via their prey, the high levels in seabirds resulting from progressive accumulation between trophic levels (e.g. Bourne 1976, Ohlendorf *et al*. 1978, Newton 1979). However, PCBs are used in the manufacture of many types of plastics (Gregory 1978), and it has been suggested that plastic particles ingested by seabirds and retained in the stomach for some time might be a direct source of PCBs (and other toxic chemicals) to seabirds (Day 1980, Pettit *et al*. 1981, Bourne & Imber 1982, van Franecker 1985). There is no published evidence to support this hypothesis, and experiments to determine the importance of ingested plastics as sources of toxic chemicals to seabirds are considered a priority (van Franecker 1985).

This study compares the amount of PCBs in the fat and eggs of Great Shearwaters *Puffinus gravis* with their plastic loads and with levels of other chlorinated hydrocarbon (organochlorine) pollutants. Great Shearwaters are particularly suitable study animals, because they contain high levels of ingested plastic, a large proportion of which is manufactured (user) plastic (Chapter 2), the type with the highest levels of PCBs and other toxic chemical additives (Gregory 1978, van Franecker 1985).

METHODS

Twenty female Great Shearwaters and their eggs were collected within two days of laying eggs at Gough Island (40 21S, 9 53W), South Atlantic Ocean, between 9 and 12 November 1984. The eggs were wrapped in aluminium foil and refrigerated for later analysis. Fat samples collected from abdominal fat deposits were wrapped in aluminium foil and frozen. The mass of the bird less stomach contents, egg mass (both to the nearest 1 g), and the mass of abdominal fat reserves (to the nearest 0.1 g) were recorded within two hours of collection. Plastic loads were determined by dissecting out the stomach (proventriculus and gizzard) and collecting all plastic particles. The particles were washed, oven dried at 30^{o} C, and then weighed to the nearest 0.1 mg. Plastic load was taken to be the total mass of plastic in each bird at the time of collection.

The chlorinated hydrocarbon pollutants, PCBs (as Aroclor 1260), pp'DDE, pp'DDT and dieldrin, were extracted from the fat and egg samples, passed through a clean-up column, and their concentrations measured using gas chromatography (see Gardner et al. 1985 for further details). Two adult fat samples were contaminated and were not included in the analyses. Due to the variability in the mass of adult fat reserves, an index of chlorinated hydrocarbon body load was used in preference to measures of concentration (cf. Ohlendorf et al. 1978). The index of body load was determined by multiplying the concentration of a given pollutant by the mass of abdominal fat reserves. The mass of abdominal fat reserves was assumed to be indicative of total fat reserves (e.g. Thomas & Mainguy 1983), which is supported by the high correlation between the mass of abdominal fat reserves and bird mass (Chapter 4). The small variation in egg mass did not warrant correction for chlorinated hydrocarbon loads.

Stepwise multiple correlation analyses were performed using Statpro (Imhoff & Hewett 1983) in order to assess the independent influences of bird mass, egg mass, the mass of abdominal fat reserves, plastic loads and other chlorinated hydrocarbon loads on the PCB load of female Great Shearwaters and the concentration of PCBs in their eggs. Multivariate analyses were also used to determine the parameters independently influencing each of the other chlorinated hydrocarbons measured, to assess the effect of high intercorrelations between pollutants. Analyses were terminated when no additional variable was correlated at below the 0.05 significance level.

RESULTS

Plastic was present in 19 (95 %) female Great Shearwaters sampled, and there was large variation in plastic loads and chlorinated hydrocarbon concentrations in fat tissue and eggs (Table 7.1). The concentration of dieldrin in eggs was too low

TABLE 7.1 Mean values, standard deviations and ranges of pollutant loads in breeding female Great Shearwaters and their eggs.

Parameter	Mean	S.D.	Range	n
Plastic mass (mg)	295.0	381.9	0.0-1441.0	20
Adult concentrations (ug.kg^{-1} fat)				
PCBs	2407	1305	800-5895	18
DDE	659	405	0-1425	18
DDT	207	200	0-740	18
Dieldrin	76	62	0-223	18
Egg concentrations (ug.kg^{-1} whole egg)				
PCBs	535	618	93-2549	20
DDE	119	104	20-471	20
DDT	5	6	0-20	20

for accurate determination. A negative correlation between PCB concentration in adult fat tissue and the mass of abdominal fat ($\underline{r} = -0.439$, d.f. = 16, one-tailed $\underline{P} < 0.05$) necessitated the calculation of indices of adult chlorinated hydrocarbon loads.

There were no significant correlations between the chlorinated hydrocarbon loads or concentrations in adult fat tissue and the chlorinated hydrocarbon concentrations in eggs. However, several of the chlorinated hydrocarbon loads in adult fat tissue were positively intercorrelated, as were all the chlorinated hydrocarbon concentrations in eggs (Table 7.2). Two pairs of chlorinated hydrocarbon concentrations in adult fat tissue also were positively intercorrelated, but to a lesser degree than the correlations of pollutant loads. This suggests that the observed correlations between different chlorinated hydrocarbons are not an artefact of variable masses of fat deposits.

The high degree of correlation between different chlorinated hydrocarbon loads in adult fat tissue dominated the results from the multivariate analyses. The magnitudes of all chlorinated hydrocarbon loads were best correlated with other chlorinated hydrocarbon loads (Table 7.3). The mass of ingested plastic was not significantly correlated with any variable, but was best correlated with adult PCB load ($\underline{r} = 0.33$). However, residual variation in adult PCB load was significantly correlated (positively) with plastic, and the residual variation in adult DDE load was negatively correlated with plastic (Table 7.3).

The chlorinated hydrocarbon concentrations in eggs also were best correlated with the concentrations of other chlorinated

TABLE 7.2 Simple linear correlation coefficients (r) between chlorinated hydrocarbon loads in Great Shearwater adults (A) and concentrations in their eggs (B). Significance level is denoted by the number of symbols (+), 1 = $P < 0.05$, 3 = $P < 0.001$.

A - Adult loads	PCBs	DDE	DDT	Dieldrin
PCBs	1.000	0.769	0.286	0.229
DDE	+++	1.000	0.497	0.297
DDT		+	1.000	0.503
Dieldrin			+	1.000

B - Egg concentrations	PCBs	DDE	DDT
PCBs	1.000	0.731	0.842
DDE	+++	1.000	0.727
DDT	+++	+++	1.000

TABLE 7.3 The independent parameters influencing chlorinated hydrocarbon loads and concentrations in breeding female Great Shearwater fat reserves and in their eggs.

Dependent variable	Independent variable	Sign	Cumulative r^2
Adult PCB load	Adult DDE load	+	0.591
	Plastic load	+	0.700
Adult DDE load	Adult PCB load	+	0.591
	Adult DDT load	+	0.674
	Plastic load	–	0.740
Adult DDT load	Adult dieldrin load	+	0.253
	Adult DDE load	+	0.385
Adult dieldrin load	Adult DDT load	+	0.253
Egg PCB concentration	Egg DDT concentration	+	0.708
	Egg DDE concentration	+	0.764
Egg DDE concentration	Egg PCB concentration	+	0.535
	Abdominal fat mass	–	0.665
Egg DDT concentration	Egg PCB concentration	+	0.708
	Abdominal fat mass	–	0.810

hydrocarbons (Table 7.3). The mass of abdominal fat was negatively correlated with the concentrations of DDE and DDT in eggs.

DISCUSSION

The mean concentrations of PCBs and DDE in Great Shearwater eggs sampled in 1984 are almost twice those recorded from eggs of the same species collected at Gough Island in 1979 (n = 3, Gardner *et al*. 1985), although neither difference was significant due to the small sample sizes. No apparent change in the mean DDT concentrations in Great Shearwater eggs occurred between 1979 and 1984.

The lack of significant positive correlations between chlorinated hydrocarbon concentrations in eggs and those stored in adult fat tissue is not unexpected, because a variable proportion of stored chlorinated hydrocarbons are removed from the body during egg laying (Vermeer & Reynolds 1970, Dahlgren *et al*. 1971, Subramanian *et al*. 1986). Chlorinated hydrocarbons found in eggs are derived from both direct intake in food during egg-formation and from body stores (Newton 1979, Harris 1984). The negative correlation between abdominal fat mass and the concentrations of DDE and DDT in Great Shearwater eggs presumably results from the greater concentration of chlorinated hydrocarbons in the fat of birds with small fat reserves. The use of the same amount of stored energy reserves (fat) during egg formation would be accompanied by the release of greater amounts of chlorinated hydrocarbons in birds with small fat reserves than in those with large reserves (Bogan & Newton 1977, Subramanian *et al.* 1986).

Positive intercorrelations between the loads of different chlorinated hydrocarbons in bird tissues have been widely recorded (e.g. Newton & Bogan 1974, Blus 1982, Norheim & Kjos-Hanssen 1984). These intercorrelations suggest that differences between individuals are important in determining the magnitude of chlorinated hydrocarbon loads in seabirds. Differences in non-breeding range, diet or bird age could result in inter-individual differences in a broad suite of pollutants in seabirds, assuming that pollutants are concentrated around source areas (for non-breeding range, e.g. Norheim & Kjos-Hanssen 1984), vary between prey types (for diet), or are accumulated with age (e.g. Subramanian *et al.* 1986).

The positive correlation between PCBs and plastic loads in Great Shearwaters may also result from differences between individuals; "dirty" birds, characterized by high levels of both chlorinated hydrocarbons and ingested plastic, differing from "clean" birds as a result of different lifestyles (non-breeding areas and/or diet). Age differences presumably would not result in correlations between plastic and chlorinated hydrocarbons, because plastic is not accumulated with age, and levels are highest in immature birds (Chapter 3).

If the correlation between PCBs and plastic loads was an effect of differences between the lifestyles of individuals, plastic should be positively correlated with the other chlorinated hydrocarbons, DDE, DDT and dieldrin. No such correlations were detected, therefore it is likely that some PCBs are derived from ingested plastic particles. An alternative explanation for this result is that plastics, like PCBs, are derived primarily from industrial areas, whereas DDE and DDT are derived primarily from agricultural areas. However, until further tests are made, it must be assumed that ingested plastic is a source of PCBs, and that it contributes significantly to the total body load of PCBs in Great Shearwaters.

The PCB loads recorded from Great Shearwaters are not large compared with those from certain seabirds in the northern hemisphere (e.g. Ohlendorf et al. 1978). Ingested plastic is unlikely to be a major contributor to the PCB loads of birds with large chlorinated hydrocarbon loads, because the concentration of PCBs in most plastic particles is low (Gregory 1978). However, plastics contain many other additives, some of which are toxic (van Franecker 1985), and the synergistic effects with other pollutants are unknown. This study presents the first evidence to suggest that seabirds assimilate chemicals from the plastic particles in their stomachs. Confirmation of this pathway for potentially dangerous pollutants could be achieved by identifying specific plastic-associated chemicals within seabird tissues.

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SYNTHESIS

This section attempts to link the preceeding chapters into a cohesive unit, summarizing the main findings of the thesis. Statements are not referenced here if they are substantiated elsewhere in the thesis.

Plastic particles at sea and in seabirds

Floating plastic particles are abundant sea-surface pollutants. Off southern Africa, foamed plastics are the most numerous type of particle, but industrial pellets and fragments of manufactured ("user") articles contribute most of the mass of floating plastic. The dispersion of plastic particles is clustered, with particles aggregated at local convergence zones. However, large-scale temporal and spatial distribution patterns can be detected which are related to distance from source areas and transport mechanisms at sea.

Plastic particles frequently are ingested by seabirds, and were recorded for 36 of 60 seabird species sampled primarily off southern Africa. This brings the number of species which have been recorded to ingest plastic worldwide to 69. The incidence of ingested plastic is highest in procellariiform seabirds, and some phalaropes and auks. Levels of plastic ingestion in some sub-Antarctic petrels are as high as the highest levels recorded elsewhere in the world.

The majority of plastic particles ingested by seabirds are industrial pellets (almost all polyolefins) and user fragments, although some species ingest large numbers of fibres. The proportions in which industrial pellets and user fragments occur in different species vary largely as a function of body size, which affects the size of particles ingested. Industrial pellets largely are restricted to masses of between 5 and 50 mg, whereas user fragments of all masses are found. Foamed plastics seldom are found in seabird stomachs, possibly because their low density confers little resemblance to prey species. However, foamed plastics are soft and may be less persistent in seabird stomachs than are other plastic-types.

Seabirds have limited value as indicators of plastic pollution at sea. Large scale distribution patterns of plastic pollution can be inferred; e.g. examining birds restricted to Antarctic waters shows that at least some plastic particles have penetrated south of the Antarctic Polar Front, but that industrial pellets are scarce in Antarctic waters. However, the value of seabirds as indicators of plastic pollution at a finer scale is compromised by their great mobility and their non-random sampling of the environment.

Factors affecting plastic ingestion by seabirds

Seabirds encounter floating plastic particles while foraging. The majority of plastic particles probably is ingested directly by seabirds as a result of particles being misidentified as potential prey items. This hypothesis is supported by two observations: 1) the frequencies with which plastic colour-types occur in seabird stomachs differ significantly from those in the environment for all species tested, and 2) plastic particles which do not float in seawater rarely are found in seabird stomachs. The first point suggests that plastic seldom is ingested accidentally with prey items, whereas the second suggests that plastic seldom is ingested as a result of eating prey already containing ingested plastic (secondary ingestion). There are few records of fish and squid containing ingested plastic, and plastic ingestion has not been reported for crustaceans, thus secondary ingestion by seabirds probably is important only in species which prey on other seabirds (e.g. Subantarctic Skua *Catharacta antarctica*). However, secondary ingestion through contaminated fish may be important locally in systems polluted with polystyrene pellets which sink and occasionally are eaten by small fish (Hays & Cormons 1974, Kartar *et al*. 1976).

The incidence of plastic in seabirds grouped by diet class and foraging technique is consistent with the hypothesis that plastic particles are ingested primarily as a result of confusion with prey items; plastic is most frequent in dietary generalists (omnivores) which presumably have broad prey-identification criteria, and plastic is most frequent in species which feed at or near the sea-surface. Three factors thus affect the ingestion of plastic particles by seabirds: 1) the degree of dietary specificity, 2) foraging technique, and 3) the density of plastic particles at sea in the foraging area.

Small seabird species tend to have a higher incidence of ingested plastic than do large species. This may be related to generally broader prey-identification criteria in small species, because small species are less selective of plastic colour types than are large species.

The incidence of ingested plastic in seabird stomachs is a function of the rate of plastic ingestion and the rate of plastic loss. In many seabird species (e.g. giant petrels, cormorants, gulls, skuas, terns and perhaps albatrosses), indigestible stomach contents are regurgitated periodically as pellets. Ingested plastic particles are incorporated in these pellets, thus the chances of finding plastic in the stomachs of these species are small unless the rate of plastic ingestion is high. By comparison, species which apparently do not regurgitate indigestible stomach contents (e.g. most procellariiform seabirds and perhaps phalaropes and auks), accumulate plastic particles in their stomachs, giving a large probability of recording ingested plastic, provided plastic is ingested at least occasionally. Variable regurgitation rates interact with variable plastic ingestion rates to produce the taxonomic patterns of plastic incidence summarized in Chapter 2.

Plastic flux through seabird populations

Once ingested, plastic particles follow one of two pathways: they are regurgitated or they are eroded in the stomach (gizzard) until they are small enough to enter the intestine and can be excreted. Most seabirds, with the exception of gulls and probably skuas, do not excrete particles larger than 0.1 mm in diameter.

Seabird species which regularly regurgitate pellets of indigestible matter lose most, if not all, ingested plastic particles in pellets. These species usually have short plastic residence times in their stomachs, and do not accumulate large plastic loads. Species which do not regurgitate pellets only lose ingested plastic via erosion and excretion, or in regurgitated meals fed to chicks.

The exact rate of wear of plastic particles within seabird stomachs is unknown, and probably is highly variable. However, experimental and circumstantial evidence suggests that at least some plastic types take between one and two years to erode away. This slow wear rate causes the accumulation of plastic loads in species which do not regurgitate pellets, given even a low rate of plastic ingestion.

Many species of breeding seabirds feed a large proportion of their accumulated plastic loads to their chicks along with regurgitated meals. This inter-generation transfer of plastic particles has two important consequences: 1) plastic loads fluctuate on an annual cycle in successful breeding birds, being highest prior to chicks hatching, and lowest after chick feeding ceases, and 2) plastic loads are higher in immature and failed breeding birds than they are in successful breeding birds. Thus plastic loads are likely to be highest in immature birds of species which do not regurgitate pellets of indigestible matter.

Effects of ingested plastic on seabirds

Ingested plastic has been postulated to have three effects on seabirds: 1) to obstruct or injure the digestive tract, 2) to impair foraging and/or digestive efficiency, and 3) to release toxic chemicals which are absorbed by birds. These effects pertain primarily to seabirds which accumulate plastic loads. Species which regurgitate plastic in pellets probably suffer few adverse effects from plastic ingestion.

To date, most attempts to demonstrate an adverse effect of ingested plastic have correlated plastic loads with three indices of body condition: body mass, fat reserves and reproductive success. Weak negative correlations between plastic loads and body mass, and between plastic loads and fat reserves have been reported. However, these correlations may have resulted from differences in the age and reproductive status of the birds sampled. Larger plastic loads in non-breeding birds than in breeding birds are best explained in terms of inter-generation transfer of plastic particles.

The only impact ingested plastic has been documented to have on seabirds is occasional injury and obstruction of the digestive tract. Examination of over 400 birds of 25 species revealed no instances of intestinal obstruction (despite many birds containing fibre balls) and only a few, minor injuries of the proventriculus wall. This effect of ingested plastic is thus probably of little consequence, although occasional mortality caused by intestinal obstruction occurs. However, intestinal obstruction by plastic objects may be a significant mortality factor for certain species of marine turtles (Balazs 1985).

Experiments on Whitechinned Petrels Procellaria aequinoctialis suggest that ingested plastic has no effect on assimilation efficiency. However, experiments on domestic chickens showed that ingested plastic reduces meal size and growth rate, apparently by reducing the food storage volume of the stomach. Although further experiments on seabirds are required, this effect probably limits the rate of fat deposition in seabirds, thus reducing their ability to breed, moult and migrate successfully, and to survive temporary food shortages. Large intra-specific differences may mask this effect when attempting to correlate plastic loads with indices of body condition.

Evidence from Great Shearwaters Puffinus gravis suggests that polychlorinated biphenyls (PCBs) and presumably other toxic additives found in certain plastics are absorbed by seabirds from ingested plastic particles. Verification of this pathway is required.

Conclusions

Plastic ingestion by seabirds is a frequent and widespresd phenomenon. The incidence of ingested plastic in seabirds has been increasing over the last 25 years, and presumably will continue to increase for some time to come. The only way to reduce plastic ingestion is by reducing the density of plastic particles at sea. Although local reductions in plastic pollution can be achieved (Kartar et al. 1976), the population of plastic particles affecting seabirds ultimately derives from a multitude of diffuse sources which cannot be controlled practically. Recent legislation to ban dumping of plastic at sea (Anon. 1986) is welcomed, but is all but impossible to enforce.

The main question remains, how important are the effects of ingested plastic on seabirds? At the level of the individual, it is likely that large plastic loads reduce fitness and increase the risk of mortality by limiting the rate at which energy reserves can be accumulated. Similarly, intestinal obstruction causes occasional mortality through starvation. PCBs and other toxic additives derived from plastics also may reduce fitness. At the level of the population, however, it is less clear whether the ingestion of plastic particles has any serious effects on seabirds. The direct mortality and/or reduced reproductive rate caused by ingested plastic may be countered to some extent by increased survivorship at other demographic stages (Dunnett 1982, Bourne 1983). This likelihood is enhanced by the great intra-specific differences in the incidence of plastic in seabirds. Detailed studies of the population dynamics of species characterized by large plastic loads are necessary before conclusions can be reached about the impact of ingested plastic on seabird populations.

In addition, further investigations into the effects of ingested plastic on seabirds are required, particularly as regards the toxicity of various additives used in the manufacture of plastics. Continued monitoring of the levels of plastic ingestion by seabirds is warranted, with particular attention to beached birds which are most likely to demonstrate serious effects of plastic ingestion.

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APPENDIX 1

THE USE OF SUBANTARCTIC SKUA PELLETS AS INDICATORS OF PLASTIC POLLUTION IN SEABIRDS

ABSTRACT

Plastic particles were found in 108 (22 %) of 483 Subantarctic Skua *Catharacta antarctica* pellets which contained remnants of a single identifiable avian prey item, collected at Inaccessible Island, South Atlantic Ocean. Plastic was associated with seven petrel prey species. Comparisons with plastic particles found in these species at nearby Gough Island showed that small particles were under-represented in skua pellets. This caused underestimates of plastic loads in prey species, particularly in small birds (storm petrels). Other biases resulting from the use of skua pellets as indicators of plastic pollution in seabirds are discussed.

INTRODUCTION

Plastic particles frequently are ingested by seabirds and accumulate in the stomachs of some species, notably petrels Procellariidae (Day et al. 1985, Chapter 2). Although the physiological effects of ingested plastic are not well understood (Furness 1985a,b, van Franecker 1985), there is a need to monitor the levels of plastic ingestion in seabirds (Day et al. 1985, Furness 1985b). The stomach morphology of petrels precludes the non-destructive sampling of gizzard contents (Ryan & Jackson 1986), where most plastic is found. This necessitates sampling by dissecting petrels either collected for the purpose or found dead (e.g. beached birds). Both techniques have their drawbacks (Bond 1971, Bourne & Imber 1982, Chapter 2). A potentially non-destructive sampling technique is to use Subantarctic Skua Catharacta antarctica pellets as indicators of plastic loads in seabirds.

Subantarctic Skuas are widespread throughout the Southern Ocean, breeding at almost all sub-Antarctic islands (Watson et al. 1971). Their diet is diverse, varying between individuals and from place to place, but often includes large numbers of burrowing petrels (Jones 1980, Sinclair 1980, Adams 1982, Schramm 1983, Fraser 1984). These are swallowed whole, or dismembered, and all but the sternum and wings are eaten (Sinclair 1980, Fraser 1984). Indigestible remains are regurgitated subsequently as a pellet. Plastic particles found within skua pellets have been attributed to the remains of the petrel species associated with them in the pellet (Bourne & Imber 1982). This chapter considers the value of skua pellets as indicators of plastic loads in petrels by comparing the plastic found in skua pellets with that found in prey species.

METHODS

Skua pellets were collected at Inaccessible Island (37 15S, 12 30W), South Atlantic Ocean, between October 1982 and January 1983. For each pellet, prey remains were identified by species and any plastic particles present were collected. Pellets containing the remains of two or more avian prey items were discarded. The incidence of plastic in petrels and other seabirds was determined by dissecting out the stomach contents of birds collected or killed by misadventure at Gough Island (40 21S, 9 53W), South Atlantic Ocean, between October 1982 and November 1985 (Furness 1985a, Chapter 2). Gough Island is 400 km southeast of Inaccessible Island, and the seabirds breeding at the two islands are similar at the subspecific level (Clancey 1981). Scientific names of birds mentioned in the text are given in Table A.1.

Two types of plastic were recognized: industrial pellets and fragments of user items (cf. van Franecker 1985). Each plastic particle was colour coded while wet into one of nine colour categories (Chapter 2). The particles were oven dried at 30^{o} C and weighed to the nearest 0.1 mg.

Non-parametric statistics (contingency tables, log-likelihood ratios and Mann-Whitney U-tests) were used to test for differences between the frequency of occurrence, size (mass) and colours of plastic particles found in seabirds and skua pellets.

Comparisons were based primarily on species for which large samples were available, namely Broadbilled Prions and Whitefaced and Whitebellied Storm Petrels. However, no colour or plastic-type data were available for Whitebellied Storm Petrels collected at Gough Island.

RESULTS

Plastic particles were found in 108 (22 %) of 483 Subantarctic Skua pellets, and in association with seven avian prey species, all Procellariidae (Table A.1). No plastic particles were found in association with Rockhopper Penguin, Great Shearwater or terrestrial birds' remains in skua pellets. The frequency of occurrence of plastic particles was significantly lower in pellets containing Whitefaced Storm Petrels at Inaccessible Island than in the same species collected at Gough Island ($X^2 = 24.00$, d.f. = 1, $P < 0.001$). The same was true for Whitebellied Storm Petrels, but the difference was marginally significant ($G = 2.90$, d.f. = 1, $P < 0.1$).

Skua pellets containing Common Diving Petrel remains had a higher frequency of occurrence of plastic than did collected birds, but the difference was not significant ($G = 1.10$, d.f. = 1). The frequency of occurrence of plastic particles in Broadbilled Prions did not differ between skua pellets and collected birds ($X^2 = 0.95$, d.f. = 1), but the mass of plastic per bird containing plastic was significantly greater in skua pellets than in collected birds ($U_{27,35} = 752$, $P < 0.001$).

In skua pellets containing the remains of Broadbilled Prions and Whitefaced and Whitebellied Storm Petrels, small plastic

TABLE A.1. The frequency of occurrence of ingested plastic particles in petrels and other birds collected at Gough Island (Furness 1985a, Chapter 2) and Subantarctic Skua pellets containing their remains at Inaccessible Island.

Species	Collected seabirds ratio with plastic	Collected seabirds %	Skua pellets ratio with plastic	Skua pellets %
Great Shearwater *Puffinus gravis*	30:34	88	0:3	0
Whitefaced Storm Petrel *Pelagodroma marina*	21:24	88	31:96	32
Antarctic Prion *Pachyptila desolata*	52:88*	59	1:2	50
Whitebellied Storm Petrel *Fregetta grallaria*	5:13	38	30:171	18
Broadbilled Prion *Pachyptila vittata*	39:133	29	36:102	35
Softplumaged Petrel *Pterodroma mollis*	3:23	13	4:18	22
Little Shearwater *Puffinus assimilis*	1:15	7	1:5	20
Common Diving Petrel *Pelecanoides urinatrix*	1:44	2	5:80	6
Rockhopper Penguin *Eudyptes chrysocome*	1:132	1	0:4	0
Inaccessible Rail *Atlantisia rogersi*			0:1	0
Tristan Thrush *Nesocichla eremita*			0:1	0

* Birds collected off South Africa

particles were under-represented compared with the range of particle sizes found in collected birds (Fig. A.1, $X^2 = 24.65$ (d.f. = 5), 174.23 (4), 16.57 (1) respectively, all $P < 0.001$). However, the size spectrum of plastic particles from skua pellets containing Broadbilled Prion remains was influenced less than those containing the remains of either of the storm petrels. The bias against small particles in skua pellets affected the proportions of types of plastics in Whitefaced Storm Petrels, because most small particles found in this species were user fragments (Chapter 2). Skua pellets containing Whitefaced Storm Petrels' remains had significantly more industrial pellets (155:209) than did Whitefaced Storm Petrels collected at Gough Island (19:46, $X^2 = 18.78$, d.f. = 1, $P < 0.001$). Broadbilled Prions contained larger particles than did storm petrels, with roughly similar proportions of plastic types throughout the size spectrum (Chapter 2). There was no significant difference in the proportions of plastic types between collected Broadbilled Prions and skua pellets containing their remains ($X^2 = 0.22$, d.f. = 1).

There were no significant differences in the colour frequencies of industrial pellets or user fragments in skua pellets and collected petrels (G = 5.56, 3.93; d.f. = 4,6 for Whitefaced Storm Petrels, G = 4.82, 6.31; d.f. = 5,7 for Broadbilled Prions).

DISCUSSION

The daily regurgitation of pellets by <u>Catharacta</u> skuas (Furness & Hislop 1981), coupled with the predominantly land-based

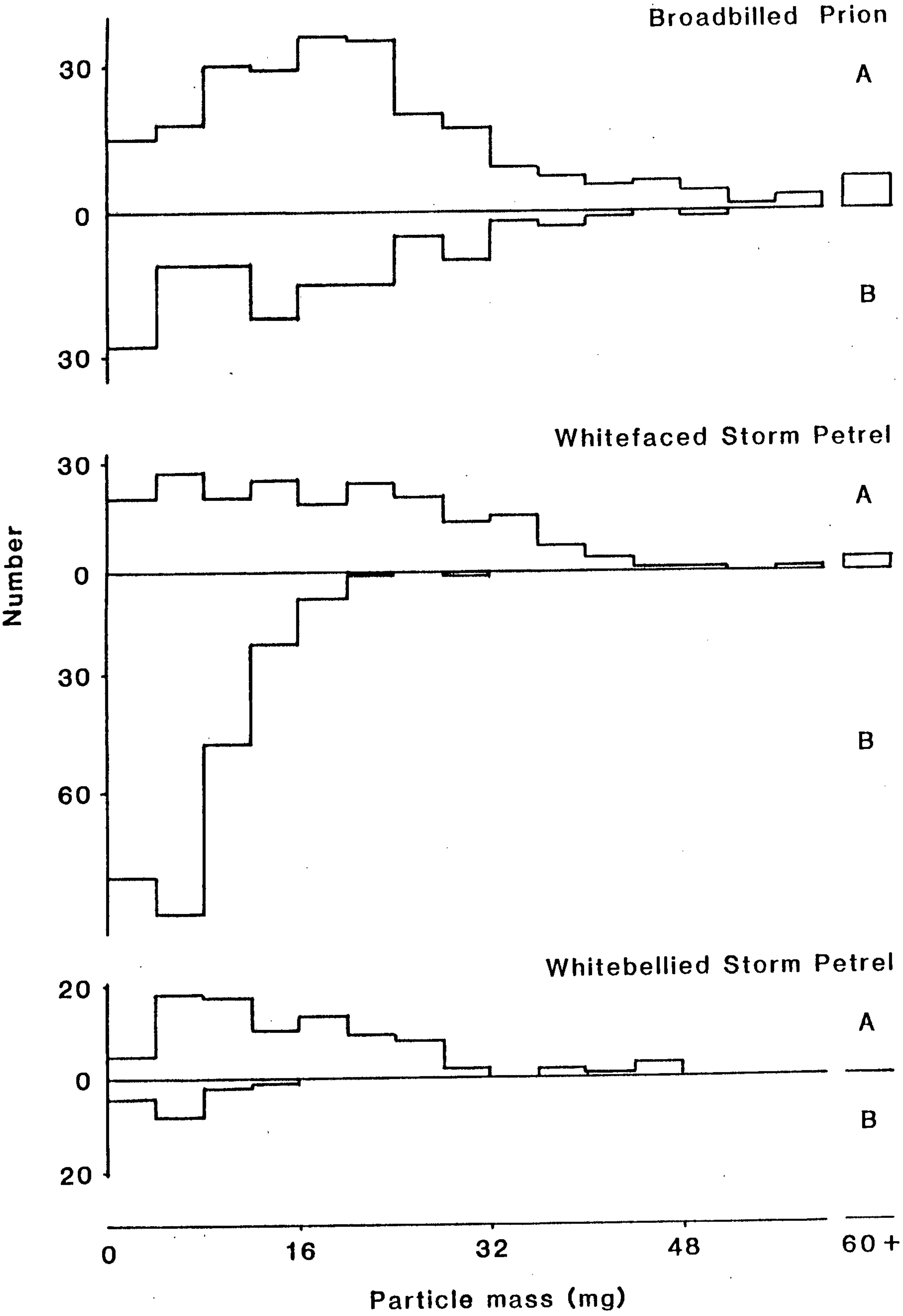

FIGURE A.1 The masses of plastic pellets associated with the remains of petrels in Subantarctic Skua pellets from Inaccessible Island (A) compared with those from birds collected at Gough Island (B) (Furness 1985a, Chapter 2). Note that the mass scale given in Furness (1985a) is ten times too large.

foraging behaviour of Subantarctic Skuas at breeding islands (e.g. Sinclair 1980, Fraser 1984), suggests that virtually all the plastic particles found in skua pellets are derived from their prey.

The disproportionately low numbers of small (< 8 mg) plastic particles in skua pellets containing petrel remains suggest that small particles are lost, either from the pellet during or prior to collection, or, more likely, through failure to be incorporated in pellets. Large gulls often produce faeces containing relatively large lumps of indigestible prey items (e.g. shell fragments up to 2 mm across, pers. obs), and it seems likely that Subantarctic Skuas also defaecate small particles. The loss of plastic through faeces would result in underestimates of plastic loads based on regurgitated skua pellets, particularly if there are many small plastic particles. This would account for the relatively low frequency of occurrence of plastic recorded in skua pellets containing storm petrel remains, because storm petrels ingest smaller plastic particles than other seabirds (Chapter 2).

An alternative explanation for the differences between the plastic found in petrels and that in skua pellets containing their remains is that petrels and skua pellets were collected at different localities. However, this is unlikely to account for the observed differences, because the two islands are close together and support the same races of breeding seabirds (Clancey 1981). If anything, plastic loads should be larger at the more northerly Inaccessible Island, which lies north of the Subtropical Front, than at Gough Island which is south of the Front (Miller & Tromp 1982). The density of plastic particles at sea probably is higher in the South Atlantic water around Inaccessible Island (Morris 1980) than in the West Wind Drift south of the Front (Chapter 1). This is supported by the plastic loads (total mass per bird containing plastic) in skua pellets containing Broadbilled Prions remains from Inaccessible Island being larger than the plastic loads from prions collected at Gough Island.

The relatively high frequency of occurrence of plastic in skua pellets containing Common Diving Petrel remains also could be attributed to geographic differences. However, floating plastic particles rarely are ingested by this diving species (Furness 1985a, Chapter 2), and the plastic recorded in these pellets may have come from earlier meals. This degree of uncertainty surrounding the origin of plastic particles in skua pellets necessitates the collection of large samples and militates against the use of skua pellets as indicators of plastic loads in species rarely found to contain plastic particles.

The absence of plastic from skua pellets containing Great Shearwater remains is surprising, given the high incidence of ingested plastic in this species (Furness 1985a, Chapter 2). However, Great Shearwaters are much larger than the other petrels considered here, and probably are too large to be consumed in a single meal. Subantarctic Skuas preferentially consume the viscera and pectoral muscles of birds (Sinclair 1980, pers. obs), leaving the bony parts until later. Several pellets were found containing large numbers of plastic particles, including large pieces of sheet plastic typical of those found in Great Shearwaters (pers. obs), but these lacked identifiable avian remains.

Plastic from skua pellets containing the remains of Broadbilled Prions are little affected by the biases oulined above, because Broadbilled Prions are swallowed whole (or all but the wings and sternum swallowed), and they contain few small plastic particles. Thus skua pellets may be appropriate indicators of plastic loads in some seabirds, but the loss of small particles must be considered. Skua pellets could be used to monitor temporal changes in the incidence of ingested plastic in selected species, provided comparisons are made at the same locality and at the same time of year (cf. Chapter 3).

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