Prey and plastic ingestion of Pacific Northern Fulmars (*Fulmarus glacialis rogersii*) from Monterey Bay, California

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ABSTRACT

Marine plastic pollution affects seabirds, including Pacific Northern Fulmars (*Fulmarus glacialis rodgersii*), that feed at the surface and mistake plastic for prey or incidentally ingest it. Direct and indirect health issues can result, including satiety and possibly leading to inefficient foraging. Our objective was to examine fulmar body condition, identify cephalopod diet to species, enumerate and weigh ingested plastic, and determine if prey number and size were correlated with ingested plastics in beach-cast fulmars wintering in Monterey Bay California (2003, $n = 178$: 2007, $n = 185$). Fulmars consumed mostly *Gonatus pyros*, *G. onyx*, and *G. californiensis* of similar size for both years. We found a significant negative correlation between pectoral muscle index and average size of cephalopod beaks per stomach; a significant increase in plastic categories between 2003 and 2007; and no significant correlation between number and mass of plastic compared with number and size of prey for either year.

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1. Introduction

Plastic waste occurs throughout the world's oceans and often becomes aggregated in convergence zones that are important foraging areas for pelagic seabirds, marine mammals, and turtles, thus increasing their chances of ingesting plastic (Shaw and Mapes, 1979; Laist, 1997; Polovina et al., 2001; Seki et al., 2002; Pichel et al., 2007). Procellariiforms, such as Northern Fulmars (*Fulmarus glacialis*), that feed opportunistically at the water's surface ingest the most plastic (van Franeker and Meijboom, 2002; Nevins et al., 2005; Avery-Gomm et al., 2012). Birds presumably mistake floating plastic for prey items or ingest prey that is attached to floating debris (Sileo et al., 1989).

Plastic ingestion by Northern Fulmars has been investigated in regions of the North Atlantic (Moser and Lee, 1992; van Franeker et al., 2011; van Franeker, 2013) and North Pacific (Robards et al., 1995; Nevins et al., 2005; Mallory et al., 2006; Avery-Gomm et al., 2012; Nevins et al., 2014). Marine litter monitoring programs in the Atlantic (Save the North Sea Fulmar Study Group led by Institute for Marine Resources and Ecosystem Studies) and in the Pacific (Biological Indicators of Ocean Plastic Pollution Network led by Oikonos Ecosystem Knowledge) that quantify Northern Fulmar plastic ingestion via carcass necropsies from multiple sources, have indicated that greater than 70% of fulmars ingested plastic annually (2003–2007; van Franeker et al., 2011; Nevins et al., 2014).

Fulmar stomachs also contain indigestible hard parts of prey items used to determine prey size and species. Fulmars in the Pacific eat primarily cephalopods and fish (Baltz and Morejohn, 1977; Harrington-Tweit, 1979; Hunt et al., 1981; Sanger, 1983; Hills and Fiscus, 1988; Gould et al., 1997), whereas fulmars in the Arctic consume cephalopods, polychaetes and crustaceans (with regional variation; Mallory et al., 2010) and Atlantic Fulmars consume more fishes (Cherel et al., 2001). In the North Atlantic, 329 stomachs were examined (1982–2000): 78% of fulmars had prey remains (all types totaled), and 96% of those contained plastic (van Franeker and Meijboom, 2002). Greater incidence of plastic may result in health complications in fulmars (van Franeker and Meijboom, 2002).

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Direct and indirect health effects are associated with plastic ingestion such as reduced hunger (satiety), internal blockage, contaminant accumulation, and decreased fat content or mass (Pettit et al., 1981; Day, 1985; Zonfrillo, 1985; Frey et al., 1987; Pierce et al., 2004; Mallory et al., 2006). Inability or difficulty regurgitating hard material (plastics and prey parts) may interfere directly by causing gastrointestinal blockage (Day, 1980; Pierce et al., 2004) or indirectly by reducing feeding stimulus and activity (Sturkie, 1965 as cited in Azzarello and Van Vleet, 1987). The small constriction between the gizzard and proventriculus in Northern Fulmars makes complete regurgitation improbable (Furness, 1985; Azzarello and Van Vleet, 1987). As a result, plastics and prey hard parts (e.g. cephalopod beaks) are retained for an uncertain amount of time (disappearance of hard plastic was recently estimated at 75% after a month in Antarctic species; van Franeker et al., 2011; van Franeker, 2013).

The fulmar gizzard is relatively small (estimate volume ∼2 cm^2) and may be susceptible to distension and health consequences, such as satiation, for fulmars carrying large plastic loads. Distension of the gizzard or the larger proventriculus may lead to decreased stomach contractions, reduced urge to forage, and reduced maximum food load (volume of food that can be ingested in one foraging bout; Connors and Smith, 1982; Day, 1985; Ryan, 1988; van Franeker and Meijboom, 2002). Evidence for satiation effects are difficult to attribute solely to plastic ingestion, however, a decreased sense of hunger, urge to forage, and ingested volume of food will negatively affect the condition of the bird, resulting in reduced physical fitness (Pierce et al., 2004). Decreased physical fitness can affect reproduction and decrease chances of survival (van Franeker and Meijboom, 2002).

Researchers have examined diet *or* plastic ingestion in Northern Fulmars, but have not examined both variables together (Baltz and Morejohn, 1977; Sanger, 1983; Hills and Fiscus, 1988; van Franeker and Meijboom, 2002; Nevins et al., 2005; Avery-Gomm et al., 2012). Frequencies of occurrence and types of prey ingested have been determined from Fulmar stomach contents, but prey identified to species, particularly cephalopods, has not occurred often since the 1990s (Baltz and Morejohn, 1977; Harrington-Tweit, 1979; Hunt et al., 1981; Sanger, 1983; Hills and Fiscus, 1988; Gould et al., 1997; Mallory et al., 2010). Furthermore, if greater plastic loads lead to satiety or reduced foraging efficiency in Northern Fulmars, a change in prey items (i.e. different size classes, species, frequency of occurrence, etc.) may occur. In this study, we examined the correlation between Northern Fulmar plastic loads and the occurrence and size of prey species, because plastic loads may influence the types of prey ingested or vice versa.

If foraging North Pacific fulmars have greater plastic loads, birds may feel satiated and select prey that are easier to catch and will forage less often. Thus, we predicted that smaller and fewer prey would be found in fulmars with greater amounts of plastic. Additionally, we identified prey to species to examine whether a shift to smaller sized prey also indicated a change from larger to smaller species eaten by fulmars (currently unknown for the region). A natural shift of diet in fulmars when prey availability is altered (Cherel et al., 2001; indicative of an opportunistic feeder) may complicate any shift in prey species selection with increasing plastic loads. Despite this shift, a change in the amount and size class of prey consumed should be observed when comparing birds with varying volumes of plastic debris. We predicted that fulmars of poor body condition would have significantly greater plastic loads than fulmars in healthier condition.

Pelagic seabirds, including Northern Fulmars, forage over large spatial scales. Studies of prey of pelagic seabirds, therefore, provide natural indices of food web composition, location of prey, and relative abundance of prey among years in relation to oceanographic conditions (Montevecchi and Myers, 1996; Sydeman et al., 2001). Changes in prey selected by Northern Fulmars, therefore, may be in response to short-term fluctuations in prey abundance (Suryan et al., 2002). Discriminatory prey choice in some seabirds, however, also has been documented (i.e. some prey items were over or under-represented, relative to their abundance; Suter, 1997; Suryan et al., 2002).

The abundance and availability of cephalopods, the primary prey of fulmars, are influenced by variable oceanic conditions, prey movements, behavior, and life-cycle characteristics that are species-specific (Boyle and Boletzky, 1996; Rodhouse and Nigmatullin, 1996). Cephalopod beaks recovered from seabirds and other marine predators can be used to determine prey species and contribute to indirect population assessments of cephalopods and determine aggregation areas (Clarke, 1986; Boyle and Boletzky, 1996). If deeper-water cephalopods (e.g. Gonatidae) dominate Northern Fulmar diet, there should be no significant difference relative to oceanic conditions, because mesopelagic and deep-water squids should be less influenced by dynamic oceanic conditions than surface-dwelling squid [e.g. *Dorytheuthis opalescens* (=*loligo*)]. Overall, we examined if fulmars carrying greater internal plastic loads would contain the least amount of cephalopods and the smallest size class of cephalopods regardless of oceanic conditions.

2. Methods

Northern Fulmars that washed ashore in the Monterey Bay area in 2003 and 2007 (from cyclic die-offs) were collected by volunteer beach-walkers (Coastal Ocean Mammal and Bird Education and Research Surveys [BeachCOMBERS]), and later necropsied at the Marine Wildlife Veterinary Care and Research Center (California Department of Fish and Wildlife, Santa Cruz, California [CDFW]). During a winter wreck (November–January) in 2003–04, 178 dead fulmars were collected (Nevins et al., 2005), and during a harmful algal bloom between November and December of 2007, 111 dead and 74 live were collected (Jessup et al., 2009). Monterey Bay is 449 square miles (1163 km^2) and located in California in the United States of America (36.6315° N, 121.8813° W). Fulmars were collected on beaches throughout Monterey Bay for both study years.

During necropsy, demographic parameters (sex and age class), body condition indices (muscle and fat scores), and stomach contents were recorded for each individual fulmar carcass. The sex was determined by identifying gonads. Age estimates were based on the development of the sex organs (size, shape, and color) and the presence and size of a Bursa of Fabricius. For males, testis length and width were measured (±1 mm) and color was noted (dark, bi-colored, pink, or whitish). For females, ovary length and width and the diameter of the largest follicle were measured (±1 mm). An oviduct development score (1–4 from juvenile to breeding adult) was assigned (van Franeker and Meijboom, 2002). Age estimates were assigned as juvenile (1st year), immature (incomplete development of sex organs; estimated 2–6 years old), and adult (organs indicated signs of previous breeding or full capability for breeding; van Franeker and Meijboom, 2002). The presence and size of the Bursa of Fabricius was noted; it was assumed that only hatch year birds (⩽1 year) contained prominent bursas (van Franeker and Meijboom, 2002).

Internal body condition indices were based on condition of the pectoral muscle and quantity (based on thickness) of subcutaneous fat under the skin (van Franeker and Meijboom, 2002). Both indices were scored 0–3, where 0 indicated total depletion and 3 was optimal condition.

To quantify stomach contents, the proventriculus and ventriculus were processed separately. Contents of the proventriculus and

ventriculus were collected in a 0.5 mm mesh sieve and rinsed to remove prey soft tissues. Hard parts, plastics, and other remaining non-food hard particles were sorted using a binocular microscope into specified categories (prey, natural items, plastic fragments, industrial plastics, etc.) following the protocol of van Franeker and Meijboom (2002). Cephalopod beaks were saturated in 70% isopropyl alcohol to prevent drying. Fish otoliths were eliminated from the analyses due to extensive wear and crumbling and low frequency of occurrence (<10 total).

Once dried, the categorized plastics were quantified (by frequency of occurrence, number of particles, total mass, and relative mass compared with proportion of other matter in stomach). The primary plastic categories for this study were industrial (premolded pellets used in manufacturing), fragments (hard fragments of molded post-consumer objects), all plastic (industrial + fragments plastics + all other plastic materials such as sheets, line, and foam), and all marine debris (includes all plastic category and other non-plastic man-made debris and chemicals; van Franeker and Meijboom, 2002).

Cephalopod beaks were examined using a dissecting scope, measured with digital calipers, and identified to lowest taxonomic level using physical descriptions, reference collections, and literature sources (Clarke, 1986, William Walker unpublished beak guide illustrations 2009, National Marine Fisheries Service, National Marine Mammal Laboratory, Seattle reference collection). Lower cephalopod beaks were measured to the nearest 0.1 mm. Estimated dorsal mantle length (DML) and mass of the cephalopod prey were determined using the lower beak rostral length (LRL) measurements and published regression equations (Wolff, 1984; Clarke, 1986; William Walker unpublished regressions 2014, National Marine Fisheries Service, National Marine Mammal Laboratory, Seattle reference collection). Based on species and DML, the cephalopods were categorized as surface-dwelling, mesopelagic, or deep-sea squids.

To examine how oceanic conditions might influence foraging, oceanic conditions and fulmar tracking were examined using published sources. California Cooperative Oceanic Fishery Investigations (CalCOFI) reports were used to examine inshore and offshore changes of abiotic and biotic factors in the California Current System (CCS; CalCOFI Rep. Vol. 45–50). Fulmars sampled from 2003 were grouped as "warm-water" and those sampled from 2007 were grouped as "cold-water." This was based on CalCOFI reports that El Niño-like conditions occurred during 2003 and La Niña conditions occurred during 2007 (CalCOFI Rep. Vol. 45–49).

2.1. Statistics

Initially, cephalopod prey items were analyzed separately from plastic items. We described feeding strategy and diet diversity using a modified version of the Costello Method and the Shannon–Wiener diversity index (Amundsen et al., 1996; Zar, 1999). The Amundsen modification to the Costello Method plots the prey-specific abundance, %PN, against the frequency of occurrence, FO (expressed in fraction rather than in percent). The modification "allows prey importance, feeding strategy and the inter- and intraindividual components of niche width" to be examined (Amundsen et al., 1996). Prey-specific abundance was defined as:

$$P_i = \left(\sum S_i / \sum S_t \right) * 100$$

where P_i is the prey-specific abundance of prey i, S_i is number of prey i, and S_t, the total number of items in the stomach only for those predators with prey i in their stomach (Amundsen et al., 1996). The Shannon–Wiener diversity (H') index measures diversity in categorical data using the number and evenness of the species. Greater species evenness or more species increases the index that is defined as

$$H' = -\sum_{i=1}^{s} (pi \ln pi)$$

where p_i is the relative abundance of each species calculated as the number of species (n_i) divided by the total number of individuals (N) evaluated for all species (s).

Estimated averages of DML and mass of cephalopods were examined for the dominant cephalopod species. Multivariate Analysis of Variance (MANOVA with 9999 permutations) tested for differences in prey and plastics between the two years, the sexes, the age classes (juveniles versus adults), and body conditions (healthy versus poor) using R Enterprise Statistical Software. Because the majority of fulmars were of poor condition in 2003 and there was not equal representation of healthy birds, both indices representing bird condition were removed from the analysis for with-in year comparisons.

Basic statistics were performed to obtain mean and standard error values on the total number and mass of four plastic categories (total marine debris, all plastic, industrial plastic, and fragment plastics). The plastic data were ln transformed, and Analysis of Variance (ANOVA) tested for differences in the plastic categories between years. A Bonferroni correction was used to address the issue of multiple comparisons. Multivariate Analysis of Variance (MANOVA with 9999 permutations) tested for differences in plastic categories between the two years, sexes, age classes, and body conditions using R Software.

Finally, the prey items and plastic items were analyzed together. Canonical correlation analysis tested for correlations between the number and masses of the plastic compared with the number and size of prey species for each of the two years fulmars were collected (pers. comm. Bros, 2009). Only fragments and industrial plastic categories were used in this analysis to avoid the multicollinearality associated with total marine debris and total plastic categories.

Canonical correlation (CCorA) was deemed appropriate for our data, because we were interested in exploratory descriptions of relationships between sets of variables as opposed to correlations between specific pairs of variables (Quinn and Keough, 2003). Although this method has been used in multivariate statistics (e.g., Hotelling, 1936), it has only recently been applied to biological datasets (e.g., Anderson and Willis, 2003). This constrained ordination method detects differences among groups in multivariate space, while minimizing the influence of other highly variable and cross-correlated variables unrelated to those group differences (Anderson and Willis, 2003). Because canonical correlation accounts for the correlation structure among the predictor variables and among variables response variables, it provides the linear combinations of cross-correlated (predictor – response) variables with the highest correlation (Anderson and Willis, 2003).

3. Results

3.1. Monterey Bay sample population

Sex ratio was 1:1 in 2003, but there were more males than females (1.8:1) in 2007 (Table 1). Both years were dominated by immature birds with lesser subcutaneous fat and lesser pectoral muscle indices indicating the sampled population was mostly young (85%) and of poor health (84%; Table 1).

3.2. Squid diet

We identified 1065 cephalopod prey items using lower beaks (542 for 2003; 523 for 2007) from fulmar stomachs. Diet of fulmars was dominated by three species of mesopelagic cephalopods of the

Table 1

Demographics and body condition indices for Northern Fulmar samples collected in 2003 ($n = 178$) and 2007 ($n = 185$) in Monterey Bay, CA. Body condition indices included subcutaneous fat (=SubQ Fat Index) and pectoral muscle (=Pec Muscle Index). The unknown categories mainly consisted of carcasses unable to be measured for that parameter due to scavenging.

Demographics	2003	2007
Sex		
Female	68	63
Male	67	113
Unknown	43	9
Age group		
Immature	145	164
Adult	0	18
Unknown	33	3
Body condition indices		
SubQ Fat Index		
0	141	125
1	0	38
2[a]	0	12
3[a]	0	3
Unknown	37	7
Pec Muscle Index		
0	0	51
1	140	95
2[a]	0	27
3[a]	0	4
Unknown	38	8

[*] Indicates 'healthy' code.

family Gonatidae (*Gonatus onyx*, *G. pyros*, and *G. californiensis*) in both years (Table 2). Shannon–Wiener Diversity Index values of 246 for 2003 and 226 for 2007 were representative of an abundant and diverse prey community that was evenly distributed (Zar, 1999). A subset of 931 beaks were suitable for measurement (474 for 2003; 457 for 2007). The average LRL was 3.76 mm (SE = 0.04) in 2003 and 3.80 mm (SE = 1.06) in 2007, which were not significantly different between years ($p > 0.05$). Means of estimated dorsal mantle length (DML) and estimated mass of the three most commonly eaten cephalopods revealed similar size classes between the sampled years (Table 3).

In addition to prey importance, the modified Costello plots represented the feeding strategy of fulmars. Most of the prey items were in the middle of the plots indicating a generalist foraging strategy and a broad niche width (Fig. 1). Prey items that were in either "the upper left or lower right corner represented prey types that made the same overall contributions to the population diet, but were indicative of totally different feeding strategies of individual predators" (Amundsen et al., 1996). In this case, no prey items occurred in the upper right hand of the diagrams, indicating no specialization of fulmars (Amundsen et al., 1996). However one prey item, *Doryteuthis opalescens* (commonly called Market Squid), occurred in the upper left-hand corner, in 2007, indicating specialization of individual fulmars when that prey item was available (Fig. 1). Overall, the fulmars ingested Gonatid squids more than other taxa. Furthermore, the plots indicated a greater within-phenotype component with most of the fulmars using many resource types at the same time (Fig. 1).

3.3. Inter-annual variability: prey and plastic

Although the dominant prey species and diversity metrics were similar between years, there were significant differences in the number of cephalopods eaten between years. The average number of beaks in 2007 ($\bar{x} = 3.5$, SE = 3.36, range = 0–15) was significantly greater ($P = 0.03$) than in 2003 ($\bar{x} = 2.7$, SE = 3.03, range = 0–13). We found no significant differences in size class or mass based on LRL

and DML measurements of the three most commonly eaten cephalopods (Table 3).

There were differences in some categories of ingested plastics in fulmars. In 2003, 45 of the 178 samples (25%) did not have any form of plastic, whereas in 2007 only 4 of 185 samples (2%) had no plastic. Incidence of total plastic was 75% in 2003 and 98% in 2007 (86.5% combined years, $n = 363$). Overall, the mean number and mass of all of the plastic categories were greater in 2007 than in 2003 (Table 4). In comparing the two types of carcass samples in 2007, mass of plastic fragments was significantly greater in 2007-live ($\bar{x} = 0.231$ g; SE = 0.03) than 2007-dead ($\bar{x} = 0.227$ g; SE = 0.06), as a result of the difference in variances between live ($\sigma^2 = 0.07$) versus dead samples ($\sigma^2 = 0.43$). Because there were no significant differences in the other plastic categories within 2007 only the mass of plastic fragments (ln-transformed) was analyzed in two steps to evaluate interannual differences (2007-live vs. 2003 and 2007-dead vs. 2003). There were significant differences between years in the following five categories: number and mass of marine debris ($P = 0.001$), number and mass of all plastic ($P = 0.001$), and number of plastic fragments ($P = 0.001$). There were significant differences in masses of plastic fragments between the 2007-live vs. 2003 ($P = 0.001$) and 2007-dead vs. 2003 ($P = 0.003$).

3.4. Body condition and demography: prey and plastic

In testing for prey differences between years, the MANOVA indicated a significant, positive relationship between body condition (pectoral muscle index) and number (intercept −0.73) and average LRL of cephalopod beaks per stomach (intercept −0.33, $P = 0.02$). A lesser pectoral muscle index (unhealthy muscle biomass) was indicated by a lesser number and average LRL of beaks. There were no significant differences in the demographics (sex, age group) or the other body condition variable (subcutaneous fat; $p \leqslant 0.05$).

When examining prey difference within years, there were no significant differences in any of the explanatory variables for 2007 (sex, age group, subcutaneous fat, pectoral muscle) for number and average LRL of cephalopod beaks per stomach ($P \geqslant 0.05$). There was a significant difference in 2003 between males, females, and unknown sex of birds for number and average LRL of cephalopod beaks per stomach when the subcutaneous and pectoral indices were removed ($P = 0.01$), but when unknown sex birds were removed from the analyses, no differences between males and females were found ($P = 0.30$). It was deemed appropriate to remove subcutaneous and pectoral indices from the 2003 analysis because all fulmars were in 'poor' condition (Table 1).

The results of the MANOVA indicated number and masses of the plastic categories differed with body condition. There appeared to be a relationship between number of plastics and subcutaneous fat when both years were examined, but this is likely due to the overwhelming number of birds of 'poor' condition in 2003 ($P = 0.01$). When years were examined separately, there was a significant, negative relationship in 2007 between pectoral muscle index and mass of total marine debris, where greater pectoral mass indicated lesser masses of debris ($P = 0.05$). There were no differences found for 2003 (with or without the removal of the subcutaneous and pectoral indices).

3.5. Prey and plastic correlations

Finally, the Canonical Correlation Analyses indicated there were no significant correlations between the number and mass of plastic compared with the number and size of prey species for each of the two years (2003: $P = 0.60$, 2007: $P = 0.79$). The relationship indicated that, although not significant, there was a negative correlation between the mass of plastic fragments (Var Y4) and the

Table 2
Occurrence (number of beaks) of identified cephalopods (family and species) and number of fulmar stomachs examined (n) from other references (1–4) and this study (5).

Family	Genus/species	1 $n = 3$ Monterey Bay	2 $n = 29$ West Pacific (near Japan)	3 $n = 46$ Gulf of Alaska	4 $n = 28$ Washington Coast	5a $n = 178$ Monterey Bay	5b $n = 185$ Monterey Bay
Loliginidae							
	Doryteuthis opalescens	8				5	17
Enoploteuthidae							
	Abraliopsis felis				1		
Octopoteuthidae						1	
	Octopoteuthis deletron	5			3	4	18
	c.f. Octopoteuthis deletron						4
	Octopoteuthis sp.		2				
Onychoteuthidae							
	Onychoteuthis borealijaponicus	4			1		
	Onykia sp. c.f. O. robusta					1	
	Onykia spp.					1	
Gonatidae						58	40
	c.f. Gonatidae						3
	Gonatopsis borealis		1		4	8	15
	Gonatus pyros				19	132	149
	Gonatus berryi					26	23
	c.f. Gonatus berryi					2	
	Gonatus californiensis					49	49
	Gonatus sp. c.f. G. californiensis					2	
	Gonatus onyx					144	83
	c.f. Gonatus onyx					4	
	Gonatus spp.			12	5	3	1
	unid. Gonatidae	6			1		
Grimalditeuthidae							
	Grimalditeuthis bonplandi						3
Histioteuthidae							
	Histioteuthis heteropsis				2		2
	Stigmatoteuthis dofleini		+			9	23
	c.f. Stigmatoteuthis dofleini					1	
	unid. Histioteuthidae				1		
Ommastrephidae							
	Ommastrephes bartramii		1				
Chiroteuthidae							
	Chiroteuthis calyx				6	32	17
Mastigoteuthidae							
	Mastigoteuthis pyrodes					4	4
	Mastigoteuthis sp.		1				
Cranchiidae						1	
	Cranchia scabra						1
	Taonius borealis				36[*]	33	34
	Taonius c.f. T. borealis						2
	Galiteuthis phyllura		6				
	Leachia dislocata		#				1
	unid. Cranchiidae				1		
Cirroteuthidae							
	Cirroteuthidae c.f. Cirrothauma spp.					1	
Bolitaenidae							
	Japetella heathi				2		
Octopodidae							
	Octopus sp.	1			1		
	c.f. Octopus rubescens						1
Alloposidae							
	Haliphron atlanticus		#				
Unidentified							
unid. Teuthoidea (juveniles)			1			1	
unid. cephalopod beaks			5			20	33

Reference
1 – Baltz and Morejohn (1977).
2 – Gould et al. (1997).
3 – Sanger (1983).
4 – Hills and Fiscus (1988).
5a – This study 2003.
5b – This study 2007.
[*] As Taonius pavo.
Present in undetermined numbers.

Table 3
Estimated mean dorsal mantle length (DML; mm), estimated mean mass (g) of the three most common cephalopod species eaten by Northern Fulmars in 2003 ($n = 178$) and 2007 ($n = 185$). Differences between years were not significant for all three species.

Species	DML 2003	SE	DML 2007	SE	Mass 2003	SE	Mass 2007	SE
Gonatus onyx	82.4	0.9	82.4	1.6	114.5	1.4	115.3	2.7
Gonatus pyros	62.4	1.1	66.7	1.1	13.3	0.5	15.7	0.6
Gonatus californiensis	138.8	3.4	138.8	2.4	74.6	4.4	70.6	3

average LRL per stomach (Var X2) indicated by the vectors pointing in opposite directions (Fig. 2).

4. Discussion

4.1. Monterey Bay sample population

Samples from this study represented a subset of the Pacific Northern Fulmar population that migrated to Monterey Bay and were mostly starving, immature, and in poor body condition. Whereas the occurrence of beached fulmars is a common winter pattern in the region, the specific reasons fulmars beached in each year differed, whereas 2003 was a winter wreck as evident by

reduced body condition and predominantly young-of-the-year birds (Nevins et al., 2005) and the 2007 event was brought on by fouling from a harmful algal bloom (Jessup et al., 2009). In the 2003 event, Nevins et al. (2005) hypothesized that fulmars originated from colonies in the Gulf of Alaska (Semidi Islands), based on color morph (predominately dark, Hatch, 1991) and satellite telemetry (Hatch et al., 2010). Persistent storms in the winter of 2003 may have reduced prey availability and prevented/reduced foraging opportunities (Nevins et al., 2005). Lethargic and dead fulmars were observed offshore over the north shelf of Monterey Bay during at-sea surveys, many of these birds likely turned up dead on Monterey beaches (Nevins et al., 2005). The 2007 mortality event was caused by a non-toxic harmful algal bloom (HAB) of
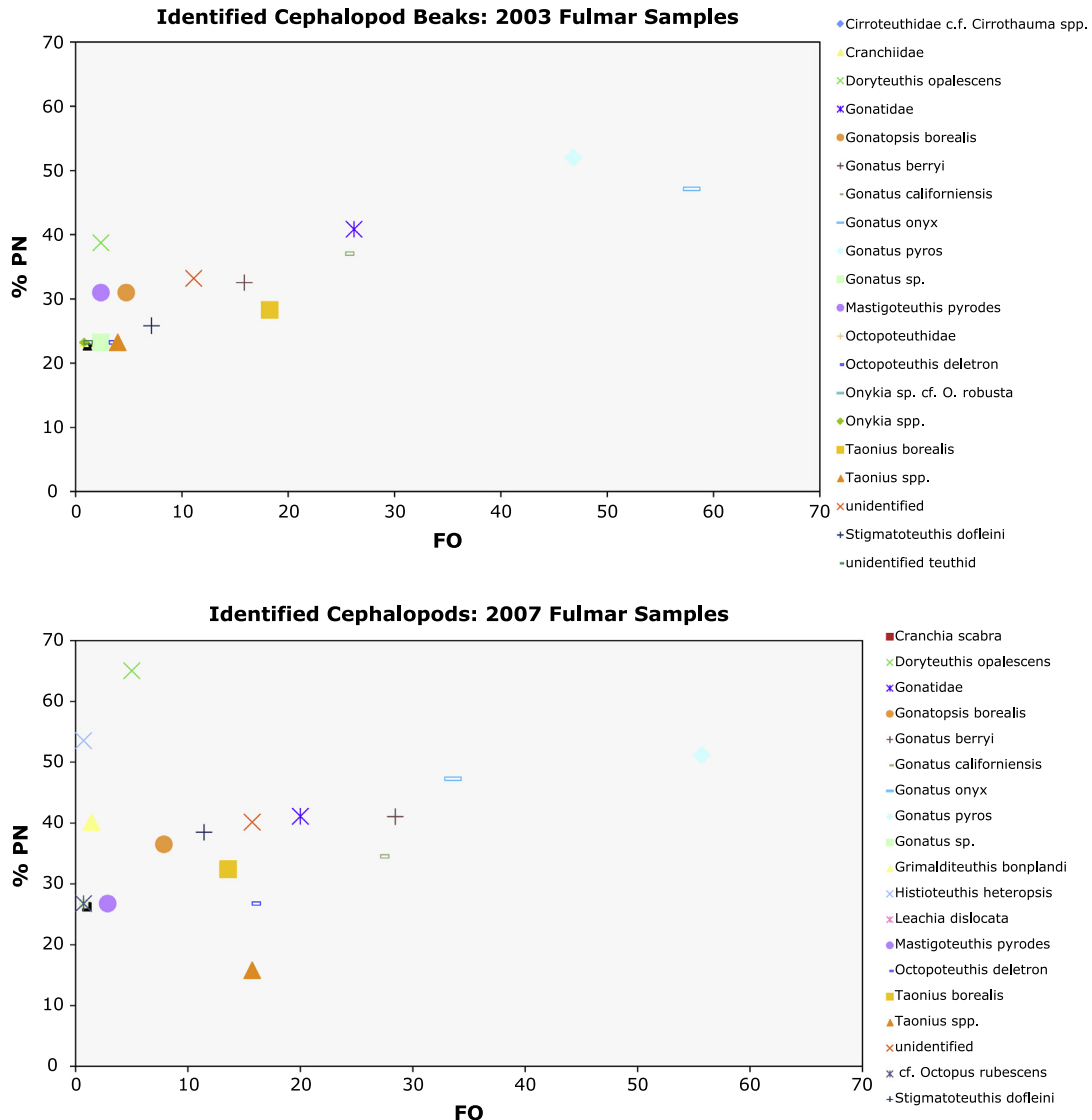

Fig. 1. Modified Costello plots (adapted from Amundsen et al., 1996) of identified cephalopods from Northern Fulmars for 2003 and 2007 where % PN is prey specific abundance and % FO is frequency of occurrence expressed as a fraction.

Table 4
Plastics and other marine debris in Northern Fulmar stomachs collected in 2003 (n = 178) and 2007 (n = 185). Mean, standard error (SE), and maximum value of number of pieces and masses (g) of all marine debris (including all plastics and other human-made materials), all plastic that includes the categories industrial pellets, fragments, and other types (line, sheets, foam, and other categories).

| Category	2003 Total sample n = 178			2007 Total sample n = 185		
	Mean	SE	Max	Mean	SE	max
Number						
Marine Debris	7.4	0.7	44	24.1	2.2	224
Plastic – All	7.2	0.6	42	22.3	2.0	223
Plastic – Industrial	1.1	0.1	9	1.4	0.1	10
Plastic – Fragments	5.3	0.5	34	12.4	0.9	69
Plastic – Other	0.8	0.1	12	8.4	1.5	209
(*includes line, sheet, foam, other*)						
Mass – grams						
Marine Debris	0.12288	0.01212	1.19	0.55411	0.09393	10.12
Plastic – All	0.11950	0.01212	1.19	0.45752	0.08355	10.12
Plastic – Industrial	0.02187	0.00298	0.23	0.02819	0.00294	0.23
Plastic – Fragments	0.08492	0.00819	0.58	0.22855	0.03920	6.73
Plastic – Other	0.01271	0.00414	0.54	0.20079	0.07261	10.02
(*includes line, sheet, foam, other*)						
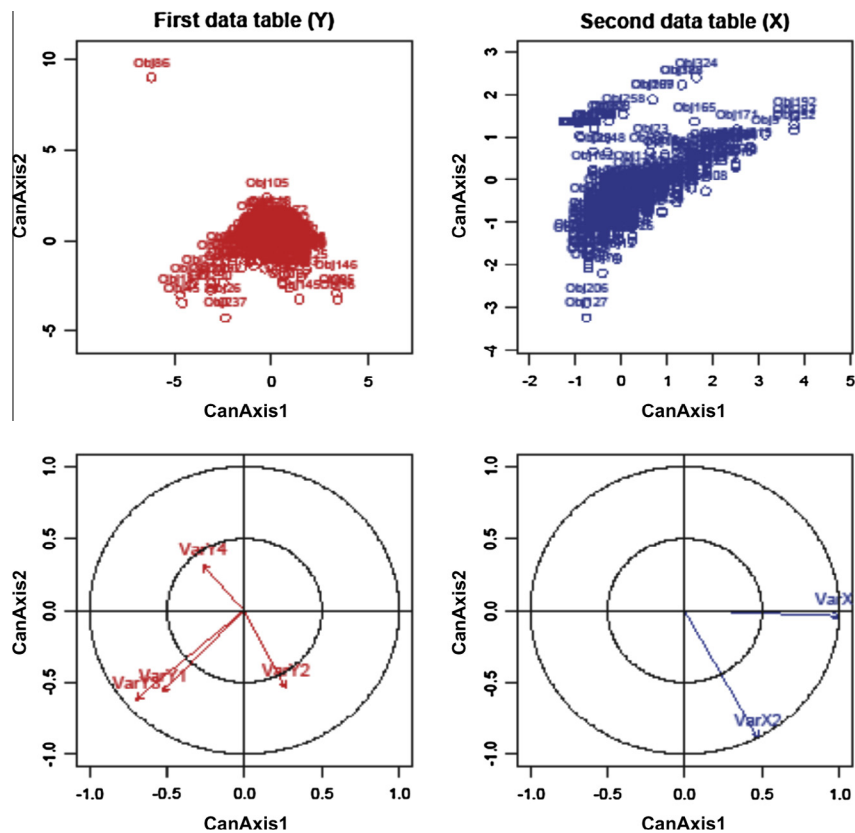
Fig. 2. Canonical Correlation Analysis of the plastic variables (red) and cephalopod beak variables (blue). The top left indicates the grouping of all the plastic variables (number and mass) within the samples, whereas the bottom left indicates the vectors of the variables that have been created by the Eigenvalues (Var Y1: number of industrial plastic, Var Y2: number of plastic fragments, Var Y3: grams of industrial plastic, Var Y4: grams of plastic fragments). The top right shows the grouping of the prey variables and the bottom right indicates the vectors (Var X1: number of beaks, Var X2: average LRL per stomach). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dinoflagellate species (*Akashiwo sanguinea*). This dinoflagellate produced a foam-like substance (Mycosporine-like amino acid) that caused extensive feather fouling and poor waterproofing in affected seabirds (Jessup et al., 2009). Adult and immature birds in poor and healthy conditions were observed, but immature fulmars in poor body condition constituted the majority of samples in both years (100% in 2003 and 90% in 2007). Despite differences in mortality events, we deemed the sample years comparable due to similarities in collection months and location, bird condition, and the likelihood that fulmars exhibited similar foraging range and residency in the California Current System before entering Monterey Bay (Fig. 3).

4.2. Squid diet

Based on diet remains, Northern Fulmars ate adult, mesopelagic Gonatid cephalopods of varying lengths and masses before coming ashore on Monterey Bay beaches. Of the three dominant species, *G. californiensis* was the largest (to 139 mm), *G. onyx* was somewhat smaller (82 mm), and *G. pyros* was smallest (62–67 mm; Nesis, 1987). Whereas *G. californiensis* likely is confined to the CCS region, *G. onyx* and *G. pyros* (smaller, muscular species) are more common and broadly distributed throughout the North Pacific (Okutani et al., 1988).

Species composition of fulmar diets described here was similar to that previously reported in the North Pacific (Table 2). However, many previous researchers did not identify the cephalopods to species, did not provide distributional information, or did not collect sufficient sample sizes to adequately characterize the prey array.

All three dominant species of cephalopods are primarily meso-pelagic, but also found in the bathypelagic zones (Fig. 3). Literature describing cephalopod behavior for *G. pyros* and *G. californiensis* are lacking, but there are reports that Juvenile *G. onyx* are abundant in near surface waters from April to July (Okutani et al., 1988), however egg-brooding adults were observed in mesopelagic waters (2000–3000 ft; Seibel et al., 2005). Fulmars feed at the ocean surface and are only capable of diving a few meters (Garthe and Furness, 2001). Therefore, foraging fulmars were accessing these deep-water cephalopods during vertical diel migrations either as juveniles or at night (Roper and Young, 1975; Nesis, 1987; Okutani et al., 1988). As fulmars are frequently observed eating dead prey and fishery discards at-sea, another explanation for the abundance of deeper water adult cephalopods at the surface is post-spawning die-offs. Gonatidae squids are documented to float after death due to the presence of buoyancy mechanisms, although little direct evidence exists for most squid taxa on their behavior post-spawning and death (Lipinski and Jackson, 1989).

Diet studies of other surface foraging seabirds (i.e. albatrosses) have provided ecological data on poorly known squid populations in other ocean regions, even discovering previously unknown distributions (Croxall and Prince, 1994; Cherel and Weimerskirch, 1995, 1999). Gonatid squids are a significant prey resource for oceanic predators in the CCS, including cetaceans, but investigations of mesopelagic to abyssopelagic squid are difficult and little is known (Clarke, 1996; Harvey et al., in press). Further study of Northern Fulmar diets combined with tracking studies to refine their foraging ranges would contribute valuable information about Gonatid squid ecology.

4.3. Plastic ingestion

In addition to prey distributions, Northern Fulmar diets also have been used in the Pacific and Atlantic oceans to compare contaminant loads, especially plastic marine debris (van Franeker, 2013). Similar to other studies that examined Northern Fulmar plastic ingestion, we found that plastic fragments were more abundant than industrial plastic (Mallory et al., 2006; van Franeker, 2013; Avery-Gomm et al., 2012). Overall, there has been an increase in the amount of plastic fragments and post-consumer plastics found in seabirds (Vlietstra and Parga, 2002; Nevins et al., 2005; van Franeker et al., 2005; Ryan, 2008), whereas industrial plastics (i.e. pellets) were more abundant in seabirds sampled in earlier decades (Day, 1985; Ryan, 1987; Harper and Fowler, 1987). The greater incidences of fragments or post-consumer plastic in seabirds may reflect an increase in its availability at sea, or conversely, it may reflect a decrease in industrial plastic availability (van Franeker et al., 2005; Ryan, 2008). The introduction of programs preventing the loss of industrial pellets in the early 1990s may have reduced the volume of industrial plastic in the ocean (Operation Clean Sweep as cited in Ryan, 2008; National Marine Debris Monitoring Program www.oceanconservancy.org).Recently, Avery-Gomm et al. (2012) examined 67 fulmar stomachs collected in the eastern North Pacific between 2009 and 2010. They reported 92.5% incidence of ingested plastic ($\bar{x}$ = 36.8 pieces; $\bar{x}$ = 0.385 g), similar to what has been reported in the North Sea (95%; van Franeker et al., 2011; van Franeker, 2013), but greater than amounts (number and mass) of ingested plastic than what we report in this study even though the carcasses were in similar, poor body condition upon collection.

4.4. Inter-annual variability: prey and plastic

Based on migration routes between breeding and wintering sites (Hatch et al., 2010) and estimated residency time of indigestible material in seabird stomachs (van Franeker et al., 2011; van Franeker, 2013), we assumed the prey and plastic from sampled fulmars were consumed within the CCS. In the CCS region, ocean
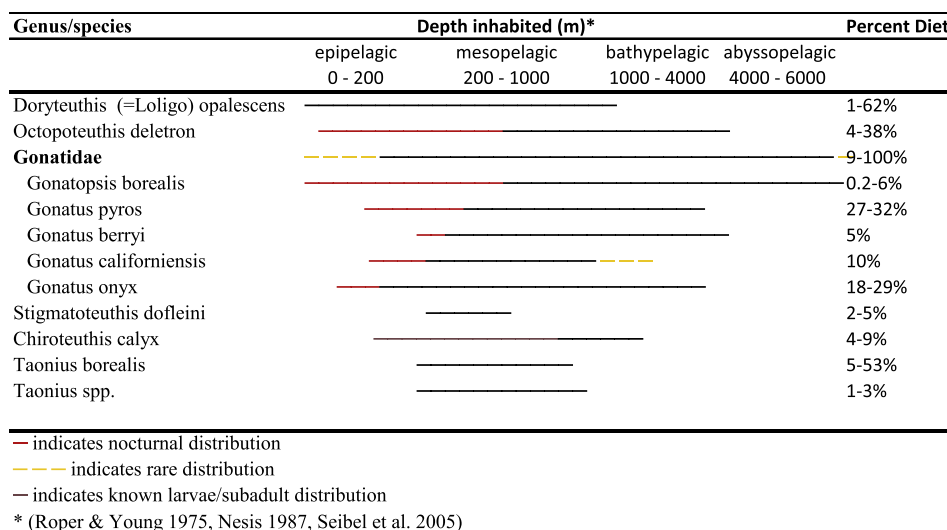
Genus/species	Depth inhabited (m)*				Percent Diet
	epipelagic 0 - 200	mesopelagic 200 - 1000	bathypelagic 1000 - 4000	abyssopelagic 4000 - 6000	
Doryteuthis (=Loligo) opalescens	————————————————				1-62%
Octopoteuthis deletron	————————————————				4-38%
Gonatidae	— — — ————————————————				9-100%
Gonatopsis borealis	————————————————				0.2-6%
Gonatus pyros	————————————				27-32%
Gonatus berryi	————————————				5%
Gonatus californiensis	————————— — — —				10%
Gonatus onyx	————————————				18-29%
Stigmatoteuthis dofleini	————————				2-5%
Chiroteuthis calyx	————————————				4-9%
Taonius borealis	————————————				5-53%
Taonius spp.	————————————				1-3%

— indicates nocturnal distribution

— — — indicates rare distribution

— indicates known larvae/subadult distribution

* (Roper & Young 1975, Nesis 1987, Seibel et al. 2005)

Fig. 3. Depth inhabited (m) by the twelve most commonly identified cephalopod genus/species in this study. Percent (%) diet was relative proportion range of genus/species in all studies combined (Baltz and Morejohn, 1977; Sanger, 1983; Hills and Fiscus, 1988; Gould et al., 1997, this study).

conditions during the two years of this study were notably different as determined by numerous metrics (PDO, SST, upwelling; Cal-COFI Rep. Vol. 45, CalCOFI Rep. Vol. 49). The fall and winter of 2003 was characterized as a weak to moderate El Niño whereas in 2007 this region experienced La Niña conditions with strong upwelling. Despite these oceanographic differences, fulmar diet indicated the squid species available to fulmars at the surface were similar in both years.

In contrast, significant interannual differences were found in multiple plastic ingestion parameters (incidence, number and mass). Northern Fulmars are an ideal bioindicators of plastic in the environment (van Franeker et al., 2011; van Franeker, 2013). Although overall plastic loads were greater in 2007 than 2003, analysis of a longer time series is necessary to interpret trends (4–8 + years; van Franeker, 2013). One explanation is that plastic increased in the CCS region, but another possibility is that the difference in oceanic conditions between the sampled years (e.g. upwelling) and the process by which plastic circulate through the CCS (non-convergent oceanic system), could have influenced the interannual differences in plastic ingestion between the two sampled years (Avery-Gomm et al., 2012). Although oceanic differences in 2003 and 2007 did not influence squid species availability (mobile prey), perhaps surface plastic differed in foraging areas and was more available to fulmars in 2007. Other explanatory factors include differing migratory paths of fulmars and/or local inputs of marine debris (land-based sources) between sampled years.

4.5. Body condition and demography: prey and plastic

Fulmars in better body condition had more prey items (by number and average beak size) and less plastic (mass of total marine debris). These relationships were driven by 10% of the sample in 2007 that included birds with relatively healthy muscle masses.

Muscle atrophy occurs after fat reserves have been depleted in a fasting or starving bird (van Franeker and Meijboom, 2002; Nevins et al., 2005). The majority of fulmars we examined were in poor health based on the lack of subcutaneous fat and reduced pectoral muscle. Equal representation of fulmars in healthy vs. poor body conditions, however, should be compared in future studies (Table 1).

Birds with greater pectoral muscle indices (i.e., healthier fulmars) contained lesser masses of total plastic debris but not fewer total pieces of plastic. The total marine debris category included non-edible items that were not necessarily plastic, but that are not naturally ingested items such as: paper fragments, hardened oil pieces, coal, rubbery pieces. In Europe, hard plastics are being phased out in manufacturing and lighter, biodegradable items that have a starch component are being used (van Franeker personal comm., 2008). If biodegradable plastics break down more readily in fulmar stomachs, the quantification of number and incidence of ingested plastics will become more complicated because these plastics are more brittle. This would result in a greater number of plastic pieces that are less in relative mass. Consequently, mass could be a better measure of plastic ingestion in seabirds over greater temporal scales and the most representative of ecological impacts on organisms (van Franeker and Meijboom, 2002). It is currently unknown if ingested biodegradable plastics affect bird health differently, however, these plastics are typically made from composites of synthetic polymers in addition to bio-additives to accelerate degradation times (starch, vegetable oil, or specialist chemicals) and do not decompose completely or quickly (Derraik, 2002; Thompson et al., 2004; Ryan et al., 2009; O'Brine and Thompson, 2010 as cited in Cole et al., 2011). The remaining synthetic polymers from biodegradable plastics could potentially remain in seabird stomachs, but perhaps in lesser masses than petroleum based plastics.

The majority of beach cast fulmars in the present study were immature birds in poor body condition, a factor that could influence plastic ingestion. In addition to variables examined in this study, seasonal variation, migration route, and cause of death, among other factors could influence the amount and type of plastic ingested (van Franeker and Meijboom, 2002). It has been hypothesized that starving birds ingest more plastic. Although apparent healthier fulmars in 2007 contained slightly less debris by mass, ingested debris by number was greater in 2007 than in 2003. Furthermore, plastic loads of fulmars in the North Sea were not related to gradual starving of the bird (van Franeker and Meijboom, 2002).

The effect of season on plastic loads in fulmars is less clear. Mallory et al. (2006) found a difference in plastic incidence between breeding and non-breeding fulmars from Canadian colonies in the Atlantic. They reported more plastic in fulmars collected earlier in the breeding season, indicating that the plastic was acquired during winter migration (similar findings were reported in thick-billed murres sampled from the eastern Canadian Arctic; Mallory et al., 2006; Provencher et al., 2010). Similarly, breeding and non-breeding adults in the North Sea had greater plastic loads until July, then a decrease in plastic loads occurred, followed by an increase in plastic loads again in the months following (van Franeker personal comm., 2008). It was thought that fulmars ingest the most plastic in wintering areas, break it down, and offload the plastic by regurgitating micro plastics to chicks during the following breeding season (van Franeker et al., 2011), although lesser retention time (weeks instead of months) has been recently suggested (van Franeker, 2013).

We report a pronounced relationship between plastic load and immature, wintering fulmars, although we were unable to make adequate comparisons with adult fulmar samples. Similarly, studies in the North Sea indicated that upon initial inspection, immatures contained greater levels of plastic (van Franeker and Meijboom, 2002), but after additional years of study (2004–2009), age difference was consistent to a level that all different age groups could be combined in a single monitoring unit (van Franeker et al., 2011). They reported that the geometric mean mass of plastics indicated the same short-term annual fluctuations and long-term patterns for both adults and non-adults, in spite of the substantial difference between these groups (van Franeker and Meijboom, 2002; van Franeker et al., 2011). Although their findings indicate that overall patterns in plastic ingestion can be applied to all age groups, we sampled only immature, wintering fulmars.

4.6. Multivariate relationships

The Canonical correlation results indicated that fulmars carrying heavier loads of plastic fragments ate smaller cephalopods, but these findings were not statistically significant and the mechanism remains uncertain. These findings may be of biological relevance if trends in plastic ingestion continue for fulmars foraging in the CCS. Plastic ingestion appears to be increasing or stabilizing in fulmars caught in Alaska's long-line fisheries. Ingested plastic incidence in fulmars was 71% in 2006, and increased yearly until 2009 to 83% after which a decrease in incidence occurred in birds sampled in 2010 (Nevins et al., 2014).

If plastic-induced satiation is occurring, one would expect a critical level where dietary changes (i.e., a reduction in the number or mass) take place as ingested plastic levels increase. Critical level would be difficult to identify because it would be species-specific, based on different stomach morphologies, metabolic rates, diets, and retention times. Currently, the retention time of ingested plastics in fulmars is poorly understood. The effect of ingested plastics on digestion assimilation efficiency was examined in white-chinned petrels (*Procellaria aequinoctialis*) in the 1980s (Ryan, 1989). Ryan (1989) found no significant difference between petrels

fed polyethylene pellets and control birds, but suggested further testing of other types of plastics. Also, he predicted a half-life of at least one year for pellets in the stomachs of petrels (Ryan, 1989). Similarly, Day (1985) suggested that retention time in petrels was approximately 6 months or more for plastic (via wear in the gizzard and passage through the gut). However, van Franeker et al. (2011) and van Franeker (2013) suggested that these papers probably overestimated the residence time of plastics in seabird stomachs. They suggested that disappearance rates of ingested plastics was size dependent, and could be conservatively estimated at greater than 75% per month, (assuming mostly hard plastics) and lesser time for softer plastics (foamed and sheet-like materials; van Franeker et al., 2011). As plastics increase in the marine environment, it becomes imperative to examine the retention times of different types and sizes of plastics. Experiments that actively feed seabirds plastics, however are not a widely supported idea for ethical and logistical purposes. Other researchers that examined retention times focused solely on the time scale or seasons that ingestion was occurring (van Franeker and Bell, 1988; Mallory et al., 2006). To understand if there is a critical level and how to define it in seabirds, the first step may be to examine retention times of prey items and hard parts on a species-specific level.

One of the biases with using prey hard parts as a proxy for seabird diet is the difference in passage rates and retention of hard parts, which is often unknown. From marine mammal diet studies, we know that cephalopod beaks are retained in predator stomachs longer than other hard parts, such as fish otoliths (Harvey, 1989; Santos et al., 2001). For this reason, the importance of cephalopods in fulmar diet may be overestimated. Although only cephalopod beaks and plastic were studied (the few otoliths recovered were degraded and deteriorating), fulmars forage on a variety of other soft-bodied prey (e.g. amphipods, copepods; Hatch and Nettleship, 1998). Evidence of fish was found in this study, in addition to small copepods (which may or may not be incidental intake). The fulmars sampled in 2003 were spotted by an at-sea survey team eating jellyfish gonads and picking ecto-parasites off of sunfish (*Mola mola*; Nevins et al., 2005), although dietary evidence of these prey was not present in our samples due to efficient digestion and less retention of soft-bodied prey. In Cape Petrels (*Daption capense*), squid beaks decreased in number by 90% between December and January indicating retention time of approximately one month. Antarctic Petrels (*Thalassoica antarctica*) and Southern Fulmars (*Fulmarus glacialoides*) had the same pattern in cephalopod beak reduction (van Franeker et al., 2011). Being that beaks are of similar durability as hard plastics, it is assumed that retention times were similar in Northern Fulmars, and that 75% of beaks ingested at the beginning of the month had passed through the digestive system by the end of the month (van Franeker et al., 2011). If this is true and most plastics, cephalopod beaks, and other prey items were retained for about a month, a critical level at which plastics interfere with prey consumption may be of less importance.

How plastic ingestion affects individuals, populations of seabirds, and other marine life is of continued importance as the use of plastics around the world increases. There are other issues with plastic ingestion that are outside the scope of this study that include contaminants, toxin accumulation, endocrine disrupters, and micro plastics infiltrating prey sources. These issues are key components for understanding how prey and plastic ingestion are correlated, and the overall negative health effects of plastic ingestion on Northern Fulmars.

Acknowledgements

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