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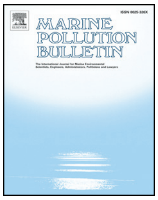

Plastic debris in great skua (*Stercorarius skua*) pellets corresponds to seabird prey species

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ABSTRACT

Plastic is a common item in marine environments. Studies assessing seabird ingestion of plastics have focused on species that ingest plastics mistaken for prey items. Few studies have examined a scavenger and predatory species that are likely to ingest plastics indirectly through their prey items, such as the great skua (*Stercorarius skua*). We examined 1034 regurgitated pellets from a great skua colony in the Faroe Islands for plastics and found approximately 6% contained plastics. Pellets containing remains of Northern fulmars (*Fulmarus glacialis*) had the highest prevalence of plastic. Our findings support previous work showing that Northern fulmars have higher loads of plastics than other sympatric species. This study demonstrates that marine plastic debris is transferred from surface feeding seabird species to predatory great skuas. Examination of plastic ingestion in species that do not ingest plastics directly can provide insights into how plastic particles transfer vertically within the food web.

1. Introduction

Plastic pollution has been recognised as an emerging global environmental issue (UNEP, 2014). Plastic debris is ubiquitous in the marine environment, and has been found in both highly populated regions, and remote areas of the world such as the Arctic (Obbard et al., 2014; Vegter et al., 2014). Plastic particles have been regularly found to be ingested by marine animals, and dozens of seabird species have now been reported to have ingested plastic pollution (Gregory, 2009; Laist, 1997). Seabirds have been shown to ingest both macro- (pieces greater than 5 mm) and micro-plastics (pieces less than 5 mm), making this group particularly susceptible to marine debris (Provencher et al., 2015; UNEP, 2011, 2014).

Marine plastic debris includes both industrial plastics and user plastics (Moore, 2007). Industrial plastics are commonly found in the marine environment in the form of hard plastic pellets (van Franeker et al., 2011). These pellets are formed as precursors to the formation of consumer products. User plastics come from consumer products, including all hard plastics (polyethylene) and styrofoam (polystyrene). Once in the environment plastic pieces are broken down over time due to chemical and physical degradations.

Seabirds have been shown to be important for monitoring plastic pollution in the environment (van Franeker et al., 2011). For example, Northern fulmars (*Fulmarus glacialis*) (hereafter fulmar) are part of the North Sea ecological monitoring programme designed to track marine pollution (van Franeker et al., 2011). Ingestion of plastics by most seabirds is thought to occur because they mistake plastic items for prey in the water column (Cadee, 2002). There are differences in plastic ingestion between seabirds with different foraging strategies which have been shown in several studies comparing ingestion across seabird foraging guilds (Avery-Gomm et al., 2013; Provencher et al., 2014). To date, much of the work on seabird ingestion of plastics has focused on species that are thought to directly ingest plastics from the environment when mistaking plastics for prey items (Avery-Gomm et al., 2013; Cadee, 2002; Donnelly-Greenan et al., 2014; van Franeker et al., 2011). Less attention has been given to species that risk ingesting plastic indirectly through their prey items (Furness, 1985; Ryan and Fraser, 1988). Species that ingest plastics indirectly can play a role in expanding our understanding of marine plastic pollution in the environment, specifically in tracking how plastics move through the environment, and what species are affected by plastic pollution, both identified as priorities for marine debris research (Vegter et al., 2014).

The great skua (*Stercorarius skua*), is a top predator seabird in the North Atlantic region. It scavenges, kleptoparasitises or predates on other marine bird species (Furness, 1987; Phillips et al., 1997), which potentially makes it a suitable model monitor of prevalence of plastics quantitatively and qualitatively in different components of the food web. Seabirds that forage at the surface of the water column, where plastic debris often floats, tend to have higher burdens of ingested

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plastics than those that forage deeper in the water column (Avery-Gomm et al., 2013; Bond et al., 2014; Provencher et al., 2014). Some species are also more prone to accumulating ingested plastic depending on their capability to regurgitate indigestible stomach content (Furness, 1985). Since plastic ingestion has been found in several species of seabirds from the Faroe Islands (Faroes hereafter) (van Franeker et al., 2011; Jensen, 2012; Provencher et al., 2014), we expected great skuas in the region to show evidence of plastic ingestion, but we expected the prevalence and number of plastic pieces to vary in respect of the type of prey species the great skuas consumed. The diet of Faroese great skuas includes fish, seabirds, and sometimes also terrestrial birds and mammals (Hammer, unpub. data). The main seabird species they feed on are black-legged kittiwakes (*Rissa tridactyla*) (hereafter kittiwake), Atlantic puffins (*Fratercula arctica*) (hereafter puffin), and fulmars. In addition to these seabird prey species, great skuas scavenge fish from behind fishing vessels or steal fish from other birds near the colony (Bayes et al., 1964; Hammer unpub. data). More rarely Faroese great skuas also feed on common guillemots (*Uria aalge*), mountain hares (*Lepus timidus*), Manx shearwater (*Puffinus puffinus*), and eggs from various birds (Bayes et al., 1964; Hammer unpub. data).

The aim of this study is to assess prevalence of plastic ingestion in Faroese great skuas based on sampling pellets, a common method of assessing great skua diet. Pellets contain indigestible material such as feathers, bones, hair and plastic (Furness, 1987). Due to the described foraging strategies of great skuas, it is likely that most ingested plastics from these birds come from the marine environment (Ryan and Fraser, 1988). First, we examine the prevalence of plastic debris in the population and whether it depends on the number of pellets sampled per territory. Second, we compare plastic debris between pellets containing different prey types, and discuss how our estimates of prevalence in seabird species that skuas prey on compares to other reported values for those same species collected through direct sampling of the birds. This allows assessing if sampling through this indirect method yields similar quantitative results to direct dissection methods.

2. Methods

1034 regurgitated pellets from 165 great skua territories were collected during the breeding season April–August 2013, at Skúvoy in the Faroes (61°46′N 6°49′W). Pellets were collected during territory visits, which occurred 2–3 times a week after first apparent sign of territory attendance. The median number of pellets found in each territory per visit was 1 and the highest number of pellets found in a territory during one visit was 36. Considering how ardently great skuas defend their breeding territories (Furness, 1987), it is reasonable to assume that the regurgitated pellets found within a great skua colony are produced only by the great skua pairs within each territory. All pellets were collected and examined in the field to determine prey type. The prey type was recorded for all pellets and if plastic material was found, the pellets were individually bagged to prevent mixing of contents between pellets. If there was no plastic found in the pellet they were collected in a separate bag. While the content of some pellets were distinguishable to species level by size and colour of feathers and odour (e.g., fulmar and kittiwake), other pellets could not readily be identified to species level such as puffin, common guillemot, black guillemot (*Cepphus grylle*), and razorbill (*Alca torda*), but could still be distinguished from other seabirds as auks. These species were thus grouped as “auks” in this study. Other pellets which contained fish or mountain hare were also identified. 73 pellets contained more than one type of prey, and 27 of these contained a mixture of bird and fish and were excluded from all analyses. The remaining mixed pellets (n = 46) contained a mixture of different seabird prey (with 6 containing plastic). None of the single species categories (auk, kittiwake and fulmar) contained mixed pellets. The mixed seabird pellets were included in the general comparison between (bird, fish and other) types of pellets only, but were excluded from the comparison between different bird types.

All plastic particles from the pellets were collected, dried, and sorted. Plastic particles were sorted using the ‘Save the North Sea’ protocol (van Franeker et al., 2011) into industrial and user (fragments, threadlike, sheetlike, foamed, and other) and weighed. Mean values of plastic weight are reported for the entire sample of pellets including pellets with no plastic (mass abundance) and only for the pellets which contained plastic (mass intensity). The colour of each piece was also noted and recorded by a single observer. The prevalence (presence or absence) and number of pieces per pellet of plastics in each pellet collected are presented, along with the prevalence and number of plastics in each pair's territory.

Statistical analyses were carried out in programme R (R Core Development Team, 2014). First we looked whether the prevalence of plastics in a territory was related to search effort (measured in number of pellets collected per territory) to determine if number of collected pellets influenced the detection of plastic pollution using a generalised linear model (GLM) with a binomial distribution. The number of plastic pieces in the pellets was compared between pellets with different prey types using a Generalized Linear Mixed Effects Model (lme4 Bates et al., 2014) with a binomial distribution, logit link function and territory as random effect to account for the non-independence of pellets collected from the same individual birds. Numbers of plastic pieces per pellet were compared across pellets containing different bird prey species only (fulmars, kittiwakes and auks). The data contain a low number of non-zero values. The general mixed model assuming zero-inflation (glmmADMB, Skaug et al., 2012), and a negative binomial distribution, showed no evidence for zero-inflation (estimated zero-inflation proportion = 0.00002), thus zero-inflation was no longer considered for further analyses as it is unnecessary and difficult given the size of the dataset. Among error distributions that could be suitable to fit the observed distribution of our data (negative binomial and Poisson lognormal), the negative binomial error distribution had the better fit to our data structure, because the negative binomial distribution better justified the assumption of homoscedasticity of the Pearson residuals. However, currently available models that allow the use of a negative binomial distribution do not support the inclusion of a random effect. To examine the importance of territory as random effect, which, if not important, could potentially lead to an overfitted model, we fitted a mixed model with an alternative error distribution (Poisson log distribution) with territory as a random effect. The variance estimate for the random effect was zero (glmmADMB). It would be therefore justified for our data to exclude territory as a random effect without compromising the conclusion from a model without random effect. Hence we used the mixed model with negative binomial (glmmADMB) to compare number of plastic items per pellet between pellets containing remains of the three seabird prey remains (fulmar, kittiwake, auk). Statistical tests where $p < 0.05$ were considered statistically significant. Means are presented with standard deviations.

3. Results

On the 165 study territories, between 1 and 63 pellets were collected per territory (median = 4) over the breeding season and the number of pellets found during a single visit ranged from 0 to 32 pellets per territory. Pellets containing at least one piece of plastic (Fig. 1) were found on 48 territories (30%). The prevalence of plastics in a territory did not significantly vary with the number of collected pellets per territory (GLM, Z = 0.97; $p = 0.33$). From the total of 1034 pellets, 59 individual pellets (6%) contained plastic debris with a total of 179 plastic pieces ranging from 1 to 15 pieces (median of 2 pieces) per pellet. The plastic pieces found in the pellets were both from consumer and industrial sources. The most common plastic type found was hard fragments of user plastics (Table 2, Fig. 1a). Although many colours of plastics were found, the most common colour of plastic found in the pellets was white/yellow (68%). Red plastic was the next most common colour found in the pellets (10%), followed by pink (5%), orange (4%), black

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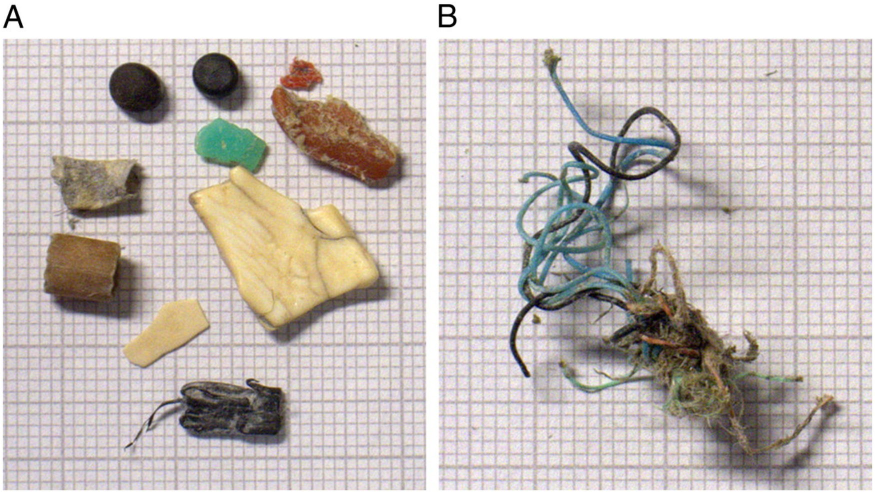

Fig. 1. Sample of plastic debris pieces recovered from great skua regurgitated pellets. A — shows industrial plastics (two small black pellets at the top left), and hard fragment plastics. B — threadlike plastic pieces. Minor grid paper shows 1 mm by 1 mm dimensions.

(3%), green (2%) and blue (2%). The final 6% of the plastics were made up of other colours.

The proportion of pellets containing plastic pieces (prevalence) varied between pellets containing the remains of different prey species (GLMM with binomial error and territory as random factor (lme4, Bates et al., 2014): $F_{6,837} = 3.78$, $p < 0.001$; Table 1). 86% of the pellets containing plastics were from bird prey, 7% from fish, 5% from mixed bird and fish and 2% from mountain hare. Where identification of bird prey type was possible we found that pellets containing the remains of fulmars had significantly higher prevalence of plastics than pellets of kittiwake with non-overlapping confidence intervals (Table 1).

The number of plastic items found per pellet also differed between seabird prey species. Pellets with fulmar remains contained the highest numbers of plastics (range 1–15), kittiwake pellets had 1–9 and auk pellets had 1–3. The pellets with fulmar remains contained 0.37 (95% CI = 0.17–0.62) plastic pieces which was significantly higher than pellets with auks remains (mean of 0.08 pieces (95% CI = 0.04–0.16; GLM with negative binomial error: $Z = 3.59$, $p < 0.001$).

The total plastic pieces per pellet weighed on average 6.6 (SD = 5.97) mg (n = 1034 pellets including pellets with no plastic, mass abundance). The mean mass of the plastic in great skua pellets which contained plastic (mass intensity) was 116.5 (SD = 225.0) mg per pellet (n = 59). On average mass abundance, fulmar pellets contained 15.9 (SD = 54.6) mg of plastic debris (n = 173), kittiwake pellets contained 2.2 (SD = 15.9) mg of plastics (n = 293) and pellets containing auks remains had an average 5.2 (SD = 28.9) mg of plastics (n = 151). The plastic mass intensity (mean mass of plastic of pellets which contained plastic) did not differ between types of pellets $F_{6,58} = 0.47$, $p = 0.822$.

Table 1
Types of pellets which contained plastic, and a modelled prevalence of plastic assuming a binomial distribution with 95% confidence interval and territory as random effect.

Prey type	Total number of pellets	Number of pellets containing plastics	Modelled plastic prevalence % (CI)
Fulmar	174	26	13% (6,26)
Kittiwake	308	9	2% (1,6)
Auk	181	10	5% (2,10)
Mixed seabird	46	6	11% (4,28)
Fish	98	4	3% (1,11)
Mixed fish and bird	27	3	8% (2,27)
Mountain hare	11	1	8% (1,48)
Other[a]	189	0	0[b]
Total	1034	59	

[a] Other types of pellets included eggs, insects, sheep and terrestrial birds.
[b] Computation of 95% CI for this category was not possible.

Table 2
Mean number and mass abundance and standard deviation of different plastic types found in different pellet types. Prevalence is percentage of occurrence in pellets of that prey type.

	Prevalence	Number of plastics		Mass (g) of plastics		
	(%)	Mean	SD	Mean	SD	Max
Fulmar (n = 26)						
All plastics	15.0	0.532	2.101	0.0146	0.0297	0.2042
Industrial plastic	2.3	0.043	0.444	0.0008	0.0064	0.0329
User plastic	13.9	0.489	2.130	0.0013	0.0303	0.2042
Fragments	13.9	0.457	2.195	0.0020	0.0261	0.1723
Foamed	0.6	0.005	0.115	0.0022	0.0003	0.0022
Threadlike	2.9	0.027	0.245	0.0023	0.0253	0.2042
Kittiwake (n = 9)						
All plastics	3.4	0.116	0.773	0.0024	0.0088	0.0868
Industrial plastic	0.3	0.003	0.062	0.0001	0.0011	0.0174
User plastic	3.4	0.113	0.772	0.0023	0.0087	0.0868
Fragments	3.1	0.102	0.771	0.0020	0.0080	0.0868
Foamed	0.3	0.003	0.062	0.0000	0.0001	0.0015
Sheet	0.3	0.003	0.062	0.0001	0.0025	0.0410
Other	0.3	0.003	0.062	0.0002	0.0030	0.0478
Auk (n = 10)						
All plastics	4.6	0.106	0.408	0.0062	0.0236	0.1472
Industrial plastic	0.7	0.007	0.086	0.0002	0.0024	0.0277
User plastic	4.6	0.099	0.402	0.0060	0.0236	0.1472
Fragments	4.6	0.079	0.384	0.0046	0.0203	0.1472
Foamed	0.7	0.007	0.086	0.0005	0.0067	0.0784
Thread	0.7	0.007	0.086	0.0000	0.0005	0.0053
Other	0.7	0.007	0.086	0.0009	0.0117	0.1366
Mixed seabird (n = 6)						
All plastics	19.4	0.645	1.556	0.279	0.3022	0.0543
Industrial plastic	9.7	0.097	0.426	0.076	0.0131	0.0023
User plastic	16.1	0.548	1.696	0.305	0.3182	0.0572
Fragments	16.1	0.387	1.443	0.250	0.0057	0.0630
Foamed	3.2	0.161	1.390	0.259	0.3509	0.0010
Fish (n = 4)						
All plastics	4.1	0.041	0.199	0.0014	0.0097	0.0909
Industrial plastic	1.0	0.010	0.103	0.0002	0.0020	0.0195
User plastic	3.1	0.031	0.174	0.0012	0.0095	0.0909
Fragments	3.1	0.031	0.174	0.0012	0.0097	0.0909
Mixed bird and fish (n = 3)						
All plastics	11.1	0.148	0.362	0.0045	0.0167	0.0853
User plastic	11.1	0.148	0.362	0.0045	0.0167	0.0853
Fragments	3.7	0.037	0.204	0.0006	0.0035	0.0170
Thread	7.4	0.074	0.277	0.0034	0.0171	0.0853
Other	3.7	0.037	0.204	0.0005	0.0025	0.0122
Mountain hare (n = 1)						
All plastics	9.1	0.091	0.316	0.0042	0.0104	0.0332
Industrial plastic	9.1	0.091	0.316	0.0030	0.0105	0.0332
User plastic	9.1	0.091	0.316	0.0012	0.0042	0.0132
Fragments	9.1	0.091	0.316	0.0012	0.0042	0.0132

4. Discussion

Less than a third (29%) of the great skua territories showed evidence of plastic ingestion, suggesting that a minority of great skuas at the Skúvoy breeding colony are exposed to plastics during the breeding season. This was not simply due to small number of pellets picked up in some territories as prevalence of plastic in a pair's diet was independent of the number of pellets collected. Only a small proportion of regurgitated pellets examined contained plastics (6%). Both user and industrial plastics were found in skua pellets. Among user plastics we found hard, threadlike, foamed and sheetlike plastics illustrating that great skuas are susceptible to multiple types of plastic pollution. Our findings suggest that plastic ingestion does occur among great skuas in the Faroes, but prevalence and number of plastic pieces ingested are low compared to other species in the North Atlantic and the North Sea (Provencher et al., 2014; van Franeker et al., 2011).

We found that the most common colour of plastic pieces in great skua pellets was white/yellow. Without knowledge of the background availability of plastics in the environment it cannot be determined if this shows a preference for debris colour among certain seabird species which the great skua preys on, or simply a sampling of the plastics available to the seabirds in the area. Future plastics work around the Faroes should combine at sea surveys of plastics (e.g., Desforges et al., 2014); with seabird assessments to determine if different seabirds selectively ingest different types and colours of plastics from the environment.

The number and weight of plastic particles found in pellets of great skuas from the Faroes was also relatively low. It should, however, be noted that individual dietary specialisation, which is commonly seen among great skuas (Votier et al., 2004), could potentially result in a low number of pairs taking up a disproportionally high amount of plastic-rich prey. For example, out of the 48 territories where pellets with plastic were found in this study, 12 territories had pellets with plastic on consecutive territory visits. Unlike petrels which accumulate plastic in the gizzard, due to their gizzard being separated from the proventriculus by a sphincter, skuas have an anatomy that allows them to regurgitate both gizzard and proventriculus contents (Furness, 1985). Although this would suggest that plastic does not likely accumulate in great skua stomachs (Furness, 1985), we should consider the implications for great skuas specialising as seabird specialists which may carry high loads of plastics could result in a chronic exposure to marine debris. Perhaps more importantly such chronic plastic ingestion could lead to increased exposure to persistent organic pollutants which are found in and on marine plastics (Hirari et al., 2011). More work is needed to assess the relationship between the high levels of persistent organic pollutants and plastics in Faroese great skuas (Teuten et al., 2009).

Plastic debris burden was found to be associated with prey species that are known to ingest plastics (e.g., fulmars; Jensen, 2012). Similarly, plastic debris was less in pellets that contained seabird species known to ingest low levels of plastics, for example puffins where stomach examination of these birds around the Faroes showed only 1–5% to contain plastic (Bergur Olsen, pers. comm.). Similarly, a recent examination of 14 adult kittiwake stomachs found 1 plastic thread, in each of two stomachs (Jens-Kjeld Jensen, pers. comm.). This difference in plastic debris load between species has also been found on a wider spatial scale (e.g., auks; Bergur Olsen, pers. comm.; Provencher et al., 2014). The association between plastics and prey type indicates that great skuas are taking in plastics with their seabird prey meals. Although great skuas may also ingest debris directly when scavenging, these results suggest that most of the plastic ingestion by great skuas is related to their seabird prey. Alternatively, if great skuas were ingesting plastics from other sources frequently, little difference would be expected in the plastics associated with the prey type; note that we found low levels of ingested plastic in pellets containing fish remains.

Our findings suggest that marine plastic pollution is being transferred up the food chain to top level predators in the North Atlantic that are likely ingesting most plastics indirectly through their prey items. Importantly, we show that plastic pollution is transferred to great skuas mainly through fulmars, although these seabirds are not the main proportion of the skua diet (Table 1). This suggests that plastic pollution may be transferred up the food chain disproportionately when prey species differ in propensity to accumulate marine debris. Additionally, these plastic particles are regurgitated on land and the fate and further implications for the terrestrial ecosystem remain unclear.

In the Faroes, 91% of fulmar stomachs examined ($n = 699$) contained ingested plastics (Jan van Franker pers. comm.). While it is recognised that each fulmar ingested by a great skua produces approximately 4–5 pellets (Votier et al., 2001), and several great skuas may share a fulmar carcass as food at sea, the prevalence of plastic assessed directly in fulmar stomachs is much higher than we demonstrate for fulmar pellets in this study (13.4%). This suggests that great skua pellets may not be a reliable tool for quantitative assessment of plastic of their various prey species. Ryan and Fraser (1988) showed similar findings for the south polar skua (*Stercorarius maccormicki*), and suggested that smaller plastic pieces are not likely incorporated into pellets but pass through to the faeces, or are small enough to be lost from the pellets before collection. Votier et al. (2001) showed that proportion of auks consumed is underrepresented in great skua pellet production than larger gulls and fulmars. Considering this difference in turn-over rate between prey species it could perhaps suggest that there is more plastic in auks than we would expect, but this contradicts stomach analysis of Faroese puffins, which suggest that only 1–5% of puffins have plastic (Bergur Olsen, pers. comm.). Although overall trends of plastic ingestion in marine birds are found by examining skua pellets, the absolute amount of plastic ingestion is not quantitatively reflected in pellets.

One pellet containing mountain hare remains also contained plastics. As hares are herbivores that graze on low lying vegetation, the plastics associated with hare pellets are therefore unlikely to have come from hares. Thus, ingested plastics in great skuas may not be completely regurgitated with each meal, and may actually be retained over some period and regurgitated with future meals. It has been suggested that for instance fulmarine petrels excrete ca. 75% of plastic particles within a month ingestion (van Franeker and Law, 2015; but see Ryan, 2015). This may suggest that although great skuas may regurgitate plastics associated with their meals, plastic debris may remain within the digestive tract of great skuas beyond the meal and regurgitation, and the difference in plastic prevalence between prey species may be even bigger than suggested by our results. Therefore, even though skuas are not likely to accumulate plastics to the same degree as other birds that do not regurgitate (i.e. the fulmar), they may still be susceptible to accumulating debris and thus susceptible to the potential negative effects of ingesting plastics (Teuten et al., 2009; Yamashita et al., 2011).

While it must be recognised that quantitative assessment of plastic through regurgitated pellets may be confounded by various factors, we believe that the study of these plastic particles reveals relevant aspects of how plastic pollution moves in the food web. We show that bird species that are primarily ingesting plastic debris indirectly are still being exposed to plastic debris from the marine environment. This illustrates how plastic debris is being transferred up the food web in the marine environment, and that the potential impacts of ingested plastics may affect upper trophic level wildlife that prey upon species that directly ingest plastic pollution.

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