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SPECIAL ISSUE-LETTER

Foraging strategy impacts plastic ingestion risk in seabirds

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Scientific Significance Statement

Seabirds are of particular concern for exposure to plastic marine debris via ingestion because they are high trophic level organisms and eat a diverse diet. Differences in seabird foraging strategies likely influence rates of plastic ingestion, but for many seabirds, the degree to which differences in diet impact the risk of plastic ingestion is poorly understood. We provide evidence that differences in foraging strategy between otherwise closely related species correspond with significant differences in plastic ingestion rate.

Abstract

Plastic debris is a pervasive environmental challenge described as a worldwide crisis for marine life, and seabirds are particularly sensitive to the pollutant. Seabirds exhibit a range of foraging strategies, from generalist scavengers to specialist predators, which likely influences their risk of plastic ingestion. Our study evaluates this relationship using two congeneric seabirds, including a generalist species (the Herring Gull, *Larus argentatus*) and a more specialist species (the Great Black-backed Gull, *Larus marinus*) nesting in the Gulf of Maine. Analysis for stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) was used to evaluate interspecific differences in diet and niche size, while dietary samples were collected for analysis of plastic ingestion. Herring Gulls exhibited significantly larger isotopic niche size and displayed significantly higher rates of plastic ingestion than Great Black-backed Gulls (p value < 0.01), though the range of physical characteristics and relative size of plastics in the diet did not differ significantly.

Plastic pollution is a growing environmental challenge with especially negative implications for marine species (Derraik 2002). Up to 12.7 million metric tons of plastic are estimated to enter the world's oceans annually (Jambeck et al. 2015), and there is evidence of plastic ingestion in nearly 700 marine species (Gall and Thompson 2015). Seabirds are of

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critical concern, with 99% of species and 95% of individuals expected to have ingested plastic by 2050 (Wilcox et al. 2015). In extreme cases, plastic ingestion can lead to stomach ulcers, starvation, stomach blockage, and toxin accumulation that can lower body condition and potentially impact reproduction (Secretariat of the Convention on Biological Diversity 2012). Seabirds are at risk of plastic ingestion both directly and through secondary consumption via their prey. Therefore, understanding the mechanisms through which plastic is ingested is critical to characterizing the threat of the pollutant.

Seabirds exhibit a broad array of foraging strategies ranging from highly specialized marine predators to generalist scavengers, and even closely related species can vary greatly along this continuum (Good 1998; Rome and Ellis 2004; Steenweg et al. 2011; Craig et al. 2015; Nisbet et al. 2017). In areas where plastic debris is pervasive, it has been suggested that a generalist foraging strategy may correlate with an increased threat of plastic consumption, as plastic debris may be more readily mistaken for food (Ryan 1987; Provencher et al. 2014). Additionally, there is evidence that, for visual foragers like seabirds, physical characteristics of plastic such as color and shape may contribute to this trend. As scavengers have a more varied prey base, they may also mistake a wider variety of plastic particles for food items (Good 1998; Santos et al. 2016; Nisbet et al. 2017).

Our study evaluates the influence of foraging strategy on plastic ingestion risk. To do so, we compared plastic ingestion in two congeneric species of gull (the Herring Gull, *Larus argentatus*, and the Great Black-backed Gull, *Larus marinus*) that vary along the foraging strategy continuum. Though these closely related seabirds breed in mixed-species colonies and share many similarities in life history traits, they have been found to vary substantially in foraging strategy; the Herring Gull is a more generalist scavenger, while the Great Black-backed Gull is a more specialized marine predator (Clapp et al. 1983; Good 1998; Craig et al. 2015; Nisbet et al. 2017). We hypothesized that plastic ingestion would correlate positively with scavenging behavior, with the generalist experiencing higher overall prevalence of plastic ingestion as well as consumption of a wider range of plastic characteristics in comparison to the specialist.

The prevalence of plastic particles in the diet of both species was assessed using standard diet sampling of seabird gastrointestinal tracts, regurgitant, and pellets. Pellets, which are cast as a mechanism to expel indigestible prey items (at a rate of ~ 1 pellet per meal), concentrate nonedible prey materials and are therefore particularly suitable for investigating the prevalence of plastic debris in seabird diet (Spaans 2002). Stable isotope analysis of feathers was used to verify differences in diet and niche size between the species. Stable isotope analysis of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in feathers reflects a bird's diet over the timescale of feather growth and contains information about the relative contribution of foraging resources during that period (Inger and Bearhop 2008; Bond and Jones 2009). Feathers from chicks in particular, integrate the resources with which adult birds have provisioned their young and are therefore suitable for answering questions about local foraging behavior and diet during the breeding season (Craig et al. 2015). The distribution of stable isotope values (expressed in δ notation as parts per thousand; ‰) can be considered to describe an isotopic niche, defined here as a two-dimensional area in δ-space (‰^{2}; Newsome et al. 2007), with a larger isotopic niche indicating a more generalist foraging strategy.

Our study was conducted in the Gulf of Maine (GOM), one of the most diverse and productive marine temperate areas in the world. Threats to the GOM, which include overfishing and climate change, have been extensively investigated (Harris and Tyrrell 2001; Pershing et al. 2015); however, few studies have explored the extent of plastic contamination in this marine region (Podolsky 1989; Podolsky and Kress 1989; Law et al. 2010). Seabirds, as high trophic level organisms that are known to be sensitive to anthropogenic pressure, are useful as indicators of marine health and contamination including plastic pollution (Burger and Gochfeld 2004; Acampora et al. 2016). Seabirds breeding in the GOM therefore present an opportunity to evaluate the extent of plastic debris contamination in this under-represented region. Additionally, establishing a relationship between foraging strategy and plastic consumption may allow for the prediction of risk in other seabird species in the GOM and beyond based on their position along the foraging strategy continuum.

Methods

Sample collection

Samples were collected from seabird nesting colonies in New Hampshire (NH) and Maine (ME), U.S.A., located approximately 10 km offshore in the GOM. The majority of samples were collected from a mixed-species gull nesting colony on Appledore Island, ME (42.9891°N, 70.6142°W), and small number of samples were collected from a protected tern colony on White/Seavey Island, NH (42.9880°N, 70.6135°W).

Feather samples were collected from gull chicks ($N = 9$ for each species) during banding activities and stored in paper envelopes for stable isotope analysis. Samples collected for plastic analysis included GI tracts, regurgitant, and pellets of adult birds and chicks. Deceased birds were opportunistically collected from the nesting colony, with an additional sample of deceased gulls ($N = 7$) lethally removed from White/Seavey Island in the course of permitted Roseate Tern (*Sterna dougallii*) predator management activities. Regurgitant samples were collected during banding activities. Pellets were collected every 2–3 d throughout the breeding season from areas surrounding gull nests and were identified to species based on the distribution of gull species nesting in the colony. All dietary samples were bagged individually in the field and frozen. We analyzed a total of 128 dietary samples collected from May through August of 2018 (Table 1).

Table 1. Summary of plastic particles ingested by Herring Gulls (*L. argentatus*) and Great Black-backed Gulls (*L. marinus*) nesting in the GOM in 2018. Sample size and frequency of plastic occurrence are reported for all samples. Mean ± SD of cumulative weight and area per sample relative to average body size of each species (mg sample g^{-1} bird tissue and mm^2 g^{-1} bird tissue, respectively) is reported for samples that contained plastic.

	Herring Gull	Great Black-backed Gull
Sample size (*N*)		
Pellet	46	39
Regurgitant	14	8
Adult	8	8
Chick	3	2
Frequency of occurrence (%)		
Pellet	63.04	23.08
Regurgitant	14.29	12.50
Adult	50.00	12.50
Chick	0.00	0.00
Relative weight ± SD (mg g^{-1})		
Pellet	0.18 ± 0.27	0.09 ± 0.13
Regurgitant	0.12 ± 0.17	0.01
Adult	0.04 ± 0.06	0.00
Relative area ± SD (mm^2 g^{-1})		
Pellet	2.00 ± 4.66	0.11 ± 0.40
Regurgitant	0.15 ± 0.18	0.01
Adult	0.05 ± 0.48	0.00

Stable isotope analysis

Feather samples were analyzed at Cornell University's Stable Isotope Laboratory. Samples were rinsed with deionized water and dried before analysis for δ^{13}C and δ^{15}N. A 1.0-mg sample (± 0.1 mg) of each feather was encapsulated in tin and analyzed using a Thermo Finnigan Delta V Advantage isotope ratio mass spectrometer interfaced to a NC2500 elemental analyzer (EA-IRMS; Thermo Scientific, Waltham, MA). A laboratory standard of White-tailed deer (*Odocoileus virginianus*) tissue was analyzed for every 10 feather samples. A chemical methionine standard was used to measure instrumental accuracy across a gradient of amplitude intensities. Isotope corrections were performed using a two-point normalization (linear regression) of all raw data with Cayuga Lake brown trout (*Salmo trutta*) and corn (*Zea mays*) used as in-house standards. Analytical error was estimated to be ± 0.52‰ for δ^{15}N and ± 0.59‰ for δ^{13}C based on standard deviations (SDs) of within-run replicate measurements of standards.

Plastic analysis

Samples collected for plastic analysis were placed directly onto stacked metal sieves with mesh size arranged in one of two configurations (top to bottom either 3.0, 2.0, 1.0 mm, or 1.0, 1.0, 0.84 mm) to collect particles 1.0 mm in size and larger. A 0.5 mm sieve was then placed over the top of the samples to avoid sample loss or outside contamination as the samples were washed through the sieves with a high-powered hose (Rapp et al. 2017). For GI tract samples, the stomach and intestinal contents were removed by cutting open and flushing the GI tracts with water before placing the contents on the stacked sieves for plastic analysis. The two sieve configurations were employed at random with regards to species and sample type, and as no significant correlation was observed between sieve configuration and any of the plastic metrics analyzed, the data were lumped for all subsequent statistical analyses.

For all sample types, the contents of the stacked sieves were viewed under a dissecting microscope. Plastic particles were picked from the sample using metal forceps. Samples were picked for a minimum of 10 min, after which point the samples were picked until the interval between finding plastic particles exceeded 1 min (Lusher et al. 2013). Plastic particles were measured along their length and width, and classified by color and particle type (sheet, fragment, foam, line, fiber bundle, or other; Provencher et al. 2017). Plastics that measured 1.0–5.0 mm along their longest length were classified as microplastics, and those ≥ 5.0 mm were classified as macroplastics (Provencher et al. 2017). When it was unclear if a particle was plastic, Rose Bengal dye (0.25 g RB/200 mL H_2O) was used to identify organic materials (Davison and Asch 2011). If the material was identified as nonorganic, it was set aside for burn analyses which were conducted by touching the heated tip of a dissecting needle to the particle to look for melting and scent characteristic of burning plastic (Rapp et al. 2017). Plastic particles from each sample were dried in an oven (60°C) and weighed before any manipulation (burning, prodding, etc.).

Statistical analysis

t-tests were performed to evaluate interspecific differences in stable isotope values of δ^{13}C and δ^{15}N. Isotopic niche size (SEA_B) of each gull species was calculated with the SIBER package version 2.1.4 in R Studio version 3.6.0 (R Development Core Team 2019) using a Bayesian approach to estimate standard ellipse area of the δ^{13}C and δ^{15}N data with the number of posterior draws in the model set at 10^6 (Jackson et al. 2011). This approach was chosen as it is well suited for small sample sizes, and it provides a measure of uncertainty around the estimated isotopic niche size allowing for statistical comparisons. A probabilistic comparison between species was used to determine significant interspecific differences in niche size (SEA_B).

For samples that contained plastic particles, we measured the cumulative plastic area and cumulative plastic weight per sample to quantify the extent of plastic ingestion. These data were corrected to account for differences in body size between species using average adult bird masses of 1.058 kg and 1.674 kg for Herring Gulls and Great Black-backed Gulls, respectively (Good 1998; Nisbet et al. 2017). A goodness of fit test (Kolmogorov's *D*) revealed that the data were log

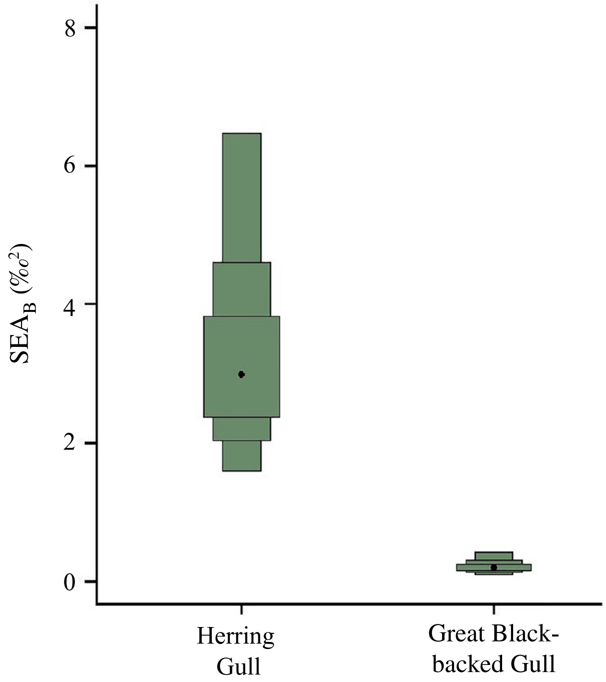

Fig. 1. Density plot comparing Bayesian estimated posterior distributions of isotopic niche size (SEA$_B$; mode values indicated by black dots; 50%, 95%, and 99% credible intervals contained in boxes) for Herring Gulls (*L. argentatus*) and Great Black-backed Gulls (*L. marinus*) sampled in the GOM in 2018.

normally distributed; therefore, the data were log transformed for further analysis. We analyzed differences in plastic response variables including plastic presence, area, and weight between gull species and sample types using *t*-tests and ANOVA. Chi-squared tests were used to compare categorical variables, including plastic type and color, between species.

Results

Stable isotope analysis

Herring Gulls exhibited a mean ± SD of 12.41 ± 1.41 for δ^{15}N and −18.73 ± 0.86 for δ^{13}C. Great Black-backed Gulls exhibited a mean ± SD of 15.39 ± 0.24 for δ^{15}N and −17.32 ± 0.36 for δ^{13}C. Differences in both δ^{15}N and δ^{13}C values were significant between species ($p < 0.01$ for both δ^{15}N and δ^{13}C), and the isotopic niche size (SEA$_B$) estimated for Herring Gulls (mode of 3.0‰^{2}) was significantly larger than that estimated for Great Black-backed Gulls (mode of 0.2‰^{2}; $p < 0.01$; Fig. 1).

Prevalence of plastic ingestion

We collected a total of 439 plastic particles from the 128 dietary samples. Plastic particles were found more frequently in pellet samples (35.19% of pellets) than other sample types (Chi-squared, $p < 0.01$), with particles also appearing in adult seabirds and regurgitant samples at lower frequencies (18.18% and 7.50% of samples, respectively; Table 1). No plastic particles within our detectable size range (≥ 1.0 mm) were found in chick GI-tracts. Because our analysis showed significant differences in plastic frequency by sample type ($p < 0.01$), subsequent analyses of interspecific differences were conducted for each sample type independently, and as pellet samples represented the bulk of our sampling effort, further interspecific comparisons were drawn from those data.

Interspecific variation in plastic ingestion

Analysis of overall plastic presence vs. absence in pellet samples revealed significant differences in plastic ingestion between the two species (Chi-squared, $p < 0.01$) with Herring Gulls having a higher incidence of plastic ingestion (63.0%) as compared to Great Black-backed Gulls (23.1%). No interspecific differences in relative cumulative plastic weight or area per sample were observed ($p = 0.45$ and $p = 0.46$, respectively; Table 1).

Qualitative plastic analysis

Of the 439 plastic particles recovered, 73.2% were microplastics (1.0–5.0 mm in length). Fragments and sheets were the most common particle types, and light particle colors (clear, white, yellow, and beige) were the most common. Herring Gulls and Great Black-backed Gulls showed no significant variation in types of plastics ingested, with sheets and fragments each making up 35–45% of plastics ingested (Chi-squared test, $p = 0.11$). The overall range of particle colors ingested was similar between the two species, as was the proportion of light- and dark-colored particles consumed, with light particles making up 60–62% and dark particles making up 30–31% of plastic particles ingested for both species.

Discussion

Of the two seabird species investigated in this study, the more generalist scavenger, the Herring Gull, experienced more frequent exposure to plastic debris in its diet than the more specialist predator, the Great Black-backed Gull. This supports our hypothesis that generalists would experience higher instances of plastic consumption than specialists. The stable isotope results align with previous observations of differences in foraging behavior between these two species, with Herring Gulls exhibiting a relatively large isotopic niche in comparison to the highly constrained isotopic niche observed in Great Black-backed Gulls (an order of magnitude smaller than that of Herring Gulls). Furthermore, the δ^{15}N distributions suggest that Herring Gulls foraged at a lower relative trophic position than Great Black-backed Gulls (with mean δ^{15}N approximately 3‰ lower in Herring Gull than in Great Black-backed Gulls; Inger and Bearhop 2008; Bond and Jones 2009). Meanwhile the δ^{13}C distributions suggest that Herring Gulls (with more negative and more variable values) foraged in a broader range of environments that likely included more freshwater and terrestrial habitats than Great Black-backed Gulls, which exhibited a less negative and likely more marine $\delta^{13}C$ distribution (Inger and Bearhop 2008; Bond and Jones 2009).

While the proportion of pellet samples containing plastic particles was significantly greater in Herring Gulls than in Great Black-backed Gulls, there was no significant difference in the cumulative area or weight of plastic consumed after adjusting for body size. The lack of variation in plastic particle size per sample indicates that the relative load per meal was similar between the two species, despite the difference in frequency of meals containing plastic. The species were also similar with regards to the range of plastic colors ingested, counter to our expectation that the more generalist species would consume a broader range of plastic particle colors. Our findings related to the relative consumption of dark- and light-colored plastic particles correspond with previous observation that seabirds consume light-colored plastics most frequently (Santos et al. 2016). Differences observed in the relative proportions of light and dark particles may reflect the mechanism of consumption (i.e., differential selection of particle colors) or may be driven by differences in the distribution of plastic colors encountered in the foraging environments of these two species. Though plastic debris has been previously described in the GOM (Barrows et al. 2017), a more detailed survey of plastic debris in the specific foraging locations of each species, paired with an analysis of color similarities between plastic and prey items, would help to elucidate the mechanism of plastic consumption in these seabirds. Further study of microplastic particles in the tissues of prey items would also help to identify whether seabirds consume plastic directly or through secondary consumption (i.e., inside prey items).

The results of this study supported our hypothesis that even closely related organisms would experience differing risk of plastic ingestion corresponding to differences in foraging strategies, and that generalist foragers would consume plastic more frequently than specialists. This finding has implications for evaluating the risk of plastic debris consumption in other seabirds based on foraging strategy and also provides new insights concerning the presence and fate of microplastics and macroplastics within the GOM food web. Future study will focus on mechanisms of plastic consumption, including exposure of these species to smaller microplastic particles (< 1.0 mm in size) that might be introduced through secondary consumption, and implications of plastic exposure for the health of seabirds in the GOM.

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