SEE COMMENTARY

Threat of plastic pollution to seabirds is global, pervasive, and increasing

Chris Wilcox[a,1], Erik Van Sebille[b,c], and Britta Denise Hardesty[a]

[a]Oceans and Atmosphere Business Unit, Commonwealth Scientific and Industrial Research Organisation, Hobart, TAS 7001, Australia; [b]Grantham Institute & Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom; and [c]Australian Research Council Centre of Excellence for Climate System Science, University of New South Wales, Sydney, NSW 2052, Australia

Edited by James A. Estes, University of California, Santa Cruz, CA, and approved July 2, 2015 (received for review January 31, 2015)

Plastic pollution in the ocean is a global concern; concentrations reach 580,000 pieces per km^2 and production is increasing exponentially. Although a large number of empirical studies provide emerging evidence of impacts to wildlife, there has been little systematic assessment of risk. We performed a spatial risk analysis using predicted debris distributions and ranges for 186 seabird species to model debris exposure. We adjusted the model using published data on plastic ingestion by seabirds. Eighty of 135 (59%) species with studies reported in the literature between 1962 and 2012 had ingested plastic, and, within those studies, on average 29% of individuals had plastic in their gut. Standardizing the data for time and species, we estimate the ingestion rate would reach 90% of individuals if these studies were conducted today. Using these results from the literature, we tuned our risk model and were able to capture 71% of the variation in plastic ingestion based on a model including exposure, time, study method, and body size. We used this tuned model to predict risk across seabird species at the global scale. The highest area of expected impact occurs at the Southern Ocean boundary in the Tasman Sea between Australia and New Zealand, which contrasts with previous work identifying this area as having low anthropogenic pressures and concentrations of marine debris. We predict that plastics ingestion is increasing in seabirds, that it will reach 99% of all species by 2050, and that effective waste management can reduce this threat.

extinction | ingestion | marine debris | risk analysis | seabird

Introduction of plastic waste into the marine environment is a global concern. Plastic production is rapidly rising, with a doubling of production every 11 y since commercial production began in the 1950s (1). This growth in production has been accompanied by a corresponding increase in the concentration of plastics in the marine environment although it has been suggested that marine organisms may be a major sink reducing this increase (2–4). The durability of plastic implies that it is retained for years to centuries, in some cases failing to degrade at all if it is not exposed to bacterial activity or UV radiation (5).

Plastic fragments can be found throughout the world's oceans, with observed concentrations up to 580,000 plastic pieces per square kilometer (2, 3, 6). Modeling studies, validated by global sampling efforts, demonstrate that plastics are ubiquitous, with high concentrations in all five subtropical convergence zones and along the coastal margins near human population centers (3, 6, 7).

In addition to the evidence of its prevalence, there is emerging evidence of the threats plastics pose to wildlife, and indirectly to human health. Plastic waste affects wildlife via two means: entanglement and ingestion (8). A recent review for the United Nations Convention on Biological Diversity documented over 600 species, ranging from microorganisms to whales, affected by marine plastic waste, largely through ingestion (9). Ingestion is known to have many effects, ranging from physical gut blockage (10) to organ damage from leaching toxins (11). Recent experimental studies have also demonstrated transmission and toxicological effects of plastics, or adsorbed chemicals, at environmentally relevant concentrations in higher vertebrates (11–13).

The effect of plastic ingestion on seabirds in particular has been of concern. This concern is due to the frequency with which seabirds ingest plastic (12) and because of emerging evidence of both impacts on body condition and transmission of toxic chemicals, which could result in changes in mortality or reproduction (13–16). Understanding the contribution of this threat is particularly pressing because half of all seabird species are in decline, a higher fraction than other comparable taxa (17). Despite a recent extensive review of the threats to seabirds by a globally recognized authority (17), however, pollution has been identified only in a coastal context, and there is little mention of the impact of plastic ingestion, particularly on the high seas where the most threatened seabirds forage (17).

We predict the extent of plastics exposure for 186 pelagic seabird species worldwide, excluding coastal taxa such as shorebirds, sea ducks, and gulls and species for which distribution data were not available (*SI Appendix*, Table S1). We compare our predictions with diet studies published over the last 40 y and incorporate additional factors such as foraging strategy, body size, and sampling method that may affect the relationship between exposure and ingestion. Based on this adjusted model of risk, we map the global distribution of plastic ingestion risk for seabirds and highlight global areas of concern.

Results

We predicted plastic exposure for 186 species, from 42 genera within 10 families (*SI Appendix*, Table S1). Our plastic exposure

Significance

Plastic pollution in the ocean is a rapidly emerging global environmental concern, with high concentrations (up to 580,000 pieces per km^2) and a global distribution, driven by exponentially increasing production. Seabirds are particularly vulnerable to this type of pollution and are widely observed to ingest floating plastic. We used a mixture of literature surveys, oceanographic modeling, and ecological models to predict the risk of plastic ingestion to 186 seabird species globally. Impacts are greatest at the southern boundary of the Indian, Pacific, and Atlantic Oceans, a region thought to be relatively pristine. Although evidence of population level impacts from plastic pollution is still emerging, our results suggest that this threat is geographically widespread, pervasive, and rapidly increasing.

Author contributions: C.W. and B.D.H. designed research; C.W., E.V.S., and B.D.H. performed research; C.W. and E.V.S. analyzed data; and C.W., E.V.S., and B.D.H. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

See Commentary on page 11752.

[1]To whom correspondence should be addressed. Email: chris.wilcox@csiro.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1502108112/-/DCSupplemental.

Table 1. Changes in plastic ingestion reported in the literature for seabirds

A. Incidence of plastic in individual seabirds within a study

Fixed Effects					Random Effects			
Term	Coefficient Estimate	Standard Error	Z value	Pr(>|z|)	Number of groups	Model Term	Grouping Variable	Variance
Intercept	−3.08	0.61	−5.03	4.87E-07	59	Intercept	Reference	4.30
Year*	1.76	0.38	4.58	4.63E-06	57	Intercept	Genus	8.61
Method Lavage	0.24	0.31	0.76	0.45	57	Year*	Genus	0.92
Method Bolus	−0.29	0.37	−0.79	0.43				
Method Necropsy	−0.29	0.25	−1.19	0.24				

B. Chance of identifying a species that has ingested plastic

Fixed Effects					Random Effects			
Term	Coefficient Estimate	Standard Error	Z value	Pr(>|z|)	Number of groups	Model Term	Grouping Variable	Variance
Intercept	1.32	0.57	2.30	0.021	59	Intercept	Reference	0.48
Year*	0.80	0.29	2.73	0.0063	57	Intercept	Genus	2.55
Method Lavage	−1.71	0.86	−1.99	0.046	57	Year*	Genus	0.019
Method Bolus	−0.93	1.20	−0.78	0.44				
Method Necropsy	−1.36	0.55	−2.48	0.013				

*Year is centered and rescaled for analysis, (year − 1982.365)/10.43.

predictions covered 90% of the species' range on average (interquartile range, 89–100%), with the only notable areas of poor coverage being in the North Sea and the Indonesian archipelago (18). Average exposure to plastic was 0.064 (range, 0–0.36; dimensionless scale) (*Methods*) but was right skewed, with most seabirds having low relative plastic exposure levels.

We obtained diet data from an exhaustive review, which revealed 272 species–study combinations in the literature, covering 135 of the seabird species (*SI Appendix*, Table S1). Two hundred and sixty-seven of these cases reported sample size and ingestion frequency, 168 of which had plastic ingestion by the birds. The distribution of plastic was bimodal, with many studies reporting no plastic, but some studies reporting relatively high incidence of ingestion (up to 70% or more of individuals) (Fig. 1*A*). The fraction of individuals containing plastic in a study is increasing at ∼1.7% per year [95% confidence interval (CI), 0.35–3.2%], with a predicted value of 90.4% in 2014 (95% CI, 51.4–98.6%), based on the fitted regression model (Fig. 1*B* and Table 1*A*). In our review, we found that 81 seabird species have been reported ingesting debris to date, 60 of which are included in our study (*SI Appendix*, Table S1). The chance of finding debris in species in which no plastic had been found previously is increasing at 0.2% per year (95% CI, 0.02–0.43%) (Fig. 1*C* and Table 1*B*), with debris predicted to have been found in 99.8% of species (95% CI, 96.6–100.0%) by 2050.

The median density of debris in a species' geographic range, weighted by centrality in that range, was a significant predictor of ingestion rates [likelihood ratio test (LTR), df = 1, X^2= 527076.9, $P \cong 0$] and fit the ingestion rate data better than other predictors for exposure based on Akaike information criterion (AIC). However, exposure alone has limited predictive power, explaining only 1.3% of the deviance in the reported ingestion rates. When we revisited this comparison with the full models, we found that the weighted mean was slightly superior and switched to that measure of exposure. We found that the best model included seabird genus, body size, starting date of the study, and sampling method (Table 2*A*), with an AIC of 2,657 compared with an intercept-only model with an AIC of 7,982. The five-factor model explained 71% of the variation in the data, based on deviance comparison with a null model. No other models were included within the 95% confidence set for the best model, based on AIC.

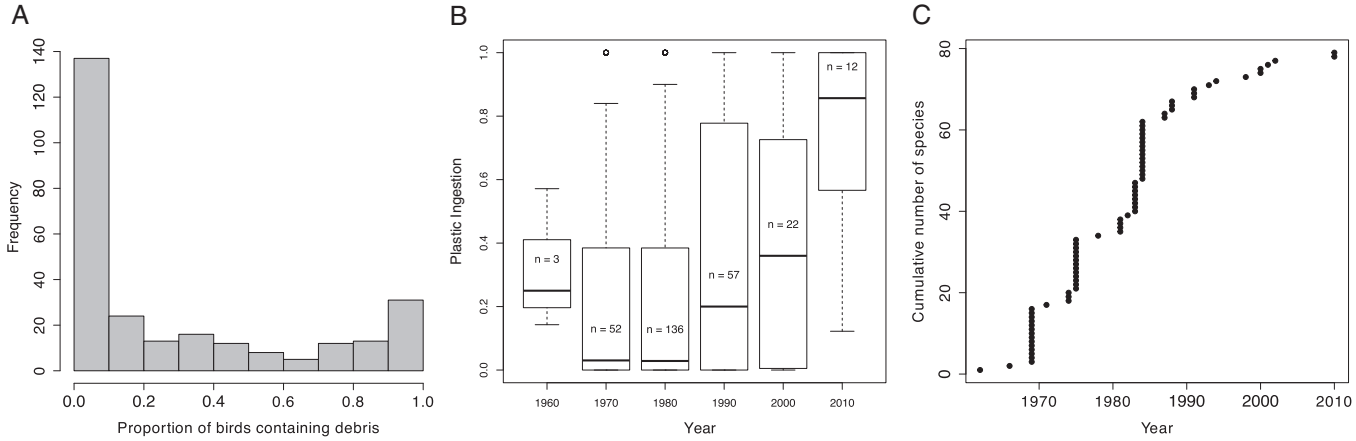

Fig. 1. Plastic ingestion by seabirds as reported in the literature (1962–2012). (*A*) Frequency of individuals with plastic fragments in their digestive system per species–study combination. (*B*) Proportion of individuals in each species–study combination having plastic in their digestive system with time. Plot shows median and quartiles, with bars extending to 1.5 times the interquartile range. (*C*) Date of first discovery of plastic ingestion for seabird species across all species identified in the literature review.

SEE COMMENTARY

Table 2. Analysis of the predictive power of debris exposure for predicting ingestion rates reported in the scientific literature

A. Comparison of model adequacy

Model	AIC
DSGT	2656.8
SGT	2679.0
DGT	2688.3
DSG	2871.9
SG	2900.1
GT	2904.1
DG	2910.9
G	3180.2
DT	4778.5
DST	4780.5
ST	5473.2
T	5513.0
DS	6010.9
D	6117.3
S	6158.6
0	7982.2

B. Parameters for the best model

Coefficient	Coefficient	Std. Error	Pr(>|z|)
Intercept	−96.88	6.41	< 2e−16
Weighted Mean	0.0032	0.0007	1.1e−06
Body Size	2.72	0.47	7.5e−09
G *Aphrodroma*	−1.64	0.74	2.6e−02
G *Calonectris*	−1.78	0.30	4.3e−09
G *Cyclorrhynchus*	3.33	0.20	< 2e−16
G *Fratercula*	0.56	0.21	8.9e−03
G *Fulmarus*	1.26	0.23	3.9e−08
G *Oceanodroma*	1.43	0.36	8.6e−05
G *Pachyptila*	1.08	0.35	1.9e−03
G *Pelagodroma*	2.77	0.51	7.0e−08
G *Phoebastria*	−5.46	1.27	1.6e−05
G *Procellaria*	−2.06	0.47	1.4e−05
G *Pseudobulweria*	−3.24	1.02	1.5e−03
G *Pterodroma*	−1.35	0.24	1.2e−08
G *Spheniscus*	−11.78	2.05	9.7e−09
G *Thalassarche*	−7.24	1.04	3.4e−12
Year	0.047	0.003	< 2e−16
Method L	−7.11	1.02	3.0e−12
Method LN	−2.64	0.29	< 2e−16
Method N	0.44	0.09	1.1e−06

Note that genera and sampling methods that did not have significant coefficients are not reported for brevity. Note that the reference genus is *Aethia*, which is represented in the data by 3 species sampled in Alaska, and is included in the intercept term in the model. Coefficients for genera included in the analysis are preceded by a "G" and italicized. D, debris exposure; G, genus; S, body weight; T, starting year of the study; 0, intercept only model. Sampling method codes are: L, lavage; N, necropsy.

Debris ingestion rates increased significantly with increasing exposure, body size, and more recent study date (Table 2*B*). *Thalassarche* albatross and *Spheniscus* penguins had significantly lower ingestion rates for their body size than other taxa. In contrast, *Cyclorrhynchus* auklets, *Pachyptila* prions, *Fulmarus* fulmars, and *Pelagodroma* and *Oceanodroma* storm-petrels had higher ingestion rates when controlling for other factors such as body size (Table 2*B*). The remaining genera in the data did not differ significantly from *Aethia* auklets, which was the reference taxa for the analysis, solely due to alphabetical order. Multiplying the median value of each covariate by its coefficient to calculate its importance, the year (93) term dominated in the model, followed by the genus (−11.78 to 3.33), body size (1.60), and debris exposure (0.27) effects.

Of the 186 species studied (56% of the world's total) (*SI Appendix*, Table S1), the expected number of seabird species ingesting debris in each 1 × 1 grid cell ranged from 0.7 to 22, with a median value of 1.8 and an interquartile range of 1.2–2.5 (Fig. 2*A* and *SI Appendix*, Table S1). Larger numbers of species were predicted to ingest plastic in a band along the northern boundary of the Southern Ocean, particularly in the southern Tasman Sea. Interestingly, the predicted areas of high impact do not correspond closely with the areas of highest debris concentration (Fig. 2*C*) but are instead strongly influenced by the distribution of seabird species, which have their highest diversity in the Southern Ocean (Fig. 2*D*). Comparing this result with predictions from the fixed effect model, which accounts for predisposition to plastic ingestion across genera, the general pattern of areas of high and low impact are similar although the scaling of the two predictions does differ due to the lower number of species included (92 species) (*SI Appendix*, Table S1). The similarity in the two predictions is due to a relatively large number of ingestion-prone species in southern latitudes, suggesting that the pattern is not driven by species richness alone (Fig. 2 *A* and *B*).

Discussion

We found that nearly three-quarters of the variation in plastic ingestion by seabirds can be predicted by considering exposure and basic ecological information, such as body size and foraging strategy. This finding is encouraging because there are readily available global plastic distributions estimated from ocean circulation models that can be used to assess threat levels and evaluate the impacts of changes in waste management practices (7). Evaluated against observed densities of plastics in coastal and offshore regions, these estimated global distributions, including the one we use, seem to be relatively accurate (3, 7, 19).

One clear implication of our research is that seabird ingestion rates scale with plastic exposure. Thus, as more plastic is introduced into the ocean, we can expect ingestion rates to increase proportionately. We detected an increasing trend in ingestion rates reported in the literature, supporting this connection between higher production and elevated exposure resulting in expected increases in ingestion. The trend in the literature could also be due to publication bias, as awareness of plastic pollution increases. We controlled for this effect specifically by incorporating a term for study (bias) in our analysis and still found a significant positive trend in both ingestion rates and reports of new species ingesting plastic, suggesting that exposure is likely driving the pattern. A similar time trend in ingestion rates of plastic was identified in a recent global study of marine turtles (20).

Global plastic production is increasing exponentially, with a current doubling time of 11 y; thus, between 2015 and 2026, we will make as much plastic as has been made since production began (1). Given expanding production and our modeling results, we expect the time trend we identified in both ingestion rates within species and identification of new species that have ingested plastic to continue to rise. Projecting patterns in the literature forward using our fitted regression models (Table 1), we predict that plastic will be found in the digestive tracts of 99%

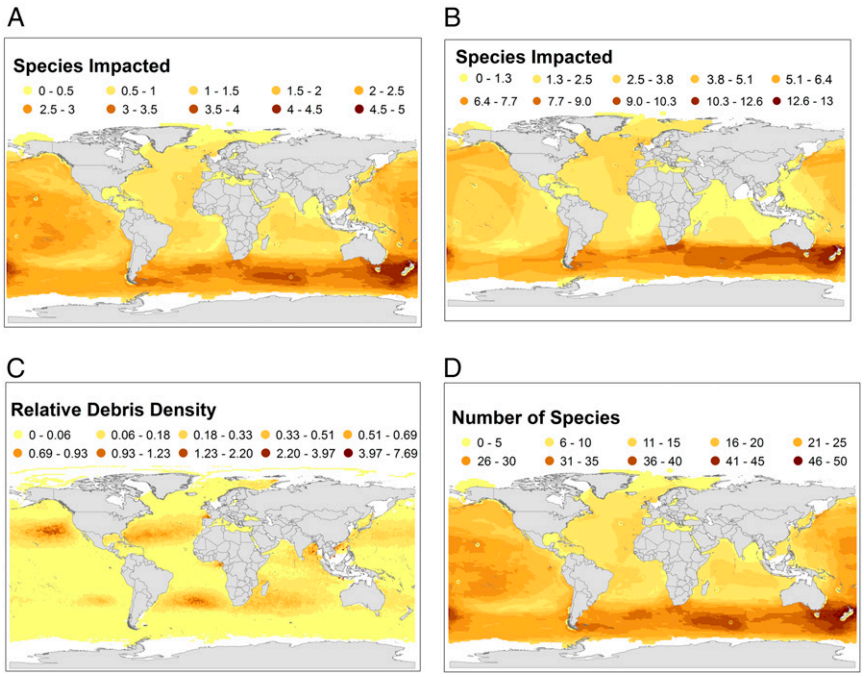

Fig. 2. The expected number of seabird species ingesting plastic and driving factors. Predictions are at the 1 × 1 degree scale. (*A*) The expected number of species ingesting plastic based on predictions from a generalized linear mixed model, using a random effect to represent taxa-specific ingestion rates ($n = 186$). (*B*) The expected number of species ingesting plastic, as in *A*, but based on a generalized linear model using fixed effects for taxa-specific ingestion rates ($n = 92$). (*C*) Modeled concentration of marine debris in the world's oceans on a log scale. (*D*) Species richness for seabirds considered in this study, based on data from Birdlife International (32).

of all seabird species by 2050 and that 95% of the individuals within these species will have ingested plastic by the same year.

Two caveats are relevant in evaluating these predictions. First, detection of plastic in seabirds may not reach this level because there is variation in predisposition to plastic ingestion across genera (Table 1). However, the overall time trend overwhelms the differences in temporal trends among genera (Table 1, Year coefficient vs. 1.96 × Year variance), suggesting that nearly all species will eventually be found ingesting plastic at some level, based on the discoveries reported so far. Second, the rates of increase in new species ingesting plastic and individuals within species ingesting plastic have wide confidence intervals, meaning that predictions about future ingestion are necessarily uncertain. However, given that the estimates of the rates are significantly greater than zero, it is clear that plastic ingestion will be more widespread than it is at present irrespective of its exact value.

Although evidence for individual and population level impacts from plastic ingestion is still relatively scant for seabirds, there is basis for concern. Ingestion of larger items can lead to gut obstruction and death (21). Plastic ingestion has also been found to reduce available gut volume, resulting in reduced body condition in experimental studies (22). There are correlative studies suggesting that this effect may occur in nature although it is unclear whether plastic ingestion causes low weight or is a result of low availability of food (10, 15). Reduced body condition (i.e., lower fledging weight) has been linked to reduced survival of juvenile seabirds (23–25). In addition to physical effects, high plastic loads are correlated with increased organic pollutant loads in field observations of seabirds (26), with supportive experimental results demonstrating a connection between pollution, concentration of pollutants by plastics, and release into seabird tissues during digestion (13, 16, 27). Plastic fragments can concentrate organic pollutants up to 10^6 times that of the surrounding seawater, with release rates once they are in an endotherm gut of 30 times higher than in seawater (27, 28). Given this emerging evidence for both physical and toxicological impacts from plastic ingestion by seabirds, our results suggest that these impacts may be widespread among species and pervasive in terms of the number of individuals affected.

A complicating factor in both estimating ingestion rates for plastic and predicting the resulting impacts is the residence time for plastic in the gut. Residence time is a balance between ingestion and excretion rates, either via reduction in size and defecation or via regurgitation of indigestible items. There is taxonomic variability in these traits because some species have the ability to regurgitate (e.g., skuas, albatross), whereas other species rarely regurgitate except when feeding young (e.g., petrels and some auks). There are also seasonal, age, and location differences among studies in our literature survey. However, we were able to successfully model the standing stock of plastic in the gut as reported in the literature, explaining more than 70% of the variability in the data, despite uncertainties in the mechanisms governing ingestion and throughput.

Expected impacts are concentrated in areas where high plastic concentration and high seabird diversity coincide, particularly in the Tasman Sea at the boundary between the southwestern Pacific and Southern Oceans, but also in the southwestern margin of the Indian Ocean. Even when ecological data on predisposure to plastic ingestion across taxa was included, our predictions remained qualitatively the same because seabird diversity and ingestion predisposure are correlated (Fig. 2*A* vs. Fig. 2*B*). These regions have received much less emphasis in the discussion of marine debris impacts because their predicted plastic concentrations are much lower than those in the convergence zones, although the region is data-poor (7). We are not suggesting there are not critical issues in other regions, such as the North Pacific (Laysan albatross) or North Atlantic (northern fulmars), where ingestion rates are particularly high (*SI Appendix*, Table S1). Clearly, other measures of risk, such as the fraction of individuals ingesting plastic, might produce differing priorities. However, our focus is on seabirds at a taxa-wide, global scale, and, in that context, the boundary of the Southern Ocean emerges as a

priority. Future refinements should also address impacts in the North Sea and Indonesian archipelago, areas with poor coverage in oceanographic models, but that are known to have high ingestion rates by some seabird species.

Our results stand in contrast to other analyses of the human impacts on marine systems, which identify oceans near the poles as areas of low impact (29). In fact, inorganic pollution and organic pollution were estimated to have the smallest global footprints out of 17 major threats, covering only 2.3 or 0.4 of the 335 million square kilometers of the world's oceans, respectively, largely due to an assumed lack of transport mechanisms capable of dispersing them away from the coast (29). Our results suggest that, at least for impacts from marine debris to seabirds, the northern fringe of the Southern Ocean may be particularly impacted. Many seabird species in this region also suffer from other sources of mortality, including ongoing bycatch in fisheries and predation by invasive species on breeding colonies, and achieving effective management in these remote and often international regions is a significant challenge (17, 30).

Encouragingly, our analyses suggest that relatively simple models can be used to evaluate the effects of management changes, even if the management region is far from the area of impact. Plastic concentration in the ocean, simulated as lost waste from coastal populations, is a good predictor of ingestion rate, and thus impact. This model can also be used in reverse, studying the local and remote effects of a change in waste management practices or other source reduction policies. Although the short-term prognosis is that plastic impacts are increasing significantly, our analyses also suggest that reductions in exposure will result in reduced ingestion. There is some evidence to support this assertion: Monitoring of ingestion rates in northern fulmars as part of the European Union's Environmental Quality Objectives demonstrated a significant decrease in the ingestion of plastic pellets, thought to be driven by management actions to reduce their loss from industrial processes into the marine environment in Northern Europe (31).

Methods

Modeling Relative Oceanographic Concentration of Plastic. The spatial distribution of marine plastics was computed using trajectories from surface drifting buoys as described in van Sebille et al. (7) (see *SI Appendix* for further details). Trajectories drifting buoys launched in the Global Drifter Program were gridded onto a one-by-one degree cell global grid. These trajectories were summarized in six transit matrices, one for each 2-mo period per year. The entries of these transit matrices depict, for each grid cell, the probability of getting to any of the other grid cells 2 mo later. By iteratively multiplying this matrix with a vector of tracer concentrations in the ocean, the evolution of plastic from any point in the ocean can be tracked (7).

We modeled the source distribution for plastic and its variation by continually releasing new simulated tracers from the global coastline. Tracer release was proportional to the population within 100 km from the coastline, and new releases were made every 2 mo. The total quantity of plastics (tracers) entering the ocean from each coastal grid cell increased exponentially with time, using parameters on global plastic production (1). The amount of plastic entering the ocean was therefore a function of both the number of people living near the coast and the total amount of plastic produced in that year.

The evolution of plastic concentration was computed bimonthly from 1960 to 2010. Note that the plastic concentration is a relative quantity because the plastic source function is only proportional to local population size and annual global plastic production.

Modeling Seabird Exposure to Plastics. We used range maps for the 188 seabird species available from Birdlife International's seabird database to model geographic occurrence (32) (*SI Appendix*, Table S1). We aggregated the breeding and nonbreeding foraging distributions to create a single spatial layer describing the species range (see *SI Appendix* for details) and converted this layer to a 1° latitude by 1° longitude grid. We took two approaches to estimating the distribution of each species based on these grids: We assumed first that species are evenly distributed across their range (uniform model), and second that density of individuals increases linearly with distance from the range edge (weighted model). For the weighted model, we normalized the values to sum to one across the range. We calculated a measure of exposure to plastic for each species by multiplying the predicted relative density of seabirds in each 1° cell under our two distribution models with the modeled relative oceanographic concentration of plastic in each cell. We summarized the exposure using its mean and its median across all cells, yielding four possible combinations of relative density of seabirds (uniform or weighted) and plastic exposure summary statistic (mean or median) that we could explore as a predictor of exposure to plastic debris. Although these data were not comprehensive (e.g., we do not include all global seabird species), there is no specific bias toward or against particular species, and all major seabird taxonomic groups for pelagic species are included in analyses (coastal species, including shorebirds, sea ducks, and gulls, were excluded).

Training and Validating the Seabird Exposure Model. We conducted a comprehensive literature review of published studies on plastic ingestion by seabirds and more general diet studies. We used online databases and evaluated all studies that were published from 1950 to 2012, inclusive, which were returned in a search using the keywords related to seabirds and plastic ingestion (see *SI Appendix* for keywords). For each published study, we recorded the family, genus, species, sample size, number of birds with plastics, average reported body weight of the species, and year of the study.

We investigated the temporal trend in both the proportion of individuals in a study that ingested plastics and the rate at which new species were identified as ingesting plastics. We estimated the change in the discovery rate of species ingesting plastic by modeling the success/failure of detecting plastic in a species with the year of the study. For both the individual and species models, we controlled for bias in the sampling method (necropsy, lavage, bolus, or a combination). We also accounted for study bias by including a random effect for each study (study bias; see *SI Appendix* for details) and a random slope term for year by genus (to account for taxonomic differences in ingestion). We verified the appropriateness of the model using a Hosmer–Lemeshow test (33).

We used logistic regression to explore a hypothesized set of models relating the fraction of individuals in a study reported to have ingested plastic to the exposure we predicted for each species (33). We evaluated each of our four metrics of exposure and chose the predictor that had the best explanatory power based on the Akaike information criterion (AIC) (34). We also compared this predictor against a null model containing only a constant to determine whether exposure was a significant predictor of the probability of ingestion.

We then explored a set of nested models to determine the additional factors to include in a model of ingestion probability. Because the predictors were chosen based on a priori hypotheses that they would have an effect on ingestion probability, we fit all possible models incorporating main effects and evaluated their fit to the data using AIC. After determining the important covariates in addition to debris exposure, we revisited the comparison of the exposure metrics incorporating the additional covariates. We compared AIC values across these full models to ensure that we had the best model, tested our final model for goodness of fit, and examined residuals to identify any issues.

Mapping Seabird Risk at the Global Scale. To predict the occurrence of ingestion across all species in our dataset, we fit an analog of the best model from our validation analysis, with the taxa factor coded as a random instead of a fixed effect because not all species were represented in the literature (35). We used this model to predict the ingestion probability for each species in each 1° cell in its distribution. We then summed these probabilities in each cell to get the expected number of species ingesting plastic in each location (*SI Appendix*). We compared these predictions with the analogous estimate from our best-fit model, using fixed effects for taxa, to allow for differences in ingestion by species.

ACKNOWLEDGMENTS. We thank T. J. Lawson for assisting with figures, M. Lansdell for helping compile seabird data, and BirdLife International for making seabird distribution information available. Constructive comments from R. Crawford, M. England, J. van Franeker, and Q. Schuyler improved this manuscript. C.W. and B.D.H. acknowledge Commonwealth Scientific and Industry Research Organisation's Oceans and Atmosphere Business Unit and Shell's Social Investment Program for support. E.V.S. was supported by Australian Research Council Grant DE130101336. This work was conducted within the Marine Debris Working Group at the National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, with support from the Ocean Conservancy.

1. Plastics Europe (2013) *Plastics—The Facts 2013: An Analysis of European Latest Plastics Production, Demand, and Waste Data* (Plastics Europe, Brussels).
2. Barnes DK, Galgani F, Thompson RC, Barlaz M (2009) Accumulation and fragmentation of plastic debris in global environments. *Philos Trans R Soc Lond B Biol Sci* 364(1526):1985–1998.
3. Cózar A, et al. (2014) Plastic debris in the open ocean. *Proc Natl Acad Sci USA* 111(28): 10239–10244.
4. Thompson RC, et al. (2004) Lost at sea: Where is all the plastic? *Science* 304(5672):838.
5. Lambert S, Sinclair C, Boxall A (2014) Occurrence, degradation, and effect of polymer-based materials in the environment. *Rev Environ Contam Toxicol* 227(227):1–53.
6. Law KL, et al. (2010) Plastic accumulation in the North Atlantic subtropical gyre. *Science* 329(5996):1185–1188.
7. van Sebille E, England MH, Froyland G (2012) Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. *Environ Res Lett* 7(4):044040.
8. Derraik JGB (2002) The pollution of the marine environment by plastic debris: A review. *Mar Pollut Bull* 44(9):842–852.
9. Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel–GEF (2012) *Impacts of Marine Debris on Biodiversity: Current Status and Potential Solutions* (Secretariat of the Convention on Biological Diversity, Montreal), CBD Technical Series No. 67.
10. Ryan PG (1987) The effects of ingested plastic on seabirds: Correlations between plastic load and body condition. *Environ Pollut* 46(2):119–125.
11. Rochman CM, Hoh E, Kurobe T, Teh SJ (2013) Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Sci Rep* 3:3263.
12. Talsness CE, Andrade AJM, Kuriyama SN, Taylor JA, vom Saal FS (2009) Components of plastic: Experimental studies in animals and relevance for human health. *Philos Trans R Soc Lond B Biol Sci* 364(1526):2079–2096.
13. Teuten EL, et al. (2009) Transport and release of chemicals from plastics to the environment and to wildlife. *Philos Trans R Soc Lond B Biol Sci* 364(1526):2027–2045.
14. Day RH, Wehle DHS, Coleman FC, eds (1985) *Ingestion of Plastic Pollutants by Marine Birds* (US Department of Commerce, La Jolla, CA), NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-54.
15. Lavers JL, Bond AL, Hutton I (2014) Plastic ingestion by Flesh-footed Shearwaters (Puffinus carneipes): Implications for fledgling body condition and the accumulation of plastic-derived chemicals. *Environ Pollut* 187:124–129.
16. Tanaka K, et al. (2013) Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. *Mar Pollut Bull* 69(1-2):219–222.
17. Croxall JP, et al. (2012) Seabird conservation status, threats and priority actions: A global assessment. *Bird Conserv Int* 22(1):1–34.
18. Lumpkin R, Maximenko N, Pazos M (2012) Evaluating where and why drifters die. *J Atmos Ocean Technol* 29(2):300–308.
19. Law KL, et al. (2014) Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year data set. *Environ Sci Technol* 48(9):4732–4738.
20. Schuyler Q, Hardesty BD, Wilcox C, Townsend K (2014) Global analysis of anthropogenic debris ingestion by sea turtles. *Conserv Biol* 28(1):129–139.
21. Pierce KE, Harris RJ, Larned LS, Pokras MA (2004) Obstruction and starvation associated with plastic ingestion in a Northern Gannet Morus bassanus and a Greater Shearwater Puffinus gravis. *Mar Ornithol* 32(2):187–189.
22. Ryan PG (1988) Effects of ingested plastic on seabird feeding: Evidence from chickens. *Mar Pollut Bull* 19(3):125–128.
23. Braasch A, Schauroth C, Becker PH (2009) Post-fledging body mass as a determinant of subadult survival in Common Terns Sterna hirundo. *J Ornithol* 150(2): 401–407.
24. Morrison KW, Hipfner JM, Gjerdrum C, Green DJ (2009) Wing length and mass at fledging predict local juvenile survival and age at first return in tufted puffins. *Condor* 111(3):433–441.
25. Sagar PM, Horning DS (1998) Mass-related survival of fledgling Sooty Shearwaters Puffinus griseus at The Snares, New Zealand. *Ibis* 140(2):329–331.
26. Yamashita R, Takada H, Fukuwaka MA, Watanuki Y (2011) Physical and chemical effects of ingested plastic debris on short-tailed shearwaters, Puffinus tenuirostris, in the North Pacific Ocean. *Mar Pollut Bull* 62(12):2845–2849.
27. Bakir A, Rowland SJ, Thompson RC (2014) Enhanced desorption of persistent organic pollutants from microplastics under simulated physiological conditions. *Environ Pollut* 185:16–23.
28. Mato Y, et al. (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ Sci Technol* 35(2):318–324.
29. Halpern BS, et al. (2008) A global map of human impact on marine ecosystems. *Science* 319(5865):948–952.
30. Ban NC, et al. (2014) Systematic conservation planning: A better recipe for managing the high seas for biodiversity conservation and sustainable use. *Conserv Lett* 7(1): 41–54.
31. van Franeker JA, et al. (2011) Monitoring plastic ingestion by the northern fulmar Fulmarus glacialis in the North Sea. *Environ Pollut* 159(10):2609–2615.
32. Birdlife International and NatureServe (2011) *Bird Species Distribution Maps of the World* (Birdlife International, Cambridge, UK).
33. Agresti A (2013) *Categorical Data Analysis* (Wiley, Hoboken, NJ), 3rd Ed.
34. Burnham KP, Anderson DR (2002) *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach* (Springer, New York), 2nd Ed.
35. Zuur AF, Ieno EN, Walker N, Saveliev AA, Smith GM (2009) *Mixed Effects Models and Extensions in Ecology with R* (Springer, New York).

The threat of plastic pollution to seabirds is global, pervasive and increasing

Chris Wilcox[a,]*, Erik van Sebille[b,c], and Britta Denise Hardesty[a]

[a] Oceans and Atmosphere Business Unit, CSIRO, GPO Box 1538, Hobart, Tasmania 7001, Australia
[b] Grantham Institute & Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom;
[b] ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney 2052, Australia

*chris.wilcox@csiro

Supporting Information

Modeling relative oceanographic concentration of plastic

The pathways of plastics in this study are computed using the technique developed in van Sebille et al (1), with a more general description in van Sebille (2). The trajectories of surface drifters (3) from the NOAA Global Drifting Buoy Program (4) are used to construct a statistical model of the ocean circulation. In total, more than 24 million locations from 17,494 individual surface drifter trajectories spanning a time period between 1979 and 2013 are used. The drifter geolocations are available every 6 hours, and more than 85% of the ocean surface has had more than 100 location fixes per 1° x 1° degree grid cell (1). The buoys are deployed with a drogue at 15m depth, but many lose that drogue at some point. This means that 48% of all data used are from buoys with a drogue and 52% is from buoys without a drogue, making the data representative of anything that drifts in the upper 15m of the ocean.

Drifter trajectories are converted into a transit matrix that represents, for each surface grid cell on the ocean, the fractional distribution of tracer two months later. More specifically,

we define the crossing matrix $\mathbf{C}_b(i,j)$ that holds, for all buoys in the data set and for all measurements within each buoy trajectory, the number of times a buoy crosses from grid cell i to grid cell j in the two-month period b (where b=1 if the buoy was in grid cell i in January or February, b=2 if it was in grid cell in March or April, etcetera until b=6 for November or December). This crossing matrix $\mathbf{C}_b(i,j)$ is then converted to a transit matrix $\mathbf{P}_b(i,j)$ by row-normalizing it so that the sum of each row i is always one and the entries in these rows can be interpreted as a 2-dimensional probability distribution of a virtual tracer two month after it is injected into a grid cell. Ocean grid cells where buoys have never exited from are removed from the transit matrix.

Once the transit matrix $\mathbf{P}_b(i,j)$ is computed, the evolution of tracer v from any point in the ocean can be computed by solving the iterative vector-matrix multiplication

$$v_{t+2\text{months}} = v_t \cdot \mathbf{P}_b$$

where the bimonthly counter b is cycled through.

As boundary conditions, we add a vector v_{rel} of coastal release to the vector v at each time step, where v_{rel} is a power law function of time as $v_{\text{rel}} = 2^t * v_{\text{rel_ini}}$ and the initial vector $v_{\text{rel_ini}}$ is the same source function as used in Van Sebille et al (1). It is zero everywhere except for at grid cells that are within 100 km from the coast. In these grid cells, the value of $v_{\text{rel_ini}}$ depends on the local population within 100 km from the coastline, as reported in the gridded database of CIESIN- CIAT (5). The tracer experiment is then run for 50 years. This method accurately captures the large-scale patterns of debris in the oceans, including what is commonly referred to as the North Pacific garbage patch (1,6).

Modeling seabird exposure to plastics

Data from the Birdlife International Bird Species Distributions of the World database was provided by Birdlife International as ArcGIS shapefiles (7). We included 186 seabird species in the analysis, excluding coastal taxa such as shorebirds, sea ducks, and gulls (Table S1). There was no bias in species included, other than the presence of distribution data available for analyses. Each shapefile could be composed of multiple polygons, including occasional observations and broader boundaries around areas of known or suspected presence (Fig. S1A). Each polygon had associated attributes, including coding for presence, season, and origin. We only selected polygons which were coded as currently extant (presence = 1) and which were occupied by either resident birds or during the breeding and nonbreeding seasons (season = 1,2, or 3). We then merged these polygons into a single polygon layer (Fig. S1B).

For many of the species, data was limited to a single polygon delimiting the entire range, supplemented by several polygons which represented breeding sites which were internal to the range polygon (e.g. Fig. S1A). Importantly, we excluded areas that were coded as passage areas (i.e. migratory routes) and areas coded as "uncertain seasonal occurrence". Passage areas were excluded as birds were expected to spend little time there, and thus encounter rates with debris in these areas would not be important in determining overall intake of plastics. Areas where occurrence was uncertain were excluded due to the lack of confirmed and substantial usage.

The final merged polygon for each species was then converted to a matrix of binary values corresponding to a 1° latitude by 1° longitude grid (Fig. S2A). We then created a

second version of this matrix by weighting each 1 (presence) in the matrix by the nearest distance to a 0 (absence) in the matrix, i.e. the distance to the edge of the range, using the corresponding locations in decimal degrees and the great circle distance. The weights were calculated as the distance to the edge of the range for a cell, divided by the maximum distance to the edge for any cell in the range (Fig. S2B). Thus the most distant entry in the weighted matrix received a 1, and all other cells received a value between 0 and 1. We were unable to weight breeding and nonbreeding portions of the range by the relative time spent in each location in estimating densities, as most species only had a single polygon for entire range (ignoring polygons corresponding to islands on which the species nests, which were present in the database for most species).

We calculated the debris exposure for the uniform and distance-weighted bird distributions by multiplying the distribution matrices by the matrix of predicted plastic concentrations in an element-wise fashion (Fig. 2B, Fig. S2C and D). The resulting matrix contained seabird-density weighted debris concentrations for each location on the grid inside the species range. We did not normalize these distributions (uniform and distance-weighted) back to a shared range of values, as the correction for the measurement scale was easily accommodated in the analysis by the intercept and slope terms in regressions including the debris exposure as a covariate. In addition, shifting the values would also make use of the results by others more complex as the regression coefficients would be moved to a new scale.

Training and validating the seabird exposure model

We used the following general search terms to identify peer-reviewed publications published between 1950 and 2012 (inclusive) relevant to this study: seabird, plastic, debris, marine debris, diet, ingest*, and feeding. The wildcard symbol, *, will include any word in which the letters preceding the wildcard appear. We also searched specifically for diet studies and plastic ingestion studies for each species in our spatial database. The databases searched included Web of Knowledge, Web of Science, ProQuest, Scopus, SpringerLink and ScienceDirect. Taxa were searched for individually based upon the taxonomic names in Table S1.

We used a mixture of fixed effects and random effects models for analyzing literature data (8). Random effects models were used in particular where we were attempting to control for study bias, or make predictions for species where no observations were available (8). All fixed effects terms in the models used treatment contrasts, treating one level of the factor as a reference level which is included in the intercept term of the model. As this reference category is arbitrary, it is typically the first value of the factor that appears in alphabetical or numerical order, but has no special significance otherwise.

Study bias in models of ingestion change with time

In both the model of the reporting of species ingesting plastic and of the proportion of individuals within a species ingesting plastic we were concerned about the potential for study bias giving a false temporal trend. This could arise through at least two

mechanisms. First, our literature review included studies of plastic ingestion in seabirds, along with more general diet studies that made mention of plastic observed while examining gut contents. Thus, studies not focused on plastic per se may be less likely to detect plastic in their samples, leading to lower reporting rates. Plastic focused studies have been more common recently, and this could create a false temporal trend in estimated ingestion rates. Second, awareness of plastic impacts is increasing with time, thus attention devoted to plastics might be higher in more recent studies, also leading to increased reporting rates, even in the absence of an underlying trend in ingestion by seabirds. In order to control for these potential biases, we included a random effect term for study in the statistical models for reporting of species ingesting plastic and for the proportion of individuals ingesting plastic (8). This term allows us to control for bias due to the different focus of the studies and bias due to increased observer effort simultaneously.

Mapping seabird risk at the global scale

To predict the occurrence of ingestion across all species, including ones for which we could not find empirical studies on plastic ingestion, we fit an analogue of the best model determined in our validation analysis, with the taxa factor coded as a random instead of a fixed effect (8). The model included the random effect as an intercept term, exactly analogous to the model including taxa as a fixed effect.

Applying a random effect was necessary as there were no studies for some taxa for which we make predictions, thus precluding the use of the fixed effects model we used for

validation. We did not include the random effect terms for the taxa for which we had data when making predictions, instead we used only the fixed effects terms in the model. This follows the general concept of random effects models, in that the expected value of the fixed effect term is zero. Since the fixed effects terms do include predicted exposure and body weight for each seabird species, the predicted ingestion rates differ among species; however they lack the additional variance that would be due to the taxa effect on the intercept term in the model.

Each of these ingestion predictions is the expected value of ingestion for a given species and location. Taking advantage of the fact that the expected value of a sum is the sum of the expected values, the expected number of species ingesting plastic in a location is then the sum across the predicted values for each species in that location.

SI Reference

1. van Sebille E, England MH, & Froyland G (2012) Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. *Environmental Research Letters* 7(4).
2. van Sebille E (2014) Adrift.org.au — A free, quick and easy tool to quantitatively study planktonic surface drift in the global ocean, Journal of Experimental Marine Biology and Ecology, Vol 461, pp 317–322.
3. Niiler PP (2001) The world ocean surface circulation. *Ocean Circulation and Climate: Observing and modelling the global ocean*, eds Siedler G, Church JA, & Gould J (Academic Press, London), Vol 77, pp 193-204.
4. Lumpkin R (2003) Decomposition of surface drifter observations in the Atlantic Ocean. *Geophysical Research Letters* 30(14).
5. CIESIN C (2005) Gridded Population of the World, Version 3 (GPWv3). ed Socioeconomic Data and Applications Center (SEDAC) CU.
6. Law KL*, et al.* (2014) Distribution of Surface Plastic Debris in the Eastern Pacific Ocean from an 11-Year Data Set. *Environmental Science & Technology* 48(9):4732-4738.
7. Birdlife International and NatureServe (2011) Bird species distribution maps of the world. (Birdlife International, Cambridge, UK).
8. Zuur AF, Ieno EN, Walker N, Saveliev AA, & Smith GM (2009) *Mixed effects models and extensions in ecology with R* (Springer, New York).

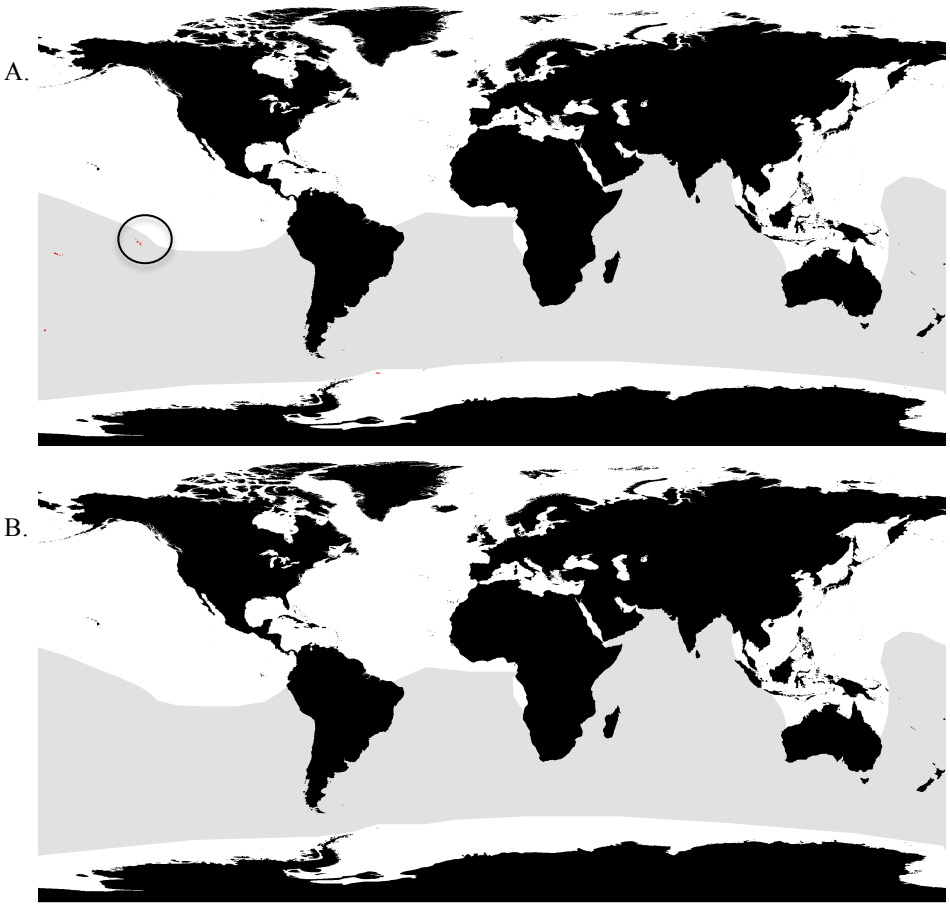

Fig. S1. Distribution of the black-bellied storm-petrel. Panel A, disaggregated data from Birdlife International Global Seabird Database showing polygons for breeding, migration, and nonbreeding habitat. In this case the data includes 5 very small polygons for breeding islands (red) and 1 polygon for the range (grey). For illustration purposes, one of the breeding islands is circled. Panel B, aggregated data after exclusion of migration polygons and merging of remaining data into a single layer. Note the similarity between the two panels.

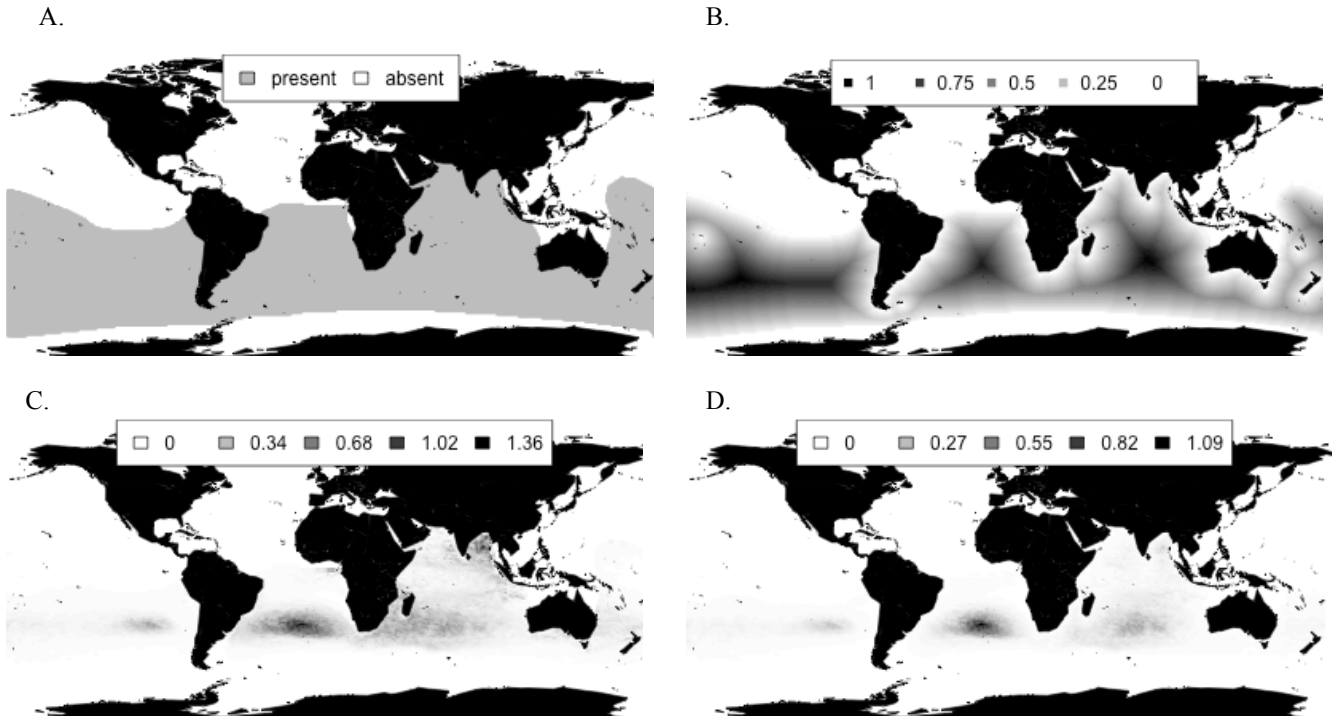

Fig. S2. Construction of predicted encounters between seabirds and debris. Panel A, distribution of the black-bellied storm-petrel based on uniform weighting throughout the range. Panel B, predicted density of the black-bellied storm-petrel based on weighting locations proportional to the distance from the edge of the range. Panel C, predicted encounters between the black-bellied storm-petrel and debris based on the product of the range and the predicted debris global debris concentration. Panel D, predicted encounters between the black-bellied storm-petrel and marine debris based on the distance-weighted distribution.

Supplementary Table 1. Seabirds included in this study, based on published ingestion rates or modeled risk in our study. The number of published studies reporting plastic ingestion for each species, the sample size, and the rate of ingestion (calculated using the number of individuals with and without plastic in their gut, summed across the available studies) for 135 species we identified in our literature survey. For comprehensiveness, we also report species for which ingestion studies were available, but which were not included in our risk predictions (denoted as 0 for Ingestion Risk Predicted). Species are presented in the table at the taxonomic resolution available in the range data we obtained for our study. Thus, where subspecies did not have distinct ranges available, they were considered together for analysis. Due to taxonomic variability, we report synonyms encountered during the literature search. Ingestion risk predictions were made using the best-fit model with fixed effects (where ingestion studies and range maps were available) and/or random effects (additionally including species for which we only had range maps, but no ingestion studies), covering 186 species.

Common Name	Family	Species Name(s)	Number of Published Ingestion Studies	Sample Size	Ingestion Rate	Ingestion Risk Predicted?
Crested Auklet	Alcidae	Aethia cristatella	3	986	0.2	Y
Least Auklet	Alcidae	Aethia pusilla	3	396	0	Y
			3	513	0.01	Y
Whiskered Auklet	Alcidae	Aethia pygmaea	0	NA	NA	Y
Razorbill	Alcidae	Alca torda	1	0	NA	N

Dovekie	Alcidae	Alle alle	2	22	0	Y
Kittlitz's Murrelet	Alcidae	Brachyramphus brevirostris	0	NA	NA	Y
Long-billed Murrelet	Alcidae	Brachyramphus perdix	2	157	0	Y
Marbled Murrelet	Alcidae	Brachyramphus marmoratus	0	NA	NA	Y
Black Guillemot	Alcidae	Cepphus grille	2	61	0.02	N
Pigeon Guillemot	Alcidae	Cepphus columba	4	53	0.02	Y
Rhinoceros Auklet	Alcidae	Cerorhinca monocerata	4	465	0.61	Y
Parakeet Auklet	Alcidae	Cyclorrhynchus psittacula Aethia psittacula	1	6	0	Y
Atlantic Puffin	Alcidae	Fratercula arctica	3	270	0.37	Y
Horned Puffin	Alcidae	Fratercula corniculata	3	846	0.21	Y
Tufted Puffin	Alcidae	Fratercula cirrhata	2	45	0.18	Y
Cassin's Auklet	Alcidae	Ptychoramphus aleuticus	2	84	0	Y
Ancient Murrelet	Alcidae	Synthliboramphus antiquus	0	NA	NA	Y
Craveri's Murrelet	Alcidae	Synthliboramphus craveri	0	NA	NA	Y
Japanese Murrelet	Alcidae	Synthliboramphus wumizusume	1	5	0	Y
Xantus Murrelet	Alcidae	Synthliboramphus hypoleucus	4	363	0.01	N
Common Murre	Alcidae	Uria aalge	3	513	0.01	N
Thick-billed Murre	Alcidae	Uria lomvia	0	NA	NA	Y
Amsterdam Albatross	Diomedeoididae	Diomedea amsterdamensis	2	90	0.1	Y
Black-browed albatross	Diomedeoididae	Diomedea melanophris, Thalassarche melanophris	3	32	0.56	Y
Black-footed Albatross	Diomedeoididae	Diomedea nigripes, Phoebastria nigripes	0	NA	NA	Y
Buller's Albatross	Diomedeoididae	Diomedea bulleri, Diomedea bulleri bulleri, Thalassarche bulleri bulleri	0	NA	NA	Y
Campbell's albatross	Diomedeoididae	Diomedea melanophris impavida, Thalassarche impavida,	0	NA	NA	Y

		Thalassarche melanophris impavida				
Grey-headed Albatross	Diomedeoididae	Diomedea chrysostoma	0	NA	NA	Y
Indian Yellow-nosed Albatross	Diomedeoididae	Diomedea chlororhynchos bassi, Thalassarche chlororhynchos bassi	7	415	0.91	Y
Laysan Albatross	Diomedeoididae	Diomedea immutabilis, Phoebastria immutabilis	0	NA	NA	Y
Northern Royal Albatross	Diomedeoididae	Diomedea epomophora sanfordi	0	NA	NA	Y
Salvin's albatross	Diomedeoididae	Diomedea cauta salvini, Thalassarche cauta salvini	0	NA	NA	Y
Short-tailed Albatross	Diomedeoididae	Diomedea albatrus, Phoebastria albatrus	0	NA	NA	Y
Southern Royal Albatross	Diomedeoididae	Diomedea epomophora epomophora	1	1	0	Y
Tristan Albatross	Diomedeoididae	Diomedea dabbenena	2	5	0	Y
Wandering Albatross	Diomedeoididae	Diomedea exulans	0	NA	NA	Y
Antipodean Albatross	Diomedeoididae	Diomedea exulans antipodensis	0	NA	NA	Y
Waved Albatross	Diomedeoididae	Diomedea irrorata, Phoebastria irrorata	0	NA	NA	Y
Yellow-nosed Albatross	Diomedeoididae	Diomedea chlororhynchos, Diomedea chlororhynchos chlororhynchos	1	8	0	Y
Light-mantled Sooty Albatross	Diomedeoididae	Phoebetria palpabrata	3	49	0.06	Y
Sooty Albatross	Diomedeoididae	Phoebetria fusca	0	NA	NA	Y
Atlantic Yellow-nosed Albatross	Diomedeoididae	Thalassarche chlororhynchos	0	NA	NA	Y
Greyheaded Albatross	Diomedeoididae	Thalassarche chrysostoma	0	NA	NA	Y
White-capped Albatross	Diomedeoididae	Thalassarche steadi	0	NA	NA	Y
Ascension Frigatebird	Fregatidae	Fregata aquila	2	287	0	Y

Christmas Island Frigatebird	Fregatidae	Fregata andrewsi	0	NA	NA	Y
Great Frigatebird	Fregatidae	Fregata minor	0	NA	NA	Y
Lesser Frigatebird	Fregatidae	Fregata ariel	0	NA	NA	Y
Magnificent Frigatebird	Fregatidae	Fregata magnificens	0	NA	NA	Y
Black-bellied Storm-Petrel	Hydrobatidae	Fregetta tropica	2	21	0.24	Y
New Zealand Storm-Petrel	Hydrobatidae	Fregetta maorianus	1	21	0	Y
White-bellied Storm-Petrel	Hydrobatidae	Fregetta grallaria	2	16	0	N
European Storm-Petrel	Hydrobatidae	Hydrobates pelagicus	1	11	0.27	Y
Polynesian Storm-Petrel	Hydrobatidae	Nesofregetta fuliginosa	1	2	0	Y
Grey-backed Storm-Petrel	Hydrobatidae	Oceanites nereis, Garrodia nereis	2	141	0.36	N
White-vented Storm-Petrel	Hydrobatidae	Oceanites gracilis	0	NA	NA	Y
Wilson's Storm-Petrel	Hydrobatidae	Oceanites oceanicus	2	11	0	N
Ashy Storm-Petrel	Hydrobatidae	Oceanodroma homochroa	1	2	0	Y
Band-rumped Storm-Petrel	Hydrobatidae	Oceanodroma castro	3	36	0.92	Y
Black Storm-Petrel	Hydrobatidae	Oceanodroma melania	0	NA	NA	Y
Fork-tailed Storm-Petrel	Hydrobatidae	Oceanodroma furcata	9	267	0.26	Y
Guadalupe Storm-Petrel	Hydrobatidae	Oceanodroma macrodactyla	0	NA	NA	Y
Leach's Storm-Petrel	Hydrobatidae	Oceanodroma leucorhoa	0	NA	NA	Y
Least Storm-Petrel	Hydrobatidae	Oceanodroma microsoma	1	12	0.08	Y
Madeiran Storm-Petrel	Hydrobatidae	Oceanodroma castro	0	NA	NA	Y
Markham's Storm-Petrel	Hydrobatidae	Oceanodroma markhami	1	1	0	Y
Matsudairas Storm-	Hydrobatidae	Oceanodroma matsudairae	0	NA	NA	Y

Petrel						
Ringed Storm-Petrel	Hydrobatidae	Oceanodroma hornbyi	1	10	0.1	Y
Swinhoe's Storm-Petrel	Hydrobatidae	Oceanodroma monorhis	1	176	0.01	Y
Tristram's Storm-Petrel	Hydrobatidae	Oceanodroma tristrami	2	32	0.78	Y
Wedge-rumped Storm-Petrel	Hydrobatidae	Oceanodroma tethys	2	36	0.17	N
White-faced Storm-Petrel	Hydrobatidae	Pelagodroma marina, Pelagodroma marina albiclunis, Pelagodroma marina dulciae, Pelagodroma marina hypoleuca, Pelagodroma marina maoriana, Pelagodroma marina marina	1	1	1	N
Bonaparte's Gull	Laridae	Chroicocephalus philadelphia, Larus philadelphia	1	3	0	N
Common Black-headed Gull	Laridae	Chroicocephalus ridibundus, Larus ridibundus	1	19	1	N
Swallow-tailed Gull	Laridae	Creagrus furcatus	1	33	0.03	N
Black-tailed Gull	Laridae	Larus crassirostris	4	681	0.11	N
Glaucous Gull	Laridae	Larus hyperboreus	1	1	0	N
Glaucous-winged Gull	Laridae	Larus glaucescens	1	15	0.13	N
Great Black-backed Gull	Laridae	Larus marinus	2	7	0	N
Heermann's Gull	Laridae	Larus heermanni	1	14	0.14	N
Herring Gull	Laridae	Larus argentatus	2	8	0.25	N
Laughing Gull	Laridae	Larus atricilla	1	2	0	N
Mew Gull	Laridae	Larus canus	1	1	0	N
Ring-billed Gull	Laridae	Larus delawarensis	5	540	0.08	N
Ivory Gull	Laridae	Pagophila eburnea	2	61	0.16	N
Black-legged Kittiwake	Laridae	Rissa tridactyla	2	2	0.5	N
Red-legged Kittiwake	Laridae	Rissa brevirostris	0	NA	NA	Y

Sabine's Gull	Laridae	Xema sabini	0	NA	NA	Y
Peruvian Pelican	Pelecanidae	Pelecanus thagus	1	19	0	Y
Common Diving Petrel	Pelecanoididae	Pelecanoides urinatrix, Pelecanoides urinatrix chathamensis, Pelecanoides urinatrix exsul, Pelecanoides urinatrix urinatrix	0	NA	NA	Y
Magellanic Diving Petrel	Pelecanoididae	Pelecanoides magellani	0	NA	NA	Y
Peruvian Diving Petrel	Pelecanoididae	Pelecanoides garnotii	1	10	0	N
South Georgian Diving Petrel	Pelecanoididae	Pelecanoides georgicus	1	3	0	Y
Red-billed Tropicbird	Phaethontidae	Phaethon aethereus	2	272	0	Y
Red-tailed Tropicbird	Phaethontidae	Phaethon rubricauda	1	1	0	Y
White-tailed Tropicbird	Phaethontidae	Phaethon lepturus	2	5	0	N
Double crested Cormorant	Phalacrocoracidae	Phalacrocorax auritus	2	13	0.15	N
Pelagic Cormorant	Phalacrocoracidae	Phalacrocorax pelagicus	2	18	0	N
Redfaced Cormorant	Phalacrocoracidae	Phalacrocorax urile	2	39	0.05	Y
Kerguelen Petrel	Procellariidae	Aphrodroma brevirostris, Lugensa brevirostris, Pterodroma brevirostris	2	19	0	Y
Bulwer's Petrel	Procellariidae	Bulweria bulwerii	0	NA	NA	Y
Jouanin's Petrel	Procellariidae	Bulweria fallax	2	152	0.27	Y
Cory's Shearwater	Procellariidae	Calonectris diomedea	0	NA	NA	Y
Streaked Shearwater	Procellariidae	Calonectris leucomelas	1	8	0.88	Y
Cape Petrel	Procellariidae	Daption capense, Daption capense australe, Daption capense capense	20	2382	0.79	Y
Northern Fulmar	Procellariidae	Fulmarus glacialis	2	35	0.2	Y

Southern Fulmar	Procellariidae	Fulmarus glacialoides	1	27	1	Y
Blue Petrel	Procellariidae	Halobaena caerulea	0	NA	NA	Y
Northern Giant Petrel	Procellariidae	Macronectes halli	2	74	0.72	Y
Southern Giant Petrel	Procellariidae	Macronectes giganteus	1	2	1	Y
Antarctic Prion	Procellariidae	Pachyptila desolata	2	36	0.36	Y
Broad-billed Prion	Procellariidae	Pachyptila vittata	0	NA	NA	Y
Fairy Prion	Procellariidae	Pachyptila turtur	0	NA	NA	Y
Fulmar Prion	Procellariidae	Pachyptila crassirostris	0	NA	NA	Y
Medium billed Prion	Procellariidae	Pachyptila salvini	1	6	0.83	Y
Thin billed Prion	Procellariidae	Pachyptila belcheri	0	NA	NA	Y
Snow Petrel	Procellariidae	Pagodroma nivea	0	NA	NA	Y
Grey Petrel	Procellariidae	Procellaria cinerea	0	NA	NA	Y
Parkinson's Petrel	Procellariidae	Procellaria parkinsoni	2	12	0.25	Y
Spectacled Petrel	Procellariidae	Procellaria conspicillata	0	NA	NA	Y
Westland Petrel	Procellariidae	Procellaria westlandica	4	98	0.39	Y
White-chinned Petrel	Procellariidae	Procellaria aequinoctialis, Procellaria aequinoctialis aequinoctialis	0	NA	NA	Y
Becks' Petrel	Procellariidae	Pseudobulweria becki, Pterodroma becki	0	NA	NA	Y
Fiji Petrel	Procellariidae	Pseudobulweria macgillivrayi, Pterodroma macgillivrayi	1	67	0.01	Y
Tahitian Petrel	Procellariidae	Pseudobulweria rostrata	1	13	0.08	Y
Atlantic Petrel	Procellariidae	Pterodroma incerta	0	NA	NA	Y
Baraus Petrel	Procellariidae	Pterodroma baraui	0	NA	NA	Y
Bermuda Petrel	Procellariidae	Pterodroma cahow	1	57	0.02	Y
Black-capped Petrel	Procellariidae	Pterodroma hasitata	1	37	0.03	Y
Black-winged Petrel	Procellariidae	Pterodroma nigripennis	0	NA	NA	Y
Bonin Petrel	Procellariidae	Pterodroma hypoleuca	0	NA	NA	Y

Chatham Petrel	Procellariidae	Pterodroma axillaris	0	NA	NA	Y
Collared Petrel	Procellariidae	Pterodroma brevipes	1	9	0.44	Y
Cooks Petrel	Procellariidae	Pterodroma cookii	1	9	0.44	Y
Defilippi's Petrel	Procellariidae	Pterodroma defilippiana	0	NA	NA	Y
Feas Petrel	Procellariidae	Pterodroma feae	0	NA	NA	Y
Galapagos Petrel	Procellariidae	Pterodroma phaeopygia	1	92	0.15	Y
Gould's Petrel	Procellariidae	Pterodroma leucoptera, Pterodroma leucoptera brevipes, Pterodroma leucoptera caledonica, Pterodroma leucoptera leucoptera	0	NA	NA	Y
Hawaiian Petrel	Procellariidae	Pterodroma sandwichensis	1	11	0	Y
Henderson Petrel	Procellariidae	Pterodroma arminjoniana	0	NA	NA	Y
Jamaica Petrel	Procellariidae	Pterodroma caribbaea	1	104	0.01	Y
Juan Fernandez Petrel	Procellariidae	Pterodroma externa	1	8	0	Y
Kermadec Petrel	Procellariidae	Pterodroma neglecta	0	NA	NA	Y
Magenta Petrel	Procellariidae	Pterodroma magentae	1	1	0	Y
Mottled Petrel	Procellariidae	Pterodroma inexpectata	1	5	0	Y
Murphy's Petrel	Procellariidae	Pterodroma ultima	1	11	0	Y
Phoenix Petrel	Procellariidae	Pterodroma alba	0	NA	NA	Y
Providence Petrel	Procellariidae	Pterodroma solandri	1	2	0.5	Y
Pycroft's Petrel	Procellariidae	Pterodroma pycrofti	1	18	0.06	Y
Soft-plumaged Petrel	Procellariidae	Pterodroma mollis	2	26	0.54	Y
Stejneger's Petrel	Procellariidae	Pterodroma longirostris	0	NA	NA	Y
Tahiti Petrel	Procellariidae	Pterodroma rostrata	0	NA	NA	Y
White-headed Petrel	Procellariidae	Pterodroma lessonii	1	10	0.1	Y
White-necked Petrel	Procellariidae	Pterodroma cervicalis	0	NA	NA	Y
Zinos Petrel	Procellariidae	Pterodroma madeira	1	119	0.05	Y
Audubon's Shearwater	Procellariidae	Puffinus lherminieri	1	10	0.3	Y
Balearic Shearwater	Procellariidae	Puffinus mauretanicus	0	NA	NA	Y

Black-vented Shearwater	Procellariidae	Puffinus opisthomelas	1	1	1	Y
Buller's Shearwater	Procellariidae	Puffinus bulleri	2	185	0.01	Y
Christmas Island Shearwater	Procellariidae	Puffinus nativitatis	1	14	1	Y
Flesh-footed Shearwater	Procellariidae	Puffinus carneipes	1	6	1	Y
Fluttering Shearwater	Procellariidae	Puffinus gavia	7	117	0.49	Y
Great Shearwater	Procellariidae	Puffinus gravis	0	NA	NA	Y
Heinroth's Shearwater	Procellariidae	Puffinus heinrothi	0	NA	NA	Y
Hutton's Shearwater	Procellariidae	Puffinus huttoni	1	13	0.08	Y
Little Shearwater	Procellariidae	Puffinus assimilis, Puffinus assimilis assimilis, Puffinus assimilis elegans, Puffinus assimilis haurakiensis, Puffinus assimilis kermadecencis, Puffinus assimilis tunneyri	4	57	0.39	Y
Manx Shearwater	Procellariidae	Puffinus puffinus	1	0	NA	Y
Pink-footed Shearwater	Procellariidae	Puffinus creatopus	7	469	0.72	Y
Short-tailed Shearwater	Procellariidae	Puffinus tenuirostris	11	387	0.47	Y
Sooty Shearwater	Procellariidae	Puffinus griseus	0	NA	NA	Y
Townsend's Shearwater	Procellariidae	Puffinus auricularis	6	341	0.09	Y
Wedge-tailed Shearwater	Procellariidae	Puffinus pacificus	0	NA	NA	Y
Yelkouan Shearwater	Procellariidae	Puffinus yelkouan	0	NA	NA	Y
Antarctic Petrel	Procellariidae	Thalassoica antarctica	0	NA	NA	Y
Emperor Penguin	Spheniscidae	Aptenodytes forsteri	0	NA	NA	Y
King Penguin	Spheniscidae	Aptenodytes patagonicus	0	NA	NA	Y
Erect crested Penguin	Spheniscidae	Eudyptes sclateri	0	NA	NA	Y
Fiordland Penguin	Spheniscidae	Eudyptes pachyrhynchus	0	NA	NA	Y
Macaroni Penguin	Spheniscidae	Eudyptes chrysolophus	1	12	0	Y

Northern Rockhopper Penguin	Spheniscidae	Eudyptes chrysocome moseleyi	0	NA	NA	Y
Royal Penguin	Spheniscidae	Eudyptes schlegeli	0	NA	NA	Y
Snares Penguin	Spheniscidae	Eudyptes robustus	0	NA	NA	Y
Southern Rockhopper Penguin	Spheniscidae	Eudyptes chrysocome chrysocome	0	NA	NA	Y
Yellow-eyed Penguin	Spheniscidae	Megadyptes antipodes	0	NA	NA	Y
Adelie Penguin	Spheniscidae	Pygoscelis adeliae	0	NA	NA	Y
Chinstrap Penguin	Spheniscidae	Pygoscelis antarcticus	0	NA	NA	Y
Gentoo Penguin	Spheniscidae	Pygoscelis papua	0	NA	NA	Y
African Penguin	Spheniscidae	Spheniscus demersus	0	NA	NA	Y
Galapagos Penguin	Spheniscidae	Spheniscus mendiculus	0	NA	NA	Y
Humboldt Penguin	Spheniscidae	Spheniscus humboldti	6	397	0.3	Y
Magellanic Penguin	Spheniscidae	Spheniscus magellanicus	1	11	0.09	N
Brown Skua	Stercorariidae	Catharacta lonnbergi, Stercorarius antarcticus lonnbergi	0	NA	NA	Y
Chilean Skua	Stercorariidae	Catharacta chilensis, Stercorarius chilensis	2	6	0	Y
Great Skua	Stercorariidae	Catharacta skua, Catharacta skua antarctica, Catharacta skua hamiltoni, Catharacta skua lonnbergi, Catharacta skua skua, Stercorarius antarcticus, Stercorarius antarcticus hamiltoni, Stercorarius skua	0	NA	0.01	Y
South Polar Skua	Stercorariidae	Catharacta maccormicki, Stercorarius maccormicki	1	0	NA	Y
Southern Skua	Stercorariidae	Catharacta antarctica,	1	17	0.12	Y

		Stercorarius antarcticus				
Longtailed Jaeger	Stercorariidae	Stercorarius longicaudus	3	8	0.12	Y
Parasitic Jaeger	Stercorariidae	Stercorarius parasiticus	1	40	0.05	N
Pomarine Jaeger	Stercorariidae	Stercorarius pomarinus	1	494	0	N
Black Noddy	Sternidae	Anous minutus	2	356	0	N
Brown Noddy	Sternidae	Anous stolidus	1	7	0.14	N
Black Tern	Sternidae	Chlidonias niger	1	3	0	N
Gull-billed Tern	Sternidae	Gelochelidon nilotica, Sterna nilotica	2	243	0	N
White Tern	Sternidae	Gygis alba	1	2	0	N
Caspian Tern	Sternidae	Hydroprogne caspia, Sterna caspia	1	8	0	N
Aleutian Tern	Sternidae	Onychoprion aleuticus, Sterna aleutica	1	67	0.01	N
Bridled Tern	Sternidae	Onychoprion anaethetus, Sterna anaethetus	2	277	0	N
Grey-backed Tern	Sternidae	Onychoprion lunatus, Sterna lunata	2	391	0	N
Sooty Tern	Sternidae	Onychoprion fuscatus, Sterna fuscata	1	111	0	N
Blue Noddy; Grey Ternlet	Sternidae	Procelsterna cerulea	1	21	0	N
Antarctic Tern	Sternidae	Sterna vittata	1	2	0	N
Arctic Tern	Sternidae	Sterna paradisaea	1	51	0.04	N
Common Tern	Sternidae	Sterna hirundo	1	3	0	N
Forster's Tern	Sternidae	Sterna forsteri	1	1	0	N
Least Tern	Sternidae	Sterna antillarum, Sternula antillarum	1	24	0	N
Royal Tern	Sternidae	Sterna maxima, Thalasseus maximus	1	12	0	N

Sandwich Tern	Sternidae	Sterna sandvicensis, Thalasseus sandvicensis	0	NA	NA	Y
Australasian Gannet	Sulidae	Morus serrator, Sula serrator	0	NA	NA	Y
Cape Gannet	Sulidae	Morus capensis	1	7	0	Y
Northern Gannet	Sulidae	Morus bassanus	0	NA	NA	Y
Abbott's Booby	Sulidae	Papasula abbotti	0	NA	NA	Y
Blue-footed Booby	Sulidae	Sula nebouxii	1	244	0	Y
Brown Booby	Sulidae	Sula leucogaster	1	305	0	Y
Masked Booby	Sulidae	Sula dactylatra	0	NA	NA	Y
Nazca Booby	Sulidae	Sula granti	0	NA	NA	Y
Peruvian Booby	Sulidae	Sula variegata	1	360	0	Y
Red-footed Booby	Sulidae	Sula sula	3	986	0.2	Y

Encounter predictions were made for all species included in the BirdLife Database. We also made predictions for species identified by synonyms or subspecies names in published diet studies to allow inclusion in the statistical models of ingestion.