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Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife

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ABSTRACT

Marine litter is a growing environmental concern. With the rapid increase in global plastics production and the resulting large volume of litter that enters the marine environment, determining the consequences of this debris on marine fauna and ocean health has now become a critical environmental priority, particularly for threatened and endangered species. However, there are limited data about the impacts of debris on marine species from which to draw conclusions about the population consequences of anthropogenic debris. To address this knowledge gap, information was elicited from experts on the ecological threat (both severity and specificity) of entanglement, ingestion and chemical contamination for three major marine taxa: seabirds, sea turtles and marine mammals. The threat assessment focused on the most common types of litter that are found along the world's coastlines, based on data gathered during three decades of international coastal clean-up efforts. Fishing related gear, balloons and plastic bags were estimated to pose the greatest entanglement risk to marine fauna. In contrast, experts identified a broader suite of items of concern for ingestion, with plastic bags and plastic utensils ranked as the greatest threats. Entanglement and ingestion affected a similar range of taxa, although entanglement was rated as slightly worse because it is more likely to be lethal. Contamination was scored the lowest in terms of impact, affecting a smaller portion of the taxa and being rated as having solely non-lethal impacts. This work points towards a number of opportunities both for policy-based and consumer-driven changes in plastics use that could have demonstrable affects for a range of ecologically important taxa that serve as indicators of marine ecosystem health.

1. Introduction

Marine litter, and in particular plastic waste, is a growing environmental concern due to its aesthetic, economic, and ecological impacts. Volunteer clean-up efforts and coastal litter surveys have raised the public's awareness of marine debris as well as provided valuable data on the categories of litter items that are most abundant and/or frequently found on beaches and waterways [1,2]. In addition, microplastics have been shown to be ubiquitous in the open ocean [3,4]. In general, debris items fall into two broad categories: fishing-related gear such as lines, nets, and buoys; and end-use consumer items such as plastic bags, plastics bottles, metal and plastic bottle caps, cigarette butts, expanded polystyrene (EPS) containers and a variety of other food packaging items (ICC website [5]). The top 10 items collected during Ocean Conservancy's annual International Coastal Cleanup have remained remarkably consistent, with cigarette butts topping the list and plastic items making up 83% of the remaining items (ICC website [5]).

While identifying the types and amount of debris that are frequently found on beaches is an important first step, understanding the impacts of those consumer items is critical if effective voluntary or regulatory measures are to be implemented to limit their impacts. The number of scientific publications on marine debris has increased dramatically in the last ten years and nearly 700 marine species are now known interact with marine debris [6]. Entanglement and ingestion are the two main mechanisms by which marine taxa are exposed to marine debris ([7]; others) with contamination from toxic chemicals a secondary consequence of ingestion. At present, there is far less known about the toxicological impacts of marine litter but this is an active area of scientific enquiry and a growing conservation concern

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([8,9,10], others). While individual cases of effects marine debris ingestion and entanglement have been reported for the last several decades [7], the population-level consequences of marine debris from ingestion, entanglement and contamination remains relatively unknown.

The population-level impact of debris to wildlife has been poorly quantified in part due to the difficulty of studying wildlife–debris interactions in the natural environment, and the potential bias of evaluating only a subset of the population represented by sick, injured or deceased animals found washed ashore ([11,12]; but see [13]). In particular, it is virtually impossible to undertake carefully controlled studies of debris impacts on wide ranging marine megafauna, including seabirds, turtles, and marine mammals, all of which are known to be affected at the individual level. This has limited our broad-scale understanding of the impacts of litter across marine taxa, particularly the relative potential impact that common debris items may have on the fitness of different taxa, including those with threatened or endangered status.

Although population scale field studies remain a challenge, there is substantial informal knowledge in the scientific community that could provide a preliminary basis for evaluating the impact of debris on marine megafauna. Elicitation techniques can be used to formalize this knowledge, providing preliminary estimates of the impact of marine debris on populations of marine megafauna. This analytical approach has been successfully applied to a range of issues including gaining an understanding of the potential impacts of climate change on seabirds (Wilcox et al., unpublished), identifying marine debris research priorities for the coming century [14], and prioritising the anthropogenic and environmental threats to sea turtles [15].

We present data from an elicitation survey asking about the impact of marine litter entanglement, ingestion and contamination on marine megafauna (seabirds, turtles and marine mammals). These data are used to estimate the proportion of each of the focal taxa affected and the impact on those individuals affected by each of the most common types of debris as identified from coastal clean-data from around the globe. These results are synthesised, controlling for expert bias, to provide bounded estimates on the population impacts from marine debris for each taxa and type of debris. This quantitative assessment can be used to prioritise interventions on those items with the greatest impacts due to ingestion, entanglement and chemical contamination.

2. Materials and methods

2.1. Survey instrument

An internet-based survey was carried out to quantify the ecological impact posed by the most persistent forms of coastal litter to three major marine taxa: seabirds, sea turtles, and marine mammals. The survey was specifically targeted to experts working on major marine taxa, individuals working on marine debris specifically, and/or those involved in or with an interest in the field. Items addressed in this survey have been identified as the most common items found during Ocean Conservancy's annual International Coastal Cleanup since 1989, and are broadly consistent with several studies that have documented the composition of debris in the marine environment [16-18]; (see Table S1 for the 20 marine debris items of interest for which information was elicited). Microplastics were included as a discrete debris type even though they arise from a variety of plastic products, given their ubiquity in the marine environment and concern over their impacts on marine taxa [19,20].

The survey was developed using the threat ranking systems implemented by the World Wildlife Fund's Threat Rank Classification, the International Union for Conservation of Nature (IUCN) and Bird Life International's World Bird Database. Respondents assigned scores with respect to severity (i.e. the outcome of an interaction with debris for an animal in the taxon) and specificity (i.e. the proportion of a total taxon expected to be affected by the debris interaction). The survey covered each taxon (bird, turtle and mammal) and each mode of debris impact (entanglement, ingestion, and chemical contamination). Respondents were provided with quantitative, but non-overlapping intervals for each score in a multiple-choice format (Table S2).

A preliminary version of the survey was developed, then trialled with a small number of experts to evaluate its clarity, ease of use, and targeting. Based on the responses, along with verbal feedback in focus groups, the survey was revised. The scope of the taxa and the breakpoints among the multiple choice categories were revised based on initial feedback, to balance ease of use and quality of the resulting data.

Respondents' expertise and professional experience working with each of the taxa covered by the survey was ascertained to evaluate any potential bias and account for it statistically (see Section 2.2 below; Table S3). The survey was distributed to four international list-servers on 30 April 2014 (with the survey accessible online until 31 May 2014). These list servers included marine debris, marine taxa (list servers that focused on seabird, sea turtle and marine mammals specifically), marine policy, and education list servers: MARMAM, IUCN-DCMC, International Coastal Cleanup Coordinators, Turtle, Scuttlebutt, and PacificSeabirdsGroup.

2.2. Statistical analyses

We first evaluated the significance of respondent identity in determining the scores for severity and specificity of each debris type. Models were compared using debris type, respondent ID, and both terms with a null model including only an intercept using Aikaie Information Criteria (AIC) [21].

For cases where respondent ID was an important predictor of the scored values for severity and specificity, a cumulative link mixed model with respondent ID as a random component of the intercept term was used, to remove any bias among the scores from each respondent. These models were implemented in the Ordinal package in the *R* statistical language [22].

Each of the three types of impacts; entanglement, ingestion, and contamination, was analysed separately. Using the fitted cumulative link models, the effect of the type of debris (of the 20 most common types) and the taxa (bird, sea turtle and mammal) in determining respondent scores for specificity and severity was estimated.

Once the scores were standardized across respondents, interval statistics were used to construct estimates of the population-level impact of each type of impact – taxa combination. This was done by using the joint lower bounds of the proportion of the taxa affected and the magnitude of the effect to estimate the minimum effect for each taxa. The joint upper bound of the proportion and magnitude was used to estimate a maximum effect in a similar manner.

3. Results

3.1. Survey respondents

Two hundred and seventy four people responded to the survey, with 31% completing all questions (see Table S3 or ⟨https://www.surveymonkey.com/s/CY8CRC8⟩ for the survey). Respondents who completed the entire survey represented 19 fields of study, with the majority of participants describing their work as conservation

Table 1
Adequacy of models for scores of debris based on AIC. Lower AIC indicates an improved model, with a difference of 2 units suggesting statistically significant improvements. Model codes are N – Null model, (i.e. intercept only) D – Debris Category, R – Respondent Id E – Entanglement, I – Ingestion, C – Contamination.

	Severity			Specificity		
Model	E	I	C	E	I	C
N	11,559	11,560	10,438	11,690	13,525	11,357
D	10,430	13,606	13,457	11,647	13,313	11,213
R	13,060	12,881	11,296	10,518	12,863	11,094
RD	11,192	11,176	11,062	10,449	12,610	10,933

biology (14%) or marine mammal biology (14%), followed by advocacy/conservation (11%), education (10%), marine ecology (10%), and marine pollution (8%). Respondents' averaged more than 12 years of experience in their respective fields of study (range = 1–40 years). Thirty-one respondents indicated that marine debris was an explicit focus of their work. The average experience working on any one marine debris impact mechanism did not exceed 4 years. Similarly, respondents' average experience working on the three marine taxa was not greater than 6 years. The average response time by respondents that completed the survey was just under 45 min; completion time ranged between 16 min and 2 h.

3.2. Severity

Debris types differed in the severity of their impacts on the three marine taxa, at least for entanglement and ingestion, based on minimum AIC scores (Table 1). However, respondents also differed in their average scoring, with some respondents consistently above or below the mean severity score, at least for ingestion (Table 1). A model including both respondent and debris type was significantly better than either a null (intercept only) or either single factor model, based on AIC scores for ingestion (Table 1). Given these results, respondent was incorporated as a random effect term on the intercept in all additional models of severity.

Comparing the three models for severity, incorporating a random effect for respondent, the analyses showed that incorporating the type of debris improved the model adequacy over a null model (Fig. 1a, model D vs. model 0). Adding in a term allowing differences between taxa, but maintaining the relative ranking of the debris types, improved model adequacy further (Fig. 1a, model DT vs. D). However, allowing severity to vary across taxa for each debris type did not further improve the model (Fig. 1a, model DxT vs. DT).

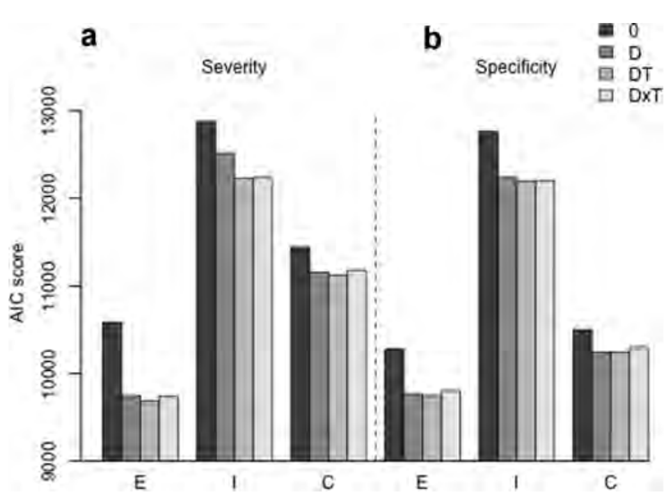

Fig. 1. Comparison of model adequacy, based on AIC, for models of severity (a) and specificity (b) of marine debris impacts on wildlife. Model codes are: 0 – null model, intercept only, D – debris type, T – taxa, x – main effects and interaction. Thus a model coded DxT would have an intercept term, main effects for both the type of debris and the taxa, and a debris type by taxa interaction term. Lower values of AIC indicate a superior model.

There were substantial differences among debris types in severity for entanglement (Fig. 2). Fishing related items (buoys and rope, monofilament, nets) were the items that caused the most damage, given that an animal interacted with them. However, close behind these three items were balloons and plastic bags. In contrast, there was less difference among items in the expected effects of ingestion on animals (Fig. 2b). Balloons and plastic bags were expected to have the greatest ingestion impact, followed by monofilament line and plastic utensils. Contamination effects were relatively high for cigarette butts, hard plastic containers, and food utensils. Again, there was were fewer differences across contamination in items in comparison with entanglement severity (Fig. 2c).

3.3. Specificity

In the initial exploration, models including both debris type and respondent ID were better than the null model or either single factor model at explaining the pattern in the specificity scores based on AIC (Table 1). Given this, respondent ID was a random effect on the intercept term in all further models. As with severity, we found that the best model for specificity included the main effects for taxa and debris type, but there was no support for a taxa by debris interaction (Fig 1b). Thus, both debris type and taxa are important, but, some taxa (.e.g. seabirds) are consistently identified as more affected and some items are consistently rated as effecting a larger fraction of the taxa (Fig 1a,b).

The same items (i.e. fishing gear, plastic bags, and balloons) were ranked high for entanglement specificity, indicating that these items were expected to more frequently entangle animals than the reference category (Fig. 3). With respect to ingestion, plastic utensils were expected to be ingested most frequently, followed by plastic bags, and then other plastic items. Items expected to more frequently cause contamination effects on wildlife mirrored those for ingestion, although with some differences (e.g. hard plastic containers) and overall demonstrated less variation among items.

3.4. Impacts

The single greatest impact from any item was predicted to be entanglement of birds by fishing line and ropes, with expected lethal impacts on 25–50% of the animals (Fig. 3a). For some other items, there were relatively high expected levels of impact, including potentially lethal impacts, from both entanglement and ingestion across all three taxa (e.g. plastic bags, Fig. 4a–f). In contrast, the maximum expected impact from contamination was much lower across all three taxa combinations (Fig. 4g–i).

The distribution of expected impacts across items also differed according to the mechanism. There were 3–4 items (composed of fishing related gear and plastic bags) that were expected to have relatively high impacts from entanglement, while the remaining items scored as relatively benign (Fig. 4a–c). In contrast, nearly all of the 20 items were scored as having relatively high ingestion impacts, with fewer items in the more benign categories by comparison. Contamination also differed in this respect, with 50–70% of items scored as having low levels of impacts and/or, non-lethal effects.

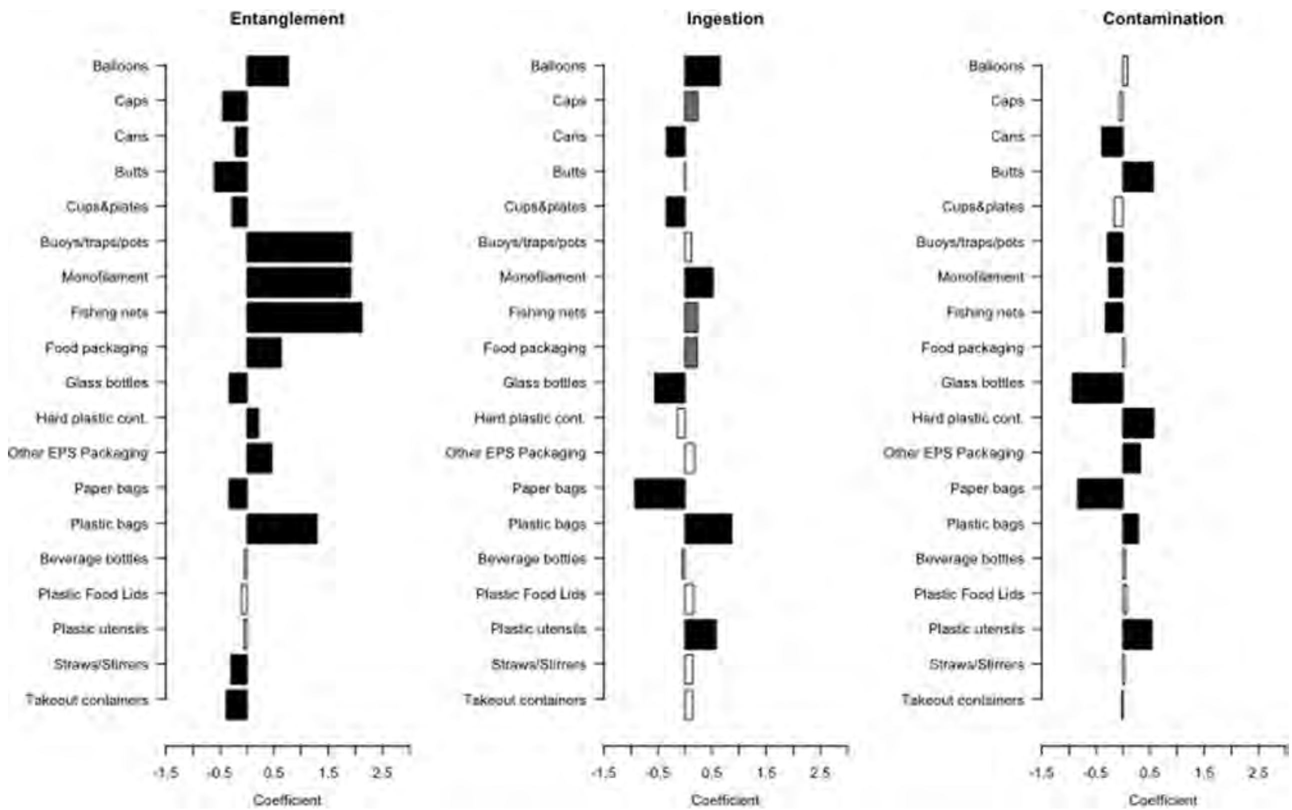

Fig. 2. Relative severity of different types of debris. Respondents were asked to score based on the likelihood of an interaction between the specific debris item and animals in each taxa. Score 1 – <25% of animals will experience the interaction; 2 – 26–50% of animals will experience the interaction; 3 – 51–25% of animals will experience the interaction; 4 – 76–100% of animals will experience the interaction. Bars represent the coefficients in the best fitting model for each debris category, relative to plastic fragments. Bar shading denotes the statistical significance of a coefficient, black is significant ($p < 0.05$ level), grey is non-significant but trending ($p < 0.10$), white is non-significant.

In general, the expected impact of an item was similar across taxa, within a mechanism of operation (Fig. 3). For instance, fishing gear scored high across all three taxa for entanglement impacts (Fig. 3a–c). Aggregating scores across taxa and mechanisms to identify the items with the most severe impacts, fishing traps and related gear unambiguously had the greatest expected impact (Table 2). Other types of fishing debris along with plastic bags, utensils, and balloons scored the next highest, although there was more heterogeneity across taxa (Table 2). Items that ranked relatively low in terms of impact included paper bags, glass and metal containers, and small plastic fragments (Table 2).

4. Discussion

While the scientific study of marine debris and its ecological impacts is relatively new, insights are growing rapidly as marine ecologists focus on this topic [14]. Scientific knowledge is most robust around impacts from entanglement, likely because this impact is easiest to observe in nature, especially between derelict fishing gear and large animals ([23,24]). Comparatively less is known about ingestion and there is currently a poorer understanding of chemical contamination effects on wildlife. This survey focused on these three modes of impact to gain a better understanding of the state of knowledge from experts in the field.

The analysis found considerable variation across types of impacts and taxa in the expected outcomes for marine wildlife. For entanglement, fishing related gear, balloons and plastic bags had high expected impacts while all other items ranked as having minimum entanglement effects. In contrast, for both ingestion and contamination, a broad range of products were predicted to have lower impacts (sub-lethal to potentially lethal) compared to impacts from entanglement. However, all the items studied (except for paper bags) were deemed to pose at least some ingestion risk to all of the taxa evaluated. The pattern for contamination was similar to that for ingestion, but with higher uncertainty and lower potential effects. Even with this increased uncertainty, fully half of all item/taxa interactions were deemed to result in at least some sub-lethal impacts from contamination.

These findings are unlikely to be the result of bias among respondents. While there were some differences among experts in the rankings, the overall effects of particular debris items were greater than were the differences amongst experts. As a result, the statistical technique employed allowed for the removal of this respondent bias from the analysis without otherwise altering the results. The respondent pool consisted of a broad range expertise, with the majority from “hard science” disciplines. However, years of experience was relatively modest (range 4–6 years) which may simply reflect the newness of the research area. Furthermore, respondents spent considerable time completing the survey, suggesting they took their charge seriously and carefully considered the questions asked. It is reasonable to conclude that the respondent sample represents the collective state of knowledge among experts well.

Entanglement of marine animals in marine debris, especially derelict nets and other abandoned fishing gear is widely recognised as a major source of mortality [24-26]. The findings reported here substantiate this idea, with pots, lines, traps, nets, and buoys ranking as the highest threat to marine taxa, including sea turtles and marine mammals. Given that fishing gear is intentionally designed to ensnare and capture fish, it is expected that lost or intentionally discarded gear would continue to ensnare

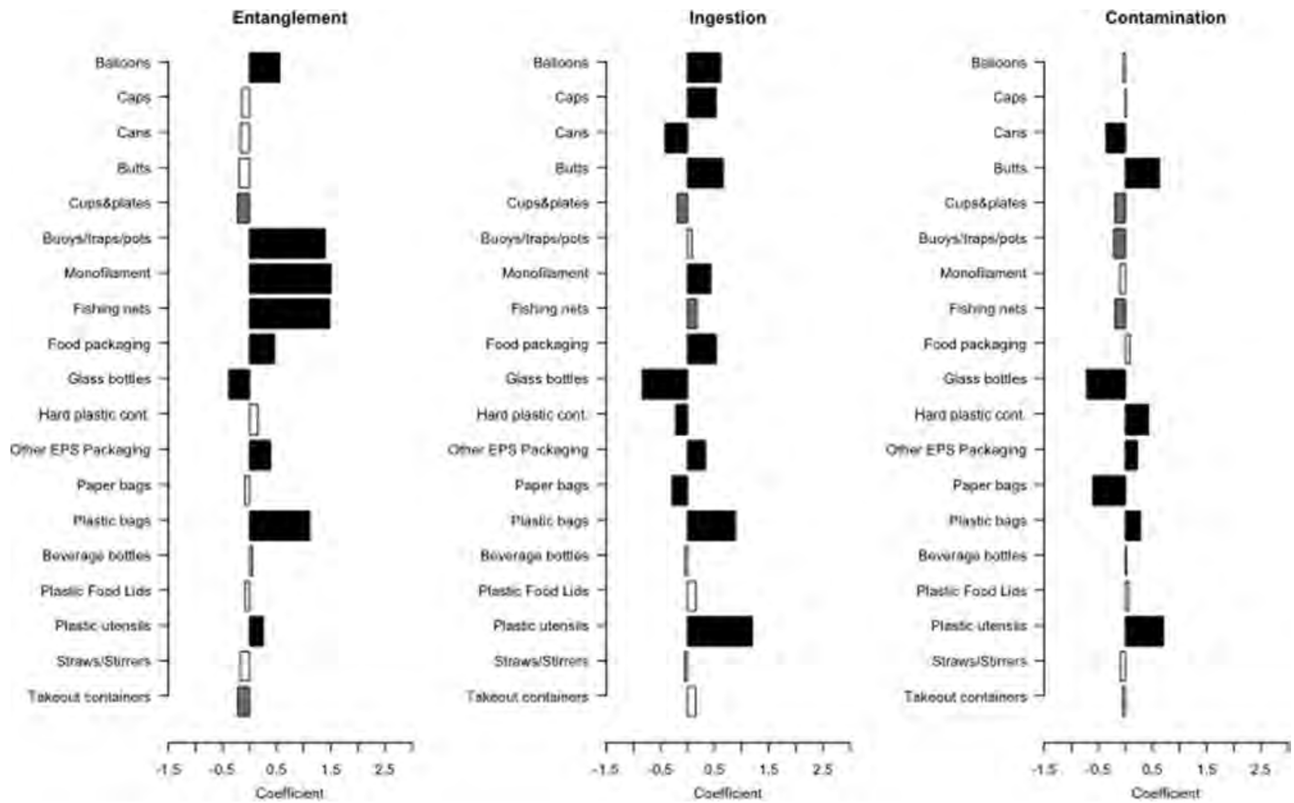

Fig. 3. Relative specificity of different types of debris (codes as described in Fig. 2). Bars represent the coefficients in the best fitting model for each debris category. Coefficients are the effect of the debris type, relative to plastic fragments. Bar shading denotes the statistical significance of a coefficient, black is significant ($p < 0.05$ level), grey is non-significant but trending ($p < 0.10$), white is non-significant.

both fish and other marine taxa, with considerable risk of death by exhaustion or suffocation. When compared to other consumer items discarded in the ocean, fishing gear clearly poses the greatest ecological threat. Redesign of fishing gear, combined with economic incentives and associated penalties may be able to reduce gear loss and intentional discarding [27] and could substantially reduce the resulting threat of entanglement.

Plastic bags and balloons, however, were also found to pose considerable entanglement risk to marine taxa. While balloons are generally small compared to plastic bags, they are often associated with a length of twine that likely poses the greatest entanglement threat. Plastic bags generally have handles which pose an entanglement risk as well as a 3-dimensional structure that creates a space in which an animal or parts of an animal can become entwined; indeed, plastic bags have been shown to entangle pinnipeds [28,29]. The expert elicitation findings reported here confirm that compared to most other consumer plastic items, plastic bags pose one of the greatest impacts to ocean wildlife and thus, from an environmental impact perspective, plastic bags warrant the specific attention they have received from governments and advocates to address their use.

In contrast to entanglement, all items except paper bags were deemed to pose at least a small threat via the risk of ingestion. The items known to be ingested by seabirds, sea turtles and whales are all found among the top 20 items collected during Ocean Conservancy's annual International Coastal Cleanup (http://www.oceanconservancy.org/our-work/international-coastal-cleanup/). In this study, food packaging, straws and stirrers and plastic utensils in particular were scored high by respondents. These are also some of the most common items found on beaches and waterways (ICC, [5]), but not all have been well documented in the scientific literature as posing threats to marine-wildlife to date. However, their rigid properties, food residue, and high likelihood of being encountered in the marine environment suggest they are important items of conservation concern.

Chemical contamination from plastics is dependent on an item first being ingested by the focal taxa. While the impact from chemical contamination ranked lower than that from entanglement or ingestion, approximately 50% of the 20 items surveyed were anticipated to have at least some impact. The understanding of the ecotoxicology of plastic pollution is limited, but these finding are consistent with the emerging results from research in this area. Studies have shown that plastics can concentrate chemicals in the environment [10,30,31] and concentrations in some species (e.g. seabirds) are correlated with plastic in the animal's guts [32]. This work has been confirmed by carefully controlled laboratory studies where fitness effects (including the formation of pre-cancer cells) from ingestion of plastics have been demonstrated [8]. To date, the link between plastic ingestion by ocean animals (especially fish and shellfish) and human health has not yet been made, but this is a growing concern and active area of research [33].

Developing effective public and private sector strategies to confront the threat of plastic pollution requires an understanding of the relative threat of different items to ocean health. The relative threat of all 20 items was evaluated by combining the three threats (entanglement, ingestion and contamination) for potential severity and specificity across the three taxa studied (Table 2). Except for fishing gear, plastic bags emerged at the top of the list with the expected population and taxa level impact of plastic bags on seabirds, turtles and marine mammals ranking highest.

Plastic bag bans recently have been enacted in municipalities in numerous countries (Bangledesh initiated the first nationwide

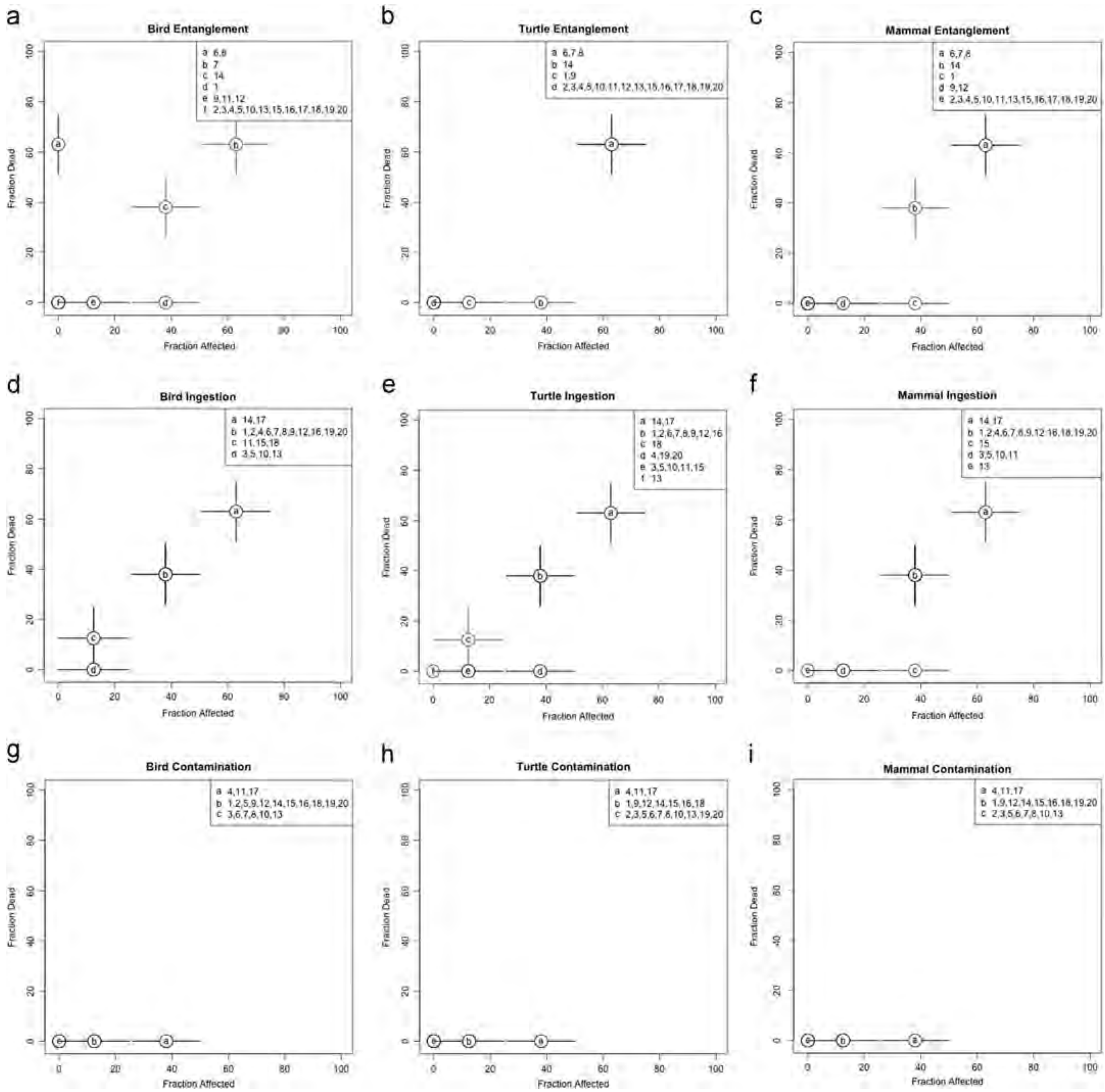

Fig. 4. Expected impacts to marine wildlife populations from interactions with the 20 most common debris items. Bars represent the range of lethal and nonlethal impacts predicted by experts, based on the best fit model. Letter labels give the index of the item. Letters are ordered according to expected impact level, with outcomes ranked as lethal > potentially lethal > sub-lethal > none, and specificity ranked by the level of the population expected to be affected 75–100 > 50–75 > 25–50 > 0–25. Indexes are: (1) Balloons, (2) Beverage bottle caps, (3) Beverage cans, (4) Cigarette butts, (5) Cups and plates, (6) Fishing buoys, traps and pots (including attached rope), (7) Fishing line (monofilament), (8) Fishing nets (including netting, float lines and rope), (9) Food packaging/wrappers, (10) Glass beverage bottles, (11) Hard plastic containers (detergent bottles, motor oil bottles, etc.), (12) Other Expanded Polystyrene Packaging, (13) Paper bags, (14) Plastic bags, (15) Plastic beverage bottles, (16) Plastic Food and Beverage Lids, (17) Plastic utensils, (18) Straws and Stirrers, (19) Takeout/away food containers, (20) Unidentifiable plastic fragments.

plastic bag ban in 2002) and some states (e.g. California in the United States). Last year, California enacted the first state-wide ban on single-use plastic bags in the nation and this has sparked a fierce backlash from the plastics industry, including a recent effort to rescind the legislation via referendum. Given that plastic bags pose a significant threat to marine wildlife, our research suggests that plastic bag bans could reduce individual and possibly population level impacts to marine wildlife.

Overall, findings from this work show that a wide variety of plastic items pose at least some risk to ocean wildlife, suggesting that protecting oceans from the impacts of plastic pollution will require comprehensive solutions that address the full range of products that end up in the ocean (e.g. beyond single items like plastic bags). For the larger suite of consumer plastics that litter the ocean, new strategies to prevent plastics from entering the ocean in the first place must be developed and implemented. An estimated 8 million tons of plastic waste enters the ocean each year [34]. Reducing the amount of mismanaged waste by 50% in the 20 countries where the

Table 2
Rankings of marine debris items by their expected impact on marine animals. Item ID corresponds to numbers in Fig. 3, and order in Fig. 2. Rankings are based on most severe expected impacts across the three impact mechanisms. Mean rank is the arithmetic mean of these scores across the taxa.

Item ID	Item name	Rank of expected impact			
		Mean	Bird	Turtle	Mammal
6	Buoys/traps/pots	1	1	1	1
7	Monofilament	2.3	3	2	2
8	Fishing nets	2.7	2	3	3
14	Plastic bags	5.7	4	9	4
17	Plastic utensils	5.7	7	4	6
1	Balloons	6.7	8	5	7
4	Butts	7.3	5	12	5
2	Caps	7.7	9	6	8
9	Food packaging	8.7	10	7	9
12	Other EPS Packaging	9.7	11	8	10
11	Hard plastic cont.	11.3	6	13	15
16	Plastic Food Lids	11.3	13	10	11
18	Straws/Stirrers	12.3	14	11	12
19	Takeout containers	15.3	15	18	13
3	Cans	15.7	17	14	16
15	Beverage bottles	16	12	17	19
20	Unidentified Plastic Fragment	16.3	16	19	14
5	Cups&plates	16.7	18	15	17
10	Glass bottles	17.7	19	16	18
13	Paper bags	20	20	20	20

mismatch between waste generation and the capacity to manage it is greatest could result in a nearly 40% decline in inputs of plastic to the ocean [34]. Doing so requires a better understanding of the fundamental market failure that is responsible for waste mismanagement in these geographies and an analysis of how various strategies (e.g. storm catchment devices, plastic recovery fees, or extender producer responsibility) can create the right incentives for proper recovery and collection of all plastic consumer goods that would otherwise pollute the global ocean. Policy mechanisms that address a full suite of consumer products are needed if ocean wildlife is to be protected from the rapidly growing global production of plastics and their subsequent deposition in the ocean.

5. Conclusion

In conclusion, the results presented here demonstrate the value of expert elicitation techniques in providing insights where field experiments are difficult to undertake. Variable impacts of common debris items on the health of marine wildlife were identified, with entanglement by fishing-related gear, balloons and plastic bags emerging as the greatest threat to seabirds, sea turtles and marine mammals. However, a wide variety of other items posed at least some threat to these organisms through either ingestion, contamination or both, suggesting that a comprehensive approach to preventing plastics from entering the ocean is vitally needed. This work points towards a number of opportunities for both policy-based and consumer-driven changes in plastics use that could have demonstrable effects on a range of taxa that are ecologically important and serve as indicators of marine ecosystem health.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2015.10.014.

References

[1] V. Hidalgo-Ruz, M. Thiel, Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project, Mar. Environ. Res. 87 (2013) 12–18.
[2] S. Hong, J. Lee, D. Kang, H.W. Choi, S.H. Ko, Quantities, composition, and sources of beach debris in Korea from the results of nationwide monitoring, Mar. Pollut. Bull. 84 (2014) 27–34.
[3] M. Eriksen, L.C. Lebreton, H.S. Carson, M. Thiel, C.J. Moore, J.C. Borerro, J. Reisser, Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 t afloat at sea, Plos. One 9 (12) (2014) e111913.
[4] K.L. Law, S. Morét-Ferguson, N.A. Maximenko, G. Proskurowski, E.E. Peacock, J. Hafner, C.M. Reddy, Plastic accumulation in the North Atlantic subtropical gyre, Science 329 (5996) (2010) 1185–1188.
[5] work/international-coastal-cleanup/2014-ocean-trash-index.html.
[6] S.C. Gall, R.C. Thompson, The impact of debris on marine life, Mar. Pollut. Bull. (2015) http://dx.doi.org/10.1016/j.marpolbul.2014.12.041.
[7] J.G. Derraik, The pollution of the marine environment by plastic debris: a review, Mar. Pollut. Bull. 44 (2002) 842–852.
[8] C.M. Rochman, E. Hoh, T. Kurobe, S.J. Teh, Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress, Sci. Rep. (2013) 3.
[9] C.M. Rochman, R.L. Lewison, M. Eriksen, H. Allen, A.M. Cook, S.J. Teh, Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats, Sci. Total. Environ. 476 (2014) 622–633.
[10] E.L. Teuten, S.J. Rowland, T.S. Galloway, R.C. Thompson, Potential for plastics to transport hydrophobic contaminants, Environ. Sci. Technol. 41 (22) (2007) 7759–7764.
[11] D.W. Laist, Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records, Marine Debris, Springer, New York (1997), p. 99–139.
[12] P.G. Ryan, C.J. Moore, J.A. van Franeker, C.L. Moloney, Monitoring the abundance of plastic debris in the marine environment, Philos. Trans. R. Soc. B: Biol. Sci. 364 (1526) (2009) 1999–2012.
[13] Q. Schuyler, C. Wilcox, C. Wilcox, K. Townsend, K.R. Wedemeyer-Strombel, G. Balazs, E. van Sebille, B.D. Hardesty, A global risk analysis for turtles and marine debris, Glob. chang. Biol. (2015), http://dx.doi.org/10.1111/gcb.13078.
[14] A. Vegter, M. Barletta, C. Beck, J. Borrero, H. Burton, M. Campbell, M. Eriksen, C. Eriksson, A. Estrades, K. Gilardi, BD. Hardesty, J. Assunção, I. do Sul, J. Lavers, B. Lazar, L. Lebreton, W.J. Nichols, J. Ramirez Llodra, C. Ribic, P.G Ryan, Q. Schuyler, S.D.A. Smith, H. Takada, K. Townsend, C. Wabnitz, C. Wilcox, L. Young, M. Hamann, Global research priorities for the management and mitigation of plastic pollution on marine wildlife, Endangered Species Research 25 (2014) 224–247, http://dx.doi.org/10.3354/esr00623.
[15] C. Donlan, D.K. Wingfield, L.B. Crowder, C. Wilcox, Using expert opinion surveys to rank threats to endangered species: a case study with sea turtles, Conserv. Biol. 24 (6) (2010) 1586–1595.
[16] S.L. Moore, D. Gregorio, M. Carreon, S.B. Weisberg, M.K. Leecaster, Composition and distribution of beach debris in Orange County, California. Marine Pollution Bulletin 42 (2001) 241–245.
[17] S. Moret-Ferguson, K.L. Law, G. Proskurowski, E.K. Murphy, E.E. Peacock, C. M. Reddy, The size, mass, and composition of plastic debris in the western North Atlantic Ocean, Mar. Pollut. Bull. 60 (2010) 1873–1878, http://dx.doi.org/10.1016/j.marpolbul.2010.07.020.
[18] P. Zhou, C. Huang, H. Fang, W. Cai, D. Li, X. Li, H. Yu, The abundance, composition and sources of marine debris in coastal seawaters or beaches around the northern South China Sea (China), Mar. Pollut. Bull. 62 (2011) 1998–2007.
[19] A.L. Lusher, M. McHugh, R.C. Thompson, Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel, Mar. Pollut. Bull. 67 (2013) 94–99.
[20] M. Cole, P. Lindeque, C. Halsband, T.S. Galloway, Microplastics as contaminants in the marine environment: a review, Mar. Pollut. Bull. 62 (2011) 2588–2597.
[21] K.P. Burnham, D.R. Anderson, Model selection and multimodel inference: a practical information-theoretic approach, Springer Science & Business Media, 2002.
[22] R.H.B. Christensen, Ordinal—regression models for ordinal data, R. Package Version, 2010, 22.
[23] C. Wilcox, B.D. Hardesty, R. Sharples, D.A. Griffin, T.J. Lawson, R. Gunn, Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia, Conserv. Lett. 6 (4) (2013) 247–254.
[24] C. Wilcox, G. Heathcote, J. Goldberg, R. Gunn, D. Peel, B.D. Hardesty,

Understanding the sources and effects of abandoned, lost, and discarded fishing gear on marine turtles in northern Australia, Conserv. Biol. 29 (1) (2015) 198–206.
[25] G.H. Balazs, Impact of ocean debris on marine turtles: entanglement and ingestion, Proc. Workshop Fate Impact Mar. Debris vol. 26 (1984) 29.
[26] FAO, Fisheries and aquaculture department, Guidelines to reduce sea turtle mortality in fishing operations, FAO, Rome (2009), p. 128.
[27] D.-O. Cho, The incentive program for fishermen to collect marine debris in Korea, Mar. Pollut. Bull. 58 (2009) 415–417.
[28] B. Page, J. McKenzie, R. McIntosh, A. Baylis, A. Morrissey, N. Calvert, S. D. Goldsworthy, Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem, Mar. Pollut. Bull. 49 (2004) 33–42.
[29] C.M. Waluda, I.J. Staniland, Entanglement of Antarctic fur seals at Bird Island, South Georgia, Mar. Pollut. Bull. 74 (2013) 244–252.
[30] Y. Mato, T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, T. Kaminuma, Plastic resin pellets as a transport medium for toxic chemicals in the marine environment, Environ. Sci. Technol. 35 (2001) 318–324.
[31] C.M. Rochman, M.A. Browne, B.S. Halpern, B.T. Hentschel, E. Hoh, H. K. Karapanagioti, R.C. Thompson, Policy: Classify plastic waste as hazardous, Nature 494 (7436) (2013) 169–171.
[32] B.D. Hardesty, D. Holdsworth, A.T. Revill, C. Wilcox, A biochemical approach for identifying plastics exposure in live wildlife, Methods Ecol. Evol. 6 (1) (2015) 92–98.
[33] R.E. Engler, The complex interaction between marine debris and toxic chemicals in the ocean, Environ. Sci. Technol. 46 (2012) 12302–12315.
[34] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, K. L. Law, Plastic waste inputs from land into the, Ocean. Sci. 347 (6223) (2015) 768–771.