Received: 28 July 2020 | Revised: 24 October 2020 | Accepted: 12 November 2020

DOI: 10.1111/conl.12781

Conservation Letters
A journal of the Society for Conservation Biology
Open Access
WILEY

REVIEW

Plastic pollution is killing marine megafauna, but how do we prioritize policies to reduce mortality?

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Abstract

Pollution by plastic and other debris is a problem affecting the world's oceans and is increasing through time. The problem is so large that prioritizing solutions to effect meaningful change may seem overwhelming to the public and policy makers. Marine megafauna are known to mistakenly eat anthropogenic debris and die from consequent gastrointestinal blockages, perforations and malnutrition, as well as suffer sublethal impacts. We collated information on which specific items were ingested and responsible for causing death across 80 marine species, including cetaceans, pinnipeds, sea turtles, and seabirds. We evaluated which items were responsible for the highest mortality, and which, if reduced by policy responses or other means, could result in the largest reduction in debris mortality. A limited number of consumer items were shown to be responsible for most megafauna deaths. Flexible plastic is responsible for the largest proportion of debris deaths, primarily due to gastric obstructions. Disproportionately lethal items included plastic bags/sheets/packaging, rope/fishing nets, fishing tackle and balloons/latex. Smaller items, including "microplastics," though abundant, were seldom implicated in mortality. We provide suggestions to directly curb debris deaths of marine megafauna by prioritizing policies that would reduce or eliminate the input of disproportionately hazardous items into the marine system.

KEYWORDS
cetacean, death, dolphin, ingestion, marine debris, pinniped, sea turtle, seabird, seal, whale

1 | INTRODUCTION

Pollution of the marine environment by solid waste "marine debris" is a growing global challenge, the ecological consequences of which are still being realized (Claro et al., 2019). Each year, new publications emerge describing more species affected by the ingestion of marine debris (Provencher et al., 2017). A proliferation of debris reduction policies at local, national, and international levels have followed, partially fuelled by concerns about the welfare of marine wildlife, especially charismatic megafauna. While the items causing megafauna death by entanglement are well recognized (Gregory, 2009), we know very little about which types of debris cause mortality when ingested. Additionally, identifying debris ingestion as a cause of death can be challenging. Assigning cause of death requires rigorously conducted postmortem examination of a reasonably freshly dead animal by an experienced person, posing a challenge for classifying deaths with respect to ingested debris for marine species.

Marine debris ingestion occurs in over 1,400 species, of which marine mammals, sea turtles and seabirds are well represented (Claro et al., 2019). Debris ingestion has been recorded in 81 of 123 marine mammal species, all seven sea turtle species, and 203 of 406 seabird species to date (Kühn, Bravo Rebolledo, & Van Franeker, 2015), and these numbers are increasing with time (Provencher et al., 2017). Debris is ingested both due to mistaken identity for food (Roman, Schuyler, Hardesty, & Townsend, 2016; Schuyler, Hardesty, Wilcox, & Townsend, 2012), as well as incidental ingestion during feeding (Alexiadou, Foskolos, & Frantzis, 2019). The dangers of debris ingestion to marine megafauna have been known since the 1950s, where deaths among captive marine animals at aquariums and oceanariums often resulted from animals swallowing indigestible foreign material (Walker & Coe, 1989). Debris ingestion mortalities have been recorded among cetaceans, pinnipeds, sea turtles, and seabirds (Alexiadou et al., 2019; Roman, Hardesty, Hindell, & Wilcox, 2019; Wilcox, Puckridge, Schuyler, Townsend, & Hardesty, 2018). Death can be caused by gastric blockage, starvation, perforation, or rupture of the gastrointestinal tract (Pierce, Harris, Larned, & Pokras, 2004; Roman, Bell, Wilcox, Hardesty, & Hindell, 2019), consequent peritonitis and septicaemia (Baulch & Perry, 2014; Panti et al., 2019; Unger et al., 2017), fecal compaction, and wasting (Nelms et al., 2016; Rosolem Lima et al., 2018; Wilcox et al., 2018). Though the scale of mortality and resultant population effects among wild animals are not known for any species, debris ingestion is increasingly recognized as an important threat to marine megafauna (Panti et al., 2019).

Death in megafauna can result from the ingestion of just one item of debris (Roman, Hardesty et al., 2019; Santos, Andrades, Boldrini, & Martins, 2015; Wilcox et al., 2018), though the risk of debris-related death increases as more items are ingested (Roman, Hardesty et al., 2019; Wilcox et al., 2018). Not all ingested debris items contribute equally to mortality, and as an animal ingests more items, the chances of ingesting a lethal item increase (Roman, Hardesty et al., 2019). Understanding which items disproportionately result in mortality to marine megafauna and determining whether the responsible debris items originate from land or sea provide an opportunity to prioritize policies that could help to reduce debris-related mortality of threatened marine megafauna.

Expert elicitation suggests that the items most likely to result in harm from ingestion by marine megafauna include plastic bags and balloons, followed by monofilament line and plastic utensils (Wilcox, Mallos, Leonard, Rodriguez, & Hardesty, 2016). These expectations have not, however, been tested empirically. Bias-free empirical scrutiny of the harm and lethality associated with debris ingestion presents a challenge within the marine debris literature. Publication pressure biases research towards positive-only results across most scientific disciplines (Fanelli, 2010, 2012), and opportunistic spatial sampling biases carcasses encountered and examined towards individuals beach-cast on land or by-caught in fishing operations. Consequently, both presence-only records of debris-mortality and beach-cast/by-caught animals are overrepresented in the marine debris literature. Presence-only reporting or spatial sampling biases may result in item commonness becoming conflated with the lethal risk of ingesting specific items. In other types of ecological data, this bias is reduced by choosing background/control data with the same bias(es) as occurrence data (Phillips et al., 2009). To reduce these sampling biases, we conducted a systematic literature review, examining all available published records of beach-cast and by-caught marine megafauna mortality where cause of the death is known and ingested debris is present, irrespective of whether debris was implicated in death. Through this method of sampling all available mortality records, we can gauge which items are commonly implicated in deaths and which commonly ingested items are not implicated in megafauna death. We discuss these findings with a focus on informing policy responses aimed at reducing harm to threatened or endangered marine megafauna.

2 | METHODS

2.1 | Systematic literature search

We performed a systematic literature search using Web of Science on 20/06/2020. We performed an advanced search to combine searches for each plastic, mode of death and taxa across all years. We performed three abstract searches to combine "plastic" or "debris," with the potential modes of death "ingestion," "strand," "by-catch/bycatch," "by-caught/bycaught," "death," "mortality," or "died" and any of the taxa "mammal," "pinniped," "whale," "dolphin," "seal," "sea lion," "turtle," "seabird," "bird," "albatross," "petrel," or "shearwater" (Figure S1). The literature search returned a total of 655 potentially relevant documents.

2.2 | Inclusion criteria

We examined each of the 655 publications, choosing only papers that reported death and debris ingestion in marine mammals, sea turtles, and seabirds. We chose only those results where the cause of death (COD) was identified (including nondebris causes of death such as fisheries bycatch or boat strike), where necropsies or postmortem examinations were conducted, and where the types of debris ingested were listed. We excluded cases which did not report types of debris ingested and cause of death, where plastic items were pooled, where frequency of occurrence of items were not reported for individual species, or studies that reported only material, mass or shape (i.e., "plastic" or "linear") without identifying the item. For cases where debris ingestion was the clear cause of death, we only included cases where the (likely) item(s) causing the death were reported. Studies, or cases within studies where debris was present but COD was unknown/not reported (such as beach-cast individuals/strandings), COD was known but debris was not present, or COD was attributed to debris but the type of debris was not specified, were excluded (exceptions were made where death was due to a bolus of mixed items). Where ingested plastic results tables combined multiple animals with multiple causes of death without differentiating between individuals, we also excluded these animals (for example, bycatch/shot and beach-cast). We also excluded cases where plastic ingestion results were pooled but frequency of occurrence of each item type was not available (for example, the study reported total number of items of each type but not frequency of occurrence). In cases where active fishing gear was reported to have caused the death of the animal, we did not consider this a "debris death" but a fisheries death. Included studies are detailed in Table S1. Referenced research articles, reports, and case studies within these articles were also included. Where only a subset of all data collected in a research article met our review's inclusion criteria; for example, a case study mentioned in text or photographs provided, we included just that subset in this review.

2.3 | Grouping and summarizing information

Megafauna surveyed were taxonomically grouped into "cetaceans", "pinnipeds", "sea turtles", and "seabirds". Debris described in published studies was grouped into the following categories: hard plastic, film-like plastic (including plastic bags), plastic fragments (hardness was not specified, includes fragmented hard and film-like items), fibers/thread, balloon/latex, rubber, foamed synthetics, paper, metal, glass, rope/net, and fishing debris. We noted whether each item type was present in each animal assessed. We used the ingested debris present in animals that died from a nondebris cause as a control group. Using this control group of known nondebris deaths allows us to assess which items are likely to cause mortality, rather than which items are abundantly ingested.

We examined which items caused the greatest count of deaths per taxa and which items caused the most deaths as a proportion of each taxa. We calculated the commonness of each item as ingested by taxa, the frequency of items ingested as a proportion of total items ingested, and the "lethality" of each item per taxa: the frequency of deaths divided by the occurrence for each item ingested.

3 | RESULTS

3.1 | Search results

Of 655 potentially relevant results, 79 relevant research articles were identified (Table S1). The articles identified 1,328 mortalities: 132 cetaceans, 20 pinnipeds, 515 sea turtles, and 658 seabirds covering 80 species, spanning all inhabited continents (Figure 1), of which debris was the cause of death for 159 animals (Table 1).

3.2 | Lethal items across taxa

Film-like plastic, plastic fragments, and fishing debris were responsible for the most deaths surveyed by count (Figure 2A). Film-like plastic caused most deaths in cetaceans and sea turtles, fishing debris caused most deaths in pinnipeds, and hard plastic caused most deaths among seabirds (Figures 2A and 3). When death frequency is represented proportionally to taxa represented, fishing debris, film-like plastic and hard fragments cause the most deaths (Figure 2B). The items ingested most commonly across taxa were film-like plastic, hard plastic, and fishing debris (Figure 2C). Rubber, fishing debris, metal and balloons/latex were the most lethal, with the highest death frequency per recorded ingestion (Figure 2D).

Within taxa, film-like plastics, plastic fragments, and ropes/nets were the items most commonly ingested by cetaceans, with film-like plastics and ropes/nets resulting in the most mortalities, showing a high frequency of fatal blockages (Figure 3A). Only fishing debris caused mortalities in pinnipeds (Figure 3B). Film-like plastic, plastic fragments, and fishing debris caused the most mortalities in sea turtles (Figure 3C). Hard plastic was the most common item ingested by seabirds and caused the most mortalities. Soft items such as balloon and fishing debris caused death at a high frequency relative to their rate of ingestion (Figure 3D).

TABLE 1 Number of debris-ingesting animals included in study and number of animals whose deaths were identified as being caused by debris ingestion. A fully referenced version of this table is available in Supplementary Information (Table S2)

Group	Common name	IUCN threat listing	Total deaths	Debris deaths
Cetacean	Atlantic spotted dolphin	Least concern	5	3
	Blainville's beaked whale	Data deficient	2	0
	Common bottlenose dolphin	Least concern	5	5
	Cuvier's beaked whale	Least concern	7	5
	Deraniyagala's beaked Whale	Data deficient	1	1
	East Asian finless porpoise	Endangered	7	0
	Fin whale	Vulnerable	2	1
	Franciscana dolphin	Vulnerable	45	0
	Gervais' beaked whale	Data deficient	1	1
	Guiana dolphin	Near threatened	1	0
	Harbour porpoise	Least concern	4	0
	Humpback whale	Least concern	2	0
	Northern minke whale	Least concern	1	1
	Longman's beaked whale	Data deficient	2	0
	Pygmy sperm whale	Data deficient	4	3
	Risso's dolphin	Least concern	7	2
	Rough-toothed dolphin	Least concern	4	2
	Short-beaked common dolphin	Least concern	7	0
	Sowerby's beaked whale	Data deficient	2	0
	Sperm whale	Vulnerable	16	8
	Striped dolphin	Least concern	5	2
	True's beaked whale	Data deficient	3	0
Cetacean total:			132	34
Pinnipeds	Grey seal	Least concern	1	1
	Harbor seal	Least concern	19	4
Pinniped total:			20	5
Sea turtles	Flatback sea turtle	Data deficient	2	1
	Green sea turtle	Endangered	371	59
	Hawksbill sea turtle	Critically endangered	5	5
	Kemp's Ridley sea turtle	Critically endangered	2	0
	Leatherback sea turtle	Vulnerable	22	18
	Loggerhead sea turtle	Vulnerable	113	20
	Olive Ridley sea turtle	Vulnerable	3	0
Sea turtle total:			515	103
Seabirds	Antarctic prion	Least concern	1	1
	Audouin's gull	Near threatened	2	0
	Balearic shearwater	Critically endangered	32	0
	Barau's petrel	Endangered	37	0
	Black-browed albatross	Least concern	1	0
	Black-footed albatross	Near threatened	15	0
	Black-legged kittiwake	Lease concern	3	0
	Blue petrel	Least concern	1	1
	Brown noddy	Least concern	3	0
	Cape gannet	Endangered	1	0
	Cape petrel	Least concern	2	0

(Continues)

TABLE 1 (Continued)

Group	Common name	IUCN threat listing	Total deaths	Debris deaths
	Common murre	Least concern	2	0
	Cory's shearwater	Least concern	47	0
	Fairy prion	Least concern	5	5
	Flesh-footed shearwater	Near threatened	49	0
	Fork-tailed storm petrel	Least concern	7	0
	Great shearwater	Least concern	1	1
	Great skua	Least concern	1	0
	Horned puffin	Least concern	1	0
	Laysan albatross	Near threatened	18	0
	Leach's storm-petrel	Vulnerable	1	0
	Lesser noddy	Least concern	9	0
	Light-mantled sooty albatross	Near threatened	1	1
	Magellanic penguin	Near threatened	3	1
	Mediterranean gull	Least concern	1	0
	Newell's shearwater	Endangered	15	0
	Northern fulmar	Least concern	11	0
	Northern gannet	Least concern	2	1
	Northern giant petrel	Least concern	1	0
	Northern royal albatross	Endangered	14	0
	Salvin's prion	Least concern	1	1
	Short-tailed albatross	Vulnerable	4	0
	Short-tailed shearwater	Least concern	174	5
	Shy albatross	Near threatened	3	0
	Slender-billed prion	Least concern	1	0
	Sooty shearwater	Near threatened	30	0
	Sooty tern	Least concern	4	0
	Southern royal albatross	Vulnerable	4	0
	Thick-billed murre	Least concern	38	0
	Tristan albatross	Critically endangered	2	0
	Tropical shearwater	Least concern	42	0
	Tufted puffin	Least concern	8	0
	Wedge-tailed shearwater	Least concern	21	0
	Westland petrel	Endangered	1	0
	White-chinned petrel	Vulnerable	1	0
	White-tailed tropicbird	Least concern	10	0
	Yelkouan shearwater	Vulnerable	22	0
	Yellow-legged gull	Least concern	4	0
Seabird total:			658	17
Megafauna total:			1,328	159

3.3 | Marine mammals: Cetaceans and pinnipeds

Among cetaceans, though debris ingestion deaths are commonly reported (Baulch & Perry, 2014), few studies reported the specific items ingested. Where items are reported, film-like plastics including plastic bags, plastic sheeting, and packaging account for most of the items ingested by cetaceans and causing fatal gastric obstructions, typically in the stomach (Alexiadou et al., 2019) (Table 1). The highest number of ingested debris items reported occurred in sperm whales, *Physeter macrocephalus* (Alexiadou et al., 2019; Jacobsen, Massey, & Gulland, 2010; Unger et al., 2016), with one individual

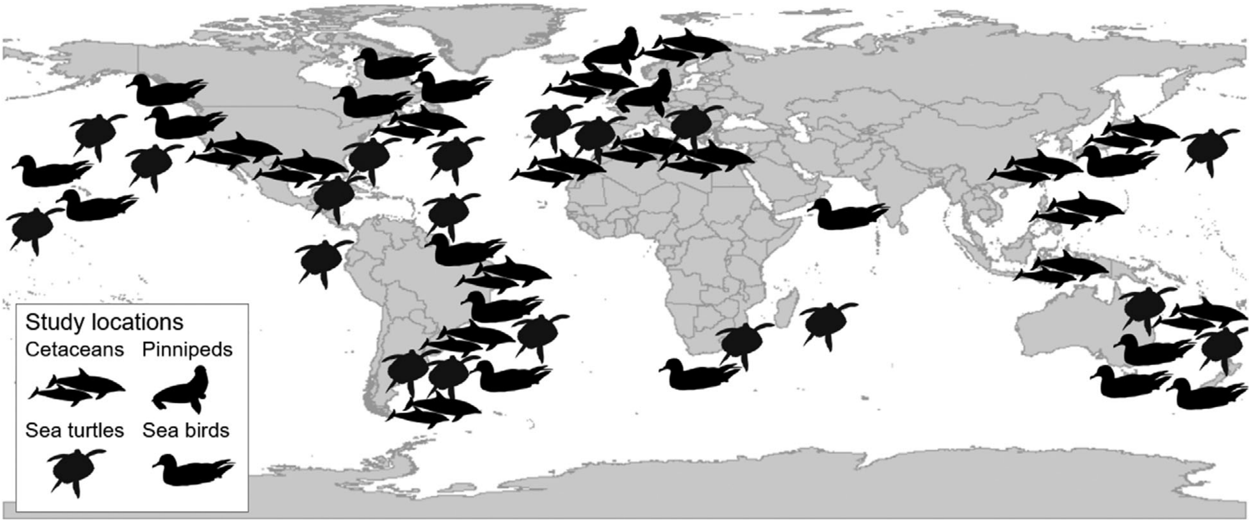

FIGURE 1 Study locations of cetaceans, pinnipeds, sea turtles, and seabirds spanned all inhabited continents

(COD debris ingestion) containing 135 items, predominantly plastic bags (Alexiadou et al., 2019). Cetaceans that die from debris have been observed swimming with difficulty in the days preceding death (Alexiadou et al., 2019), which may increase the risk of being struck by ships or boats. Ship strikes may result from difficulty swimming due to ingested plastic, with half of ship-struck cetaceans having ingested plastic (Alexiadou et al., 2019). For this reason, mortality resulting from plastic may be more common than direct mortalities from confirmed gastric obstructions or perforations would suggest.

In contrast to cetaceans, pinnipeds have a low frequency of debris ingestion, ranging from < 0.5% of observations (Unger et al., 2017) to 12.2 % of observations (Bravo Rebolledo, Van Franeker, Jansen, & Brasseur, 2013). Where pinniped debris ingestion does occur, ingestion of fishing associated debris (fishing line and hooks) can be fatal (Bravo Rebolledo et al., 2013; Unger et al., 2017), but no other ingested item types caused mortality in the studies we evaluated.

3.4 | Sea turtles

Debris ingestion is frequently recorded in sea turtles (Nelms et al., 2016), which commonly ingest film-like plastic, threads and plastic fragments (Domènech, Aznar, Raga, & Tomás, 2019). Literature citing debris as a cause of death in sea turtles seldom identified a responsible item, due to both lack of specificity in reporting as well as numerous debris deaths involving a bolus of hard and soft plastic items, commonly reported as "plastic" or "plastic fragments". Sea turtle debris literature qualitatively describes film-like plastics—plastic bags, sheets, and packaging—as trapping hard fragments, with the resulting bolus a reoccuring factor in the reported sea turtle deaths (Colferai, Silva-Filho, Martins, & Bugoni, 2017; Vélez-Rubio et al., 2018). Plastic blockages occur in both the stomach and intestines, with fecal compaction commonly recorded (Colferai et al., 2017; Nelms et al., 2016; Rosolem Lima et al., 2018; Wilcox et al., 2018). Like cetaceans, sea turtle buoyancy is affected by debris ingestion, which may increase the risk of being struck by ships or boats (Nelms et al., 2016).

3.5 | Seabirds

Debris ingestion is frequently recorded in seabirds (Wilcox, Van Sebille, & Hardesty, 2015), though studies specifically linking debris ingestion to debris death are uncommon (Roman, Hardesty et al., 2019). Plastic fragments, mostly consisting of hard plastic, are the most frequently ingested items in seabirds (Figure 2). Buoyant hard plastic polymers such as polyethylene and polypropylene float at the oceans' surface where foraging seabirds mistake them for food, and debris ingestion is common among surface-foraging planktivorous seabirds (Roman, Bell et al., 2019). Though ingested hard plastic items had a low risk of causing death as compared to soft items (Figure 3D), hard plastics caused the most seabird debris deaths as they are frequently eaten (Roman, Hardesty et al., 2019). Seabirds typically die when items become stuck in the isthmus juncture (in tubenose seabirds), gizzard, pylorus, or proximal duodenum (Pierce et al., 2004; Roman, Hardesty et al., 2019).

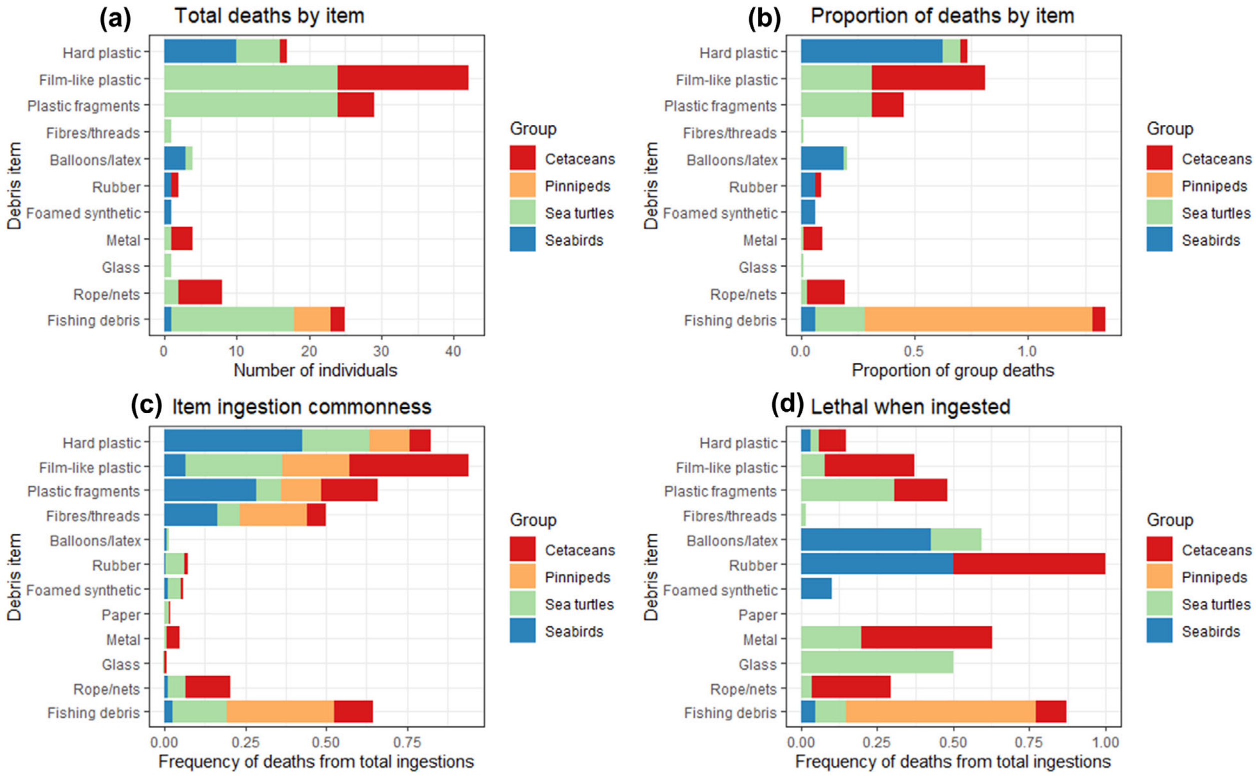

FIGURE 2 Mortality of marine megafauna by debris item. The number of individuals (a) and proportion of total individuals (b) within each megafauna group that died following the ingestion of each debris item type, showing film-like plastic and fishing debris are responsible for most debris deaths. Hard plastic, film-like plastic, plastic fragments and fishing debris are the items most commonly ingested by megafauna (c). Rubber items and fishing debris are most likely to be lethal when ingested (d)

4 | DISCUSSION

4.1 | Which items are associated with megafauna mortality?

Film-like plastic, plastic fragments (includes fragmented film-like items), and fishing debris cause the most mortalities in this global review of 60 taxa. Expert elicitation correctly identified three of four items; plastic bags, fishing debris (monofilament line), and balloons (scoring high for deadliness, though not common) to be key items resulting in high mortality for marine animals (Wilcox et al., 2016). However, experts also identified plastic cutlery as a high harm item, which does not appear in the literature nor data we evaluated. This shows the value of expert elicitation to support decision making, while also highlighting the importance of using empirical data to ground truth expert opinion.

Lethal items originated from a combination of land and sea-based sources. Mortality from land-based debris resulted from film-like plastics comprising plastic bags, plastic sheets, and packaging. Balloons/latex, though not a common item, were ranked as commonly lethal when ingested. Plastic bags and film-like/sheet-like packaging were a major cause of mortality for cetaceans (Panti et al., 2019) and sea turtles (Nelms et al., 2016), reflecting observations from captive cetaceans (Walker & Coe, 1989). Items causing death were mostly larger, whole items, with mortality seldom identified from items fragmented in small pieces, unless numerous fragments had formed a "wad." While a single item can cause death (Pierce et al., 2004; Wilcox et al., 2018), soft plastics are more likely to be lethal when many items combine to form a large obstruction (i.e., a larger item, such as a plastic bag, can collect other items including small plastic fragments). Soft plastics, such as bags and sheets, are often made from polyethylene and are typically neutrally buoyant in seawater. Hence, they occur in the water column where fauna forage (Figure 4). Similarities were noted between the debris ingested by some species of cetaceans and sea turtles; both forage in the water column and may encounter similar types of neutrally buoyant debris.

Sea-based debris including fishing nets and ropes, fishing hooks, line, and tackle were important sources of mortality across all megafauna groups. This mortality resulted both from obstructions by ingested nets and ropes and

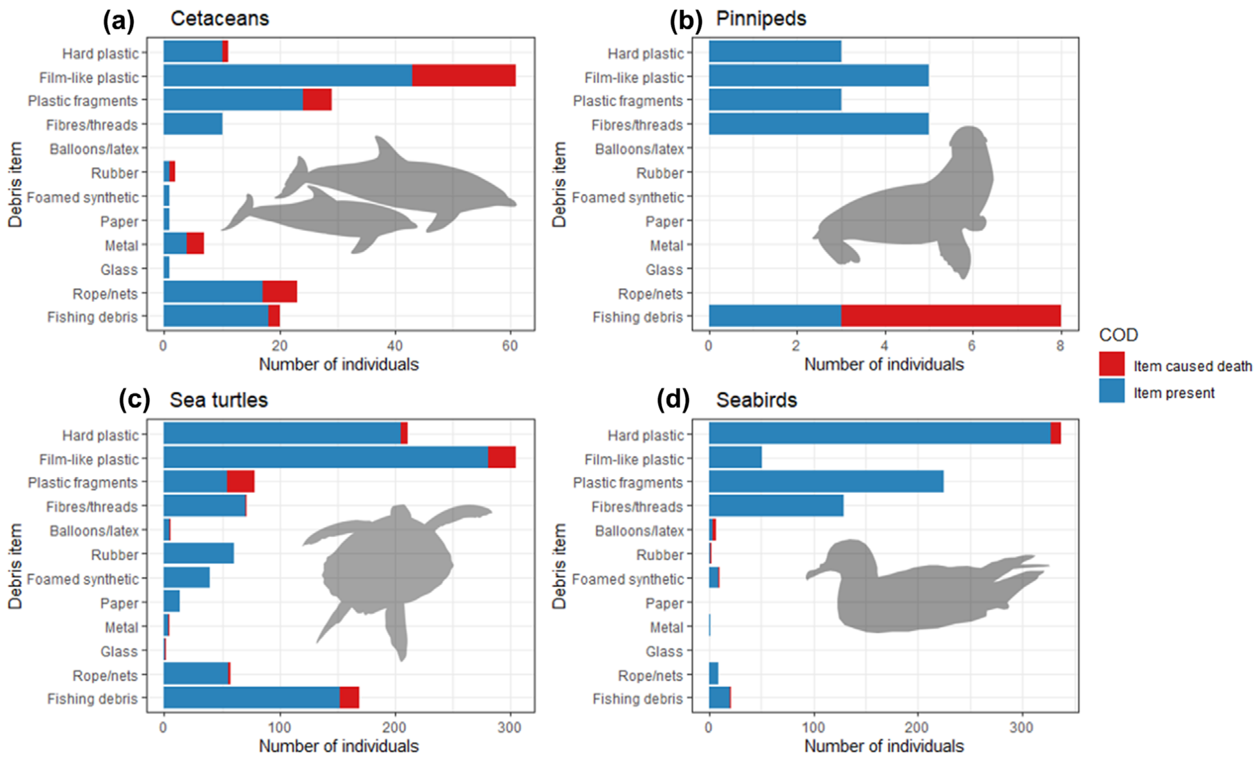

FIGURE 3 Debris items eaten by and lethal to marine taxa on necropsy. Summary of debris ingestion in studies of cetaceans, pinnipeds, sea turtles, and seabirds where the cause of death was known. Specific debris items causing death are shown in red, while debris items present in the gastrointestinal tract, but not responsible for mortality, are shown in blue

perforations by fishing hooks. Fishing debris contributes half of debris in some regions (by weight), including within the Great Pacific Garbage Patch (Lebreton et al., 2018). The impact of sea-based debris ingestion on megafauna may be underestimated due to spatial biases in data collection, with low likelihood of carcass retrieval for deaths that occur at sea or in remote locations. If spatial biases from underreporting in less accessible areas occur, we predict that these may cause underestimation of commonness of ingestion of sea-based debris and death due to sea-based debris. As the lethality estimates are driven by the relative frequency of presence and absence of ingested items, spatial/geographic factors are less likely to bias conclusions about the relative lethality. Even if future sampling across broader geographies reveals variation in the relative commonness of ingestion of items presented in Figures 2A, C (especially sea-based debris, which we argue may be underrepresented), the proportion of deaths by item (Figure 2B) and item deadliness (Figure 2D) will likely remain constant, as these estimates are independent of item commonness. Ultimately, spatial factors are less important than the physiological impact of different debris items within the gut of the animal, reflected in Figures 1B, D, which are affected by which item the animal ate and not where the ingestion occurred geographically.

A challenge of compiling this dataset was both the lack of comparable reporting of ingested items between studies and detailed reporting of physical damage. Though many postmortem reports involving cases of plastic death were available in the literature, only a subset were able to be used in this review due to limited reporting on debris items recovered during necropsy. While recent attempts to provide methodologies to standardize reporting of debris ingestion of megafauna are a valuable starting point (Provencher et al., 2017), recent standard methodologies provide neither policy-relevant item reporting categories, nor recommend reporting of physical damage/harm. Reporting evidence of harm, or the lack of, and item reporting categories that are relevant to policy (especially those highlighted in this study) empower decision makers to act effectively on research findings. We recommend that scientists thoroughly report their findings and make policy-relevant information about debris encountered available in their manuscripts, or as supplementary information. We further recommend updating standard methodologies for debris reporting to include both policy-relevant item categories (e.g., "plastic bag"), rather than just item material (e.g., "plastic") or shape (e.g., "linear") to permit policy-relevant information to be gathered from such deaths.

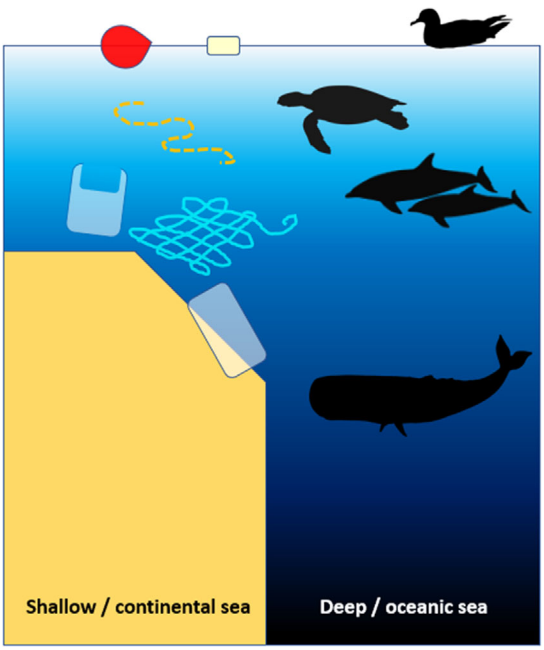

FIGURE 4 Material buoyancy affects which items marine animals are exposed to while foraging. Items occur in the water column where they are accessible to different species. Buoyant hard plastics and inflated balloons float at the surface where they are available to surface foraging species such as seabirds and sea turtles. Film-like plastics, such as bags and sheets are often made from polyethylene and are typically neutrally buoyant in seawater, where they are available to sea turtles and cetaceans. Ropes and nets are made from a variety of material and can either float or sink and may be attached to floating buoys. The highest plastic loads occur in sperm whales, which forage in the deep ocean where there is minimal light penetration

4.2 | Does size matter? Smaller, microplastic-sized items

Large, whole debris items make up just a small percentage of total marine litter (Eriksen et al., 2014). Items <5 mm are considered "microplastics" and are the most abundant debris reported floating in the marine environment (Eriksen et al., 2014). These microplastics include fibers, threads, plastic fragments, hard and soft items and are commonly ingested by marine fauna (Hernandez-Gonzalez et al., 2018; Roman, L., Paterson, H. et al., 2019). Though this study does not assess the potential sublethal effects of plastic ingestion, these small items were not associated with direct mortality in megafauna with a large body size—cetaceans, pinnipeds and larger seabirds and sea turtles (Hernandez-Gonzalez et al., 2018; Lusher, Hernandez-Milian, Berrow, Rogan, & O'Connor, 2018), but can be associated with mortality by blockages and perforations in small seabirds (Roman, Hardesty et al., 2019) and small sea turtles (Santos et al., 2015). The presence of ingested small items is likely underestimated in our summary, as many studies of larger taxa did not count small items. When studies do quantify small items/microplastics, they are often abundant. In sea turtles, one study found microplastics in all sea turtles examined across three ocean basins but did not find that microplastics contributed to blockages and perforations (Duncan et al., 2019). Instead, the authors suggested that microplastics likely pass through the gut lumen (Duncan et al., 2019). Small plastics, both hard and soft, can occur in large numbers (sometimes hundreds of plastic items; Clukey, Lepczyk, Balazs, Work, & Lynch, 2017) in larger sea turtles, causing no apparent damage to the gastrointestinal tract (Clukey et al., 2017). Likewise, in marine mammals, ubiquitous presence of ingested microplastics across 10 species was suggested to be transitionary (Nelms et al., 2019).

Among seabirds, hard fragments and industrial plastic pellets "nurdles" are common in healthy specimens killed as bycatch or intentionally (Ryan, 1987), causing no obvious health effects. As small items are frequently ingested by seabirds, they are the most common item causing debris death, even though there is a low chance that any single piece will cause death (Figure 3C).

4.3 | Policy opportunities to reduce marine megafauna mortality

Flexible plastics that crumple may cause gastric obstruction and are responsible for the most deaths of marine megafauna. Reduction of input and removal of large items from the environment are recommended as priority. Large items are more commonly lethal, and furthermore, removal will prevent fragmentation into smaller pieces. Disproportionately lethal items include plastic sheets/bags/packaging and fishing nets/rope for larger fauna and balloons, rope and rubber for smaller fauna. We propose that the most cost-efficient way to prevent megafauna mortality would be by prioritizing the prevention of large and more lethal items. We have already seen a global response in the form of plastic bag bans and fees for bags (Lam et al., 2018; UNEP, 2018; Xanthos & Walker, 2017) (Table 2), which are reducing or eliminating single-use thin film bags in cities and countries around the world. Sea-based items with high lethality are primarily linked to fishing activities. Such loss of these items can be reduced at their source by improving fisheries management practices and engineering solutions to reduce losses of fishing gear (Table 2) (Richardson, Hardesty, & Wilcox, 2019).

Small debris fragments such as microplastics and fibers are a lower management priority than large items in terms of causing mortality to major marine taxa and they are

TABLE 2 Policy solutions to manage items that are disproportionately lethal to marine megafauna: Film-like plastic, fishing gear, and balloons/latex

Item	Relevance to marine megafauna	Management options	Policy examples
Film-like plastic	-Most deaths among megafauna surveyed -Most common item ingested across taxa -Most deaths in cetaceans and sea turtles - Among most deaths caused proportional to taxa surveyed	Regulation and prohibitions of lightweight plastic bags	-Plastic bags regulations include restrictions or taxes on the manufacture, distribution, use, and trade of plastic bags (27 countries), taxation and levies (30 countries charge consumer fees for plastic bag use), and postuse disposal (63 countries have mandates for extended producer responsibility for single-use plastics, including deposit-refunds, product take-back, and recycling targets) (UNEP, 2018) -Prohibition on free retail distribution of plastic bags is the most common policy to regulate plastic bags (UNEP, 2018) -127 out of 192 countries reviewed by UNEP (2018) have adopted some form of legislation to regulate plastic bags - The effectiveness of bag bans depends on enforcement of the ban and sanctioning systems (Bharadwaj, Baland, & Nepal, 2019)
		Regulation and prohibitions of plastic packaging	-Burkina Faso, Chad, Democratic Republic of Congo, Togo, and Turkey have instituted regulations including bans on production, import, marketing, and distribution of nonbiodegradable plastic packaging (UNEP, 2018) -In Cambodia, there are tax incentives for the importation and production of packaging material produced from biodegradable or bioplastic substances (UNEP, 2018) -In Saudi Arabia, disposable plastic products made of polypropylene and polyethylene with film thickness of ≤250 μm that are generally used for packaging, must be oxobiodegradable, and display the company logo (UNEP, 2018). -Plastic packaging presents a significant opportunity for reduction of waste to ocean, given that in 2015, plastic packaging waste accounted for 47% of the plastic waste generated globally, with half of that appearing to come from Asia (UNEP, 2018) - Opportunity for high wealth nations to introduce packaging regulation, as the United States of America is the largest generator of plastic packaging waste on a per-capita basis, followed by Japan and the European Union (UNEP, 2018)
		Replacement of “plasticulture” agricultural sheeting with environmentally sustainable alternatives	- Investment in gradual replacement of disposable plastic sheeting greenhouse with solid glass, acrylic or polycarbonate greenhouses - Replacement with biodegradable or photodegradable alternatives (Kasirajan & Ngouajio, 2012) - Development of recyclable sheeting and recycling infrastructure - Short-term cost benefits of plastic agricultural sheeting may be offset by the long-term cost and effort of recovering and recycling used mulching films (Steinmetz et al., 2016)

(Continues)

TABLE 2 (Continued)

Item	Relevance to marine megafauna	Management options	Policy examples
Fishing gear	-Among most deaths by item -Most deaths of pinnipeds -Among most common -Most deaths caused proportional to taxa surveyed -Among most lethal by ingestion	Better fisheries management and enforcement of existing regulations to reduce loss of ropes and fishing nets	-Incentivize or subsidize regular net maintenance and repair, which is associated with lower rates of net loss (Richardson et al., 2018) -Prohibit overboard discard of damaged nets and incentivize port disposal of damaged nets -Better policing of illegal, unreported and unregulated (IUU) fishing, where gear loss is common (Richardson et al., 2018) -Manage fisheries to reduce operator overcrowding, which is associated with higher-risk fishing behavior and working in suboptimal conditions (such as fishing in poor weather or close to reefs), resulting in higher rates of net loss (Richardson et al., 2018) -Reduce and regulate bottom trawling on hard-bottomed seafloors such as rock and reef, where snags and net loss/breakage is more likely (Richardson et al., 2019) - Increase coverage of observer programs to enforce compliance with existing regulations
		Better fisheries management to reduce loss of hooks, line and tackle	-Education or recreational fishers on the impacts of discarded line -Incentive or legislate replacement of nonbiodegradable fishing line and tackle with degradable fishing line and tackle -Regulation of recreational fishing activity or allowable gear in locations where gear loss is likely, such as near reefs - Provide tackle bins for line and tackle disposal at popular fishing locations
Balloons/latex	- Among most lethal when ingested	Prohibition of release of balloons and latex gloves to the environment	-Prohibition of the release of balloons into the environment during public events such as celebrations, sporting events, and advertising -Prohibition of free distribution of helium balloons to public for advertising or public events -Class balloons as litter and prosecute the private release of balloons to the environment under existing littering legislation -Where release of balloons to the environment is necessary, such as weather balloons, use readily biodegradable varieties, and colors that are less attractive to wildlife, such as blue. - Provide disposal bins and enforce proper disposal of latex gloves where loss to the marine environment is likely, such as on fishing vessels
All items		Investment in behavior change messaging campaigns	-The combination of legislative policies and practices with behavior change outreach campaigns were most successful in reducing coastal litter at a national scale in a case study of 40 Australian council region (Willis et al., 2018), - Investments in behavior change campaigns resulting in larger waste reductions than do investment in policies alone (Brown et al., 2010)

more difficult to manage. However, substantial efforts to reduce primary microplastic production in personal care products are underway, some as voluntary measures, others through legislation (Lam et al., 2018; Xanthos & Walker, 2017). As small items are ubiquitous in the marine environment and have many sources (Duis & Coors, 2016), they are more difficult to manage/remove. No simple solution exists to either prevent the input of small items into the ocean nor to remove what has already accumulated, and multilateral action is likely required to address plastic pollution of the ocean (Doughty & Eriksen, 2014; Vince & Stoett, 2018).

4.4 | Policy opportunities: Film-like plastics

Flexible film-like plastics are typically manufactured for single use or short service life products, including bags, film packaging, and agricultural sheeting (Horodytska, Valdés, & Fullana, 2018). Due to low rates of recycling, millions of tons of postconsumer plastic waste are generated annually (Horodytska et al., 2018), some of which enter waterways. Plastic bags and food packaging, in particular, rank among the 10 most common items collected in coastline and waterway marine debris surveys globally (Roman et al., 2020). Agriculture, including "plasticulture", is recognized as a major source of large plastic sheets ingested by cetaceans (De Stephanis, Giménez, Carpinelli, Gutierrez-Exposito, & Cañadas, 2013). These items are lost through a combination of waste mismanagement and accidental loss. Control at their source is the least expensive, most likely to be successful mitigation option (Lam et al., 2018). Some research articles suggest legislation to favor prohibition (Xanthos & Walker, 2017) or replacement (i.e., reusable or biodegradable alternatives for bags, packaging, and agricultural plastic sheets; Kyrikou & Briassoulis, 2007). However, options such as improved local disposal and/or engineering solutions to enable recycling (Briassoulis, Hiskakis, & Babou, 2013; González-Sánchez et al., 2014) improve plastic life span and/or minimize loss (Kyrikou & Briassoulis, 2007) may also reduce losses to the environment (Table 2).

4.5 | Policy opportunities: Fishing debris

Fishing-related debris of many sorts is regularly implicated in megafauna mortality. Reduction of the input of any of these dangerous debris items will undoubtedly reduce death of marine taxa. Overall, fisheries have high gear loss rates; 5.7% of all nets and 29% of all lines are lost annually in commercial fisheries (Richardson et al., 2019). Far less is known about the loss rates for recreational fishers, though gear loss is evidently high in leisure fishing (Battisti et al., 2019; Bilkovic, Havens, Stanhope, & Angstadt, 2014; Roman et al., 2020). Introduction of minimum standards of loss-resistant/higher-quality gear is recommended, wherever possible. Solutions to reduce loss of fishing gear include repair or port disposal rather than at-sea disposal of damaged nets, enforcing penalties associated with dumping, failure to retrieve lost items, and restricting fishing activity in conditions/locations where loss is likely (Richardson, Gunn, Wilcox, & Hardesty, 2018). Incentivizing gear repairs and port disposal of damaged nets, penalizing or prohibiting high-risk fishing activities where snags or gear loss are likely (poor weather and rough terrains), and enforcing penalties associated with dumping would directly prevent megafauna deaths through decreasing the interactions with derelict fishing gear. Where loss of items cannot be effectively prevented, the use of biodegradable, rather than synthetic materials, could potentially limit the lifespan of potential damage to megafauna when these items are lost at sea (Wilcox & Hardesty, 2016).

To reduce gear loss in recreational fishing activities, we also suggest direct outreach and education programs to highlight the harmful effects of fishing gear on coastal and marine ecosystems. The combination of policy change with behavior change campaigns is effective at reducing waste in coastal areas (Willis, Maureaud, Wilcox, & Hardesty, 2018). Currently, programs that combine infrastructure, such as provision of tackle bins at popular wharfs and piers and the promotion of appropriate fishing tackle disposal in recreational fishing codes of conduct, could change behavior around inappropriate fishing gear disposal.

4.6 | Policy opportunities: Balloons/latex and rubber debris

Balloons, latex, and rubber are uncommon in the marine environment (Roman et al., 2020). Though rare, balloons and latex debris, such as disposable gloves, are disproportionately lethal to smaller species, particularly sea turtles (Wilcox et al., 2018) and seabirds, causing death 32 times more often than hard plastic when ingested by tube-nosed seabirds (Roman, Hardesty et al., 2019). Balloons and latex have been prioritized over other disproportionately lethal items, such as rubber or metal debris (Figure 2D), as their sources are limited and can be controlled through legislation. Balloons enter the environment through intentional balloon releases (celebratory/event and weather balloons) and accidental release during events/celebrations (O'Shea, Hamann, Smith, & Taylor, 2014). Prevention of balloons from entering the environment would require legislative changes and a shift in public will support such activities (Table 2). Rubber was the most disproportionately lethal debris items highlighted by this review (Figure 2D). Unfortunately, the source of the rubber ingested by marine animals was unknown as rubber items were seldom described, limiting the policy responses that can be recommended. We recommend a review into sources of rubber entering the marine environment and legislative options to reduce the input.

4.7 | Conclusions

Marine debris is becoming increasingly recognized as an important threat to megafauna. Stranded animals with debris-induced mortality rates of up to 22% in cetaceans (Baulch & Perry, 2014) and nearly half of sea turtles (Rosolem Lima et al., 2018) have been observed, and high mortality has been estimated in seabirds (Roman, Hardesty et al., 2019). Debris ingestion is a significant conservation threat to numerous marine taxa, including threatened species, signifying the importance of reducing input of lethal items.

We identified three classes of debris—film-like plastics, fishing debris, and latex/balloons—that are disproportionately responsible for megafauna death. To reduce megafauna mortality, we recommend policymakers focus on reduction through regulation, prohibition, and replacement of high-mortality risk large items such as plastic bags, plastic packaging, plastic sheets, fishing rope, nets, tackle, and balloons (Table 2). Reducing the abundance of these items in the environment would directly reduce mortality of marine megafauna through lesser megafauna–debris encounters and interactions.

While policies targeting these items are likely to result in reduced mortality to marine fauna, we also recognize the importance and role of behavior change and awareness raising campaigns. Previous work showed that a combination of policies, practices, and behavior change social activities were most successful in reducing coastal litter at a national scale (Willis et al., 2018), with investments in campaigns resulting in larger waste reduction than did investment in policies alone (Brown, Ham, & Hughes, 2010). Furthermore, the campaign message and its delivery style influence social behavior (Brown et al., 2010), with personal interaction acknowledged as a preferred, though typically more costly approach (Lewin, Weltersbach, Denfeld, & Strehlow, 2020; Roggenbuck, Williams, & Bobinski, 1992). A combination of policies that legislates reduction, prohibition, and replacement of high-risk items, with targeted investment in behavior change and awareness campaigns, will likely generate the largest reductions in plastic-related mortality of charismatic megafauna.

ACKNOWLEDGMENTS

We acknowledge CSIRO Oceans and Atmosphere for supporting this work and Threatened, Endangered or Protected Species (TEPS) team for open access fee support. We would further like to acknowledge the authors who provided their data to enable us to carry out the analyses herein.

AUTHOR CONTRIBUTIONS

All authors conceived of the manuscript. LR and QS conducted the literature review and analyzed the data with input from BDH and CW. All authors wrote the manuscript.

ETHICS STATEMENT

All data used in this review were sourced from published manuscripts and the authors did not perform human or animal research.

DATA ACCESSIBILITY STATEMENT

All data will be made accessible from the authors on request.

CONFLICT OF INTEREST

No conflict of interest has been declared by the author(s).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Roman L, Schuyler Q, Wilcox C, Hardesty BD. Plastic pollution is killing marine megafauna, how do we prioritize policy to reduce mortality? *Conservation Letters*. 2021;14:e12781. https://doi.org/10.1111/conl.12781