



Global research priorities to mitigate plastic pollution impacts on marine wildlife

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ABSTRACT: Marine wildlife faces a growing number of threats across the globe, and the survival of many species and populations will be dependent on conservation action. One threat in particular that has emerged over the last 4 decades is the pollution of oceanic and coastal habitats with plastic debris. The increased occurrence of plastics in marine ecosystems mirrors the increased prevalence of plastics in society, and reflects the high durability and persistence of plastics in the environment. In an effort to guide future research and assist mitigation approaches to marine conservation, we have generated a list of 16 priority research questions based on the expert opinions of 26 researchers from around the world, whose research expertise spans several disciplines, and covers each of the world's oceans and the taxa most at risk from plastic pollution. This paper highlights a growing concern related to threats posed to marine wildlife from microplastics and fragmented debris, the need for data at scales relevant to management, and the urgent need to develop interdisciplinary research and management partnerships to limit the release of plastics into the environment and curb the future impacts of plastic pollution.

KEY WORDS: Marine wildlife · Plastic · Pollution · Priority · Global

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INTRODUCTION

As a material, plastic has existed for just over a century (Gorman 1993), and mass production began in earnest in the 1950s (Beall 2009). By 1988, 30 million tons of plastic products were produced annually (O'Hara et al. 1988), reaching 265 million tons by 2010 (PEMRG 2011) and accounting for 8% of global oil production (Thompson et al. 2009). Most plastic products are lightweight, inexpensive, and durable. These defining characteristics make plastics a convenient material for the manufacture of everyday products. However, these same attributes make plastics a threat to ecosystems due to their persistence in terrestrial, aquatic, and marine environments. Mar-

ine litter, and plastic pollution in particular, is ubiquitous, and, in fact, the proportion (in terms of mass) of ocean debris that is plastic increases with distance from the source (Gregory & Ryan 1997). Plastic pollution is now recognized worldwide as an important stressor for many species of marine wildlife and their habitats (Moore 2008).

Marine wildlife is impacted by plastic pollution through entanglement, ingestion, bioaccumulation, and changes to the integrity and functioning of habitats. While macroplastic debris is the main contributor to entanglement, both micro- and macrodebris are ingested across a wide range of marine species. The impacts to marine wildlife are now well established for many taxa, including mammals (Laist 1987,

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1997, Page et al. 2004), seabirds (Laist 1997, van Franeker et al. 2011), sea turtles (Beck & Barros 1991, Tomás et al. 2002, Wabnitz & Nichols 2010, Guebert-Bartholo et al. 2011, Lazar & Graan 2011, Schuyler et al. 2014), fish (Boerger et al. 2010, Possatto et al. 2011, Ramos et al. 2012, Dantas et al. 2013, Choy & Drazen 2013), and a range of invertebrates (Chiapponi et al. 2005). Over 170 marine species have been recorded to ingest human-made polymers that could cause life-threatening complications such as gut impaction and perforation, reduced food intake, and transfer of toxic compounds (Müller et al. 2012). Although marine debris affects many species (Laist 1997, Convention on Biological Diversity 2012), there are limited data from which to evaluate the collective impact at community and population levels, even for a single species.

Until recently, the vast expanse of the ocean coupled with the perceived abundance of marine life led resource managers to dismiss the proliferation of plastic debris as a potential hazard and to overlook this significant threat (Derraik 2002). Researchers began studying the occurrence and consequences of macrocategories of plastic debris in coastal and marine environments during the 1970s. However, once in the marine environment, plastics degrade and fragment into smaller pieces. Scientists are now increasingly aware that these fragments of plastic or small virgin plastic pellets pose a substantial threat to marine biota (Carpenter & Smith 1972, Derraik 2002, Barnes et al. 2009, Ivar do Sul & Costa 2013). Since the discovery of microplastics in the North Atlantic (Carpenter & Smith 1972, Carpenter et al. 1972) and through subsequent research on the continued accumulation of plastic in all ocean basins (e.g. Moore et al. 2001, Law et al. 2010, Titmus & Hyrenbach 2011, Eriksen et al. 2013), the significance of plastic pollution as a threat to marine wildlife has been increasingly recognized at international (e.g. UNEP 2009) and national (e.g. Australia's Marine Debris Threat Abatement Plan and the US NOAA Marine Debris Task Force) scales. However, despite increased scientific and public awareness, gaps in our knowledge of the prevalence and impacts of plastic pollution persist, and it remains challenging to both better understand and to mitigate the effects of this type of material on marine species and ecosystems.

Given ongoing plastic production and the related problem of increasing amounts of plastic debris in oceans, it is timely to identify key areas in which we need to further our understanding of plastic pollution to enable effective mitigation of the impacts of plastic debris on marine wildlife. In a similar fashion to Don-

Ian et al. (2010), Hamann et al. (2010), Sutherland et al. (2011), and Lewison et al. (2012), we develop a list of priority research questions that could aid the control and mitigation of impacts from plastic pollution on marine wildlife and habitats. Our study differs from previous priority-setting studies because this is the first study that brings together leading marine pollution and marine wildlife experts from around the world to address the knowledge gaps for an important, threatening process impacting on marine habitats and many species of marine wildlife.

METHODS

To quantify the global research effort on the topic of plastic pollution in the marine environment, we searched the Scopus literature database (up to December 2013) for publications related to plastic pollution in the marine environment using combinations of the search terms 'marine + plastic pollution', 'marine + litter', and 'marine debris'. We repeated the search adding terms to allow quantification of research effort on air-breathing marine wildlife 'marine turtles' or 'sea birds' or 'marine mammals'. From the literature output on marine wildlife we compiled a list of 46 authors with either >1 peer-reviewed paper on plastic pollution published between 2007 and 2012, or 1 or more publications cited >5 times by others. The 46 authors were invited to suggest up to 10 priority research questions to assist in the mitigation of plastic pollution impacts on marine wildlife and associated ecosystems.

A total of 27 (13 male and 14 female) marine scientists contributed 196 initial research questions. These scientists were based in 9 countries and represented working experience from all oceans where plastic pollution is known to affect marine fauna and their habitats, specifically: the eastern Pacific ($n = 4$), central Pacific (3), western Pacific (4), western Atlantic (3), central Atlantic (2), eastern Atlantic and Mediterranean (3), Indian Ocean (4), Southern Ocean (3), and South Atlantic (2). Questions were then compiled and sorted to reduce redundancy and to create overarching categorical questions as per Hamann et al. (2010) and Lewison et al. (2012). Based on these responses, we assembled a final list of 16 priority research questions, which are presented in no particular order of importance (Table 1). Following each question, we include a summary of information related to the question topic and suggestions for further research.

Table 1. Summary table of priority research questions

Global research priorities to mitigate plastic pollution impacts on marine wildlife
1. What are the impacts of plastic pollution on the physical condition of key marine habitats?
2. What are the impacts of plastic pollution on trophic linkages?
3. How does plastic pollution contribute to the transfer of non-native species?
4. What are the species-level impacts of plastic pollution, and can they be quantified?
5. What are the population-level impacts of plastic pollution, and can they be quantified?
6. What are the impacts of wildlife entanglement?
7. How will climate change influence the impacts of plastic pollution?
8. What, and where, are the main sources of plastic pollution entering the marine environment?
9. What factors drive the transport and deposition of plastic pollution in the marine environment, and where have these factors created high concentrations of accumulated plastic?
10. What are the chemical and physical properties of plastics that enable their persistence in the marine environment?
11. What are some standard approaches for the quantification of plastic pollution in marine and coastal habitats?
12. What are the barriers to, and opportunities for, delivering effective education and awareness strategies regarding plastic pollution?
13. What are the economic and social effects of plastic pollution in marine and coastal habitats?
14. What are the costs and benefits of mitigating plastic pollution, and how do we determine viable mitigation options?
15. How can we improve data integration to evaluate and refine management of plastic pollution?
16. What are the alternatives to plastic?

RESULTS

Literature search

Our literature search identified 561 publications from 192 scientific journals on various aspects of marine plastic pollution (Fig. 1). Approximately half (47%) were published in *Marine Pollution Bulletin*.

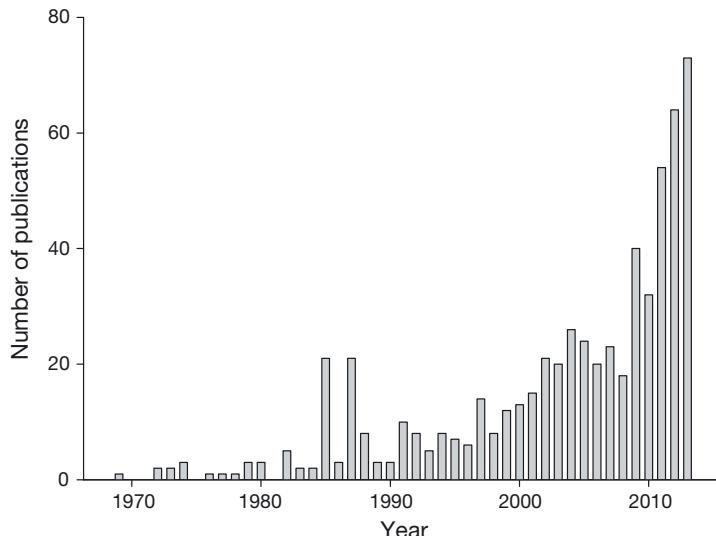


Fig. 1. Trends in the number of publications on 'marine + plastic pollution' or 'marine debris' or 'marine + litter' using a Web of Science search from 1972 to 2013. The publication spikes in 1985 and 1987 relate to the Proceedings of the 1st International Marine Debris Conference and a special edition of *Marine Pollution Bulletin* covering the theme of plastics at sea from the 1986 International Ocean Dispersal Symposium, respectively

The first publications on plastic pollution appeared in the scientific literature in the 1960s, and by the mid-1980s marine ecologists were starting to acknowledge that plastic debris in the ocean would have significant long-term impacts on marine ecology (see Shomura & Yoshida 1985 and the special edition of *Marine Pollution Bulletin*: 1987, Volume 18, 6B). Of the 561 publications, 143 were related to interactions between marine plastic pollution and air-breathing marine species. In addition, the Proceedings of the First International Marine Debris Conference included 11 abstracts documenting marine plastic pollution interactions with marine wildlife (Shomura & Yoshida 1985). Some of these were likely published in subsequent peer-reviewed literature. The earliest paper on the impacts of plastic pollution on wildlife reported a gannet (*Sula bassana*) with a yellow ring of plastic coated wire around its leg (Anon. 1955); however, from the account provided, it is not possible to determine whether it was a case of entanglement or a deliberate banding. We found the earliest accounts of ingestion were published in 1969, documenting seabirds consuming plastic (Kenyon & Kridler 1969). In the early 1970s, the first accounts of microplastics at sea in the Atlantic Ocean emerged (Carpenter & Smith 1972, Carpenter et al. 1972, Gochfeld 1973, Rothstein 1973, Hays & Cormons 1974), and the first interactions between microplastics

and marine mammals and sea turtles were published in 1978 (Waldichuk 1978) and 1987 (Carr 1987), respectively, although records with marine turtles were reported in the first marine debris symposium (Balazs 1985). It is possible that we missed some of the early literature or literature contained in journals that are not indexed by online databases. However, it is evident that since the 1970s, and particularly since the year 2000, there has been an increasing trend in the number of publications on plastic pollution and its relationship to marine ecosystems (Fig. 1).

Priority research questions

1. What are the impacts of plastic pollution on the physical condition of key marine habitats?

Plastic pollution now impacts all marine and coastal habitats to varying degrees. In particular, there are substantial empirical data identifying, and in some cases quantifying, the impacts of plastic and other debris in oceanic waters, on the sea floor, on sandy beaches, and in other coastal environments (Fig. 2). It is also clear that effects on habitat condition are not uniform and depend on the ecological, economic, and social value attributed to the habitat, the physical environment, and the type, size, accumulation, and/or degradation rates of plastic. In addition, there is substantial spatial and temporal variation in accumulation patterns, polymer type, and source of plastics (e.g. Willoughby et al. 1997, Ribic et al. 2010, Eriksen et al. 2013).

Quantifying the impact of plastic pollution on the physical condition of habitats has received little attention (but see Votier et al. 2011, Bond & Lavers 2013, Lavers et al. 2013, 2014) relative to the impacts of plastic pollution on organisms (e.g. Derraik 2002, Gregory 2009). However, in intertidal habitats, accumulation of plastic debris has been shown to alter key physico-chemical processes such as light and oxygen availability (Goldberg 1997), as well as temperature and water movement (Carson et al. 2011). This leads to alterations in macro- and meiobenthic communities (Uneputty & Evans 1997) and the inter-



Fig. 2. Clockwise from top left—beach debris from a remote beach on Catholic Island, Grenadines (courtesy Jennifer Lavers); debris accumulation on an urban beach (Stradbroke Island, Australia) (courtesy Kathy Townsend); entanglement and damage to soft coral by fishing line (courtesy Stephen Smith); and fishing line entanglement of a pier with algae and sponges growing on it (courtesy Kathy Townsend)

ruption of foraging patterns of key species (Aloy et al. 2011). On sandy beaches, the occurrence of microplastics may change the permeability and temperature of sediments, with consequences for animals with temperature-dependent sex-determination, such as some reptiles (Carson et al. 2011). In addition, heavy fouling can lead to loss of important biogenic habitat, which may have considerable flow-on effects to broader ecosystem processes (Smith 2012). Large plastic debris may change the biodiversity of habitats locally by altering the availability of refugia and providing hard surfaces for taxa that would otherwise be unable to settle in such habitats (Katsanevakis et al. 2007). Similar observations have been made in subtidal habitats, including the deep sea (Watters et al. 2010, Schlining et al. 2013).

In tropical and subtropical shallow-water coral reef habitats, a decline in the condition of corals has been attributed to progressive fouling caused by entangled fishing line, as well as direct suffocation, abrasion, and shading of fouled colonies caused by nets

(Yoshikawa & Asoh 2004, Richards & Beger 2011). This may contribute to ecological phase-shifts at heavily affected sites (Asoh et al. 2004, Yoshikawa & Asoh 2004, Richards & Beger 2011). Taxa with branching morphologies (e.g. gorgonians, sponges, milleporid and scleractinian corals, macroalgae, and seagrass) are most likely to be affected by entanglement. While some taxa may be able to overgrow entangling debris, it is unclear how this may affect their integrity, longevity, and resilience to change (Chiappone et al. 2005, Smith & Hattori 2008).

Overall, there is a general bias toward studies reporting on how plastic pollution impacts the conditions of sandy beaches and urban coastlines, and less knowledge on the conditions of other habitats (e.g. estuaries, mangroves, benthic habitats, deep-sea zones), especially those in remote areas with limited human access. Hence, advancing knowledge about how plastic pollution impacts the conditions of diverse marine habitats remains a priority. Useful starting points would be (1) field-based experimental research that either documents change in condition/function of habitats or establishes thresholds of concern that can then be used as indicators for monitoring and (2) design and testing of survey techniques to determine baseline conditions and/or condition changes in remote or difficult-to-access habitats. These could include the application of rapid assessment techniques, remote sensing, or citizen science. Filling these knowledge gaps would be important, because information on habitat condition can assist management agencies in quantifying the degree of impact, in setting priorities, and in implementing mitigation.

2. What are the impacts of plastic pollution on trophic linkages?

Ingestion of microplastic has been reported at almost every level of the marine food web, from filter-feeding marine invertebrates (Wright et al. 2013), to fishes (Boerger et al. 2010, Choy & Drazen 2013), seabirds, sea turtles, and marine mammals (Fig. 3, see Questions 4 & 5). Plankton and plastic particles $<333 \mu\text{m}$ in size co-

occur in marine systems, and smaller ($<100 \mu\text{m}$) diameter polymer fibers have been identified in sediments, suggesting that plastics exposure is occurring at the base of the food web (Thompson et al. 2004, Browne et al. 2011). Recent studies have identified impacts to marine invertebrates associated with foraging on nano- and microparticles of polystyrene (Wegner et al. 2012, Besseling et al. 2013), and laboratory studies have demonstrated and examined plastic ingestion by zooplankton (e.g. De Mott 1988, Bern 1990, Cole et al. 2013). There is also recent evidence that ingested microplastics can bridge trophic levels into crustaceans and other secondary consumers (Farrell & Nelson 2013). Furthermore, recent research has detected plastic-derived compounds in the tissues of seabirds that had consumed plastics (Lavers et al. 2013, 2014, Tanaka et al. 2013; see Questions 4 & 5).

When taken in conjunction, it is clear that plastic pollution is impacting food webs through ingestion



Fig. 3. Top left to bottom right — magnificent frigatebird *Fregata magnificens* carcass from Battowia Island, Grenadines, with orange foam contained within stomach (courtesy Jennifer Lavers); Antarctic fur seal *Arctocephalus gazella*, with plastic ring entanglement at King George Island, Antarctica (courtesy Juliana Ivar do Sul); juvenile green turtle *Chelonia mydas* trapped in discarded crab trap and plastic fragments recovered from the gut of a juvenile green turtle (bottom 2 photos: courtesy Kathy Townsend)

and bioaccumulation of particles and toxic chemicals and thus is likely to be influencing ecosystem processes in ways that have yet to be elucidated. In particular, there is a need to better understand the influence of nano- and microplastics on zooplankton and planktivorous species (especially in a natural setting), the role(s) of plastic ingestion at several trophic levels in the transfer of organic pollutants along the food chain, and the influence of plastic pollution on epipelagic ecosystems (e.g. Ryan & Branch 2012, Setälä et al. 2014). Filling these knowledge gaps will require developments in both field and laboratory science. From a laboratory research perspective, useful starting points would be improving knowledge of plastic chemistry and of the fate of chemicals in biological systems, as well as identifying the thresholds of concern. From a field science perspective more knowledge is needed about rates and patterns of accumulation; a starting point could be the development of biological indicators, such as investigating the use of 'plastic in fish-gut treatments' (e.g. on large factory trawlers) that have low-labor inputs but sample large numbers of planktivorous fish with acceptable precision and measurable variance.

3. How does plastic pollution contribute to the transfer of non-native species?

A number of transport mechanisms exist for the transfer of marine species to non-native environments, such as hull fouling, ballast water, aquaculture, dry ballast, rafting, and the aquarium trade (Orensanz et al. 2002, Hewitt et al. 2004a,b, Haydar 2012). However, relatively little is known about species rafting (as biofouling) on plastic debris or non-native bacterial biofouling of plastics (i.e. biofilms) (yet see Winston et al. 1997, Lobelle & Cunliffe 2011). Introduced species have a higher propensity to foul man-made substrates, such as plastics (Whitehead et al. 2011), than native species (Wyatt et al. 2005, Glasby et al. 2007, Tamburri et al. 2008). Couple this propensity with the durability and persistence of plastics, and the likelihood of plastics transporting non-native species increases substantially. Consequently, species that have a propensity to foul plastic will have a greater likelihood of dispersing further by rafting or hitchhiking on debris.

A wide range of species is known to foul debris, and the level and composition of fouling of debris varies spatially and temporally (e.g. Ye & Andrade 1991, Artham et al. 2009) with the type of substrate and the distance from source areas (and hence resi-

dence time at sea). For example, Whitehead et al. (2011) determined that of stranded debris in South Africa, kelp and plastics were the most frequently colonized (33 and 29%, respectively). In contrast, Widmer & Hennemann (2010) reported that only 5% of marine debris was biofouled in southern Brazil (27°S), of which 98% of the items were plastic (Widmer & Hennemann 2010).

To date, relatively few published articles have focused on rafting of introduced species on plastic debris. Although the biomass of fouling species carried by plastic debris is far less than that carried on the hulls of ships (Lewis et al. 2005), debris represents a considerable amount of the surface area available for colonization. A key starting point would be to quantify the potential and actual contribution of rafting on plastic debris for the primary introduction of a species into a new region and then the secondary spread within that region. Another key area that warrants further investigation is to better understand the transport of non-native biofilms; molecular science could offer a useful starting point in this regard (Barnes & Milner 2005, Lewis et al. 2005, Goldstein et al. 2012).

4. What are the species-level impacts of plastic pollution, and can they be quantified?

Plastic pollution affects marine species of all trophic levels, ranging from zooplankton to whales (Laist 1987, Passow & Alldredge 1999, Jacobsen et al. 2010). Both macro- and microplastic debris can affect individual species either through ingestion or entanglement (including entrapment) (Day et al. 1985, Laist 1987, Moore 2008, Ceccarelli 2009, Kaplan Dau et al. 2009, Schuyler et al. 2012) (see Question 6). Large plastic debris items, such as rope, cargo straps, fishing line, fishing pots and traps, and net, are the main contributors to entanglement, while both whole and fragmented micro- and macroplastic debris is ingested across at least 170 marine vertebrate and invertebrate species (Carr 1987, Laist 1987, Bjorndal et al. 1994, Derraik 2002, Ceccarelli 2009, Boerger et al. 2010, Jacobsen et al. 2010, Baulch & Perry 2012, Fossi et al. 2012, Schuyler et al. 2012, Besseling et al. 2013). In general, the size of ingested plastic items is related to body size (e.g. Furness 1985, Ryan 1987) and ontogenetic phase (Ramos et al. 2012, Dantas et al. 2013). The degree of impact is likely related to the size, shape, and quantity of the ingested items and a range of physiological, behavioral, and geographical factors.

Ingestion effects include gut perforation, gut impaction, dietary dilution, toxin introduction, and interference with development (Ryan 1988a, Bjorndal et al. 1994, McCauley & Bjorndal 1999, Mader 2006, Teuten et al. 2009, van Franeker et al. 2011, Gray et al. 2012, Tanaka et al. 2013). Importantly, swallowed plastic does not need to be large in quantity to cause serious injury to an animal (Bjorndal et al. 1994). Gastrointestinal perforation caused by swallowed hooks and hard plastic can cause chronic infection, septicaemia, peritonitis, gastrointestinal motility disorders, and eventual death (Day et al. 1985, Jüngling et al. 1994, McCauley & Bjorndal 1999, Cadée 2002, Guebert-Bartholo et al. 2011). Impaction of the gastrointestinal tract affects many species; the offending blockage can paralyze the gastrointestinal tract, inhibit the digestive process, and result in symptoms such as bloating, pain, necrosis, and mechanical abrasion or blockage of absorptive surfaces in the digestive tract (Mader 2006). Nutrient dilution is the result of a reduction of nutritious food intake due to ingestion of non-nutritive and space-occupying plastic reducing fitness and affecting both adult and juvenile animals (Day et al. 1985, Ryan 1988a, Bjorndal et al. 1994, McCauley & Bjorndal 1999, Auman et al. 2004, van Franeker et al. 2011, Gray et al. 2012).

Some species are more susceptible than others to the ingestion of marine debris. For example, sea turtles are particularly susceptible due to their feeding strategies (i.e. some specialize on jellyfish for which floating debris may be mistaken), as well as downward-facing papillae on their esophageal mucosa that have evolved to allow efficient ingestion of food but that inhibit the ability of sea turtles to regurgitate (Wyneken 2001). Seabirds, especially those that feed in oceanic convergence zones, consume plastic debris directly, but also feed it to their chicks (Ryan 1988a,b, Cadée 2002, Moore 2008, Ryan 2008, van Franeker et al. 2011, Kühn & van Franeker 2012, Verlis et al. 2013). Species that are adapted to regurgitating indigestible dietary items like squid beaks may off-load ingested debris, but species that lack these adaptations are more vulnerable to the effects of cumulative ingestion (Ryan 1988b). A useful starting point for managing species-plastic interactions could be a review that quantifies the risk each species faces within a global setting. A proxy for this review could be the mean load size of ingested plastic as a proportion of body mass or identification of long-term trends (e.g. Schuyler et al. 2014).

Causes of ingestion and entanglement need to be better understood across most marine species im-

pacted by plastic pollution. Many studies on plastic consumption have shown species-based preferences for different colors, tastes, types, and sizes of debris, but evidence remains largely speculative (Day et al. 1985, Ryan 1987, De Mott 1988, Bjorndal et al. 1994, Bugoni et al. 2001, Cliff et al. 2002, Colabuono et al. 2009, Mrosovsky et al. 2009, Boerger et al. 2010, Denuncio et al. 2011, Gray et al. 2012, Schuyler et al. 2012, Lavers et al. 2014). Current hypotheses for why animals consume marine debris include mistaken identity (mimicking natural prey items), curiosity/play, and failure of distinction (plastic debris mixed with normal dietary items) (Balazs 1985, Eriksson & Burton 2003, Schuyler et al. 2012). These hypotheses need more testing across a wide range of species and would constitute a useful starting point for future field and laboratory research. Furthermore, because the size categories and definitions for macro- and microdebris vary in the literature, a review (with recommendations) of ecologically relevant size classes for plastic items, in light of research findings such as overlap with plankton size ranges, would be useful (Eriksson & Burton 2003, Cole et al. 2011).

5. What are the population-level impacts of plastic pollution, and can they be quantified?

Details of long-term survivorship impacts from marine debris are poorly known, and the links between plastics and their harmful effects at the population level are not clear. Notably, survival and reproductive rates of Laysan albatrosses *Diomedea immutabilis* from the early 1960s on Midway are virtually identical to rates today, despite increases in the rates of plastic ingestion (Fisher 1975, van der Werf & Young 2011). For most species it is challenging to identify even the proportion of individuals impacted, let alone the population mortality rate attributable to plastic ingestion. Furthermore, most studies look at lethal impacts, as sub-lethal impacts to populations are likely to be harder to identify (Baulch & Perry 2012).

A further area of concern is the potential toxicological effect of plastic on growth rates, survivorship, and reproduction, all of which are important areas for population stability. Plastic marine debris contains not only potentially harmful plasticizers incorporated at manufacture (Meeker et al. 2009), but plastics can adsorb and accumulate additional toxic chemicals such as polychlorinated biphenyls (PCBs) and heavy metals from seawater (Mato et al. 2001, Ashton et al. 2010, Holmes et al. 2012, Rochman et al. 2014; and see

Question 10). Tagatz et al. (1986) showed that high concentrations of dibutyl phthalate, a commonly used plasticizer, significantly affected the composition and diversity of macrobenthic communities. While chemicals can leach into the tissues of wildlife that ingest plastic (Teuten et al. 2009, Tanaka et al. 2013, Lavers et al. 2014), quantification of population-scale effects warrants further research. Animals exposed to compounds such as phthalates and bisphenol-A (BPA) showed adverse impacts on reproductive functionality, particularly during developmental stages (Talsness et al. 2009), and exposure to chemicals in ingested plastic has led to hepatic stress in fish (Rochman et al. 2013a). Adsorbed chemicals from ingested plastics such as dichlorodiphenyltrichloroethanes (DDTs), PCBs, and other chlorinated hydrocarbons may decrease steroid levels and lead to delayed ovulation (Azzarello & VanVleet 1987). The potential function of plasticizers as endocrine disruptors has been hypothesized to have resulted in a disproportionately high level of mortality in female fulmars (*Fulmarus glacialis*) during a 2004 stranding event (van Franeker et al. 2011, Boland et al. 2012). However, the links between plastic ingestion and population drivers, such as reproductive timing and female survivorship, have yet to be shown conclusively.

To understand the long-term, population-scale impacts of plastic pollution, it is critical to assess plastic impacts on life-history traits such as fecundity, reproductive success, mortality rates, and even potential behavioral changes which might influence courtship, migration, and other reproductive activities. Useful starting points for research would be quantifying baseline levels of chronic and acute exposure and the degree of both direct and indirect impact. Doing this will require both field- and laboratory-based physiology and ecology and the design of monitoring programs to ensure that relevant tissue samples and environmental information are collected. Furthermore, quantifying the magnitude of impacts on different populations and life stages (e.g. entanglement vs. ingestion; physical blockages vs. perforations vs. toxicological effects, and how the magnitude of these impacts compares with other stressors) would improve the efficacy of various management approaches.

6. What are the impacts of wildlife entanglement?

Marine debris entanglement is now an internationally recognized threat to marine taxa (Shomura & Yoshida 1985, Kaplan Dau et al. 2009, Gilardi et al.

2010, Allen et al. 2012), with at least 135 species recorded as ensnared in marine debris, including sea snakes, turtles, seabirds, pinnipeds, cetaceans, and sirenians (Laist 1997, Possatto et al. 2011, Udyawer et al. 2013). Wildlife becomes entangled in everything from monofilament line and rope to packing straps, hair bands, discarded hats, and lines from crab pots. Entanglement effects include abrasions, lesions, constriction, scoliosis (Wegner & Cartamil 2012), or loss of limbs, as well as increased drag, which may result in decreased foraging efficiency (Feldkamp 1985, Feldkamp et al. 1989) and reduced ability to avoid predators (Gregory 1991, 2009). To date, there are scant data overall to provide a global estimate of the number of animals affected by entanglement, mostly because reports are either restricted to opportunistic observations of animals or are from heavily visited coastal regions. Given that we likely observe only a small fraction of entangled or injured wildlife (e.g. scarring; B. D. Hardesty pers. obs.), actual or total rates of wildlife entanglement are not known.

Entanglement is a key factor threatening survival and persistence of some species (see Question 1; Henderson 2001, Boland & Donohue 2003, Karamanlidis et al. 2008), including the northern fur seal *Callorhinus ursinus* (Fowler 1987) and endangered species such as Hawaiian and Mediterranean monk seals (*Monachus* spp.) (Votier et al. 2011). Among marine mammals there are important age-class drivers of entanglement rates; for example, in pinnipeds, younger animals (e.g. seal pups and juveniles) may be more likely to become entangled in nets, whereas subadults and adults are more likely to become entangled in line (Henderson 2001). In general, younger, immature animals are more often reported as entangled, at least in pinniped studies for which age class is reported (Fowler 1987, Hanni & Pyle 2000, Henderson 2001). Ghost nets also ensnare cetaceans, turtles, sharks, crocodiles, crabs, lobsters, and numerous other species (Poon 2005, Gunn et al. 2010, Wilcox et al. 2013).

Overall, we lack sufficient information to determine whether injury and mortality from incidental entanglement has population-level effects on many marine species (Gilman et al. 2006). A priority research avenue is to investigate whether most entanglement occurs when wildlife encounters lost, abandoned, or derelict fishing gear, or 'ghost nets', and if there are spatial and temporal links to species entanglement in derelict fishing gear and other forms of plastic debris. If so, these could have considerable financial, environmental and safety implications for fisheries management, as the amount of fishing gear

lost to the ocean is estimated to be 640 000 tons yr⁻¹ (Macfadyen et al. 2009, Gilardi et al. 2010).

7. How will climate change influence the impacts of plastic pollution?

Changes to sea level, atmospheric and sea-surface temperatures, ocean pH, and rainfall patterns are all associated with global climate change. These factors will alter biophysical processes that, in turn, will influence the source, transport, and degradation of plastic debris in the ocean. Coastal cities and towns represent one of the main sources of plastic pollution, serving as point sources for the flow of plastic into the sea via urban and natural drainage systems (e.g. Faris & Hart 1994). Changes in precipitation patterns could alter the rate and periodicity of plastic pollution transport into the sea and/or change the functionality of storm-water filters and trash guards, reducing the ability of these systems to remove solid debris before it enters the ocean. Additionally, a rise in the sea level and the increased frequency and duration of severe weather events may inundate waste disposal sites and landfills. Storms and rising sea levels also release litter buried in beaches and dune systems. These factors could lead to larger amounts of plastic debris being deposited into the marine ecosystem through runoff, and may introduce toxic materials into the marine environment (Derraik 2002). Thiel & Haye (2006) discuss the importance of extreme weather events, such as intense hurricanes/cyclones, for transporting organisms and pollutants into and through oceanic systems. Overall, the pattern of extreme weather events is expected to change, potentially affecting the transfer of plastic pollution and, possibly, non-native, invasive species (see Question 3).

Ocean currents and gyres play a significant role in the distribution and concentration of floating marine plastics (Lebreton et al. 2012). Alterations in sea-surface temperatures, precipitation, salinity, terrestrial runoff, and wind are likely to influence the speed, direction, and upwelling or downwelling patterns of many ocean currents. This could, in turn, influence areas of plastic accumulation and spread plastics to previously less affected regions, altering the exposure rates of marine wildlife. For example, changes in the currents interacting with the Southern Ocean may lead to the transport, establishment, and spread of plastics and/or invasive species into areas such as Antarctica (Ivar do Sul et al. 2011). In addition, changes to ocean circulation could cause further damage to benthic environments through increased

deposition of plastic onto the sea floor, altering the composition of normal ecosystems and causing anoxic or hypoxic conditions (Goldberg 1997).

It is clear that the impacts of climate change will vary temporally and spatially, and will affect the environment in a variety of ways. The interaction of climate change and other ecosystem stressors is an important area of research, but how climate change affects plastic pollution has yet to be investigated.

8. What, and where, are the main sources of plastic pollution entering the marine environment?

Sources of plastic pollution are extensive and are generally categorized as being either ocean- or land-based (Sheavly & Register 2007), with land-based debris recognized as the most prevalent (Gregory 1991, Nollkaemper 1994, UNESCO 1994). Land-based debris generally originates from urban and industrial waste sites, sewage and storm-water outfalls, and terrestrial litter that is transported by river systems or left by beach users (Pruter 1987, Wilber 1987, Karau 1992, Williams & Simmons 1997, Santos et al. 2005, Corcoran et al. 2009, Ryan et al. 2009, Campbell 2012, O'Shea et al. 2014). Consequently, large urban coastal populations are the main source of debris (Cunningham & Wilson 2003) entering the marine environment and advected elsewhere by ocean currents (Martinez et al. 2009). Ocean-based marine debris is material either intentionally or unintentionally dumped or lost overboard from vessels (including offshore oil and gas platforms) and includes fishing gear, shipping containers, tools, and equipment (Jones 1995, Santos et al. 2005). Specific fishing-related debris includes plastic rope, nets (responsible for 'ghost fishing'; Cottingham 1988), monofilament line, floats, and packaging bands on bait boxes (Jones 1995, Ivar do Sul et al. 2011).

Currently we lack sufficient understanding of the sources of plastic pollution at management-relevant scales, such as catchments, municipal areas, or coastal areas. If it were possible for managers to identify the step(s) along the product disposal chain where plastic is being lost to the environment, targeted mitigation approaches could be implemented and would likely enable cost-efficient and successful management. Key starting points for research could include: research and development of new technologies for processing waste; design and evaluation of alternate packaging types or strategies; infrastructure to prevent waste from entering the environment; techniques to remove plastic from the environment;

improving the ability to recycle waste, especially in developing nations and/or remote towns and communities; or the development of rapid assessment techniques to identify polymer types (see Questions 11 to 13). In addition, in areas with predictable rainfall patterns (i.e. locations with distinct wet seasons), research and monitoring could focus on understanding and mitigating impacts of urban stormwater and riverine loads entering the marine environment during the 'first flush'.

9. What factors drive the transport and deposition of plastic pollution in the marine environment, and where have these factors created high concentrations of accumulated plastic?

In the mid-1980s, Archie Carr described the convergence zones in the Atlantic as white lines of expanded polystyrene and likened the plastic debris littering the Tortuguero Beach in Costa Rica to hailstones (Carr 1986, 1987). It is now clear that plastics are distributed throughout the world's oceans, deposited on most coastlines, and found in very remote areas including the deep sea (e.g. Convey et al. 2002, Eriksson & Burton 2003, Barnes et al. 2009; see Question 8). The diverse physical and chemical nature of plastic polymers affects buoyancy and, thus, influences the transport and distribution of plastics in the marine water column. Transport mechanisms and the location of sources and sinks have been a research area of interest for some time. Indeed, a one-day workshop focusing on this topic was held at the 5th International Marine Debris Conference in Hawaii (Law & Maximenko 2011). Recent approaches to understanding the transport of debris have used combinations of ocean circulation models, including Lagrangian particle tracking (Lebreton et al. 2012, Maximenko et al. 2012, Potemra 2012, Van Sebille et al. 2012, Carson et al. 2013) and direct tracking (e.g. using aircraft or satellites) of ghost nets (Pichel et al. 2012, Wilcox et al. 2013) and debris from the 2011 Japanese tsunami (Lebreton & Borrero 2013). Central to these recent approaches has been the rapid improvement of computing power, as well as GIS and remote-sensing technology (Hamann et al. 2011).

To date, most models have been developed at large scales (global, ocean, or basin), but there is now a need for researchers to develop localized models to better understand near-shore transport mechanisms at scales relevant to management, such as state or national levels (e.g. Potemra 2012, Carson et al. 2013,

O'Shea et al. 2014). Furthermore, the identification of sinks, not only for pollution within the water column, but also for benthic debris (Schlining et al. 2013), especially in relation to key habitat areas for marine wildlife (such as foraging areas, migration pathways, and breeding sites) is needed. First steps could be the refinement of existing high-resolution hydrodynamic models and combining these models with satellite or aerial imagery, in order to understand river input, wave and wind drag influence on transport, and beaching and washing of debris back into the water. This could include testing the influence of wind drag on plastic with different degrees of buoyancy and the use of 3-dimensional hydrodynamic models to improve modeling of the movement of less buoyant plastics.

10. What are the chemical and physical properties of plastics that enable their persistence in the marine environment?

Plastics absorb ultraviolet (UV) radiation and undergo photolytic, photo-oxidative, and thermo-oxidative reactions that result in degradation of their constituent polymers (Gugumus 1993, Andrade et al. 1998). The rate and process of various types of degradation of synthetic polymers is likely to depend upon a number of factors, including the bonds present within the material and the amount of light, heat, ozone, mechanical stress, or number of microorganisms present. Overall, the structure of a polymer determines its surface area, degree of crystallinity, polymer orientation, material components, accessibility to enzymes, presence of additives, and degree of persistence in the environment. The polymer structure is thus critical in determining the degree of the material's degradability (Palmisano & Pettigrew 1992). However, there are limited data from which to draw conclusions about degradation rates for most polymer types. Additionally, little is known about how physical properties such as weight and shape determine whether or not plastics will float or be air-driven, and how long they will persist as surface pollution before sinking.

Environmental factors affecting the persistence of plastics in the environment include physical and chemical factors such as wind and wave exposure, pH, temperature, sediment structure, oxidation potential, moisture, nutrients, oxygen, and the presence of inhibitors. Microbiological factors are also likely to affect degradation rates of plastics, and these will be influenced by the distribution, abundance, diversity,

activity, and adaptation of microorganisms (Palmissano & Pettigrew 1992). Additionally, activities of macrofauna, such as maceration of plastics by insects or rodents, and potentially fish, may influence the rate of degradation by increasing the surface area available for colonization by microorganisms.

Research has also demonstrated that plastic pellets can adsorb hydrophobic compounds such as persistent organic pollutants (POPs) from the water (Mato et al. 2001, Teuten et al. 2007, Karapanagioti et al. 2011, Holmes et al. 2012). The degree to which plastics adsorb organic pollutants from the water is likely to depend on the underlying chemical structure. This also underpins the resilience and durability of the plastic once in the environment and, when it breaks down, its degree of buoyancy (Cooper & Corcoran 2010). There are likely strong links between the chemical and physical properties of the plastic and its persistence in the marine environment; yet, for most polymers, these links remain to be quantified.

Research is needed to better understand the effects of different degradation products from plastic polymers on marine wildlife. There is a need for further information on the interactions between the molecular structure and physical form of plastics (including biodegradable plastics), methods of microbial attack, and environmental factors influencing degradation. A key area to start would be to gain an understanding of which polymer types have the greatest impact on marine wildlife, and then to determine the physico-chemical factors that influence polymer degradation in order to identify steps in the manufacturing process that might be altered to reduce the generation of these polymer types. Such an understanding is critical when conducting life-cycle assessments for products and common types of waste and in developing risk or threat abatement strategies. Hence, this remains a key knowledge gap with substantial scope for future research.

11. What are some standard approaches for the quantification of plastic pollution in marine and coastal habitats?

Understanding rates and patterns of dispersal, accumulation and abundance of plastic in the environment is an important step toward understanding habitat and species vulnerability. However, comparisons among regions (and among studies in the same region) are handicapped by a lack of uniformity in approach to quantification (Ryan et al. 2009). A particularly common problem is the failure to standard-

ize, or even report, the lower size range of litter items sampled, with drastic implications for resultant density estimates (Ryan 2013).

One established method of following changes in marine plastic abundance is by regular shoreline (strand-line) surveying (Cheshire et al. 2009). Although commonly employed, the technique has many challenges (Ribic & Ganio 1996, Velander & Mocogni 1999). The first is that the human propensity to stroll along beaches and pick up litter is both common and laudable. More challenging factors affecting beach surveys are the local processes that affect beach debris deposition, such as tides, wave surge, wind speed, and direction, all of which increase the temporal and spatial variances of beach surveys, making change (e.g. due to mitigating actions) harder to detect (Ryan et al. 2009, Kataoka et al. 2013). Though not commonly done on a daily basis, collection of debris each day can provide improved variance estimates (Eriksson et al. 2013, Smith & Markic 2013). Despite being challenging, shoreline cleanups can be used to increase social awareness of the issue, identify particular plastic items to target mitigation efforts (e.g. uncut strapping bands, six-pack beverage rings, plastic pellets, and weather balloons) and, if done systematically, provide a comparative baseline on distribution, abundance, and accumulation of plastic debris (Edyvane et al. 2004, Ribic et al. 2010, 2011, 2012, Eriksson et al. 2013, Roosevelt et al. 2013, Thiel et al. 2013, Wilcox et al. 2013). Improving data collection from beach surveys and ensuring that data collection is useful for managers will require an improved understanding of how local circulation and weather patterns (e.g. tide cycle, wind strength and direction, and storms) affect the number and type of plastic marine debris items that wash ashore and are washed back into the water (i.e. can be bounced along a coastline).

While debris loads on shore can reflect debris loads in coastal waters (Thiel et al. 2013), understanding debris loads in the open ocean is challenging due to economics (e.g. ship costs for dedicated surveys) and the spatial area that needs to be surveyed (Morishige et al. 2007). However, these issues could, at least partially, be overcome by implementation of techniques that use ships of opportunity (Reisser et al. 2013, Ryan 2013), which have been used successfully for continuous at-sea monitoring of parameters such as chlorophyll, salinity, and even zooplankton. Regular data flows from instruments deployed on commercial vessels that agree to participate could be used to monitor plastic pollution loads. Additionally, it is possible that relatively 'low-tech' sampling can be developed to ac-

cess materials filtered from seawater intakes for engine cooling water used by shipping; ballast-water sampling protocols that have been developed may be a reasonable starting point for this. Also, field techniques currently used for biological oceanographic studies could be refined or developed to quantify debris loads, particularly microplastics, e.g. plastic debris can be quantified in known volumes of sea water sieved by neuston net, plankton net, or even by known surface areas and depths sampled by other means such as by pump (e.g. Hidalgo-Ruz et al. 2012, Howell et al. 2012, Eriksen et al. 2013). Larger macroplastic items (too large to be sampled by nets) can be surveyed with ship-based or aerial surveys (e.g. Lecke-Mitchell & Mullin 1997), though understanding the many biases associated with these types of surveys for plastic marine debris needs development (Ryan 2013). There may be future possibilities in using satellite imagery of the sea surface to estimate the abundance of debris and also to characterize the wavelength reflectance of plastics to distinguish them from foam and organic materials.

Irrespective of the habitat being sampled the greatest limitation to the quantification of marine plastic debris loadings remains its general dependence on the human eye. While many other disciplines overcome similar challenges to provide quantitative measures, avenues for future research would be to improve the way data on plastic pollution are collected by visual cues, the refinement of sampling techniques for fragmented plastic pollution, and the development of a quantitative 'characteristic chemical signature' analysis system for plastic polymers. These would expand our understanding of the ubiquity of plastic items and their potential impact on marine wildlife.

12. What are the barriers to, and opportunities for, delivering effective education and awareness strategies regarding plastic pollution?

Public concern over marine debris received a tremendous boost after the 1999 discovery of a region in the North Pacific in which plastic litter was accumulating, later termed the 'Great Pacific Garbage Patch' (e.g. Moore et al. 2001, Moore 2008). By the mid-2000s the sensationalized media portrayal of a mythical floating island of plastic waste created a wave of outrage against the amount of plastic in the ocean. The plastics industry, environmental organizations, legislators wishing to calm constituents, and entrepreneurs of all kinds raced to understand and explain the problem and solutions on their own

terms, creating a glut of misinformation about the size, contents, source, and fate of plastic in the ocean. Media strategies have ranged from dozens of short films, to a variety of advertising campaigns aired on television, the web, billboards, and in print. While it is clear that traditional and social media can work in tandem to distribute a story widely, research in the health sector is demonstrating that more emphasis should be placed on the outcome evaluation of communication strategies (Schneider 2006).

Delivery of an education and awareness strategy to minimize current and future impacts of plastic pollution on marine wildlife and habitats requires developing and distributing messages aimed at altering human behaviors associated with the manufacture, purchase, use, and disposal of plastic products. The message needs to be built on a communication and interpretation science and on accurate scientific information and to be delivered to the public and decision makers through traditional and social media, conferences, popular press, websites, and advertising. However, the provision of information is only part of the solution (Bates 2010, Weiss et al. 2012). A key role for research in developing and communicating education and awareness strategies involves developing and testing incentives aimed at inducing effective behavior change. There is a substantial body of empirical literature on eliciting behavioral change in the public health and environmental sectors (see review by Darnton 2008). However, few studies relate specifically to minimizing plastic pollution (see Slavin et al. 2012 for a focus on marine debris, including plastics). As a starting point, there is a need for researchers to test the models used in environmental psychology (e.g. theory of planned behavior; Ajzen 1991), environmental economics (see Butler et al. 2013), persuasive communication (see Ham et al. 2008), and social marketing (e.g. Peattie & Peattie 2009) to understand factors that will influence changes in behavior and to test the effectiveness of marine debris campaigns. It is important to involve these disciplines because they directly provide a greater understanding of the barriers and opportunities that drive human behavior and governance, and means of determining the costs versus benefits of these changes.

13. What are the economic and social effects of plastic pollution in marine and coastal habitats?

One of the more obvious knowledge gaps concerning plastic pollution mitigation relates to social and

economic aspects. Indeed, <5% of the relevant literature (i.e. in Fig. 1) comprises social or economic studies (but see Nash 1992, McIlgorm et al. 2011). Changes in the condition of natural assets due to plastic pollution can influence social and economic systems by altering environmental quality for future generations (e.g. beach litter; Balance et al. 2000), decreasing the value of ecosystem services, and potentially causing negative health implications (Talness et al. 2009). The cleanup of existing debris, which can be very costly, often falls on local authorities and environmental organizations, and often relies heavily on a volunteer workforce. For example, the cost of debris-related damage to marine industries in the Asia-Pacific rim countries and in Sweden was recently estimated at US\$ 1.26 billion and US\$ 3.7 million per annum, respectively (Hall 2000, McIlgorm et al. 2011). Power companies in Europe report spending more than US\$ 75 000 each year to keep their water intake screens clear of debris. However, it is not clear how many intakes are screened (Hall 2000).

Research is needed to examine the direct and indirect costs and benefits of plastic manufacture, use, and disposal, and to enable relative comparisons between the use of plastic and alternative materials. Useful starting points for this research could include surveys of people on the use and disposal of plastic products and the collection of empirical information on the costs of disposal and recycling gathered from waste management companies. There is a clear need for future research to include collaboration with economists, neuroscientists, and psychologists to quantify the cognitive and economic benefits provided by healthy, unpolluted waterways. These benefits likely include relaxation, insight, self-reflection, a sense of well-being, and creativity (White et al. 2010). Fouled environments may add to emotional stress and diminish social well-being.

14. What are the costs and benefits of mitigating plastic pollution, and how do we determine viable mitigation options?

A range of tools is available to manage environmental issues such as plastic pollution, including government regulation, market instruments (e.g. incentives), and technical and operational procedures (Kolstad 1986). The costs and benefits of these management options vary according to a number of factors, which, for marine pollution, typically include distance to point source, population size, and wealth

(poverty) of the coastal populations. Preventative technical measures, such as debris-retention booms that intercept plastic debris prior to dilution at sea, can significantly reduce damage to wildlife and economic costs to industry (Durrum 1997, Carson et al. 2013). Regulatory approaches to environmental management are commonly used, as they typically have low transaction costs due to operator compliance (McIlgorm et al. 2008). Legislation has been designed to specifically address the marine pollution issue (e.g. MARPOL Annex V), although reductions in the amount of debris entering the sea or the impact of debris on marine wildlife have not been detected (Arnould & Croxall 1995, Henderson 2001).

Economic incentives, e.g. container deposit recycling schemes (Bor et al. 2004) and programs that explicitly pass costs for packaging such as shopping bags (e.g. Ryan et al. 1996, Convery et al. 2007, Ayalon et al. 2009, Barlow & Morgan 2013) on to the consumer are increasingly used in environmental management (Ferrara & Missios 2005), but their success is rarely evaluated. Operational programs such as beach cleanups can require substantial financial and social input to build and maintain networks, with benefits either limited to a small area, or not observed at all (e.g. no direct benefit for wildlife reported; Page et al. 2004, McIlgorm et al. 2008). A key research question is: Do the cost–benefit ratios differ between measures aimed at preventing plastic pollution entering the marine system and reactive measures (e.g. beach cleanups [McIlgorm et al. 2008] or derelict fishing gear recovery [Gilardi et al. 2010])? Furthermore, cleanup events are likely to have social benefits, and these can be difficult to quantify and may be underestimated (Topping 2000, Storrier & McGlashan 2006). A useful starting point for research could be to quantify the costs and benefits of removing marine debris and how/if cleanup events can be organized to achieve higher ecological, social, and economic value (see Question 10).

The complexity and increasing scale of the marine plastic pollution issue is too large for any single agency or country to resolve (Donohue 2003); hence, empirical data at scales related to management and the development of cost-effective regulatory tools to reduce and prevent debris at its source are needed. Key priorities for research include developing and testing economic and social mechanisms that can be used to compare the relative costs and benefits of different mitigation techniques, and research to develop and test new products and technologies that may prevent the release of debris into our waterways (see Question 16). An aspect of this could include re-

search that improves our knowledge of alternatives to plastic use in high-risk applications (e.g. single-use plastics), the promotion of recycle-friendly packaging that does not generate litter-prone items, and the development of more efficient waste disposal systems.

15. How can we improve data integration to evaluate and refine management of plastic pollution?

One problem with combating the global issue of plastic pollution through local or regional initiatives is that it requires coordination and management across a number of different fronts. This requires the development of aligned sampling and collection initiatives coupled with the intent to share data (e.g. Carr et al. 2011, Duffy et al. 2013, Meiner 2013, Yang et al. 2013). For example, at a regional scale, the United Nations Environment Program (UNEP) is using its Regional Seas Programme (RSP) to develop response activities to the marine debris issue (UNEP 2009) and to collect and disseminate information. However, while 18 regional seas are recognized within the RSP, only 12 are participating in UNEP-assisted marine litter activities. Most of these regions have limited data on the magnitude of the problem, have no standardized reporting or archiving of data, and few recognize marine debris as an emerging issue. This lack of information needs to be addressed in order to convey a scientifically based global understanding of the plastic pollution issue.

First steps towards addressing this issue should include the promulgation of standard approaches and methods for collecting (Question 11), archiving, and reporting data, in addition to efforts to reduce barriers concerned with educating people and raising awareness (Question 12). Another priority for national and regional mitigation of plastic pollution is the development of databases that store standard information that can then be shared via internet (e.g. Simpson 2004, Simpson et al. 2006, Carr et al. 2011, Costello et al. 2013). By providing a standardized suite of database fields, or creating open commons data sharing, information can be made available for national or global assessments (Simpson et al. 2006), with appropriate strategies being developed to help refine management of plastic pollution. For example, in the USA, the West Coast Governor's Agreement Marine Debris Action Coordination Team has recently established an online database to collate standardized marine debris data available for the entire US West Coast (<http://debris-db.westcoast>

[oceans.org](#)), and, in Australia, a non-profit organization, Tangoroa Blue, has created a similar online database for storing beach cleanup data (www.tangaroablue.org/database.html). These are relatively recent and spatially limited initiatives; however, continued research, monitoring, as well as the use of these databases and development of similar databases in additional regions will enable identification of strengths, weaknesses, and, if possible, improvements and co-ordination. This will be especially true if these and similar databases are able to record baseline marine wildlife impacts and thus enable identification of future changes to impact rates of occurrence.

16. What are the alternatives to plastic?

The plastics industry is one of the largest and fastest-growing manufacturing industries worldwide, driven to a large extent by increased global consumerism and social pressure to favor convenient, single-use products. However, although plastic products offer short-term benefits, the longer term, or lifetime, costs are rarely calculated (Rochman et al. 2013b). An important area for future work will be in the development of indicators and techniques to assess the benefits of a product relative to the costs of its lifetime environmental, carbon, and toxic footprints. Single-use plastic products (e.g. packaging, straws, disposable cutlery, cups, food trays, and bags) may be suitable products for such a risk assessment.

Very few empirical data exist on the carbon and toxin footprint of single-use plastics (Hendrickson et al. 2006, Yates & Barlow 2013), but work on alternatives to plastic has focused on this group of products. Included in the growing list of alternate materials are biodegradable materials such as those made with prodegradant concentrates (PDCs), additives known as TDPA (totally degradable plastic additives), or MasterBatch Pellets (MBPs). However, the environmental cost of biodegradable alternatives is rarely assessed and warrants further research attention. As an example, plastics made from polylactic acid (PLA), a polymer-derived plant sugar, require a specific controlled environment in order to degrade: temperatures must be very high and oxygen absent for bacteria to break down PLA plastics. The majority of landfills and at-home composting systems cannot provide these conditions, resulting in degradation times for PLA products similar to those of traditional plastic items. Other emerging problems with 'biodegradable plastics' are that they often cannot be bundled with traditional plastic items for recycling,

and are often considered contaminants in recycling centers. Furthermore, biodegradable plastics may fragment at a great rate, resulting in an increase in the environmental burden of microplastics, and packaging labeled biodegradable may lead to increased littering. Hence, there is a clear need for further research to develop and test approaches for comparing the relative life-cycle costs and benefits of alternative materials when compared to the plastic products they replace.

One method of reducing plastic is to use products made from a wide range of alternative materials such as cotton/hemp (e.g. shopping bags), stainless steel (e.g. lunch boxes or drink containers), or glass (e.g. straws). Yet, rarely have the efficiency and effectiveness of these alternatives been assessed (Barlow & Morgan 2013). Moreover, while it is clear that engineering and product design efforts are ongoing, and the development of alternative products or materials to reduce plastic footprints is gaining momentum, there is a clear need for research on economic and social drivers to ensure the acceptance of alternatives. Explicit calculations of the cradle-to-grave cost of 'free' plastic packaging is an effective way of changing consumer behavior (Ryan et al. 1996), but there is substantial scope for further economic and social-based research in this field.

Overall, the key challenge is to understand the relative economic, environmental, and social costs and benefits of existing products compared to those of new alternative materials. Collectively these data are essential to allow effective evaluation of product changes in order to ensure a net long-term environmental benefit.

DISCUSSION

Harnessing the knowledge and ideas of multiple experts on a single topic is powerful because it highlights important research questions or topics to help focus attention on areas considered to be issues of immediate importance for the conservation of affected wildlife and habitats (Hamann et al. 2010, Sutherland et al. 2010, Laurance et al. 2011, Lewison et al. 2012). Herein, we identified as critical improvements in our understanding of the magnitude of the plastic pollution issue, the threats of plastic pollution to marine wildlife and their habitats, how these threats are currently managed, how mitigating actions are currently implemented and evaluated, and how mitigation measures can be improved in the future. Collectively, the questions generated in our

study demonstrate that understanding and mitigating the impacts of plastic pollution on marine wildlife will require a multi-disciplinary approach delivered across various spatial and temporal scales.

While it is clear that plastic pollution impacts a large number of marine wildlife species, our study reveals an obvious need to (1) understand vulnerability at the level of species or other management units (e.g. genetic stocks; Dethmers et al. 2006) or regional management units (Wallace et al. 2010) and (2) improve knowledge of species, populations, or habitats at scales relative to management. Ultimately, understanding vulnerability to plastic pollution at a mix of ecologically and management relevant scales (species or geographic) can assist with both local and regional priority setting and mitigation across a range of pressures.

We have provided a context for the key research questions to guide management of the plastic pollution impacts on marine wildlife. We identified a strong need to involve disciplines related to understanding economic and social barriers and opportunities to change behavior (individual and governance) and markets (Stern 2000, Brulle 2010, Ham 2013), and to evaluate the benefits. Understanding human behavior has traditionally been the purview of psychology, and substantial scope exists to test and apply behavior-change models such as the Theory of Planned Behavior (see Darnton 2008 for a review) or Prospect Theory (see Kahneman & Tversky 1979, Wakker 2010) to adjust social attitudes towards managing plastic pollution (e.g. Tonglet et al. 2004) and changing littering behaviors (see Cialdini 2003). Similarly, there is scope to include business themes such as social marketing (see Peattie & Peattie 2009), viral marketing (see Leskovec et al. 2007), social network analysis (see Scott 1988, Weiss et al. 2012), and cost-benefit analysis to support alterations in consumption, use, disposal, and recycling in order to achieve the best outcomes (e.g. Butler et al. 2013). Research in these social domains should increase knowledge and allow targeted dissemination of information, improve attitudes towards plastic pollution impacts and the mitigation of those impacts, improve aspirations toward enabling changes (e.g. Ham 2013), and enable evaluation of management instruments and strategies (e.g. plastic bag use; Luis & Spinola 2010, Dikgang et al. 2012) to quantify benefits.

This paper reflects ideas from an expert group of researchers with a broad range of backgrounds. It is the most current attempt to assemble the opinions of experts in the field of plastic pollution and its impact on marine wildlife and marine habitats. By focusing

effort and expertise on what are collectively agreed upon as priority research questions for the mitigation of plastic pollution impacts on marine species around the globe, we aim to move research and management forward. Although there are still many questions surrounding the issue, the numerous negative impacts of plastic pollution make it clear that we must strive to reduce the amount of plastics reaching our oceans. If the methods for doing so are attainable (e.g. reducing plastic use, improvements in waste management, better access to recycling) and the costs are non-prohibitive, it would be feasible to deal with what is ultimately an entirely avoidable problem.

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