2014 NOAA Marine Debris Program Report

Ingestion

Occurrence and Health Effects of Anthropogenic Debris Ingested by Marine Organisms

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EXECUTIVE SUMMARY

Pollution of the marine ecosystem with anthropogenic debris has been an acknowledged issue for some time. Such debris can be ingested by marine organisms either directly or through the consumption of debris-contaminated prey. Debris ingested by marine organisms is predominantly plastic; whether from industrial, recreational, or personal care products. These items range in size from microscopic beads to large sheets over a meter long and can persist in the environment for decades. The research efforts to date have sought to characterize the types, sources, and impacts of such ingestible debris, yet the overall effects of ingesting such items remain poorly understood.

Globally, many types of marine organisms—from invertebrates and fish to turtles and whales—have been confirmed to ingest debris. Direct health impacts include dietary dilution, gut blockage, starvation, laceration, ulceration, and secondary infection. More subtle effects such as hormone disruption, reproductive impairment, immune system impairment, and disease development also have been postulated as likely results, but the role of debris ingestion in disease is poorly understood. Other aspects, such as the ability of plastic to concentrate persistent pollutants, such as PCBs and pesticides, are only now being investigated. Ingestion of debris affects the entire food web, and while the larger questions of ecological impact are difficult to address experimentally, such studies will provide the most valuable information toward understanding the issue.

The likelihood of any given organism ingesting debris is largely driven by debris concentration and feeding behavior. Buoyant plastic debris is concentrated by physical factors in many of the same areas that stimulate the base of the food web and serve as feeding grounds for many marine organisms. This combination likely enhances the chances of non-food items being ingested.

Progress has been made to characterize the types of marine debris available for ingestion, its sources, where it collects in the environment, and the physical forces driving its availability. However, many aspects of the health and ecological impacts from ingestible debris are poorly understood. Key areas where answers are needed include (but are not limited to):

- updated estimates of ingestion by sea turtles and marine mammals;
- better tools for detecting and quantifying debris;
- assessments on the role of debris in altering uptake, distribution, and effects of toxic chemicals;
- assessments of the chronic health effects caused by debris (as opposed to acute health impacts);
- assessments of the trophic transfer of debris and associated chemicals between different levels in food webs; and
- assessments of the population- and community-level effects of debris.

In addition, targeted science from interconnected disciplines (*e.g.*, physical oceanography, aquatic toxicology, materials science, and veterinary science) is needed to identify the factors associated with ingestible debris that are most likely to impair the health of marine ecosystems, and hence are the most useful to understand to guide the development of effective policies.

This report reviews the state of the science regarding the occurrence and known health effects of marine debris. A broad-level synthesis is provided. The presence and accumulation of ingestible anthropogenic debris in the marine environment, records of ingestion for a wide range of organisms, as well as observed and postulated health effects from field and laboratory studies are discussed. Knowledge gaps in the literature are identified, and suggestions for how they may be addressed are provided.

Please report stranded or entangled marine mammals and sea turtles by calling the stranding network member for your area (U.S. only). Hotline numbers are listed online at http://www.nmfs.noaa.gov/pr/health/stranding.htm.

INTRODUCTION

Anthropogenic debris in the marine environment is an acknowledged global issue with broad impacts. Millions of tons of debris enter the oceans each year from trash, damaged fishing gear, or shipping accidents. While far from every animal will encounter debris over its lifespan, the sheer amount of debris collecting on beaches, in ocean gyres, and on the ocean floor suggests that many types of marine wildlife cannot avoid encountering debris. The majority of debris items are small enough to be ingested by wildlife, and ingestion has been confirmed from the ocean surface to great depths. Whether debris is confused with, or accidentally ingested alongside, preferred food sources, debris is ingested by what increasingly appears to be nearly all types of marine organisms.

Kenyon and Kridler first turned systematic attention to the ingestion of marine debris in 1969, reporting that 74% of fledgling Laysan Albatross (Diomedea immutabilis) carcasses from Hawai'i, USA, had plastic debris (*e.g.*, bottle and tube caps, toys, polyethylene bags, etc.) in their gut. Two articles followed shortly in the journal Science (Carpenter *et al.* 1972, Carpenter and Smith 1972) reporting the presence of polystyrene (a type of plastic) spherules in the coastal waters of New England, USA, and on the surface of the Sargasso Sea in the North Atlantic Ocean. These reports highlighted the capacity for organisms to ingest plastic debris particles, as well as the bacteria and plankton attached to debris. The authors speculated that attachment by encrusting organisms could make the particles more attractive for ingestion, and noted that polychlorinated biphenyls (PCBs, a known persistent organic pollutant) were associated with the plastic particles.

Over the last four decades, increasing attention has been paid to the source, distribution, and fate of marine debris—the scale of the problem—while the effects of ingesting debris have only recently been investigated. As reports of dead "charismatic megafauna" (*e.g.*, whales, seals, sea turtles, etc.) that ingested large amounts of marine debris became more frequent, public interest in the issue rose and more targeted studies were conducted. Despite the relatively recent interest, reports over the last two decades on the incidence and effects of ingested debris have been described by Gregory (2009) as "voluminous and often repetitive."

This review seeks to summarize the "state of the science" regarding the effects of ingested marine debris and highlight areas where knowledge is currently lacking.

"… the sheer amount of **debris** collecting on **beaches**, in **ocean gyres**, and on the **ocean floor** suggests that many types of **marine wildlife cannot avoid encountering** with debris."

WHAT WE KNOW

The extent of the issue

To understand the risks associated with ingested marine debris, it is necessary to understand the extent and distribution of materials encountered by marine organisms. Many studies have examined the incidence, sources, factors influencing distribution, and trends in marine debris on seashores and estuaries (Ribic *et al.* 1989, 2010, 2011, 2012a, 2012b; Thornton and Jackson 1998; Morishige *et al.* 2007; Rosevelt *et al.* 2013), sea floor (Moore and Allen 2000; Bauer *et al.* 2008; Wei *et al.* 2012), and open water (Mace 2012; Howell *et al.* 2012 and sources therein; Eriksen *et al.* 2013) of the United States. These studies indicate significant regional differences in type, source, and abundance. These results are now close to being comparable with other countries due to long-term monitoring efforts targeting the same methods to assess debris (Cheshire *et al.* 2009).

Due to spatial variability of marine debris, efforts to detect, characterize, and quantify the extent of marine debris have increased over the last decade (see Mace 2012 and sources therein). Several techniques leveraging recent advances in technology are being explored to expand the knowledge of which areas accumulate marine debris. These include airborne sensors (Kataoka *et al.* 2012; Veenstra and Churnside 2012), satellite imagery (Pichel *et al.* 2012), and webcams (Kataoka *et al.* 2012), as well as numerical models predicting likely accumulation locations under both normal (Maximenko *et al.* 2012; Lebreton *et al.* 2012; Pichel *et al.* 2012; Potemra 2012) and storm conditions (Bagulayan *et al.* 2012; Miller and Brennan 2012; Lebreton and Borrero 2013). Additionally, statistical techniques have been refined that can tie field observations of debris with their source(s) (Tudor *et al.* 2002, Ribic *et al.* 2010, 2011, 2012). New detection techniques can better characterize microplastics in sediment (Harrison et al 2012) and should be investigated for applicability to the water column. Studies have also begun to characterize microplastic pollution in large water bodies of the U.S. (Eriksen *et al.* 2013).

Several studies outside the United States have also examined the sources, distribution, and transport of marine debris (Galil *et al.* 1995; Galgani *et al.* 1995, 1996; Gregory and Ryan 1997; Mfilinge *et al.* 2005; Shiomoto and Kameda 2005; Quintela *et al.* 2012; Thiel *et al.* 2013). While these are not direct observations within U.S. waters, the dynamics of debris distribution and fate are the same, and these observations can inform our expectations in areas where oceanographic processes are similar. These studies are important to understanding ingestion of marine debris because the overwhelming majority of ingestible marine debris is plastic, due to its ubiquitous use in manufacturing since the 1970s (see Derraik 2002 and sources therein).

While many species will ingest non-plastic debris (*e.g.*, hooks and line, metallic trash, etc.), ingestible plastic marine debris has become a serious ecological issue affecting hundreds of marine species (SCBD & STAP 2012). Certain characteristics (*e.g.*, color, size, shape) of debris items can stimulate feeding behaviors. Derraik (2002) and more recently Hammer *et al.* (2012) reviewed the types of debris and potential hazards from that debris in marine wildlife. Annual production of plastics topped 265 million tons in 2010 with an expected 40% increase in consumption per capita worldwide by 2015 (Hammer *et al.* 2012 and sources therein). It has been estimated that 10% of globally produced plastics in 1997 ended up as plastic oceanic waste (UNEP 2005). If these estimates are correct and these trends continue, an estimated 38 million tons of debris will enter the marine environment in 2015 alone. Approximately half of all produced plastics are buoyant and collect mainly at the water's surface, although surface observations may be underestimating the total amount available for ingestion given the effect of wind-driven mixing in the water column, which may push debris items below the surface (Kukulka *et al.* 2012). Additionally, plastics become brittle over time and fragment (reviewed by Andrady 2011). Physical and chemical processes can degrade some types of plastic in as little as a few weeks, while other pieces last for decades. Pieces that may be too large to be consumed by organisms when initially thrown away may gradually degrade, becoming smaller and more likely to be ingested. This means most plastic debris is ingestible by marine life over the course of its multi-decade lifetime at sea.

UNEP estimated that 10% of globally produced plastics in 1997 ended up in the ocean. If these estimates continue, potentially 38 million tons of debris will enter the marine environment in 2015 alone.

Where does marine debris accumulate?

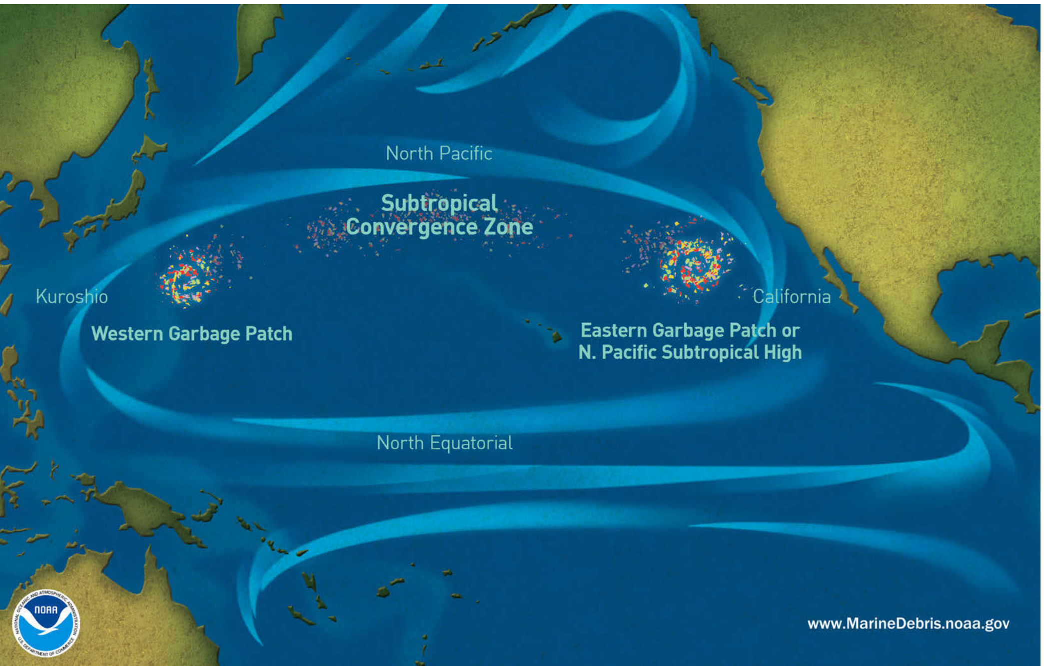
Debris from the fishing industry (*e.g.*, floats, sinkers, hooks, monofilament line, lures) generally appears to be ingested by species in close proximity to fishing activities (Macfadyen et al 2009). Due to its buoyant nature, however, lower density debris (*e.g.*, foamed plastics, bags, wrappers, etc.) can be transported extremely long distances by wind, wave, and currents. It has been estimated in the North Sea that, eventually, 15% of plastic debris washes ashore, 15% floats at the surface, and 70% will sink to the sea floor over an extended amount of time (Barnes *et al.*, 2009). Storms can greatly affect the location of plastic debris in the short term (Moore *et al.* 2002).

Even without extreme weather events, the physical processes of the ocean (*e.g.*, wind, waves, salinity gradients, and currents) play a large role in where debris accumulates in the ocean and along coastlines. Buoyant plastic debris remains at sea for an extended period of time and becomes entrained in dominant surface currents. This often results in larger amounts of debris accumulating in ocean gyres over time—large areas where currents swirl, forming regions from which buoyant items cannot easily escape. Trash from the 2011 Tohoku tsunami in Japan was tracked along one such path and was headed toward the North Pacific subtropical gyre (Bagulayan *et al.* 2012). This area is commonly known as "Great Pacific Garbage Patch" due to the gyre's ability to collect a very large proportion of floating trash entering the North Pacific Ocean. Moore *et al.* (2001) noted that while plankton numerically outnumbered plastic in this region by a factor of almost five, the mass of plastic debris was almost six times that of the plankton. In reality, while such areas contain high concentrations of debris for the open ocean, floating debris is constantly moving and dispersed along the water's surface or to shallow depths. Such zones also shift location seasonally, making them difficult to study.

Plastics transported by surface currents will also reach higher concentrations in areas where dominant currents meet (*i.e.*, convergence zones); these are zones where nutrient sources are plentiful, stimulating growth of algae and phytoplankton (plants) at the base of the complex marine food web. As areas with readily available food sources, they attract marine life across the food web, from zooplankton to large cetaceans. Higher debris concentrations are then located in areas where animals are most likely to forage, incidentally increasing the likelihood of encounters between wildlife and ingestible debris. Salinity fronts in estuarine systems can also serve as a similar barrier to debris entering the ocean from riverine systems and are likewise common foraging grounds for the same reasons as convergence zones (Acha *et al.* 2003).

Buoyant plastic debris gradually sinks as physical degradation processes increase the density of the plastic or as organisms decrease its buoyancy by colonizing debris items. Algae (Maso *et al.* 2003), bacteria (Webb *et al.* 2009, Zettler *et al.* 2013), and barnacles (Minchin 1996) have all been studied for their impact on buoyancy, each with a slightly different effect. In reality, it is rare to observe only a single species attached to debris pieces, and effects can vary greatly between pieces. Plastics with encrusting organisms attached may also become more attractive to grazing fishes or invertebrates, and thus contribute to higher grazing rates on debris items (Carson 2013). The increased presence of such grazing species at the ocean surface also makes birds more likely to forage in such areas; this often means birds will peck at, and ingest, plastic at sea as well as on beaches (Cadée 2002).

As debris sinks through the water column, it becomes available to different species living at depth. While some species may be present in areas or depths where debris is also present, unless those species are actively feeding, it is unlikely they will ingest debris from that location. Ingestion may still occur indirectly, however, if prey items have ingested and retained debris. Some species feed in the middle of the water column, such as air-breathing divers (*e.g.*, seals, walrus, penguins, baleen whales) and mid-water residents (*e.g.*, sharks, squid, tuna). If enough encrusting organisms are removed from the debris, the debris may once again rise to the surface and the entire process can repeat. Eventually, it will sink to the sea floor and become available for another community to ingest (*e.g.*, shrimps, crabs, echinoderms). Although ingestion in the deep ocean has been confirmed by several studies, much is still unknown regarding the distribution and ingestion of debris by benthic and deep water organisms.



A map of the Eastern and Western Garbage patches. These regions have higher debris concentrations because of ocean circulation patterns.

Affected Wildlife

To date, more than 660 marine species (SCBD & STAP 2012) have been confirmed to be affected by marine debris, and the number is likely to increase with future studies. While some are limited to other impacts (*e.g.*, entanglement and "ghost fishing"), a significant majority have been confirmed to ingest marine debris, primarily plastics. The amount and type of ingested debris often relates directly to the species' foraging behavior. Passive feeders (*i.e.*, filter and deposit feeders) ingest debris (mainly microplastics) with food. Active feeders (*i.e.*, those searching for and capturing mobile prey) ingest debris not only incidentally while feeding, but also any debris ingested by their prey if the prey is taken whole. Some species are able to expel debris without passing it fully into the digestive system, while debris is also able to pass completely through the digestive system over an extended period of time for many species. The ability to expel debris once ingested is highly dependent on the anatomy and physiology of the organism, as well as the type of debris. It is apparent that the likelihood of debris ingestion is largely determined by the overlap of debris accumulation and foraging behavior. If an organism preferentially feeds in a non-selective manner in areas where debris accumulates, ingestion of debris becomes much more likely.

Microbes and Invertebrates

Microorganisms are known to colonize debris and form biofilms (Bonhomme *et al.* 2003; Webb *et al.* 2009), but the ways in which this affects the debris and the base of the food web is poorly understood (Harrison *et al.* 2011). Ingestion of microscale plastic debris in the wild has been confirmed for a wide array of invertebrates, including: amphipods (Thompson *et al.* 2004), barnacles (Goldstein and Goodwin 2013), lobster (Murray and Cowie 2011), sea cucumbers (Graham and Thompson 2009), and zooplankton (Cole *et al.* 2013), among others. Furthermore, the presence of debris on soft bottom areas appears to stimulate settling and colonization by invertebrates (Katsanevakis *et al.* 2007; Renchen and Pittman in Clark *et al.* 2012). This likely causes sea life to congregate in areas with debris, increasing the chances and frequency of debris ingestion. Sea cucumbers appear to preferentially select for plastic fragments while feeding (Graham and Thompson 2009), and this selectivity is not likely to be limited to one type of deposit feeder. Invertebrates not only ingest microscopic plastic debris, but they can also facilitate debris degradation. For example, some invertebrates bore into Styrofoam floats, which accelerates fragmentation and produces enormous amounts of microplastic debris. A single isopod burrow can generate thousands of such particles, while a colony can generate millions (Davidson 2012).

Fishes

Ingestion of debris by bony fishes and sharks has not historically been as widely reported as ingestion by birds, mammals, and turtles, although the attraction of fish to man-made objects is the underpinning of artificial reef and fish aggregation programs. Planktivorous fishes eat in areas where their food source and buoyant plastic debris are often mixed together. Boerger et al (2010) noted that approximately 35% of fishes had ingested types of debris consistent with that in the water from which they were feeding. Even when items are not ingested whole, Carson (2013) noted that approximately 16% of inspected debris items showed signs of attack by a wide variety of fishes, with a preference for cylindrical shapes of blue or yellow color, indicating fishes were confusing debris for possible prey or exploring it for edibility. Recent studies from around the world have shown relatively consistent results; 36% of fish in the English Channel (Lusher et al 2013), 18–33% of marine catfish from Brazil estuaries (Possatto et al 2011), and 19% of pelagic piscivorous fishes from the North Pacific Central Gyre (Choy and Drazen 2013) ingested debris. Even in areas of lower debris accumulation, 5% of fish in the relatively unpolluted northern areas of the North Sea (Foekema et al 2013), and deep-water species in the Mediterranean (Anatasopoulou et al 2013) ingested plastic debris. These findings suggest a relationship between foraging behavior, location and type of debris, area of origin, and aggregation forces, although a larger comparative study is needed to confirm this. It is likely that as fishes become larger and more selective in their prey items, they consume less debris incidentally.

Sharks are a diverse group of very small to very large predatory fishes and have a range of feeding behaviors. An assessment of stomach contents from sharks caught in beach protection nets in South Africa found a relatively low frequency of debris ingestion (<0.5% of over 15,600 individuals comprising fourteen large shark species from 1978–2000; Cliff et al 2002). Most sharks ingest items similarly to other fishes, mainly plastic fragments and fisheries-related items, such as monofilament line and hooks. Tiger sharks (*Galeocerdo cuvier*) are often considered the "goats of the sea" and will ingest nearly any item encountered, anecdotally ingesting tin cans, chunks of rubber, and even license plates. Cliff et al (2002) found tiger sharks had by far the highest frequency of ingestion among species (7.5%, almost ten times higher than the other 13 shark species in the study). Tiger sharks were roughly of the same size and oceanographic distribution as other species examined in the study, again indicating feeding behavior as the primary driver of whether or not debris is commonly ingested by fishes.

A cluster of macro and mico plastic debris accumulates at the ocean's surface in Hawaii's Hanauma Bay.

Credit: NOAA PIFSC

Sea Turtles

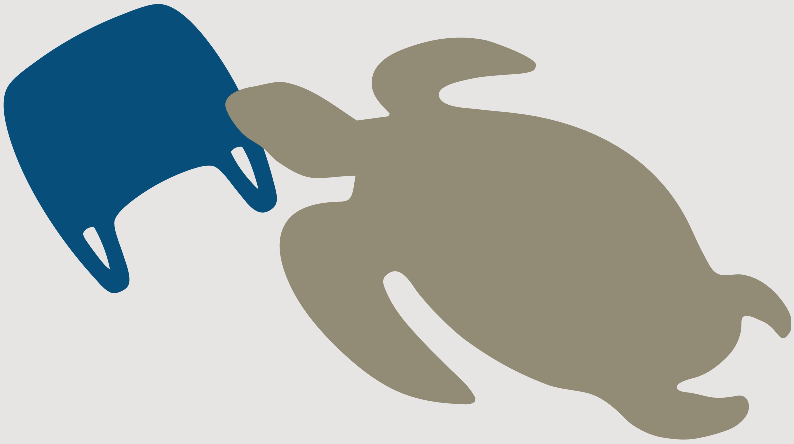
Reports of sea turtles ingesting marine debris are numerous and consumed debris has been implicated in nutrient deficiency (McCauley and Bjorndal 1999). Geography, species, year, and life stage all appear to affect the frequency with which turtles ingest debris. Ingestion has been confirmed in all seven species of sea turtle, though ingestion by flatback turtles (*Natator depressus*) has been reported only once. This could be due to a lack of systematic studies or that the flatback's range, restricted to the region around northern Australia, is in an area of relatively very little debris accumulation (Lebreton *et al.* 2012).

A recent review examined 37 studies from around the globe published between 1985 and 2012 (Schuyler *et al.* 2013). The authors concluded that green (*Chelonia mydas*) and leatherback (*Dermochelys coriacea*) sea turtles in all regions are ingesting plastic debris more often than in years past, and that hawksbill turtles (*Eretmochelys imbricata*) were overall most likely to ingest debris (~47% of individuals with plastic in the gut). Ingestion frequencies ranged from 0–100%, likely highly dependent upon location and feeding behavior. Their analysis, however, was limited to studies with systematic necropsies. While this is the most effective manner of accurately quantifying plastic ingestion, it necessarily biases results toward dead individuals. While direct mortality from ingestion of non-food items (typically debris) is usually only verified in approximately 1 in 10 animals, non-lethal health impacts are poorly understood. Feeding behavior is a very important driver as to the type and frequency of debris ingestion (Gramentz 1988; Mrosovsky *et al.* 2009; Schuyler *et al.* 2012). Turtles will ingest several types of debris, though plastic bags are widely considered the most commonly ingested and dangerous item due to the resemblance to jellyfish and the high potential of becoming lodged in the throat.

Interestingly, Schuyler *et al.* (2013) noted a poor relationship between estimated regional debris density and the observed frequencies of ingestion. This merits further investigation as their study was a high-level overlay of several stranding studies with Lebreton *et al.*'s (2012) global debris density model, but did not factor in behavioral factors such as migratory paths, mobility, or feeding location (*e.g.*, preferred foraging grounds may be well outside capture or stranding areas). Life history differences may also be obscuring the expected relationship between debris concentrations and ingestion rates. Younger turtles in the open ocean often seek shelter in the same productive convergence zones where debris accumulates (*e.g.*, the Sargasso Sea), and are less selective in what they ingest, thus increasing the likelihood of debris ingestion (Carr 1987). Schuyler *et al.* (2012) confirmed this by demonstrating that smaller oceanic-stage turtles are more likely to ingest debris. González Carman *et al.* (2013), however, noted a large overlap in debris accumulation areas and preferred foraging grounds for green turtles in the Río de la Plata (a large estuary at the Argentina–Uruguay border). Behavior, then, appears again to be a primary driver of how likely it is that an organism ingests debris.

All seven species of sea turtles have been confirmed to eat debris.

Plastic bags are the most commonly ingested type of debris amongst sea turtles.



Birds

Birds are by far the most studied marine organism with regard to ingested marine debris. It has been estimated that over one-third of sea bird species ingest plastic (Laist 1997). This may be much higher in certain areas, such as North Carolina (55%) (Moser and Lee 1992), and as more studies are conducted, the number of affected species is expected to rise. Sea birds have, in fact, been proposed as good indicators of plastic pollution due to the ease with which such studies can be conducted (Nevins *et al.* 2005). Birds are easy to capture, congregate in large numbers, and can be prompted to regurgitate their stomach contents, making dietary studies much easier than in other species. Sea birds from as far apart as Alaska and the Antarctic (Auman *et al.* 2004) have been confirmed to ingest debris, making them ideal indicators to compare different geographic areas. Different species exhibit a wide variety of feeding behaviors, and many studies have highlighted the difference this makes for plastic ingestion (see Azzarello and Van Vleet 1987 and references therein).

Birds, particularly the Procellariformes (*e.g.*, albatrosses, fulmars, and shearwaters), may also be more susceptible to physical health effects, as debris most often gets stuck in the gizzard and cannot easily pass through the digestive system. Ryan and Jackson (1987) suggested a half-life of approximately one year for plastic pellets ingested by white-chinned petrels. Compared with other animal groups, birds may be ingesting debris with a similar frequency, but retaining it for longer periods of time. This makes them excellent study organisms for health effects such as obstruction, ulceration, blockage of digestive enzymes, diminished feeding stimulus, lower steroid hormone levels, and decreased reproductive function (reviewed by Azzarello and Van Vleet 1987). Direct health effects from ingesting debris do not presently seem to be a significant issue (Ryan and Jackson 1987; Sileo *et al.* 1990; Moser and Lee 1992; Sievert and Sileo 1993), but weights at fledging were found to be significantly lower for Laysan Albatross chicks that ingested large amounts of plastic (Sievert and Sileo 1993). This may be a dietary dilution effect, where plastic in the stomach prevents the chicks from consuming a full meal. Adults not only build nests using collected debris (Hartwig *et al.* 2007), but pass any ingested debris on to their offspring when the chicks are fed (Pettit *et al.* 1981). Both of these actions are likely to increase the incidence of debris ingestion by chicks through the exposure of adults to marine debris.

An exposed carcass of a Laysan albatross reveals ingested pieces of plastics which includes a cigarette lighter, plastic bottle caps and numerous pieces of microplastics.

Credit: NOAA

Credit: NOAA Fisheries, Pacific Islands Fisheries Science Center, taken under Marine Mammal Permit #10137 (Ilana Nimz photographer)

A Hawaiian monk seal chews on consumer debris, a single-use plastic bottle, found in the Pacific ocean near the Northwestern Hawaiian Islands.

Marine Mammals

Reports of debris ingestion by marine mammals have existed for well over a century (reviewed by Walker and Coe 1989), with over 26 species of odontocetes (toothed whales), manatees, and multiple seal species confirmed to ingest debris. Due largely to regulatory restrictions on research, very little scientifically reliable information exists on the frequency or amount of debris ingested by wild marine mammals (de Stephanis *et al.* 2013). Most data are collected from stranded and dead individuals, or from captive animals ingesting a variety of man-made materials not necessarily comparable to typical marine debris. Baleen whales may be particularly susceptible to large sheets of plastic debris that can become entangled in their baleen (feeding structure) (Lambertsen *et al.* 2005). Since baleen whales filter extremely large volumes of water while feeding, it is possible that they encounter (and consume) plastic sheets at higher rates than other animals. Plasticizer chemicals have been measured in both fin whales and their planktonic prey in the Mediterranean, and there is the potential that such plasticizers may be associated with microplastics from the same areas (Fossi *et al.* 2012).

Deaths of endangered manatees (*Trichechus manatus*) have been attributed to large pieces of ingested plastic (see Derraik 2002 and references therein). Reports from fur seal scat indicate transfer of plastic fragments from directly consuming prey items, and not incidental ingestion during feeding (Eriksson and Burton 2003). Ingested plastic is mostly retained by harbor seals, with younger animals more susceptible to debris ingestion (Rebolledo *et al.* 2013). It is possible that younger seals are less selective in their feeding behaviors, or that older animals are consuming larger prey items, which are in turn more selective. This highlights the nearly unknown role that transfer of ingested debris from prey to predator plays in the frequency and scale of debris ingestion for mammals.

Health Impacts

The health impacts from ingested debris can be thought of as falling into two main categories—physical and physiological effects—although both are intricately linked. Currently, acute dangers from sharp objects and sheet plastics (*e.g.*, bags) appear to cause the most damage to larger animals in the shortest amount of time.

Physical Effects

The mere presence of ingested debris can have a variety of health effects. Among others, these include: laceration or ulceration of the digestive tract, leading to infection and internal bleeding; direct blockage of the digestive tract, reducing nutrient uptake; satiation, reducing the urge to feed; failure of digestive tract compartmentalization, allowing highly acidic gastric juices into areas not adequately shielded; and retention, leading to an increasing amount of debris in the digestive system of the organism.

Laceration and Lesions

Fish hooks are commonly ingested in areas with active fisheries. These are commonly lodged in the mouth, but can pass further into the digestive system and often become lodged in the esophageal area. As plastic degrades in the environment, it often fragments into pieces with sharp corners. Once ingested, sharp debris objects can puncture the lining of the digestive system. This leads to ulceration, persistent lesions, secondary infection and parasitism, and inflammation of the surrounding tissue (Gregory 1991; Oros *et al.* 2005) leading to reduced fitness and disease.

Blockage

Ingested debris has often been noted as a secondary item during necropsies of many cetaceans and turtles with factors such as parasitism or other pathological conditions as the listed cause of death. Identifying debris as a definitive cause of death is extremely tenuous; animals at this stage are often diseased and determining pathologically which came first—disease or debris ingestion—can be extremely difficult, except in rare cases. Plastic sheeting and large plastic bags are commonly ingested by larger animals, especially turtles (which mistake plastic bags for jellyfish) and cetaceans. Such items can become lodged while strands of the plastic extend into the gastric system, exposing organs to an onslaught of digestive fluids. Approximately half of the forestomach lining and protective mucosa was eroded in a bottlenose dolphin (*Tursiops truncatus*) that ingested plastic sheeting, resulting in necrosis and inflammation deep into the stomach musculature (Walker *et al.* 1989). Cetaceans have been often noted to suffer gastrointestinal blockage due to ingesting non-food items (Laist 1997; Derraik 2002). It has been hypothesized that in sperm whales such blockages lead to malnutrition, starvation, and gastric rupture from ingesting large amounts of debris (Jacobsen *et al.* 2010; de Stephanis *et al.* 2013). Supporting this hypothesis, a stranded pygmy sperm whale showing extreme signs of malnutrition successfully recovered after a series of endoscopic procedures that removed several sheet-like pieces of plastic debris such as garbage bags, a mylar balloon, and cellophane wrappers (Stamper *et al.* 2006).

Regardless of the animal, indigestible debris in the digestive tract, particularly the stomach, likely leads to a false sense of satiation, reducing the animal's urge to feed properly (Secchi and Zarzur 1999; Pierce *et al.* 2004) until it can be cleared. This has been shown in birds to reduce meal size and impair formation of fat deposits among other effects (see Derraik 2002 and references therein). The downstream health impact then becomes one of wasting and malnutrition, impacting migration distances and physical condition, often leading to secondary infections as the immune system becomes impaired.

Retention

The longer debris resides in the digestive tract, the greater the potential for negative health effects. Retention timing is highly dependent on the nature of the debris and the anatomy and physiology of the affected organism. Some ingested debris can pass relatively quickly through the body, while other debris items are retained for extended periods of time. Browne *et al.* (2008) showed that microplastics ingested by mussels stayed in the animal's blood for over six weeks. Crabs were able to clear microspheres more quickly (Farrell and Nelson 2013), but still distributed the debris throughout the body over four weeks prior to clearance. Lobsters were unable to effectively clear plastic microfibers over two weeks (Murray and Cowie 2011). The only study looking at how long ingested debris remains in the gut of sea turtles found that 85% of the mass of 5-mm diameter soft foam dishes passed after 13 days, and that plastic spheres took almost twice as long to pass (Valente *et al.* 2008).

Credit: United States Fish and Wildlife Service/ Peter Leary

The body of a Laysan albatross decays in the Northwestern Hawaiian Islands exposing its stomach, which contained several pieces of plastic, primarily plastic bottle caps.

Physiological Effects

Most of the direct physical effects of ingesting debris lead directly to physiological impairment, whether that be nutritional, developmental, immunological, or toxicological. Debris in the digestive tract can have negative effects on gastric enzyme secretion, impairing the proper digestion of food and resulting in loss of body weight (Spear *et al.* 1995). Ingestion of debris has been indicated to cause poor production of steroid hormones in sea birds, leading to delayed ovulation and reproductive failure (Azzarello and Van Vleet 1987). Debris colonized by microbes can serve as a vector for harmful bacteria when ingested. Plastic microspheres similar in size to marine bacteria may stimulate hemocyte aggregation (an immune response) in crabs and become trapped in the gill microvasculature, reducing respiratory function (Johnson *et al.* 2011). Köhler (2010) reported pronounced immune response and formation of granulomas in blue mussels (*Mytilus edulis*) ingesting similar microspheres. Rochman *et al.* (2013b) reported hepatic stress in Japanese medaka (Oryzias latipes) ingesting virgin polyethylene fragments.

Although studies on the direct physiological impacts of ingested debris on marine organisms are relatively rare, studies from other research fields (*e.g.*, veterinary science) give an indication of likely effects. For example, female goats fed plastic rope exhibited no clinical signs of disease over fifty days, yet serious damage to the digestive tract was observed on necropsy, including: lesions, increased thickness in the muscle tissue surrounding the plastic, and reduced thickness of mucosal layers (Raoofi *et al.* 2012). Considering the anatomical structure of goats, it is unsurprising the rope localized in the rumen; similar structures in marine organisms likely have similar effects. While these findings are not directly comparable to many marine organisms (none being ruminants), tissue damage can be expected to occur in a similar manner. Similar pathologies have been observed in the gastric tissues of marine mammals (Walker *et al.* 1989; Stamper *et al.* 2006; Jacobsen *et al.* 2010; de Stephanis *et al.* 2013). This also serves to highlight that non-invasive clinical measures may miss meaningful pathology resulting from ingested debris that cannot be observed until the health of the animal has deteriorated substantially, or the animal has died and a necropsy can be performed.

Toxicants

Chemical toxicants associated with marine debris (*e.g.*, metals or metal oxides leaching from fish hooks and marine paints, legacy organic pollutants, halogenated compounds, and plasticizers) inevitably enter the body if the debris is ingested. Through direct ingestion of debris or through consuming polluted prey, these can have a variety of health impacts on marine organisms in addition to the physiological effects of debris presence. At high enough doses, such toxicants are well-documented to cause health effects such as cancer, endocrine disruption, immune impairment, neurological damage, reproductive failure, developmental delays, and muscle damage (see Jones and de Voogt 1999 and references therein).

Plastic is essentially solidified oil. While current-market plastics are typically considered biologically inert (Teuten *et al.* 2009), properties considered desirable for consumer markets require the incorporation of various chemical additives. This includes (among others) phthalates and bisphenol A to alter the rigidity of the product, brominated flame retardants to increase heat resistance, antimicrobial agents such as triclosan to reduce biodegradation, or antioxidants to delay the plastic becoming brittle (see Cole *et al.* 2011 and references therein). Such additives are rarely completely incorporated into the polymer structure of plastics, causing them to leach out over time. Plasticizers represent up to half the total weight of plastic in the case of phthalates and therefore have been studied extensively (see Oehlmann *et al.* 2008; 2009 and references therein) and are shown to cause a variety of negative health effects on reproduction and development. Mollusks, crustaceans, and amphibians appear to be particularly sensitive.

Added to this are a host of other anthropogenic pollutants, some banned from production for decades, which adsorb onto hydrophobic plastic in the environment. This is due partly to the relatively large surface area to volume ratio of plastics, which only increases as debris fragments into smaller pieces. Microplastics have a high surface area to volume ratio and a large potential to collect toxicants. Such adsorbed pollutants include aqueous metals, halogenated persistent organic pollutants (*e.g.*, polychlorinated biphenyls (PCBs)), organochlorine pesticides (*e.g.*, DDT), and polycyclic aromatic hydrocarbons (PAHs). Teuten *et al.* (2007) reported PCB concentrations in free-floating polystyrene pellets were 106 times greater than in the surrounding water. Pollution of this type adsorbed onto plastic debris has been widely reported in the literature at concentrations that may pose a significant health hazard (Cole *et al.* 2011 and references therein; Rochman *et al.* 2013a, b), though the evidence is currently not definitive regarding health risks. The same study confirmed the potential for these adsorbed compounds to disassociate once ingested and translocate to tissues; this has since been reinforced by a variety of studies. While plastic buried in the sediment may desorb such compounds, plastic remaining at the sea surface has no such capacity and continues to accumulate such toxicants. Since organisms are historically exposed to toxicants of this nature from non-plastic sources through the food web (primarily sediment-bound), this represents a new transfer pathway for lower trophic level organisms not typically associated with sediments. While the presence of adsorbed pollutants has been investigated heavily in the last decade, more research is needed to clarify transfer dynamics from plastics to primary, secondary, and tertiary consumers. As biological systems become more complex, potential disruptions from toxicants become more likely and more varied. As many toxicants bioaccumulate and biomagnify through the food web, tying plastic exposure or ingestion and the presence of toxicants to health effects in a given animal is extremely tenuous at this time. In the future more discriminatory indicators may be found. There is some thermodynamic model-based evidence that toxins associated with plastics may be of limited importance compared with other vectors (the total amount of plastic is currently still dwarfed by the total amount of organic carbon in the ocean) and that ingested plastic may, if excreted, reduce the total body burden of certain toxicants by adsorbing toxicants from the digestive system (Gouin *et al.* 2011; Koelmans *et al.* 2013). Presently, the presence of plastic debris and its potential role in mediating bioconcentration and bioaccumulation dynamics is an open question for which further study is warranted.

WHAT WE NEED TO LEARN

The concentration and distribution of ingestible marine debris in the world oceans is currently not well understood. While one section of the North Pacific Ocean has been most often studied, questions still remain about the full character of debris collecting in that gyre. Other areas have been studied only sparsely. Currently, the indication is what would be expected, that most ingestible debris is generated by urban areas, becomes entrained by surface currents, and collects along converging current boundaries. New technology focusing on passive airborne sensors, internet-enabled cameras, oceanic gliders, drones, and improved satellite imagery may be able to more quickly establish the true extent of marine debris, not only on beaches and at the ocean's surface, but also at depth and throughout the water column. Understanding which types of debris are most harmful, prioritizing the most polluted areas, and tracking the debris to identify sources will have a tremendous impact on targeting effective policies to reduce ingestible debris.

It is difficult to provide a single estimate for how long a piece of plastic takes to degrade in marine environments due to differences in research methodology and differences in environmental factors (*e.g.*, temperature, salinity, colonization, etc.), and the limited number of studies conducted are at times contradictory. This is especially true when considering newer production formulas as polymer manufacturers attempt to improve their products, making them more cost effective and "green." Similarly, the degradation of plastics in different digestive environments will play a key role in understanding health impacts for current and future plastic formulations. In part, this determines how quickly toxicants move into the body. Some programs are beginning to address this lack of information, and these efforts should be increased and more tightly coordinated.

Much of what we know about the ingestion of debris by mammals and turtles is based on reports that document mortality events. These observations, although useful, do little to address the amount and type of debris ingested by a typical member of these species. Given that mammals and turtles are reported to ingest debris at higher frequencies than some other more well-studied species, currently reported rates of ingestion are likely inflated by this bias. This represents a very large void in the current state of the science. There is an acknowledged difficulty in working with large, federally protected and relatively rare species (*e.g.*, larger cetaceans and polar bears likely cannot be assessed using live animals), but routine monitoring projects around the country already capture many dolphin, seal, and turtle species. Esophageal lavage has been used successfully (Witherington *et al.* 2012), but only recovers items ingested recently. Similarly, fecal collection only recovers items passing through the gut within a limited time window. The addition of a brief endoscopic screen of stomach contents during captures would add tremendous value in verifying the accuracy of necropsy-based studies for relatively little added difficulty, cost, or health impact to the animal.

These and other basic questions about the ingestion and health effects of ingested marine debris remain unanswered (and largely unasked), including:

- As mentioned above, debris can be found floating on the surface of the ocean, but it can also be found at depth. If high concentrations of debris overlap with preferred foraging areas for many mid-water species (*e.g.*, deep chlorophyll maximum), current estimates may be underestimating the overall impacts of debris on organisms in the world's oceans. Future work should identify the location and concentration of debris at depths where organisms are actively feeding in order to assess the potential impacts on those animals actively feeding in these areas.

- Detection and quantification of plastics and plastic-associated contaminants in the environment currently lacks sophistication (most studies are microscopy or type-identification based). Drawing conclusions regarding trophic uptake and transfer is important; however the available data are tenuous at this time (Fossi *et al.* 2012). More discriminating analyses based on analytical chemistry would advance the science tremendously by allowing more directed questions and more easily eliminating alternative hypotheses.

- Very little information exists on how long plastic stays in the body and how it becomes distributed throughout the body once ingested. Residence time and distribution likely varies greatly from species to species, but has been addressed only by a handful of studies on birds (Ryan and Jackson 1987), crabs (Farrell and Nelson 2013), mussels (Browne *et al.* 2008), turtles (Valente *et al.* 2008), and zooplankton (Cole *et al.* 2013). More studies are warranted along the lines of those from Browne *et al.* (2008), which examined the relocation of microplastics throughout the body, and Farrell and Nelson (2013), which noted a specific clearance rate.

- How filter and deposit feeders select what they consume and what they reject is not well understood (Ward and Shumway 2004). Indications point to a very complex system, and the ability of these organisms to separate their food from microplastic debris could alter understanding of the system.

- Bacterial microflora and -fauna in the gut environments of larger animals likely play a mediating role in plastic digestion and toxicant effect. This has not been well addressed and represents a knowledge gap.

- Desorption and uptake of debris-associated toxicants is known to occur in ways inconsistent with standard theory (Voparil and Mayer 2000; Endo *et al.* 2013), but the dynamics are poorly understood. How do toxicants distribute through the body? How does the gut environment of different organisms alter desorption, degradation, and toxicant uptake rates? Is this altered by the plastic carrier, and in what ways? A wealth of information exists for acute toxicology regarding such chemicals, but currently the desorption dynamics of a gut environment containing debris and multiple co-occurring factors such as adsorption of non-plastic pollutants, sediment, and species-specific gut environment is poorly understood. Toxicological and chemical studies using debris (particularly plastic debris and microplastics) as a vector should therefore be given a high priority.

- In contrast to acute toxicology, relatively little is known regarding chronic exposures for longer-lived organisms. Similarly, almost no information exists regarding the mixtures of toxicants to which organisms are actually exposed. This may alter the toxicity of individual chemicals. The interface of toxicant and debris presence and health interactions between these exposures is also poorly understood.

- Minimal useful information exists regarding trophic transfer of ingested marine plastics and associated chemicals; that is, if prey ingests plastic, what effect does that have on the predator? How much (plastic and chemical load) transfers? How does this affect digestion of the prey? Only two studies examining this issue were identified. Farrell and Nelson (2013) showed that plastic microspheres fed to mussels were observed in the blood of crabs. Toxic effects were not evaluated although no overt mortality was reported. The clearance rate (21 days) was also a key observation, as faster clearance rates may decrease the plastic load transferred to predators. Murray and Cowie (2011) noted that when lobsters ingested rope fibers contained in fish, they could not excrete the fibers. Information of this type is vital, and more attention should be turned to answering questions about transfer dynamics throughout the food web.

- No studies to date have attempted to tackle the larger question of interspecies ecological effects of ingested debris. Studies at the population and community levels would necessarily be observational and correlative, but data sets large enough to evaluate such effects may be available if data from enough single studies could be combined. These could be augmented by targeted mesocosm studies to understand the health impacts of debris entering the ecological system at different levels. What role does submerged aquatic vegetation play in ingestion mediation? Is ingested debris leading to a higher incidence of sick animals more susceptible to predation and at what rates?

- Degradation of plastics in the environment can be enhanced with emerging "green" formulations, such as compostable plastics, which degrade completely in less than six months (O'Brine and Thompson 2010). This reduces the amount of time the plastic is available for ingestion, but may relatively increase the short-term transmission of plasticizer chemicals into the environment. The trade-off regarding health effects has not been investigated.

Before the issues related to ingestion of marine debris can be fully addressed, each of these questions must be answered. The application of mesocosm and flow-through toxicology studies could answer several of the basic questions regarding ecological distribution, adsorption and desorption of contaminants in plastic debris, digestive transfer, and trophic relationships of debris transference.

CONCLUSIONS

Many types of marine organisms routinely ingest marine debris, whether from the water column, with target prey items, or picked up from the sea floor or beaches. The majority of this debris is plastic, buoyant at first and gradually sinking over time as degradation and colonization by encrusting organisms increases its density. The interaction between plastic formulation (*i.e.*, initial density), degradation, and colonization that leads to the transfer of plastic from the ocean surface to the ocean floor is currently only loosely understood. Buoyant plastic debris is entrained in ocean gyres or aggregated by wind, wave, and currents onto beaches and along ocean convergence zones.

Plankton, shellfish, birds, fishes, marine mammals, and sea turtles from all parts of the globe and from various depths of the ocean have been confirmed to ingest debris. Birds appear to suffer the broadest impacts, particularly long-range surface foragers such as albatross, fulmars, and shearwaters. Impacts are seen not only in the individual ingesting the debris, but also in offspring due to the manner in which chicks are fed by adults. Effects and dynamics from transfer of debris, either directly (as in the case of birds) or indirectly through consuming prey items with debris in the gut, are currently poorly understood.

Behavior appears to be the driving factor determining the likelihood of ingestion when debris is present. Individual species of filter feeders, deposit feeders, grazing fishes, and active predators exhibit different frequencies of ingestion (and thus different potential health impacts) depending on species-specific feeding behaviors. Convergence zones, which concentrate floating debris, produce areas of abundant nutrients and aggregate sea life, likely increasing the probability of interactions between marine life and debris.

Direct health effects have been difficult to quantify, but there appears to be little direct mortality from the majority of small plastic items. Physical health effects typically include laceration, perforation, or fouling of the digestive system. Physiological effects resulting from such physical outcomes include inflammation, secondary infection, and potential toxicant transfer. It is likely that observations of health effects in large animals that have ingested debris are confounded by the unknown health status of the animal when it ingested the debris, as well as the duration of debris retention. Animals may be impaired by an initial insult, such as the ingestion of debris or infection, subsequently making them more susceptible to infections and inflammation. This can alter animal behavior, particularly energy-intensive feeding behaviors, leading to a cascade effect whereby each insult reinforces the others, leading to sickness and death. Debris is an easier target than actual prey items and may be more appealing to an impaired animal. This “chicken or the egg” style problem should be addressed in a more systematic manner controlling for behavior and states of physiological stress. Similarly, care must be taken to eliminate alternative hypotheses when observing debris-associated toxic chemicals in difficult-to-study animals.

Many different policies have been considered to reduce the overall input of marine debris in a natural setting. Any reduction in the amount of debris entering the environment will also generate long-term benefits by reducing the potential future impacts of newly-introduced debris on many organisms. However, while policies to reduce debris from entering the environment may be useful, fewer policies have been constructed to assess and address the overall impacts of existing debris in the environment. Since some debris items can last for decades or longer in the environment, they will likely be available for consumption and potential harm to organisms across multiple generations. Even if we stopped the flow of debris into the ocean, debris that has already made its way into the ocean will continue to impact the organisms therein for decades to come. Thus, future research should continue to quantify the concentrations of debris in the environment, while also assessing the impacts of that debris (including the most ”impactful” debris types) on marine wildlife. Policies should then use the information gleaned from this research to identify areas that require immediate action in reducing the impacts of debris in those areas. It is possible that additional baseline data can better inform numerical modeling exercises to provide broader and more accurate information regarding collection areas, source tracking, and amounts of debris. The recent improvements in modeling of debris patterns and increasing data on health effects are encouraging. Without a comprehensive top-level understanding of the system and effects, however, crafting highly specific policies may be an overwhelming and premature exercise.

More targeted science from interconnected disciplines (*e.g.*, physical oceanography, mesocosm toxicology, and veterinary science) is needed to identify the factors associated with ingestible debris that are most likely to impair the health of marine ecosystems, and hence most useful to help establish effective policies. Future studies on ingestible debris should connect with veterinary research centers for diagnosis and treatment of foreign body ingestion. These would benefit greatly from simple gastroscopic investigations to better quantify ingestion rates and amounts in larger animals that cannot be sacrificed for regulatory reasons (*e.g.*, turtles and cetaceans). Refined analytical chemistry and toxicology methods could provide more useful insights into community-scale distribution of debris-associated toxicants and indicate which parts of the food web are most at risk from direct ingestion and trophic transfer. Micro- and mesocosm studies could effectively model environmental partitioning, especially in estuarine systems where debris often becomes concentrated.

Broader policies, both national and international, established to reduce the amount of plastic debris entering the oceans will likely be the only effective approach moving forward. Policies to reduce the amount of plastics entering consumer and manufacturing markets are currently unlikely to gain traction. Formulation changes, for example increases in density or degradation rates, will likely reduce the chances of debris being ingested by surface or mid-water organisms but may have effects on the benthic community that are currently poorly understood. Incentives to contain and reduce the amount of plastic debris entering the environment will likely have more meaningful impact in the nearest term while these are investigated. Modifications to plastic formulation should be rigorously investigated prior to market entry, with environmentally beneficial formulations (*e.g.*, those with lower toxicity and environmental persistence) being given regulatory priority and older formulations regulated out of the market. Likewise, some manufacturers have begun to recognize the environmental impacts of plastics, particularly in the personal care product market, and have started voluntarily to address the issue. Such responsible businesses should be encouraged and provided support to implement and expand these practices.

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