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Plastic as a Persistent Marine Pollutant

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Keywords

plastic production, pollution, ecological effects, marine environment, persistent organic pollutant

Abstract

Synthetic organic polymers—or plastics—did not enter widespread use until the 1950s. By 2015, global production had increased to 322 million metric tons (Mt) year^{-1}, which approaches the total weight of the human population produced in plastic every year. Approximately half is used for packaging and other disposables, 40% of plastic waste is not accounted for in managed landfills or recycling facilities, and 4.8–12.7 Mt year^{-1} enter the ocean as macroscopic litter and microplastic particles. Here, we argue that such mismanaged plastic waste is similar to other persistent pollutants, such as dichlorodiphenyltrichloroethane (DDT) or polychlorinated biphenyls (PCBs), which once threatened a "silent spring" on land. Such a scenario seems now possible in the ocean, where plastic cannot be easily removed, accumulates in organisms and sediments, and persists much longer than on land. New evidence indicates a complex toxicology of plastic micro- and nanoparticles on marine life, and transfer up the food chain, including to people. We detail solutions to the current crisis of accumulating plastic pollution, suggesting a Global Convention on Plastic Pollution that incentivizes collaboration between governments, producers, scientists, and citizens.

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1. INTRODUCTION

Plastics are synthetic organic polymers that can be easily molded into different shapes and products for a large variety of uses. Invented only 110 years ago (1), plastics are now the most widely used man-made substances and have become omnipresent in every aspect of our lives. From medical supplies and water bottles to food packaging, clothing, and construction materials, every person now disposes an average of 52 kg of plastic waste every year (with a median value of 192 countries, as Reference 2 reports). Geologists are now considering a plastic horizon in the world's soils and sediments as one of the key indicators marking the current geological epoch, the Anthropocene (3).

Originally deemed harmless, several decades of plastic release into the environment have brought about a wide range of associated problems. Plastic pollution has now become widely recognized as a major environmental burden (4, 5), particularly in the oceans where the biophysical breakdown of plastics is prolonged (6, 7), effects on wildlife are severe (8–10), and options for removal are very limited (2, 6, 8).

In this review, we provide an up-to-date overview of what is currently known about the production, release, persistence, and environmental effects of plastics worldwide, with a focus on new insights from the marine environment. On the basis of this evidence, we argue that plastics in the environment are a persistent form of pollution, with similarities to persistent organic pollutants (POPs). POPs are defined under the Stockholm Convention on Persistent Organic Pollutants (11) as potentially harmful organic compounds that resist environmental degradation through chemical, biological, and photolytic processes. Because of their persistence, POPs tend to accumulate in organisms and in the environment, and they have become ubiquitous around the globe, with significant impacts on environmental and human health, a sentiment famously popularized by Rachel Carson in her 1962 book *Silent Spring* (12).

When released into the environment, plastics fulfil some criteria for POPs in that they are organic substances; they persist and accumulate in the environment and in organisms over long periods of time; and they can cause a wide range of sublethal and lethal effects, including the complex toxicology of micrometer- to nanometer-sized plastic particles coming to light recently (13–17). Unlike for POPs, which are being phased out under the Stockholm Convention, the production and subsequent release into the environment are still continuing to rise significantly for plastics (**Figure 1*a***). Also, in contrast to POPs, plastics make up an even broader category of thousands of combinations of polymers and additives that are used in nearly every aspect of our daily lives, with many critically important applications (e.g., in the medical field) and with better options for recycling and safe disposal. Hence, we argue here that the global problem of persistent plastic pollution requires a tailored set of solutions that should be detailed in a dedicated Global Convention on Plastic Pollution. Such an international protocol, akin to the Stockholm Convention, could facilitate a global collaborative effort to mitigate the rising tide of plastic pollution and constrain its long-term effect on the environment—and on people.

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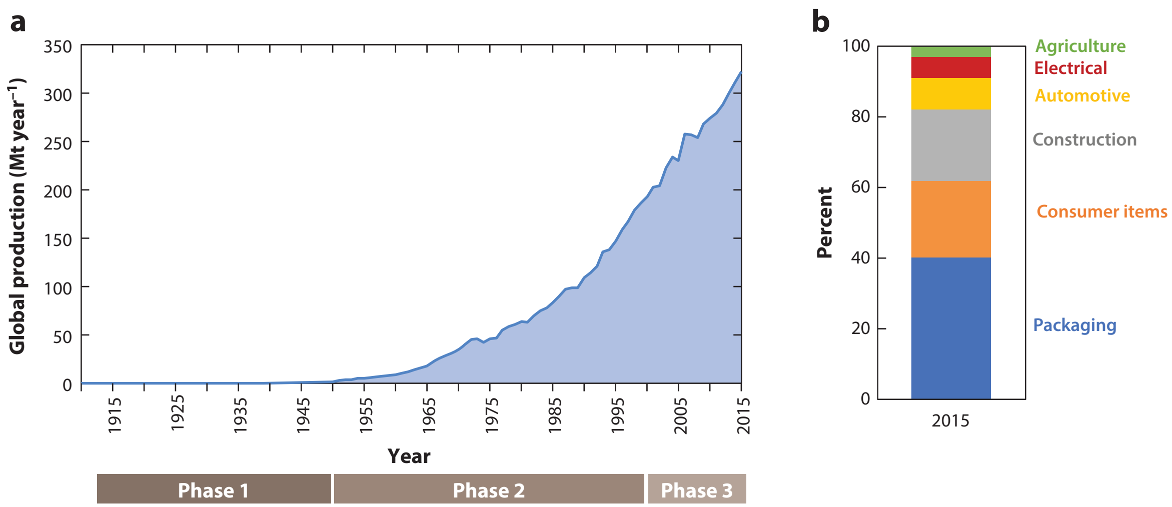

Figure 1

Time trends in total plastics production worldwide. (*a*) Global production in million metric tons per year (Mt year^{-1}). (*b*) Usage patterns of plastic in 2016 are estimated from available sources (18). Three phases are seen: Phase 1 signifies slow development and invention of most plastics commonly used today (innovation phase), Phase 2 is marked by rapid global expansion and exponential growth (growth phase), and Phase 3 shows more linear dynamics that more closely mirrors global economic growth (consolidation phase). Data compiled from References 18, 19, and 20.

2. HISTORY AND CURRENT TRENDS OF PLASTIC PRODUCTION AND POLLUTION

2.1. The Origin of Plastics

Humans have modified naturally occurring materials such as metals, stone, clay, and plant fibers for millennia. However, the twentieth century saw a fundamental departure from this history through de novo synthesis of an entirely new class of materials: synthetic polymers. Although natural organic polymers such as cellulose or DNA are ubiquitous in nature, chemists struggled to comprehend their properties and structure until the beginning of the twentieth century. Regardless, early inventors such as John Wesley Hyatt began to tinker with these molecules, chemically modifying cellulose to produce Celluloid in 1870. The popular material was used, for example, to make silent-movie film. The world's first fully synthetic polymer of commercial importance, however, was Bakelite, invented in 1907 by Leo Baekeland who also first coined the term plastics, after the Greek world *plastikos*, meaning moldable. Baekeland mixed two common chemicals, phenol and formaldehyde, and subjected them to heat and pressure. The resulting resin called Bakelite (1) opened the door to the Age of Plastics and spurred the growth of a worldwide trillion-dollar industry that set out to transform every aspect of human material consumption.

2.2. Twentieth-Century Trends

Bakelite production was slow in the beginning, some 180 L d^{-1} in 1910, when commercial production started (19). But by 1930, the product was already ubiquitous, particularly in the emerging electrical and automotive industries, but also in communication (radios) and even fashion (jewelry). In what now seems like a visionary statement, the Bakelite corporation adopted the mathematical symbol for infinity and the slogan "the material of a 1000 uses" (19). Soon, other polymers with improved properties, such as transparency or the ability to hold different colors, were invented and commercial production increased dramatically from the 1930s to 1950s. During World War II, plastic production quadrupled (to ~360,000 t), particularly in the United States, propelling plastics into the mainstream. For example, polyamide, commonly known as nylon, was used extensively in World War II in making parachutes. After the war, the material was adapted to other uses and widely marketed for clothing. Since then, plastic production increased almost 1,000-fold (**Figure 1*a***), vastly outpacing global population or economic growth. Since 2000, however, the annual growth rate in global plastic production has slowed and adds approximately 3–4% (or 10–12 Mt) per year (18), a percentage figure that is close to annual growth in global GDP. This suggests three distinct periods in plastic production: From 1910–1950 there was slow initial growth as plastics were invented, tested, and marketed as novelty materials; 1950–2000 saw rapid exponential growth as plastic use expanded globally and spread to many new applications; and from 2000–2015 there was more linear growth in lockstep with economic growth (**Figure 1*a***). More generally, it is well known that consumption and associated waste generation tend to increase with increasing wealth and economic growth (21), but that there is evidence for an inflection point after which the two become decoupled (22). Thus, a future Phase 4 in **Figure 1*a*** might entail saturation of global markets and stabilization (or decline) in global plastic production.

Concerns about plastic release into the environment were at first nonexistent. The material was seen as benign, due to its inertness and perceived lack of toxicity. As a result, an estimated sum total of 5,000 Mt tons of plastic has been discarded into landfills and the environment since 1950 (110). This led to increasing concerns about pollution, particularly in the oceans, with some actions by governments to stem the growing tide of plastic debris. The International Convention for the Prevention of Pollution from Ships (MARPOL) was signed in 1973, although a complete ban on

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the disposal of plastics at sea was not enacted until the end of 1988 (23). At the same time, waste disposal practices and recycling capacities improved, particularly in highly industrialized countries, leading to better waste management and lower release of plastic waste into the environment.

2.3. Current Magnitude of Production and Release

Uniquely, and in contrast to other common materials, plastic use has now permeated all aspects of life, from clothing to food, buildings, appliances, communication, transportation, and medicine, to name a few. New applications are developed every year, and the substitution of other materials with plastic is still expanding in many sectors. The largest sector currently is single-use packaging, accounting for close to 40% of total plastic use in Europe (18), followed by consumer goods (22%); construction materials (20%); and automotive (9%), electrical (6%), and agriculture applications (3%) (see **Figure 1*b***). With an estimated cumulative production from 1950 to 2015 of 8,300 Mt (110) and current global production at 322 Mt in 2015 (18), annual production is approaching the combined weight of the human population (assuming 7.3 billion people and an average weight of 45 kg). This means that we are producing and using our own weight in plastic every year. Production in 2015 was centered in Asia (49% of global output), with China being the world's largest producer (28%), followed by Europe and North America, each contributing 19% (**Figure 2**). Other regions are of lesser importance as producers, but not necessarily as consumers, of plastic.

Although plastic is consumed globally, the magnitude of waste mismanagement and pollution varies markedly across regions (**Figure 2**). Most plastic now enters the ocean from land-based sources, often via rivers, wastewater outflows, and transport by wind or tides (2). The total release

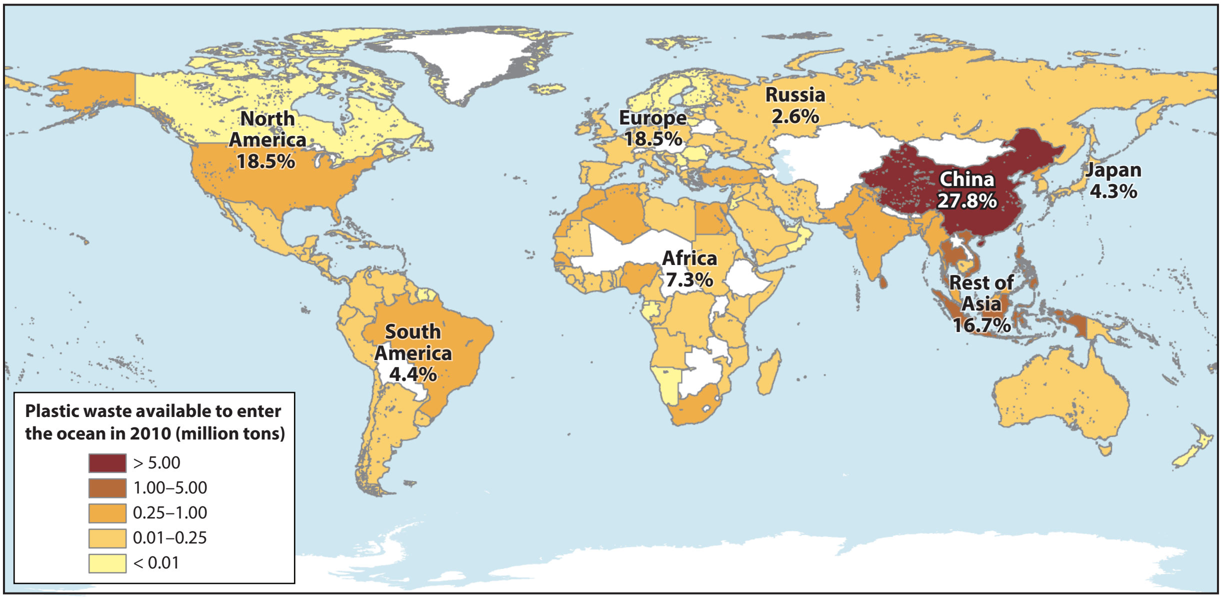

Figure 2

Spatial patterns of plastic production and pollution. Shown are the percentage contributions of different regions to global plastic production and the estimated mass of mismanaged plastic waste in million tons (Mt) generated in 2010 by populations living within 50 km of the coast. Figure redrawn after production data from Reference 18 and pollution data from Reference 2.

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of plastic waste into marine waters globally is estimated to range between 4.8–12.7 Mt in 2010 (2), roughly equal to dumping a garbage truck of plastic every minute (24). Variation between countries (**Figure 2**) is thought to be driven by differences in coastal population density, plastic consumption, and waste management practices. Between 2 and 90% of individual countries' waste gets mismanaged, meaning that it is not recycled or fully contained at a managed landfill site. Between 2 and 25% of that mismanaged waste is plastic (2). As an example, India and the United States have similar coastal populations, 188 and 113 million people, respectively. US citizens, however, produce much more waste per person per day (2.58 kg; 13% of which is plastic) than Indian citizens (0.34 kg; 3% plastic, which might be a conservative estimate given recent growth). In contrast, only 2% of that waste stream is mismanaged in the United States, whereas 88% is mismanaged in India. After combining these figures, India ranks higher (12th) than the United States (20th) in terms of total contribution to marine plastic pollution worldwide (2). China, Indonesia, and the Philippines are the top three polluting countries on that list, as they hold very large coastal populations, are rapidly increasing consumption of plastics, and tend to have poor waste management practices. Together these three countries account for an estimated 44% of total marine plastic pollution.

Certainly, current global trends reflect increasing population growth as well as rapidly growing plastic use and disposal. However, at the same time, we observe stabilization of plastic production and improving waste management and recycling practices in some jurisdictions. For example, European plastic production stagnated at ∼60 Mt year^{-1} between 2005 and 2015 (18). In 2006, ∼24.6 Mt of plastics were discarded in Europe, of which more than half (52%) went into landfills, 29% were incinerated (recovering energy), and 19% were recycled (recovering materials). Only eight years later, the total amount of plastic waste had not changed but less than one-third went to landfills (31%), due to rapid growth in recycling capacity (64% increase since 2006) and waste incineration for energy production (46% increase) (18). These changes were partly driven by plastic landfill bans introduced across nine European countries (Austria, Belgium, Denmark, Germany, Luxembourg, Netherlands, Norway, Sweden, Switzerland). These countries effectively legislated plastics out of landfills and now treat all plastic waste as a resource. Two more countries (Finland, Poland) followed this trend with landfill bans in 2016, whereas countries without such a ban still report a large proportion of plastic waste entering landfills (18).

2.4. Future Projections

Future projections of plastic production and pollution are inherently uncertain because many factors influence global use and discard patterns. However, it can be useful to simply project current trends as an illustration of possible scenarios given business as usual. For example, if current trends in production would continue, this would mean that by 2050 ∼33,000 Mt of plastic (resin plus additives) would have been produced over a 100-year history of widespread use (4), or 100 times the weight of the human population now. Assuming no changes to waste management infrastructure, the total amount of plastic waste available to enter the marine environment from land could increase by an order of magnitude even over the next decade (2015–2025) to a cumulative total of 150 Mt in the mid-range scenario (2). This is almost twice the weight of annual marine fish catches reported to the United Nations Food and Agriculture Organization (25). However, these scenarios seem less likely when considering observed decoupling of waste generation with economic growth (22), stagnation of plastic production and use in some regions such as Europe (18), improved waste management in some countries (21), and growing concerns around release into the environment and associated health risks (reviewed in more detail below). Without a

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doubt, changes in our cultural attitudes about plastics, as well as changes in production and waste management practices, will greatly influence future trajectories.

3. PLASTIC AS A PERSISTENT POLLUTANT

3.1. Types of Plastic and Their Ingredients

Different types of plastic differ in their chemical composition and environmental impacts. The most widely used plastics by far are polypropylene (PP) and polyethylene (PE), much of it used to make pliable films and materials for packaging, but also automotive parts, pipes, and houseware. Polyvinyl chloride (PVC) and polyurethane (PU) are often used in construction and automotive industries. Polyethylene terephthalate (PET) is used for textile fibers and drink bottles, and polystyrene (PS) for a range of uses, including packaging (Styrofoam™) and building insulation. Polycarbonate (PC) is used in hard, transparent products such as eyeglasses and clear roofing sheets. Together these made up >80% of plastic use in Europe in 2016, and a large fraction of global plastic production (18).

Most plastic polymers have inherently low toxicity due to their insolubility in water and because they are biochemically inert, owing to a large molecular weight. However, all plastics are made of monomer chemicals that are then combined into synthetic polymers. Many monomers, such as styrene or vinyl chloride, are toxic and carcinogenic, and monomer residues in plastic products can be hazardous (26). Four plastics (PVC, PU, PS, and PC) that make up ~30% of global production are seen as particularly problematic as they often contain hazardous monomers or additives (4). Such additives include fillers and plasticizers that modulate texture, or coloring agents, antimicrobials, flame retardants, and other substances that change material properties in desired ways (27). These substances can present health risks for humans and other species (28, 29) and limit reuse and recycling potential. A well-publicized example is Bisphenol A (BPA), which is widely used to produce PC plastic water bottles and other resins used in food containers, but has come under scrutiny due its estrogen-mimicking, hormone-like properties and accumulation in humans (29). Similarly, some common plasticizers (adipates and phthalates) have hormone-like properties and are frequently added to brittle plastics such as PVC to make them pliable enough for use in food packaging, toys, and many other daily-use items (29).

3.2. Size Classes: Micro- Versus Macroplastics

Apart from their chemical composition, plastics can be classified by size class, typically referring to their largest dimension. Different classification schemes have been proposed. Here, we broadly follow recommendations by da Costa et al. (30) and Eriksen et al. (31), distinguishing small nanoplastic (<1 μm in diameter) and microplastic particles (1 μm–5 mm) from larger mesoplastic (5–200 mm) and macroplastic items (>200 mm). Microplastics can be produced as such, for example as plastic pellets that are used as the raw material for fabricating larger items, or via mechanical breakdown of larger plastic items, for example when a plastic rope disintegrates into finer filaments (e.g., microfibers). Microplastics have also been released in large quantities as ingredients in cleaning and cosmetic products (e.g., microbeads in facewash and toothpaste), but their use in some personal care products is now being phased out in the United States, Canada, and some other jurisdictions. In recent years, small microplastics (<1mm in size) have become a growing concern, because of their large abundance in the air, water, sediments, and organisms (9, 15, 16), and their invisible nature and ability to be transferred through the food chain and infiltrate living tissues (see section 4.3. below). Very small nanoplastics (<1 μm) have only recently

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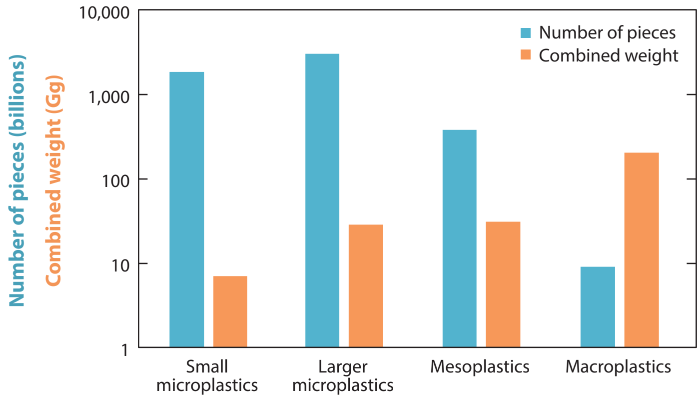

Figure 3

Estimated abundance and weight of plastic pieces in the oceans. Shown are four different size classes, as defined by the authors of Reference 31: small microplastics (0.33–1 mm), larger microplastics (1.01–4.75 mm), mesoplastics (4.76–20 mm), and macroplastics (>200 mm). Although microplastics represent 93% of individual pieces, they contribute only 13% to total weight (Gg = 10^9g). Figure adapted from data in Reference 31.

been studied (30, 32) and form during industrial processes such as 3D printing, and via physical breakdown of microplastics. They can have a variety of demonstrated cytotoxic effects in lab studies (30), but their abundance and in situ effects in the environment have not been well quantified.

3.3. Concentration in the Marine Environment

Plastics vary in their specific weight: Some items are lighter than seawater, whereas others sink to the bottom. Available information on the abundance of micro-, meso-, and macroplastics floating at the ocean surface has been synthesized in a global study that combined data from 24 expeditions (2007–2013), conducting a total of 680 net tows for micro- and mesoplastics, as well as 891 survey transects quantifying large macroplastic debris (31). The authors estimated a global abundance of at least 5.25 trillion pieces of plastic, or 720 items for every person alive today, most of these being microplastics (0.33–4.75 mm; see **Figure 3**). More recently, a follow-up study estimated between 15 and 51 trillion particles floating in the oceans in 2014 (33). In both studies, the global geographic distribution of plastic debris is uneven and concentrates around coastlines and in the open ocean gyres, where well-publicized "garbage patches" of high debris concentration form (10, 31). The total weight of floating plastic debris worldwide was estimated to be between 93,000 and 267,000 t (8, 31), with most of the weight being contributed by macroplastics (**Figure 3**). This number, however, is at least an order of magnitude lower than the estimated global release of plastics into the marine environment in 2010 (2).

The "missing plastic" that is not found at the surface potentially ends up in the deep sea and marine sediments, which may have become prominent sinks for microplastics debris. Concentrations in sediments (by volume) are four to five orders of magnitude higher than they are in the water column (**Table 1**). Concentrations also vary much more strongly among sediment samples (3–4 orders of magnitude) than in the water column (1–2 orders of magnitude), and are particularly high on urban beaches (34) and in deep-water sediments (16). Due to their large spatial extent and high plastic debris concentrations, the deep sea has been suggested to act as a global sink for microplastic pollution (16), although more sampling is needed to verify this. Remarkably, the same conclusion has recently been reached for POPs, such as polychlorinated biphenyls (PCBs) and

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Table 1 Concentration of microplastic particles in marine sediments and surface waters[a]

Habitat	Region	Pieces per 50 ml	Source (reference)
Concentration in sediments			
Beach	Canada	172–689	34
Subtidal	United Kingdom	6	6
Estuary	United Kingdom	4	6
Beach	United Kingdom	0.5	6
Beach	Chagos	4.5	94
Beach	Worldwide	0.4–6.2	95
Subtidal	United Kingdom	0.2–1	95
Deep sea	Worldwide	13.4	16
Median		4.25	n/a
Concentration in surface waters			
Coast	United States	0.0000675	96
Gyre	Pacific	0.0001115	97
Coast	California	0.0003625	98
Coast	Pacific	0.00000485	99
Sea	Mediterranean	0.0000058	100
Median		0.0000675	n/a

[a]Only studies that reported concentrations per sample volume (or weight with conversion factors) were included.

polybrominated diphenyl ethers (PBDEs; used as flame retardants), which have been detected in record concentrations in animals living in the deepest ocean trenches, more than 10,000 m below the surface (35). Downward transport of plastic particles might be accelerated by entrainment in naturally forming coagulates, called marine snow, that rapidly sink to the bottom (36).

Another documented sink for microplastic debris (and other pollutants) are marine organisms, which often show concentrations that are orders of magnitude higher than water samples and in a similar range as sediment samples in the same area; for example, individual wild mussels in Nova Scotia, Canada, had between 106 and 126 microplastic filaments lodged in their gills, whereas farmed mussels grown for human consumption had 178 fibers on average (34), possibly because they are grown on plastic ropes, which tend to shed microplastic fibers. But even the largest filter feeders, such as baleen whales and basking sharks, accumulate high concentrations of micro- and mesoplastics in their guts (37), as well as plasticizers and organochlorine POPs in their blubber (38). Similar to POPs, there is also evidence for trophic transfer between organisms and accumulation in predators that consume mussels, such as green crabs (17) (see also Section 4.4).

3.4. Persistence

Because of their very high molecular weight and lack of natural analogues, conventional plastics do not easily biodegrade in the marine or terrestrial environment, and may just disintegrate physically. Mechanical forces such as waves or the abrasive force of sediment grains act to break down plastics into smaller pieces, but this does not change the mass of plastic, just its size distribution. When plastics are exposed to UVB radiation in sunlight and oxygen, however, polymers can be oxidized, forming hydroperoxides that lead to polymer chain scission; this process can take decades to centuries in natural soils (39, 40). In the oceans, these processes can be even slower because mechanical and photolytic forces are greatly diminished, particularly in deeper waters, where negatively buoyant plastics may accumulate (5, 16). Additionally, plastic objects entering the oceans inevitably become fouled by bacteria, algae, other organisms and sediment, reducing surface area exposure to UV radiation and oxygen soon after introduction into the marine environment (41). As such, most plastic items that reach the marine environment may remain intact for centuries, and thus accumulate in the marine environment in similar ways as POPs do. A possible exception are some biodegradable polymers, such as polyhydroxyalkanoates (PHAs), which have been shown to biodegrade in various environments (42).

3.5. Microbial Biodegradation

As a carbon source, plastic materials could in principle be a resource for bacteria, algae, or fungi that manage to break down polymer chains. How common this is in nature and how much this process contributes to the remediation of plastic pollution is poorly known, especially in the ocean. Microbial communities on plastic debris develop in the process of biofilm formation (43), and enzymes secreted by some species of microbes can cleave polymer chains of the fragment creating erosion on the plastic's surface (44). Microorganismal degradation of synthetic plastics typically requires previous mechanical and photodegradation processes (45), and smaller fragments are broken down faster than larger ones (46). There have been several experiments documenting microbial degradation, focusing on more easily degradable polymers. For example, *Streptomyces* species increased decomposition of degradable polyethylene films when compared to uninocculated samples (47). Similarly, *Amycolatopsis* species, which are sparsely distributed in natural soils, effectively degrade polylactide (PLA) polymer samples (47). At present, however, PLA is compostable only in industrial facilities that reach high enough temperatures. Likewise, inoculation of some fungal species to soil containing plastic fragments enhanced both the degradation of plastic and accumulation of biomass in the soil (48). Even some macrofauna may possess the ability to break up and digest certain plastic materials. Caterpillars of the wax moth *Galleria mellonella* have recently been decsribed to rapidly biodegrade polyethylene films, which have a similar chemical structure as the caterpillars' natural food source, beeswax (49). Likewise, a novel bacterial species has been discovered recently at a plastic recycling plant; this species is able to use PET as its major energy and carbon source, but with unknown effects on PET degradation rates in soils or in the oceans (50). Thus, a growing body of knowledge surrounding microbial biodegradation and associated organisms and enzymes is setting the stage for production of plastic materials that are designed to biodegrade, or bioengineering of microbial enzymes that can help to clean up plastic waste (51).

4. EFFECTS OF PLASTIC POLLUTION ON MARINE LIFE

4.1. Ingestion and Entanglement

The most commonly documented impacts of plastic pollution stem from entanglement and ingestion of macroplastic debris (**Figure 4**, **Table 2**). The Secretariat of the Convention on Biological Diversity recently estimated the proportion of mammals, turtles, and bird species that ingest plastic (40, 100, and 46% of species in these three taxa, respectively) or become entangled in it (46, 100, and 26%, respectively) (52). Disturbingly, each successive review of the evidence identifies an increasing number of species affected by marine debris, rising to 693 in the most recent estimate (53).

Entanglement is known to affect at least 243 species to date, often with fatal consequences (53). In many cases, these effects come from derelict or discarded fishing gear, commonly referred

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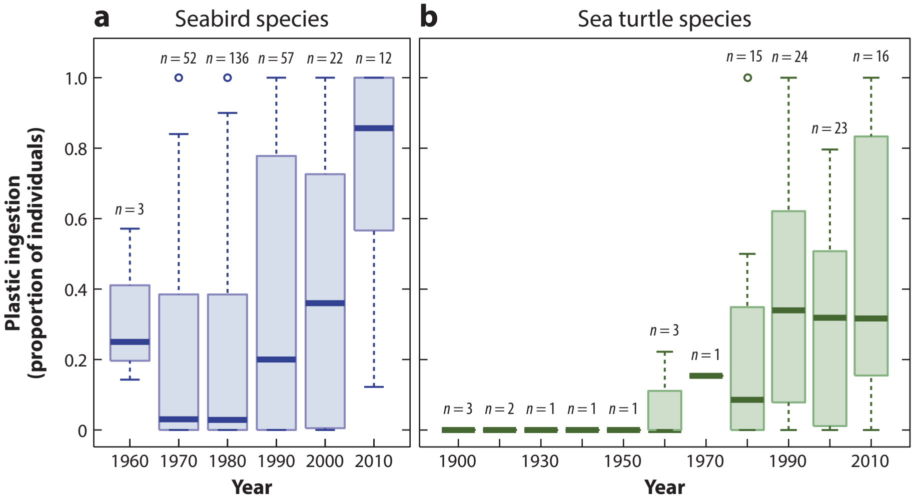

Figure 4

Increasing effects on wildlife over time. Shown are results from two comprehensive studies on time trends in plastic ingestion for (*a*) seabirds and (*b*) sea turtles. Data from Reference 8 and 56. Data in *a* and *b* represent the median proportion of individuals in a taxon with plastic in their digestive system. The median is calculated over all studies in a given decade. (Upper and lower estimates are quartiles, with bars extending to 1.5 times the interquartile range, n = number of unique species by study combinations).

to as "ghost gear." For example, the Arafura Sea, between Australia, Indonesia, and Papua New Guinea, harbors large amounts of derelict fishing gear, catching between 5,000 and 15,000 turtles across 8,500 nets examined (54). Similarly, estimates from the Puget Sound in the United States clearly demonstrate the destructive capacity of derelict fishing gear, with a single derelict fishing net expected to catch 2 invertebrates per day, 1 fish every 3 days, and 1 seabird every five days (55). Other types of plastic debris that also result in high entanglement rates include packing straps and balloon strings (53).

Plastic ingestion affects at least 208 species (53). Closely tracking the observed increase in plastic pollution and floating plastic debris (33), sharp increases in plastic ingestion have been documented in seabirds and marine turtles over time (**Figure 4**), with a rate of increase of 1.7% per year for seabirds (8) and 0.7% for turtles (8, 56). This appears in part due to marine species mistaking plastic for food, following visual or olfactory cues: Marine turtles, for example, appear to mistake flexible floating plastics, such as bags or sheeting, for jellyfish, causing gastrointestinal blockage, injury (57), and reproductive impediments (58). Some seabirds, such as albatrosses, have a highly evolved sense of smell and appear to be attracted to chemicals released by their planktonic prey, which are absorbed by floating plastics (59). Although lethal effects due to ingestion exist, they appear less common than those due to entanglement [4% versus 79% of reported cases (60)]. It is likely, however, that sublethal effects due to ingestion are more prominent than lethal effects (60). Given the prevalence and rate of increase in ingestion rates, it is likely that future empirical work will demonstrate population-level changes due to accumulated sublethal impacts (60).

4.2. Toxic Effects

Toxic substances in plastics include monomer residues, plasticizers, coloring agents, flame retardants, and others (26, 27). They can be released upon ingestion and may accumulate in fatty

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Table 2 Examples of documented mechanisms by which plastic pollution affects marine wildlife

Species	Plastic type	Mechanism	Study area	Source (reference)
Seabirds				
Greater shearwater	Plastic bottle cap	Starvation due to gastrointestinal obstruction	Massachusetts	101
Magellanic penguin	Fragments, line, and straws	Stomach perforation	Lagos, Rio de Janeiro, Brazil	102
Sea turtles				
Green sea turtle	Plastic bags and other debris	Impediment of hatchling movement toward the sea, exposure to predators	Samandag Coast, Turkey	103
Green sea turtle	Balloons, plastic and nylon string	Gastrointestinal distress and starvation	Melbourne Beach, Florida	104
Leatherback turtle	Plastic bags and debris	Blocked and injured cloaca impedes laying of eggs	French Guiana	58
Fish				
Bigeye tuna	Fragments and line	Ingestion of plastic fragments	Central North Pacific	105
Japanese medaka	Particulate plastic	Hepatic stress from exposure to plastic pollutants	Experimental procedure	61
Orchid dottyback	Plastic bags	Leached nonophenol additive-caused mortality	Experimental procedure	62
Larval perch	Microplastic particles	Inhibited hatching, decreased growth rate, and altered behavior	Experimental procedure	14
Mammals				
Fur seal	Plastic particles	Bioaccumulation of particulate plastic from prey fish	Macquarie Island, Southwest Pacific	77
Sperm whale	Plastic bags and debris	Stomach rupture and starvation	California	106
Australia sea lion	Plastic fishing gear	Entanglement-caused mortality	Kangaroo Island, South Australia	107
Invertebrates				
Urchin larva	Polyethylene pellets	Plastic leachates caused abnormal development	Experimental procedure	66
Mussel	Microplastic particles	Accumulation of microplastics in circulatory system	Experimental procedure	72
Oyster	Microplastic particles	Interference with energy uptake and reproduction	Experimental procedure	13
Norway lobster	Strands and particles	Ingestion and accumulation of plastics in the gut	Clyde Sea, Scotland	108

tissues, much like POPs do. Toxic effects on marine wildlife are less commonly demonstrated than entanglement and ingestion (53), in part because they are more difficult to demonstrate and usually require experimentation. Experimental studies demonstrate toxicological impacts of leachates from these materials (**Table 2**), due to the presence of the leachate in ambient water and via ingestion of the plastic (61). For instance, coral reef fish exposed to water that had previously

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been exposed to food-grade polypropylene bags had elevated levels of nonylphenol, and suffered increases in both short- and long-term mortality (62). Similar results on toxicity and interference with chemical cues for predator avoidance were demonstrated for European perch larvae (14).

In addition, many plastics have the capacity to adsorb both organic and metal pollutants (including most known POPs) from the environment and concentrate these up to 1 million-fold relative to concentrations found in seawater (63). Although there is clear evidence for transfer of a variety of pollutants adsorbed by plastics to organisms, the process is complex and context-dependent (64). For example, in the warm guts of endotherms, such as birds or humans, associated environmental pollutants are released at rates up to 30 times greater than in cold-blooded organisms or the surrounding seawater (65). In other cases, the constituents of the plastic itself are more harmful. For instance, freshly produced polyethylene pellets were more toxic to sea urchin than pellets previously exposed to marine pollutants in an experimental study in Brazilian waters (66).

A wide variety of marine debris items have recently been tested for toxicological effects in experimental settings, including cigarette filters (67); various polymers and their leachates (68); PS particles (69), PE pellets (66), PE and PS particles with adsorbed polyaromatic pollutants (pyrene) (70); and PP fibers (71). These studies cover a wide range of species, including polychaetes, mussels, crabs, fish, and seabirds, with negative effects including reduced feeding and reproductive success, reduced survival, cellular-level toxicity, changes in immune function, changes in enzyme function, and gene expression. Experimental studies with concentrations of plastic as low as 1% of the diet demonstrated significant negative effects (71). A recent review summarized both a wide range of possible direct toxic effects from plastics and enhanced transfer of environmental pollutants via adsorption and transfer to organisms (64).

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4.3. Effects of Micro- and Nanoplastics

Small plastic fragments may act differently from larger items due to their increased surface area, their capacity to be transferred across tissue or cellular boundaries, or their interactions with other chemicals in the environment. Recent reviews of experimental evidence for the impacts of plastic across a range of sizes and levels of biological organization found a complex array of effects for micro- and nano-sized plastic fragments (5, 15, 30) seen both in invertebrates (13) and vertebrates (14). For example, in oysters (**Figure 5**), it was found that experimental exposure to nano- and microplastics interferes with feeding and reproduction, with negative impacts on fecundity and offspring quality, both of which are key components of an organism's fitness (13, 32). Similarly, when exposed to PS microplastics at concentrations that occur in coastal environments in the Baltic Sea, fertilized perch eggs have reduced hatching success, and larvae from those waters show a host of negative effects, from delayed development to increased mortality and compromised predator avoidance behaviors (14).

In both cases cited above, the impacts result from a mix of leaching of chemicals from the plastics and physical impacts on digestion. The large surface-to-volume ratio of the small fragments may exaggerate this, and small size may facilitate ingestion by filter feeders, but there was no evidence that particles crossed cellular or tissue boundaries (but see 72 for an example where such transgression occurred). In vitro experiments are demonstrating effects of nanoparticles in realistic contexts such as mussel haemolymph, which point to potential mechanisms that may eventually be born out in future in vivo studies (see, e.g., 73). Synergistic effects of microplastics on other toxins are also possible, although the evidence is mixed so far (74). However, some established examples exist such as enhancement of chromium toxicity in the presence of microplastics in fish (75).

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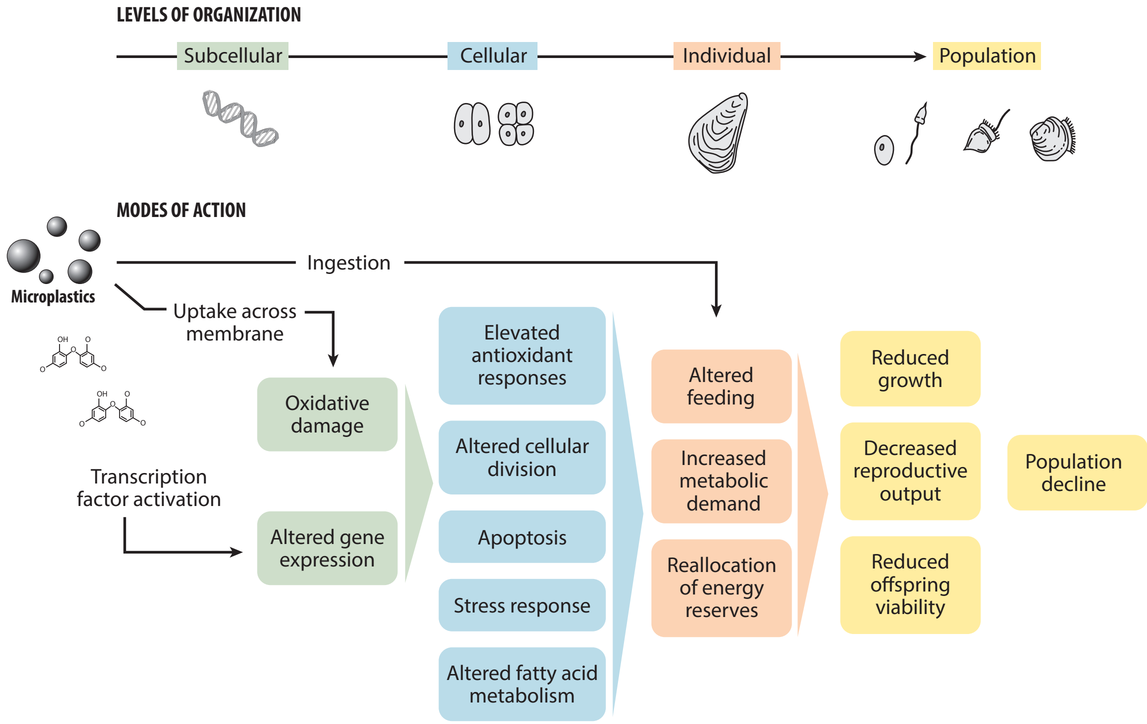

Figure 5

Tentative outcome pathways of microplastic pollution at different levels of organization. Microplastic pollutants can enter organisms through either ingestion or membrane uptake and affect energy allocation, growth, and reproduction via several pathways, likely influencing every level of organization from subcellular to population. Figure adapted from Reference 15.

4.4. Trophic Transfer and Bioaccumulation

There is increasing evidence for the trophic transfer and potential for bioaccumulation of plastic and associated chemical pollutants through the food web (**Figure 6**). A well-studied example concerns benthic filter feeders, such as mussels that accumulate plastic microfibers and other particles from the water column, transferring them to benthic predators (17) and human consumers of farmed or wild shellfish (34). Abundant microplastic particles have also been observed in the gastrointestinal tracts of larger pinnipeds and cetaceans, suggesting trophic transfer from prey fish to top predators (76, 77). Some key questions remain, including the ecological relevance of these transfers in the context of other sources of toxins (64). Laboratory studies have demonstrated transfer of toxins, such as the flame retardant PBDE, from plastics to organisms including crickets, amphipods, lungworms, and fish (64). However, plastics have also been found to work in the opposite direction in laboratory studies, reducing body loads or transfers from the environment. A key variable is the relative load of pollutants across the environment, the plastic in question, and the receiving organism, with transfers in differing directions depending on the situation. Correlative evidence from fish (64), seabirds (78), and mussels (79) does support the potential of plastics to cause bioaccumulation of environmental pollutants. However, it is still an open question how the increasing plastic burden of fish and shellfish will affect seafood consumers and human health. The ubiquity of plastic marine debris in seafood (80) and the toxicity of chemicals associated with the material have begun to raise concerns, and the weight of evidence suggests that

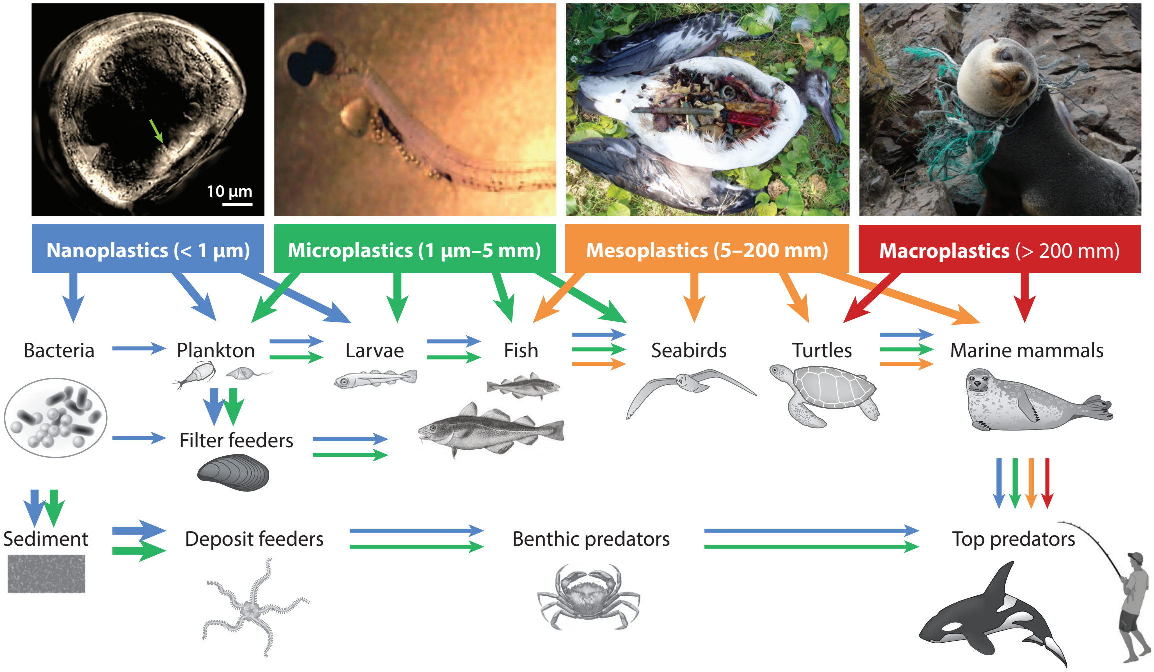

Figure 6

Uptake and possible trophic transfer of plastic pollution in marine food webs. Plastic debris of different size classes has been shown to affect species directly by ingestion or entanglement (*thick arrows*) or indirectly via uptake with food sources (*thin arrows*). Fauna of different sizes and trophic positions will be exposed to particles of different sizes (*blue* to *red*) with some degree of bioaccumulation expected, for both particles themselves (17) and associated chemical pollutants (61, 78). Photographs depict (*left* to *right*) nanoplastic particles taken up by oyster larvae (32), microplastic beads ingested by European perch (14), dead albatross chick with micro- and mesoplastic debris in the stomach (courtesy of Claire Fackler, Marine Photobank), sea lion entangled in macroplastic fishing gear (107).

chemicals can transfer from plastic to animal. Further research is necessary to evaluate to which degree plastic debris can transport chemical contaminants to humans via seafood consumption, and what the long-term effects of such exposure are.

5. SOLUTIONS

As with other global environmental challenges, such as climate change or overfishing, there is no "silver bullet" that could solve the plastic pollution problem by itself. Instead, a wide range of interlocking solutions are available that, taken together, could turn the tide of plastic pollution around, minimizing long-term harm (**Table 3**). This, however, will require a concerted effort that builds on the engagement of all levels of society, from governments and plastic producers to industry users and individual consumers, waste management organizations, as well as scientists (**Figure 7**). In the following, we describe solutions that encompass all these sector engagements from "upstream" to "downstream" with a goal of zero plastic waste input into the ocean (**Figure 8**). Obviously, this goal is achievable only if there is some form of global cooperation, as recently called for by the United Nations Clean Seas Campaign (24). This campaign urges governments to implement plastic reduction policies (such as bans on microbeads or single-use shopping bags already present in some countries), encourages industry to minimize plastic packaging and redesign products, and calls on citizens to change consumptive habits with regard to disposable plastic items.

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Table 3 Suggested policy objectives for a comprehensive Global Convention on Plastic Pollution (see also Figure 8)

Value chain step	Policy objective
1. Plastic production	Reduce demand and volume of production Require transparency in use of additives and substances of concern to facilitate recycling and ensure safe chemical management
2. Plastic material and product design	Support new material development through green engineering and the creation of a marketplace for new materials and appropriate incentives Prohibit excessive packaging to reduce packaging waste and provide a level playing field for marketing via packaging
3. Waste generation	Provide incentives and support for the shift toward a fully circular economy Ban certain plastic products or applications such as plastic grocery bags, single-use plastic utensils, and microbeads in personal care products Educate public about environmental and health risks of particular products and incentivize alternatives Encourage a reuse and sharing economy
4. Waste management	Require producers and consumers to contribute to the cost of recycling or waste management for plastic products Create assistance programs that enable technical experts to support countries in need of waste management system expertise Create a thriving marketplace for recycled content through recycled content requirements for certain materials, government procurement policies, or other standard-setting policies Use landfill bans where appropriate to promote composting and recycling, and to direct hazardous items toward better end-of-life options
5. Litter capture	Use technology and mechanical interventions to capture litter in streams and rivers before it gets to the ocean Promote citizen-based or industry-driven cleanup programs
6. Ocean	Near-elimination of plastic waste inputs into global marine environment

Commitments have already come from Indonesia to reduce marine litter by 70% by 2025; in terms of single-use plastic, Uruguay proposes to tax plastic bags in 2017, Ghana is set to outlaw thin-film plastics, and Costa Rica is planning to dramatically reduce single-use plastic through better waste management and education (24). We suggest these and additional policy objectives as part of a comprehensive Global Convention on Plastic Pollution (**Table 3**).

5.1. Public Policy

Currently, plastics are legally classified together with other solid waste and are not treated as a pollutant when mismanaged. One way that globally comprehensive regulation can occur is through a reclassification of the material based on evidence of its impacts on the environment and humans (4). This could be considered in the development of a new global convention to track and manage problematic plastic materials. As we argue, plastics in the marine environment exhibit some characteristics of persistent organic pollutants (organic man-made substances that persist, accumulate, and harm wildlife and people), although the specifics of the Stockholm Convention would not apply to most plastic materials. However, classifications can provide an instrument to remove harmful substances from the environment, regulate their production, and prevent further waste accumulation. For example, Rochman et al. (4) suggested classifying some plastics as hazardous substances, recognizing evident harm to wildlife and human health, toxicity, and persistence in the environment. Another possibility is classification as a priority pollutant, as defined under the US Clean Water Act. Priority pollutants are taken into account when developing

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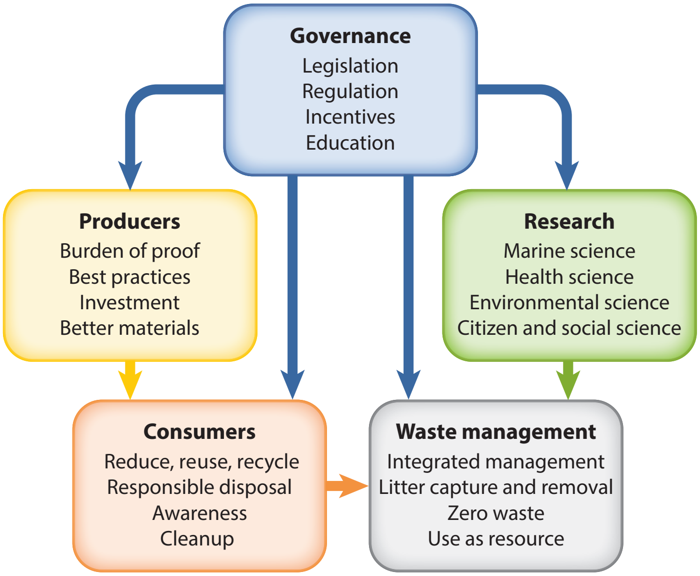

Figure 7

Solving the plastic crisis by cooperation between all sectors of society.

water quality standards and effluent limitations, especially for wastewater discharges, and consistent testing protocols and discharge limits must be developed.

A Global Convention on Plastic Pollution could also require producers to declare the ingredients of plastic products and warn consumers about their potentially harmful effects. There are successful precedents with the reclassification of chlorofluorocarbons (CFCs) as hazardous in 1989 (Montreal Protocol) and POPs in 2004 (Stockholm Convention), respectively (4). Almost 200 countries stopped the production of 30 dangerous chemical groups and, in the case of CFCs, ceased all production within 7 years. A reclassification through a Global Convention on Plastic Pollution could also stimulate new research into less harmful alternatives, improve waste management practices, and prevent further buildup of plastic waste in the environment.

Another avenue available to governments is the implementation and enforcement of regulations to control major vectors and pathways in the production, use, consumption, and disposal of plastics, regardless of whether they are considered hazardous. The goal would be to follow the three Rs—Reduce, Reuse, and Recycle—in all sectors and, ultimately, to create a cyclical, closed-loop use of resources with zero diversion to landfills or the environment (5, 9). This could be supported

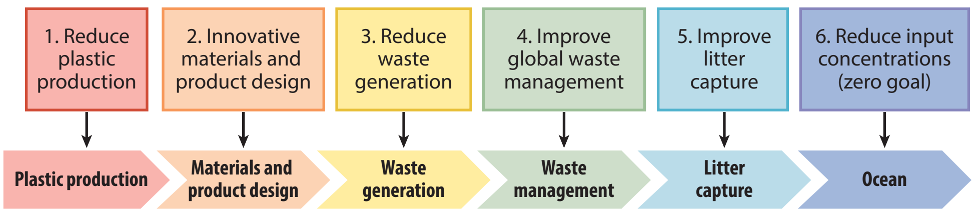

Figure 8

Elements of a comprehensive strategy to reduce plastic pollution to near zero. See **Table 3** for specific public policy objectives related to each step.

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with government incentives, such as extended producer responsibility (EPR) or tax breaks or subsidies for recycling projects. Another avenue, implemented in parts of Australia, is to institute a levee for recyclable plastics that are disposed to landfills or energy conversion, with the goal of diverting >80% to recycling. A further important role for governments is to fund basic and applied research to quantify the current plastic problem and the risks to human health and the environment. When these effects become well documented, regulatory action can be implemented swiftly, as in the recent national bans on plastic microbeads in cleaning and cosmetic products. Finally, both governmental and nongovernmental organizations should engage in education and raising awareness about the potentially harmful effects of plastics on human health, wildlife, and the environment as well as the promotion of alternative choices and products. This will enable all sectors of society to prioritize the issue and contribute their part, such as following the three Rs (**Figure 7**).

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5.2. Production and New Materials

The plastic-producing industry needs to take greater responsibility when it comes to material research, engineering, and manufacturing of plastic products. First, the burden of proof in terms of health or other harmful effects on people, wildlife, or the environment needs to fall on the producers. This should include the finished product as well as its ingredients and waste products. Second, the entire production process needs to follow best practices, including the reduction of harmful substances and waste; the prevention of plastic pellet loss; the take back, reuse, and recycling of former plastic products; and transparency about ingredients and production processes (9). Finally, producers need to invest in the development of safer and more sustainable materials. Alternative products that are less harmful and less persistent are one direction, such as degradable natural products or biodegradable plastics (81). Material development and product design can include Green Engineering principles (82); they would help to avoid many of the externalities of plastics that are currently occurring. In addition, circular economy concepts are emerging all over the world and are being applied to plastic materials, especially packaging (81, 83). Both of these guiding principles promote nontoxic materials, ultimately with the capability of biodegrading and being recycled. Materials and products made with more homogenous compounds would also make recycling more efficient and effective. Materials and products can be designed to retain their value, for collection, recovery, and recycling.

Another direction is to enhance the use phase and lifetime of plastic products including repair options, reduction of single-use plastics, easier reuse and recycling options, as well as energy recovery (9, 18). And lastly, producers can take more responsibility for product stewardship contributing to the end-of-life management of materials and products that they distribute in a particular country. Realizing the marine litter problem, 69 plastic associations in 35 countries have signed on to the Declaration of the Global Plastics Associations for Solutions on Marine Litter since 2011 (**http://www.marinelittersolutions.com/**). These efforts should be expanded to also deal with plastics at end-of-life and as harmful and persistent pollutants.

5.3. Use and Consumption

There are many different users and consumers of plastic products, from food packaging to fishing industries, medical supply to communication companies, and communal institutions to individual consumers. Independent of the scale of operation, all users and consumers need to promote and follow the three Rs as one key contribution to reducing plastic waste generation and its input into the marine environment (5, 9), for example, by reducing the use of single-use plastics and their replacement with alternative products that are reusable, recyclable, or second-hand. A key measure to ensure recycling are container deposits, which are widely used for beverage containers, and are an effective incentive to avoid diversion to landfills. For non-recyclables, the key contribution is responsible waste disposal, whether in an industrial or personal context. For example, ghost fishing gear that has been lost or discarded at sea contributes ~10% of all marine litter, or 640,000 t (84). Responsible waste handling as well as biodegradable fishing gear could greatly reduce the harm to marine wildlife. By number of items, cigarettes, caps/lids, and plastic bottles associated with recreational activities were among the top three items collected during the 2012 International Coastal Cleanup, the world's largest volunteer effort to collect data on marine litter (85). Thus, a third key contribution of all users and consumers is increased awareness about the issue of plastic pollution and the willingness to help solve it through responsible disposal, and by participation in beach or roadside cleanups as well as boycotts of particularly problematic products such as BPA-containing water bottles or microbeads in cosmetics and cleaning products.

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5.4. Waste Management

Proper waste collection, disposal and treatment are key issues in many regions around the world that must be improved to reduce plastic litter and pollution in the ocean (2). Ideally, all countries would implement integrated waste management systems that combine waste reduction methods (e.g., reuse, recycle, compost) with proper waste collection, disposal and treatment methods that reduce harm to the environment. In addition, there is the need to investigate removal methods for macroscopic plastic litter in different parts of the marine environment, particularly for lost fishing gear and other materials that frequently cause entanglement and death of marine fauna. In the end, the goal should be zero waste (**Figure 8**), as promoted for example by the Zero Waste International Alliance (**http://zwia.org/**) and the New Plastics Economy (81). Herein, the reduction of waste and conservation of materials should have the highest priority, followed by cyclical use of resources and eventual elimination of the concept of waste. A major part of this is to shift the paradigm of plastic as a waste, to plastic as a valuable resource in a circular economy. However, this would require durable and nontoxic products that are specifically made for reuse and recycling. In some cases, plastic could potentially be used for energy recovery although life-cycle benefits and burdens are inconsistent and depend on local contexts (86). In addition, in a social cost analysis and comparison of energy recovery from waste in the United States, United Kingdom, Germany, and Sweden, it is clear that local context and social acceptance need to be considered when considering energy production from waste products (87). Several European countries have already implemented landfill bans, resulting in greatly enhanced recycling and energy recovery rates (18).

5.5. Research

The study of plastic pollution is inherently interdisciplinary. Although the impacts of plastic on animals were first discovered by biologists (88), the field has expanded to include a wide variety of disciplines including, but not limited to, marine science, ecology, human health, environmental science and engineering, economics, policy, and social and citizen science (**Figure 7**).

We still do not have sufficient understanding of the sources and sinks of plastic entering the ocean. Although estimates from the land are mostly complete for meso- and macroplastic debris (2; also note 110), maritime sources have not been entirely quantified, and micro- or nanoplastic pathways are not well understood at all. At this point, we find plastic everywhere we look—floating on the ocean surface, in sediments, on the ocean floor and in the deep sea, in the water column, in polar ice, and on coastlines. More research is needed to address the issue of "where is the missing plastic?" Fate and transport are also not well understood, especially the physical and biological processes and the timescales of plastic fragmentation. This information will help with better risk assessments for marine species, ecosystems, and people (89).

For the human dimension of plastic pollution, it is recommended that strategies for reducing marine litter should be guided by both social and natural sciences (90). Social science has tools for evaluating human perception, communication, and intervention, and these can be used to examine consumer choice and waste management behavior, measure risk perceptions, optimize engagement, and evaluate decision making (90). The engagement of citizens has a high priority in this regard; after all, we all collectively cause the marine litter problem through our consumptive habits.

A very positive development in this regard is the growth of citizen science, with millions of people involved in coastal cleanup and data collection schemes. Citizen science programs have been developed for shoreline monitoring, microplastic sampling (net tows and water sampling), and microbiological sampling (91). Technology has facilitated data collection at a speed and accuracy that was not previously available with mobile apps (92). Marine Debris Tracker, sponsored by the NOAA Marine Debris Program, is the oldest of the litter-data collecting apps with more than 1 million items collected and logged into the database since its release in 2011. Apps allow for near-real-time data collection and for immediate feedback to users, as well as access to their data in graphical, mapped, or spreadsheet format (92).

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6. CONCLUSIONS AND OUTLOOK

6.1. Major Findings and Knowledge Gaps

Recent research on the scope of global plastic production (**Figure 1**) and pollution (**Table 1**, **Figure 2**) has clearly identified that this is a first-order environmental issue, especially in the ocean. Plastic debris of all size classes is rapidly accumulating at a rate of 4.8–12.7 Mt per year (2) without any practicable options for large-scale removal, but with clear global hotspots of release (**Figure 2**). Microplastics are contributing the vast majority of particles by number, but not by weight (**Figure 3**). Biological effects on wildlife and potentially humans are complex, but detailed mechanisms and patterns are being described (**Table 2**, **Figures 4–5**). The effects of entanglement and ingestion of plastic debris are much more documented than toxic effects and affect a minimum of 693 documented species. Major knowledge gaps exist around the pathways that plastic debris and associated pollutants (additives are other pollutants that are adsorbed by plastic particles) take from surface waters to deep water habitats and sediments, as well as around how these pollutants move through food webs, including into human seafood consumption (**Figure 6**). Both the abundance and biological effects of submicrometer nanoplastics in the marine environment are practically unknown and represent an important research frontier.

6.2. Another Silent Spring?

The metaphor of a "silent spring" without birdsong became a powerful illustration of the possible long-term effects of POPs like dichlorodiphenyltrichloroethane (DDT) and PCBs in the 1950s and 1960s, when these substances were in widespread use (12). Half a century later, the release of most POPs into the environment has been dramatically reduced, or even eliminated. Plastics, however, may cause harm at a similar scale, although most of their well-documented effects so far are physical, nontoxic, and play out in the oceans, where most people do not witness their effects. However, the scope of having 90% of surveyed seabirds affected by plastic ingestion, with increasing trends (**Figure 4*a***), moves a silent spring analogy into the realm of possibility (93). Here we have attempted to highlight analogies between the problems that emerged around POPs 50 years ago, and the unfolding plastic pollution crisis today. We believe that we can learn from the experience with POPs, but need to tackle plastic pollution differently as it presents a unique problem in our society, and the environment.

6.3. Solving the Plastic Problem

Specifically, the plastic problem will not likely be solved by simply banning the production of all problematic substances. Although this is an option for certain applications (e.g. microbeads in personal care products or BPA in baby products), plastics will remain an important material in humanity's future. However, much can and will be done to eliminate plastic pollution as much as possible (24), with many encouraging initiatives in recent years. Attention to this issue from the public, scientists, and policymakers is at an all-time high and progressive policies are beginning to emerge. Sources and sinks of plastic pollution are starting to become more clear, and consumers are sensitized to the hazards associated with disposal of plastics in the environment. What is lacking is coordination across sectors, stakeholder groups, and nations to tackle this problem in a concerted and systematic fashion (**Table 3**, **Figures 7–8**). Here we suggested that a Global Convention on Plastic Pollution might achieve what the Stockholm Convention achieved for POPs, albeit undoubtedly with a broader suite of measures and tools. But the end goal of near-zero plastic inputs into the ocean appears achievable, and should become a unifying focus for environmental policy at the global scale.

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DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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4. Makes a comprehensive case for reclassifying plastics as hazardous pollutants, rather than debris.

8. A global meta-analysis that shows rapidly increasing incidence of plastic ingestion in seabirds.

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