In This Issue:

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Focus articles are part of a regular series intended to sharpen understanding of current and emerging topics of interest to the scientific community.

Plastic Debris and Policy: Using Current Scientific Understanding to Invoke Positive Change

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Abstract—*Captain Charles Moore introduced the world to the "Great Pacific Garbage Patch" in the mid-1990s, and images of plastic debris in the oceans began to sweep the media. Since then, there has been increasing interest from scientists, the public, and policy makers regarding plastic debris in the environment. Today, there remains no doubt that plastic debris contaminates aquatic (marine and freshwater) habitats and animals globally. The growing scientific evidence demonstrates widespread contamination from plastic debris, and researchers are beginning to understand the sources, fate, and effects of the material. As new scientific understanding breeds new questions, scientists are working to fill data gaps regarding the fate and effects of plastic debris and the mechanisms that drive these processes. In parallel, policy makers are working to mitigate this contamination. The authors focus on what is known about plastic debris that is relevant to policy by reviewing some of the weight of evidence regarding contamination, fate, and effects of the material. Moreover, they highlight some examples of how science has already been used to inform policy change and mitigation and discuss opportunities for future linkages between science and policy to continue the relationship and contribute to effective solutions for plastic debris. Environ Toxicol Chem 2016;35:1617–1626.* © *2016 SETAC*

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Plastic Debris: A Global Waste-Management Issue Calling for Solutions

Captain Charles Moore is credited with discovering an accumulation of plastic debris floating in the middle of the Pacific Ocean in the mid-1990s and introducing this newfound issue to the world as the "North Pacific Garbage Patch" [1]. Since his discovery, Captain Moore's work likely served to intensify existing concern about the issue of plastics contamination and increased interest from the public, the scientific community, and policy makers. Increased public interest is evidenced by the increase in beach cleanups, environmental activist groups, and media attention regarding plastic debris. Increased scientific interest is evidenced by the large increase in scientific literature on the topic since the turn of the century [2,3]. For example, new literature now reports "garbage patches" in every major open ocean [4] and the presence of our plastic waste of all sizes in almost every major nook and cranny of marine and freshwater environments [4–8]. Increased interest from policy makers is evidenced by the formation of focus groups, which have sprung up in many agencies. For example, programs and working groups that focus on plastic debris have been created at the National Oceanic and Atmospheric Administration (NOAA) and the US Environmental Protection Agency (USEPA) in the United States, the Ministry of the Environment in Canada, The European Commission, the

Northwest Pacific Action Plan in Asia, the Department of Environmental Affairs in South Africa, and globally at the United Nations Environment Programme (UNEP). Several of these groups aim to bring together the existing information to assemble a formal risk assessment, a common part of technology assessment [9,10]. Here, the material plastic is like the technology for which risk assessments that measure the risk of plastic littered in the environment is desired.

Several from each of these communities have expressed concern about plastic debris as an emerging contaminant globally [11,12], a threat to the conservation of biodiversity [13], and a potential danger for human health [11,14]. Although there is little disagreement about the pervasiveness of plastic contamination in the environment and the adverse interactions with wildlife, there remains much to understand about the mechanisms that drive the sources, fate, and impacts of plastic debris and the extent to which it impacts ecosystems and humans. This is especially true for the smaller size range, often referred to as microplastic (defined as particles that are less than 5 mm or 1 mm in size) and nanoplastic (defined as particles that are less than 1 μm or 100 nm in size).

The goal for the special section, *Plastic Debris in the Aquatic Environment*, was to bring together and highlight new scientific understanding regarding the mechanisms that drive the sources, distribution, fate, and impact of microplastics and nanoplastics. Although some consider mechanistic questions to be more basic than applied, they are necessary to guide policy decisions and assessments, such as those needed to determine risk [15]. Therefore, in this special section, we wanted to highlight some of the existing policy-relevant scientific understanding about plastic debris that can be used by interested parties now to invoke positive change at the same time as scientists continue to fill the gaps in our understanding. In general, this special section highlights new science regarding microplastic and nanoplastic debris. In the present *Focus* article, we emphasize some of what we already know about plastic debris of all sizes (mitigating larger debris ultimately mitigates microplastic and nanoplastic debris) and discuss how science and policy have been and can continue to intersect to mitigate the problem using the current and future body of scientific evidence (see Figure 1 for a flowchart demonstrating a sequence of steps by which scientists and policy makers can intersect).

What We Know About Plastic Debris and How It Can Inform Positive Change

The goal for this special section was to bring together articles that provide a better understanding about some of the mechanisms regarding the sources of microplastic and nanoplastic to the environment, their transport and fate when they become environmental debris, and any impacts they inflict on the environment, wildlife, or people. The desire to understand these mechanisms comes from the large existing body of knowledge regarding plastic debris of all sizes. We review some of that knowledge in regard to the extent of the contamination, the sources and fate of plastic debris, and any impact. To keep the review brief, we highlight only a few studies to provide examples of the information that we think can be applied to guide management strategies and policy changes that may help mitigate plastic pollution.

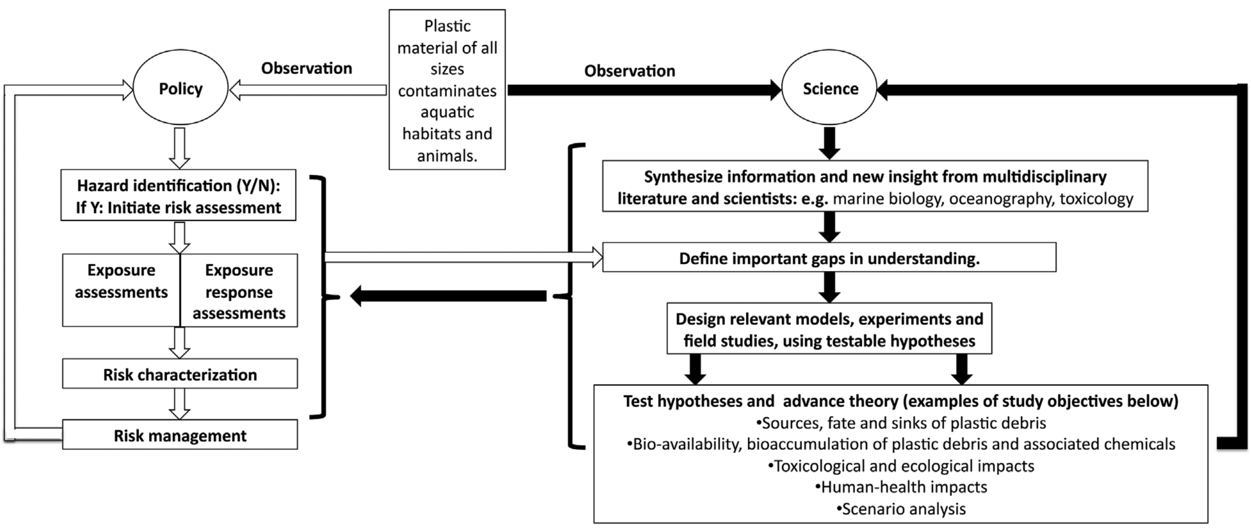


FIGURE 1: The intersection between science and policy depicted as a flowchart demonstrating a sequence of steps that follow the scientific method (black) and the policy process for risk assessment (white). Arrows represent the iterative processes and how they can inform each other. The box in the middle is what scientists refer to as an "observation" in the scientific method and what a policy maker may refer to as a potential hazard in the risk assessment process. The scientific evidence can inform the risk-assessment process, and the risk-assessment process can in turn inform new questions asked by scientists. Collectively, Figure 1 provides an example of how policy makers and scientists can work together to inform positive change. The nonbold text provides examples that should be modified based on the specific topic of interest. The process should be seen as an iterative and adaptive cycle where new observations will inform new hypotheses, objectives, risk assessment, and/or mitigation.

Evidence regarding widespread contamination of plastic debris

As a consequence of increasing plastic production [16] and inefficient waste-management strategies [17], plastic debris contaminates many aquatic habitats and animals (Figure 2). In marine habitats, global plastic contamination has been reported in the pelagic area [4,18], in the deep sea [6], and stranded on coastlines [2]. Researchers have found plastic debris in a wide range of habitats, including estuaries [19], sandy beaches [2], seagrass beds [20], coral reefs [21], sea mounts [22], and even sea ice [23]. More recently, scientists have begun quantifying plastic debris in freshwater, and plastic debris has now been reported on the beaches [24,25] and surfaces of lakes [5] and in the surface waters [26] and sediments [27] of rivers.

One consequence of having a great diversity of contaminated habitats is that a great diversity of wildlife encounter and become contaminated with plastic debris [28,29]. Aquatic animals interact with plastic debris via a number of mechanisms, including entanglement, ingestion, smothering, and hitchhiking [30]. Gall and Thompson [28] found that encounters with marine debris have been reported worldwide in more than 700 species and note that plastic constituted 92% of the type of marine debris encountered. Of concern for policy makers is that contamination is found in species of particular concern by the International Union for Conservation of Nature, including the endangered Hawaiian monk seal and loggerhead sea turtle, the vulnerable northern fur seal, and the near threatened sooty shearwater [28]. Moreover, there has been an increase in the number of species reportedly affected since the 1990s [28,29]. Reported contamination increased from 86% to 100% of all species of sea turtles, from 43% to 66% of all species of marine mammals, and from 44% to 50% of all species of seabirds [29].

Combined, it is clear that data sets regarding the amount and spatial distribution of plastic debris in the environment are abundant and increasing. The large amount of data showing widespread plastic debris in our oceans has already prompted policy makers to act (Table 1). Although the data sets comprise mostly the larger pieces of plastic debris (>333 μm, a consequence of common methodology using surface manta net trawls with this mesh size) and suffer from a lack of standardized methods and metrics for quantifying the material, managers can still pull out a diversity of information to better understand trends related to types of debris in the environment, species and populations most exposed to the contamination, and locations where debris is most abundant (sometimes referred to as "hot spots"). These data also enable managers to predict changes in environmental contamination and measure trends over time. For example, if we continue business as usual, environmental contamination of plastic debris is predicted to increase by as much as an order of magnitude by 2025 [17], and trends over the last 2 decades show that contamination in the form of ingestion and entanglement by plastic debris in wildlife has increased by 49% [28]. Such information can help advise many policy decisions, including determining locations where mitigation may be most critical and deciding what legislation regarding product bans or waste management may be most effective.

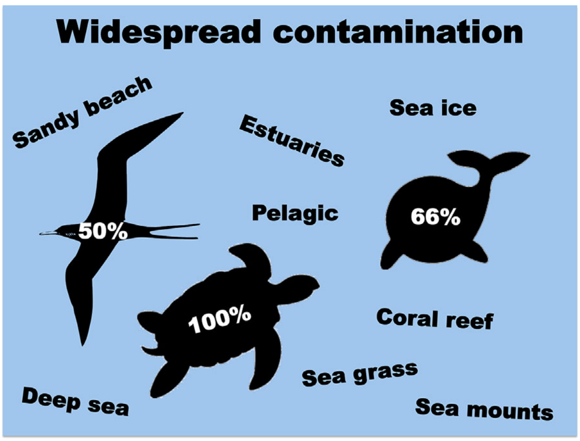


FIGURE 2: Widespread contamination of plastic debris reported in the scientific literature. The current and growing scientific evidence reports widespread contamination of plastic debris among many aquatic habitats and animals, including 50% of all species of seabirds, 66% of all species of marine mammals, and 100% of all species of sea turtles.

Table 1. Examples where science and policy worked together to establish positive change toward mitigation of plastic debris

Observation	Scientific evidence	Policy reform
Widespread contamination of plastic debris in oceanic gyres	Law et al. [52]; Goldstein et al. [49]; Eriksen et al. [4]	Amendment to MARPOL Annex V
Preproduction pellets littered in aquatic habitats globally	Ogata et al. [36]; van Franeker and Law [54]	International Clean Sweep, California Nurdle Law (AB258)
Plastic entering coastal habitats via urban runoff	Browne et al. [32]	Total maximum daily loads, trash collecting technologies in storm drains
Microbeads in aquatic habitats	Eriksen et al. [5]; Castañeda et al. [27]	Legislation to ban microbeads from personal care products

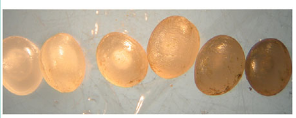
Evidence regarding the sources and sinks of plastic debris in the environment

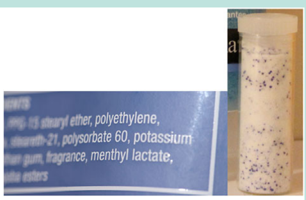
Aside from understanding the extent of the contamination, understanding the sources and sinks of plastic debris in the environment is critical information for management, informing source-reduction strategies and retrieval and mitigation options. There are several sources of plastic debris to the aquatic environment, and their entry into the environment may occur at all stages of the life cycle of the plastic product. These include both land-based and maritime sources. For microplastics in particular, sources are generally categorized as primary or secondary [31]. A source of microplastic is considered primary when it enters the environment as microplastic. Examples of this would be fibers from washing machines [32], microbeads from personal care products [5], or the spillage of preproduction pellets from industry [33]. A secondary, and likely more significant, source results when a larger piece of plastic debris breaks into micro-sized or nano-sized pieces via chemical, biological, or physical degradation processes [34,35].

Several studies have tried to identify the input and quantify the relative extent of some of the sources of plastic debris. For example, some researchers have tried to identify locations where the relative input of plastic debris may be large. A recent study determined that the input of plastic debris from land is much greater than that of maritime sources [17] and identified the countries that may be the greatest contributors of plastic debris to the oceans via the mismanagement of waste and production of plastic per capita. Many other studies focus on identifying sources of particular types of plastic debris. For example, beach and ocean monitoring and research programs identified preproduction pellets on beaches globally [36] and determined that the contamination was the result of losses from industry during transport [37]. Two sources of microplastics, microbeads in personal care products and fibers from textiles, wash down household drains and travel to wastewater-treatment plants. Because of their small size, quite a few are not filtered out of the final effluent and, thus, are emitted directly to aquatic habitats [38]. Browne et al. [32] observed the presence of fibers from clothing in the effluent of wastewater-treatment plants and determined that a single garment can produce more than 1900 individual fibers per wash, demonstrating that the process of laundering garments made from synthetic fibers produces a source of microplastic fibers to aquatic habitats [32]. Gouin et al. [39,40] made an attempt to estimate the amount of microbeads that may be washing down drains from personal care products to get some idea of how many plastic beads have the potential to become litter. They calculated that 263 tons of polyethylene microbeads were purchased in liquid soap products in the United States in 2009 [39] and that 4073 tons of polyethylene microbeads were used in cosmetic products across all European Union countries plus Norway and Switzerland in 2012 [40]. Such estimates of the quantity and type of plastic entering from specific sources can provide information for policy makers to focus their efforts to mitigate the debris upstream. Such mitigation might involve cleanup, prevention via waste management, or use of social science to inform behavioral change.

For the most part, research regarding the mechanisms of transport and fate of plastic debris continues to increase. There remain many unanswered questions regarding the origins of the material and its ultimate destination. Still, research in the last few years has begun to provide insights that help answer such questions, and some of this information is already being used to inform policy change (Table 1).

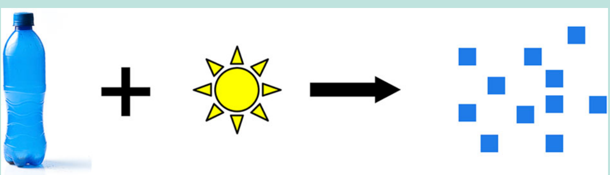
Primary microplastics
Small plastic debris that enters the environment as microplastic.


pre-production pellets



microbeads in facewash

Secondary microplastics
Small plastic debris that becomes microplastic in the environment.



Evidence regarding harm or impact

To answer the "so what" questions posed by policy makers, we must understand the impacts of plastic debris. Generally, when we think about the existing evidence regarding impacts caused by plastic debris we think about the environment and wildlife. However, many have raised concern regarding how humans may be affected in regard to both health and economy. Unfortunately, to complete a formal risk assessment to assess the ecological or human health impacts, a larger weight of evidence is still necessary [14,41].

Many questions remain unanswered and/or unanswerable regarding the impact of plastic debris to humans given the deficit of available information. For example, concerns have been raised regarding adverse impacts to human health from the consumption of seafood that is contaminated with plastic debris and associated chemicals [14]. Because very little data on this topic exist, research designed to answer such concerns is necessary. When it comes to the economy, studies have shown adverse impacts to specific sectors, such as tourism, aquaculture, and commercial shipping, in addition to the cost to governments of cleanup [42]. For example, roughly €1–2 million was spent on operations to rescue vessels entangled in plastic debris in the United Kingdom in 2008 [43]. Moreover, the annual cost of removing beach litter in the United Kingdom is estimated to amount to €18–19 million [43], and the annual cost to 100 coastal cities in the western United States totaled \$500 million [44]. Although more information is critical to fully understand the impact to humans, especially with respect to human health, the above information is useful for beginning to understand some of the economic effects of plastic debris. Overall, a greater understanding of the impacts to humans is critical to influence a policy movement, which seems to require demonstration of adverse impact to our own species.

For wildlife, there are many mechanisms by which plastic debris of all sizes has been documented to adversely affect individual animals. For example, plastic debris can harm or even kill an organism via entanglement, ingestion, or smothering [30,41]. Several studies have shed light on how plastic debris impacts wildlife at suborganismal levels, such as at the cellular or molecular level [41]. But the research examining large-scale impacts from plastic debris remains in its infancy and is ongoing. Many questions remain unanswered regarding how plastic debris of all sizes impacts wildlife at the level of population, species, or community [41].

Thus far, the majority of impacts to animals have been demonstrated at the suborganismal or organismal level of biological organization. This is likely because much of these data come from laboratory exposure experiments using micro-sized and nano-sized plastic [41]. Many laboratory experiments that measure the effects of contaminants on animals measure impact by looking at a range of biomarkers, from oxidative stress to the promotion of tumors to mortality. For example, individual studies have found evidence of changes in gene expression [45], inflammation of tissues [46], and changes in behavior and mortality [47] in different organisms under a diversity of exposure scenarios. Together, individual laboratory experiments can provide compelling data regarding suborganismal effects from plastic debris to a variety of organisms that may be synthesized and linked together in a risk-assessment framework to begin to understand how plastic debris impacts wildlife at higher levels of organization. To do this properly, it is necessary for experiments to be environmentally relevant, reproducible, and of high quality.

Other evidence of impact comes from the field and is generally from observational studies. For example, during a monitoring study an individual organism is found dead and the cause of death is attributed to entanglement or ingestion of larger items of plastic debris. A recent synthesis found that of the 30 896 individual animals reported to have been entangled, 79% of cases led to injury or mortality, and of the 13 110 individual animals reported to have ingested debris, 4% of cases led to injury or mortality [28]. For all cases, 92% of the time the marine debris was composed of plastic [28]. The animals affected span a wide range of taxa and include marine mammals, sea turtles, seabirds, fish, and invertebrates. Still, the data are piecemeal, and the individual studies generally do not ask questions related to how the impacts lead to population-level, species-level, or community-level effects. To understand ecological impacts to wildlife, it is necessary to see if this evidence can be coalesced into a risk-assessment framework.

A recent systematic review of the literature regarding the impacts of plastic debris concluded that although there is evidence of impacts from plastic debris, the quantity and quality of research require improvement to allow the risk of ecological impacts of marine debris to be determined with precision [41]. There are few examples of studies that demonstrate how plastic debris may cause an ecological impact. One study demonstrated that the smothering of a coral reef can cause mortality of several species associated within its community [48]. Another demonstrated that the addition of plastic debris to a habitat can alter the size of the population or the community by providing extra hard substrate, which may be considered a positive impact of plastic debris because of increased biodiversity [20,49]. Overall, although a full understanding of the ecological impact has not been reached, there is much evidence that plastic debris impacts individual animals. As such, policy makers can begin to use the existing weight of evidence regarding ecological impacts and effects caused by debris at lower levels of organization to decide and help design and support necessary higher-quality research for proper risk assessment [50].

The weight of scientific evidence is much greater than it was at the turn of the century [2]. We now know that the amount of waste escaping proper management and thus entering the environment is large and increasing [17]. We no longer wonder whether plastic debris contaminates our planet. We know that plastic debris is an eyesore and can disrupt local tourism and fishing. Although formal risk assessments are warranted for the reasons mentioned above, exposure of this material can be harmful to animals that ingest the material or are entangled or smothered by it. Today, many of the new questions related to plastic debris are mechanistic or process-based and have been built from the large weight of evidence regarding the contamination of plastic debris in the environment and a smaller weight of evidence regarding the sources and the impacts to organisms and local economies (Figure 3). We are now curious about the extent of the many sources of plastic debris (e.g., leaky waste management, consumer behavior, littering, and ocean dumping), its fate and transport in the environment, the chemical and biological

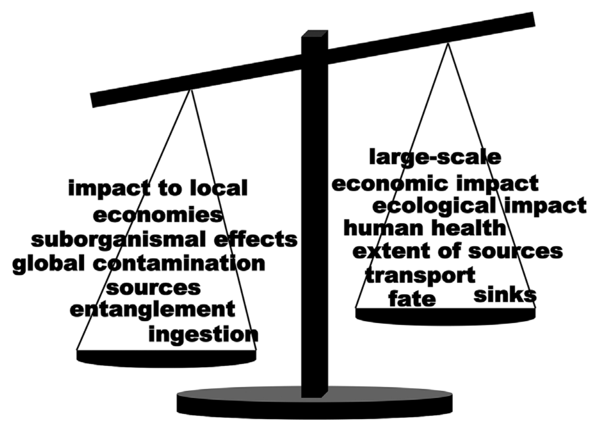


FIGURE 3: Weight of evidence regarding plastic debris. The scale shows what topics related to marine debris are better understood and have a heavier weight of evidence (left) and topics where the weight of evidence is much lighter and many questions remain unanswered (right).

processes by which it can impact individual organisms, and whether there are large-scale impacts to wildlife, ecosystems, or even humans via adverse effects on our economy or our health (Figure 3). As scientists continue to conduct research and answer new questions, policy makers can help identify research objectives that are policy-relevant and begin and/or continue to use existing evidence to mitigate the problem.

Applying the Science to the Policy

These days we often hear discussion about how there is a need to build a stronger pipeline between scientists and policy makers [51]. Some say scientists work in silos and do not communicate new findings beyond academia. Others argue that policy makers are not communicating with scientists and making informed decisions based on scientific data. We hear talk about how scientists and policy makers do not work under the same time scales or speak the same language. Although this may be true in some cases, there are clear examples of how science has been used to inform policy change and mitigation for plastic debris. Below, in *Bright spots: Science that informed positive change*, we highlight some examples of how a connection between science and policy has led to positive change. In addition, we discuss opportunities for future linkages between science and policy to highlight how a continued relationship can contribute to solutions for plastic debris.

Bright spots: Science that informed positive change

The increasing interest in the issue of plastic debris has led to an increase in activity from both scientists and policy makers. Among this increased activity are examples of collaborations among scientists and policy makers to use new scientific understanding to invoke positive change and to conduct policy-relevant research. Some examples of this are provided below and summarized in Table 1.

Moore's discovery of the accumulation of plastic debris in the middle of the North Pacific Ocean prompted many scientists to attempt to quantify the contamination in oceanic gyres [4,49,52]. The results, showing widespread contamination in every major open ocean, sparked abundant interest from the media and the public. In response, and in an attempt to more effectively reduce quantities of plastic debris discharged either accidentally or deliberately at sea, the International Maritime Organization amended MARPOL Annex V to more effectively reduce or eliminate disposal of waste at sea. In January 2013 the revision went into force, and now it prohibits the discharge of all garbage into the sea [53].

During beach surveys and ocean monitoring, researchers and managers found that plastic preproduction pellets made up a significant part of what was found littered on beaches and at sea. These plastic pellets were reported in the oceans [36], on beaches [36], and in the digestive systems of seabirds [54]. Both policy and industry responded and implemented change to resolve the contamination. Operation Clean Sweep [55] was initiated by the plastics industry as an international initiative to reduce the loss of plastic pellets by manufacturers to the environment. In the United States, the state of California implemented a regulation, (AB) 258 Preproduction Plastic Debris Program [56], decreeing zero tolerance for release of plastic preproduction pellets into the environment. As a result, researchers have reported a decrease over the last few years in the amount of plastic preproduction pellets found in the environment [54].

When trying to better understand the sources of plastic debris to the ocean, researchers found a correlation between greater accumulations of plastic debris in coastal waters and urban areas [32]. Storm drains provide an outlet for plastic debris to enter coastal waters from urban areas. To mitigate the loading to aquatic water bodies from debris entering storm drains, Korea has begun installing trash booms in major rivers and waterways [57] and some US cities, such as those along the Anacostia River [58] and those in the Los Angeles River basin [59], have implemented regulations for the total maximum daily load of trash that is allowed to enter the water from land. In California specifically, trash has been designated as a pollutant, through the use of the storm water permitting process required under Section 303 of the federal Clean Water Act; and all large cities are required to install trash-capture devices in storm drains and catchment basins and/or implement best-management practices to eliminate trash loading into rivers, streams, and lakes over the next decade [60]. Such regulation aims to reduce one of the major pathways by which plastic debris contaminates urban watersheds using waste-management strategies and regulatory tools.

Other types of mitigation strategies have been introduced all over the world in attempts to prevent waste and/or litter from entering aquatic habitats. This has been implemented through public awareness campaigns driven by social science that aim to guide behavior toward more sustainable consumption and use of plastic products in the European Union [61], through government support of circular economies in China [62] and Europe [63], and legislation banning certain products that scientists report as being a major contributor to what will become plastic debris. Such legislation includes bans on single-use plastic bags from stores, the practice of using Styrofoam takeaway containers from restaurants, and the use of plastic microbeads in personal care products. For example, lightweight plastic bags have been banned or taxed in parts of North and South America, Africa, Europe, Asia, and Australia. Moreover, plastic microbeads are commonly added to hundreds of personal care products, and scientists predict that billions of these microbeads are released into aquatic habitats daily [38]. To stop this source of plastic contamination, legislation to ban microbeads has been introduced in the United States, Canada, the European Union, and Australia. In response, some manufacturers and companies have agreed to remove plastic microbeads from some of their product within the next few years [64]. At this time, scientists can begin to measure the effectiveness of the mitigation strategy by determining if there is a reduction of microbeads in aquatic habitats over time and/or if safe alternatives that are designed and marketed are still effective at keeping persistent plastic debris out of aquatic habitats.

In addition to policy makers using the science to drive positive change, they can inform scientists of the types of questions whose answers would help inform change. Scientists are aware of the gaps in the knowledge but not always of the questions policy makers want answered to effectively understand, communicate, and mitigate the problem. To demonstrate the advantages of this, we provide real-world examples from our own experiences below.

The USEPA is interested in issues relevant to plastic debris as it relates to existing legislation that regulates hazardous chemicals and substances in the environment, using the authorities and the tools under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Pollution Prevention Act, and the Clean Water Act. They want to determine whether it is warranted to treat plastic debris as a new medium of concern and establish threshold levels for each contaminant known to adsorb to plastic and pose a threat to a receptor. The CERCLA program within the agency is currently laying the groundwork to perform risk assessments to determine the extent to which plastic, with its propensity to harbor and accumulate hazardous substances, poses a threat to sensitive ecosystems and potentially to human health. Together with partners from the state of California, the University of California–Davis, the US Fish and Wildlife Service, NOAA, and the state of Hawaii, they have been examining the mixture of contaminants typically found in water bodies and associated with plastic debris and designing studies to answer questions regarding the bioavailability and hazards of this mixture to wildlife. Combined, they are using open ocean gyres, Tern Island in the northwestern Hawaiian Islands, and the Tijuana River Estuarine Natural Resource Reserve to do initial case studies. Using the expertise, resources, and assets of multiple agencies and research institutions, they can better understand the mechanisms that drive these problems.

In The Netherlands, the Ministry of Economic Affairs and Health, the Ministry of Welfare and Sport, the National Food and Product Safety Authority, and 8 regional water boards have identified the need to perform the first full risk assessment for nanoplastics and microplastics in fresh and coastal waters. This aims to include the development of standard methods for measuring and monitoring nanoplastics and microplastics; assessment of dose–effect relationships for representative species, species sensitivity distributions, and community and food web effects of plastic and plastic-associated chemicals; and development of spatiotemporally explicit fate models for use in an overall risk-assessment framework. These governmental agencies articulated the research needs with scientists from Wageningen University and Utrecht University, who worked together to design and launch a joint program in which scientific results are utilized directly in support of policy development.

The above are just some examples of how the current weight of evidence has driven policy change directed at mitigation of plastic debris. Similar programs exist in many other parts of the world, such as the JPI Oceans Initiative (Joint Programming Initiative Healthy and Productive Seas and Oceans) in the European Union and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection working group on marine litter initiated by the UNEP. These examples highlight where policy makers and scientists have come together in some capacity. In *Continue building the pipeline between science and policy* we discuss what we see as some future opportunities for further collaboration and cooperation among scientists and policy makers to continue to help mitigate environmental accumulations of plastic debris.

Continue building the pipeline between science and policy

Do we need to do more scientific research to better understand the sources, sinks, and effects of plastic debris? The answer will always be yes—Research is the engine for more research because new information always breeds more questions. Existing evidence regarding widespread contamination has led to questions regarding the sources and fate of the material and the large-scale impacts to wildlife and humans, information critical to conduct sound risk assessments. Still, we think that the current weight of the evidence is enough to warrant the positive changes we have observed and continue to affect new change. Below are examples of how we think some of the new evidence regarding plastic debris might be relevant to future policy initiatives.

Recent evidence demonstrates how mitigation is likely not a 1-size-fits-all strategy. One study highlights locations across the globe where contributors of plastic debris may be larger than others because of differences in waste-management infrastructure and, thus, leakage of plastic debris to the oceans [17]. That study has provoked some environmental managers and nonprofit organizations to target different mitigation strategies in different locations. In locations where infrastructure is sparse, they are considering building new or more advanced waste-management infrastructure. For example, a recent report by an alliance of nongovernmental organizations, government agencies, and industry members outlines their plan to reduce more than half of the plastic debris leaking into the ocean by working with developing countries to build waste-management infrastructure [65].

In locations where infrastructure is more advanced but plastic debris is still a problem, management strategies aim to reduce plastic debris by conducting campaigns to influence changes in behavior that affect consumption and use patterns and/or targeting different point sources of debris. For example, studies examining microplastic in aquatic habitats have found that a large amount of the material is composed of fibers from textiles. This contamination source has been linked to the degradation of clothing in our washing machines [32]. Researchers and environmentalists have suggested that adding filtration devices to washing machines may help mitigate the debris and suggest that further work should test their effectiveness at reducing emissions of microplastic [66]. Moreover, studies that quantify debris on beaches have identified which products may be more commonly found as plastic litter than others. Such information could be used to push legislation toward bans, which initiate scientific studies about and production of safer alternatives and/or changes in consumer behavior. For example, the legislation regarding microbeads has influenced production of safer materials such as polyhydroxyalkanoates [67]. In other cases, safer alternatives exist and are within reach, such as waxed paper straws that may eliminate the roughly 600 000 plastic straws that were recovered from beaches and coastal areas during the International Coastal Cleanup run by the Ocean Conservancy in 2014.

Conclusion

Of course, there remain many gaps in our understanding regarding plastic debris. As we increase our understanding about 1 aspect of our field, we inevitably create a whole set of new unanswered questions. If you look further into any specific environmental issue, including issues that have been researched at greater depth, such as climate change or overfishing, you will find many gaps in the scientific understanding of that particular topic as well. This is the inherently exciting nature of science: New knowledge breeds new questions. For microplastic and nanoplastic debris, the field is arguably still in its infancy, and more science regarding some of the above big-picture questions is crucial. In summary, we are not stating that we do not need more science; we are simply claiming that policy makers can take a precautionary approach and continue to enforce positive change while the scientists answer more questions and continue to fill research gaps.

Over the last several decades, scientists have generated a lot of evidence regarding the widespread contamination of plastic debris. It appears that there already exists sufficient information for policy makers to invoke positive change because there are clear examples of how they have begun to take action to mitigate the problem. Thus, although there remains a lot to learn regarding the mechanisms that drive the fate and impact of plastic debris in aquatic habitats and the impact of the debris to wildlife and humans, we hope that policy makers continue to use existing scientific data to invoke positive change while scientists continue to increase our understanding of this problem and its consequences.

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The opinions and comments expressed in this *Focus* article are those of the authors alone and do not reflect an agency policy, endorsement, or action; and the USEPA does not verify the accuracy of the contents of this *Focus* article.

Data availability

Data, associated metadata, and calculation tools are available from the corresponding author (cmrochman@ucdavis.edu).

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