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Solving the Oceans' Plastic Problem

ELIZABETH MENDENHALL AND ELIYA M. BARON LOPEZ

The health of the oceans is essential for sustaining and supporting the global human population. The oceans fuel most of the world's oxygen production and absorb a majority of its carbon dioxide emissions. They also support fishing, shipping, energy, and tourism industries. Throughout the twentieth century, increases in industrial-scale extraction and an expanding number of other maritime activities vastly increased the human burden on marine ecosystems.

In the 1970s, international agreements intended to reduce marine pollution focused on dumping and pollution from the regular operation of ships. These agreements were reasonably effective, but today, concerted international commitments to deal with other marine pollution challenges are still lacking. And the continued expansion of global industrial civilization has increased the overall human impact on the marine environment, so that ecosystems now face multiple stressors. Plastic pollution is a primary example of this growing human footprint in the oceans. Unlike overexploitation of renewable resources such as fisheries, which may one day bounce back, it will be difficult if not impossible to remove all plastic from the oceans.

Although plastic debris has entered the oceans for decades, the problem has recently started to draw mainstream attention. A large part of the explanation for this is Internet media: videos of animals rescued from entanglement with plastic go viral, photos of dead albatross chicks with stomachs full of plastic are widely shared, and news stories about whale carcasses stuffed with plastic recur with alarming frequency. Other reasons for increased awareness include the advocacy efforts of celebrities who have taken up the anti-plastic cause, from Kim Kardashian to Leonardo DiCaprio. Popular online influencers are selling metal straws to profit from rising disapproval of plastic straws. And major corporations are starting to take advantage of these trends: Adidas is now marketing athletic wear made from collected marine plastic, while Starbucks has redesigned its lids to reduce the demand for plastic straws.

Concern about plastic pollution is still growing, but we lack a detailed understanding of the problem. Important questions remain about why there is so much plastic in the oceans, what are the consequences, and what can be done.

Scientific research into marine plastic debris was relatively slow to develop. Although individual studies about the impact of plastic in the oceans were published in the 1960s and 1970s, only in the past five to ten years has a concerted, international, multidisciplinary research effort begun. Searches of the Scopus citation database show exponential growth in the number of publications on marine plastic debris, including work by both natural and social scientists.

This increase in scientific research reflects and reinforces public concern about marine plastic. Since marine science can be very expensive—especially when it involves gathering samples in the oceans—the amount of research depends directly on the interest of funding sources. Sustained public attention to the problem, and discussion of how we might solve it, is crucial to reducing our knowledge gaps about marine plastic pollution.

At this stage, we do not know the extent to which marine plastics in seafood may affect human health, the total cost of cleanup, or the overall burden on maritime industries. These research gaps prevent a full understanding of the magnitude and urgency of problems caused by plastic pollution and hamper efforts to shape effective

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environmental policies. Although studies on these topics are ongoing, the lack of research standardization makes it difficult to grasp the whole story of marine plastic and its future impacts.

Yet the information we do have is increasingly visible and widespread, stoking concern among the public, policymakers, and industry. Limited action has been taken to reduce the flow of plastic into the oceans and to clean up some of the waste that is already there, but these efforts make only a minor dent in the overall flow of plastic into the marine environment. Developing a better understanding of the complex chains of plastic production, consumption, and disposal, at scales that range from local to global, can help identify the sites where solutions would be most feasible, effective, and efficient.

A PERFECT POLLUTER

Marine plastic debris is a relatively new problem: the dominance of plastic in global markets began in the mid-twentieth century. As a material, plastic has a unique combination of positive qualities—it is cheap, flexible, and durable—making it ideal for manufacturing. The most common types of plastics include polyethylene terephthalate and high-density polyethylene, commonly used for bottles, food containers, and rope, as well as polypropylene, used for chip bags and straws. Estimates vary, but roughly 40 percent of plastics are produced for packaging. Disposable plastic products are now central to expectations about hygiene for medicine, food, and sanitation systems.

This ever-accumulating plastic soup has dangerous consequences for ocean creatures.

The global plastics market is currently valued at over $1 trillion, and the industry is thoroughly globalized. A single consumer product may result from transactions among a number of companies across multiple borders. One company might produce the plastic pellet "feedstock," another company uses that feedstock to make plastic products or packaging, and still others market and sell the final products.

These transnational flows are growing, and plastic production is accelerating. This is a result of more new products being made of plastic, existing products shifting to plastic, and the export of plastic items to new markets. The prevalence of disposable plastics, and the common design element of planned obsolescence, mean that even saturated markets will continue to buy massive amounts of plastic products.

Growth in plastic production and consumption may be good for industries and consumers, but it creates big challenges for waste management systems and environmental health. Plastics derive from both the chemical and fossil fuel sectors and share some of the problems of those industries. Plastic production involves converting crude oil or natural gas into synthetic polymers that contain toxins such as bisphenol-A, lead, and phthalates. Plastic production is also a source of carbon dioxide emissions, both directly and through energy use. In the United States, approximately 12 million barrels of oil are used to manufacture 380 billion single-use plastic bags every year.

Although the general public perceives most plastic materials to be recyclable, in practice, only 9 percent are actually recycled. And several features of plastic make it highly susceptible to accumulation in the natural environment—it is light, frequently disposed of, and often very small. Even when plastic items are put in formal waste management systems, they often leach out of landfills or are blown by wind into the surrounding area. It is sometimes reported that 10 percent of the plastics produced every year end up in the ocean, though in fact the phenomenon is too widespread and decentralized to get an accurate account.

Marine plastic pollution is largely a result of inadequate waste management systems that cannot capture the high and increasing volume of incoming plastic products. A problem as simple as a landfill without a cover can facilitate the wind-driven movement of plastic into the marine environment. Many of the least developed countries, including coastal ones, lack the resources and infrastructure of modern waste management systems.

And many plastic items are so small that even advanced waste management systems cannot capture and dispose of them safely. These microplastics (less than 5 millimeters in diameter) are often the result of the breakdown of larger plastic products over time, but some are intentionally manufactured. Examples of microplastics include synthetic fibers from clothing, preproduction pellets, and microbeads used in cosmetic products.

It is hard to quantify plastic pollution because there are myriad outflows into the oceans that are

difficult to observe reliably. Researchers have produced estimates, most of which are accepted and cited for years before they are reanalyzed or updated. The prevailing wisdom today is that 80 percent of marine plastic pollution comes from land-based sources, with the remaining 20 percent originating from boats and ships.

One prominent study suggests that the vast majority of marine plastic debris flows from 10 rivers in Asia and Africa, and this claim has been widely publicized. The study, however, is limited by a lack of field observations, uncertainty about the proportion of debris that lodges in river sediment, and lack of knowledge about the quantity of non-river outflows. Nor does this study account for the fact that much of the plastic flowing out of these rivers was imported from the United States, Europe, and elsewhere.

Regardless of the exact sources and numbers, we know that large amounts of plastic flow into the ocean environment. But exactly where plastic ends up remains something of a mystery. The varied topography of the seafloor and differences in local and regional currents ensure that the distribution of trash in the ocean is not uniform. Since the late 1990s, scientific fieldwork has documented the existence of at least five "plastic gyres"—areas in the oceans where wind-driven currents draw in debris and result in relatively high-density accumulations of plastic waste. But far less plastic was found within these gyres than scientists expected, given what we know about outflows from land.

Only 9 percent of plastic materials are actually recycled.

Recent research suggests that the majority of marine plastic debris may actually settle in coastal sediment. Although sampling is extremely limited, scientists have found concentrations of plastic waste in parts of the seabed in areas like the European Arctic. Plastic waste has been recorded in submarine canyons, such as the deep-sea regions near the coasts of California and Mexico. Sediment cores from off the coast of Santa Barbara, California, display an exponential increase in plastic accumulation that correlates with increases in global plastic production.

In short, though it is not evenly distributed across the ocean environment, plastic exists on or near the sea surface, around the seabed, and throughout the water in between. Plastic deposition in sediments is now considered a marker of the so-called Anthropocene geological epoch, wherein humans are leaving permanent marks of industrial civilization across broad swaths of the planet.

MOUNTING COSTS

Although we lack a full picture of the harms caused by marine plastic debris, we know enough to understand that it creates major problems. The durability of plastic means that when it degrades, it merely breaks into smaller pieces. Plastic degradation occurs when the material is exposed to physical phenomena such as ultraviolet radiation, bacterial breakdown, and wave action. This process can take hundreds of years, depending on the type of product.

Some types of plastic release harmful chemicals into the surrounding waters as they break down. These toxins—including carcinogens and endocrine disruptors—are known to contain harmful trace elements that can accumulate in the environment. Meanwhile, some plastic particles absorb and concentrate other environmental toxins from the water column. This ever-accumulating plastic soup of degrading products of all sizes and types has dangerous consequences for ocean creatures and humans.

Concerns about wildlife becoming entangled in plastic debris emerged in the 1970s, and made it into popular culture in the 1980s and 1990s. In the early 1990s, the characters of the television cartoon *Captain Planet and the Planeteers* taught millions of children about the dangers to marine life posed by six-pack beverage holders and other disposable plastics. The harms of entanglement are easy to understand, in part because they befall so-called charismatic megafauna like whales, seals, sea turtles, seabirds, and sharks.

Less is known about the harms of plastic ingestion, which may cause plastic to damage or accumulate in the digestive tracts, and even the tissues, of marine organisms. Seabirds that feed via opportunistic diving are especially vulnerable to plastic ingestion and entanglement, along with filter feeders large and small, including oysters, clams, whale sharks, and baleen whales. Estuarine fisheries, such as catfish, have particular problems with entanglement and ingestion of fishing gear because much plastic is trapped in coastal wetland areas.

Nanoplastics—the tiniest plastic particles—are the least researched category of plastic debris, but potentially the most dangerous in terms of accumulation within the tissues and cells of organisms. Micro- and nanoplastics can affect whole ecosystems through what is known as trophic transfer: primary consumers (filter feeders and zooplankton) are a pathway for the accumulation of plastic particles in higher-level consumers (fish and marine mammals). The overall effects of these phenomena on ecosystem productivity and health remain unknown, since most studies focus on single-species impacts.

Plastic pollution also burdens human communities and businesses. Maritime industries have suffered damage to their physical infrastructure from encounters with plastic. Marine debris can entangle or block vessels' propellers, anchors, pipes, and rudders, which puts the safety of their crews at risk and requires expensive repairs. Coastal areas like beaches, estuaries, and islands are littered with marine debris. Local organizations often organize beach cleanups with volunteers who participate in both cleaning and data collection. These citizen-scientists contribute to growing databases that identify the amount and types of waste collected on beaches.

The Ocean Conservancy, a nongovernmental organization, has recorded that volunteers collected over 317 million pounds of waste from coastal areas in the past thirty years. The most common items collected include plastic fragments, foam pieces, food wrappers, cigarette butts, and plastic bottles. While most of these items derive from land-based activities, beach cleanups also remove fishing buoys, nets, lines, and other types of gear from sea-based sources. These cleanups are costly—whether in volunteer hours or municipal expenditures—but the alternative may be costlier still, since coastal communities can suffer millions of dollars in economic losses due to the impact of plastic litter on tourism and local fisheries.

The overall character and magnitude of the problems caused by marine plastic pollution are still coming into focus. One major area of uncertainty concerns the seafood economy. Roughly one-fifth of the global human population depends on seafood as its primary source of protein. Limited studies have found microplastics in seafood at various locations around the world. Marine shellfish aquaculture is especially vulnerable to microplastics because of the difficulties of creating a clean environment for filter feeders. But whether plastic ingestion by marine organisms will impact the availability or quality of seafood remains to be seen.

Humans are at higher risk of consuming microplastics if they eat the entire animal, especially the digestive system where the plastic accumulates. We do know that the presence of marine plastic may exacerbate the risks of toxins accumulating in the food chain, and therefore is potentially detrimental to human health and fish reproduction. But we do not have dispositive evidence that consuming plastic in seafood increases the risks of transmitting toxins through human digestive systems, or that the availability of seafood will decrease because of the effects of plastic ingestion by fish and shellfish. Additional scientific research is needed to understand the full impact of marine plastic pollution on human health and well-being.

Consumers and Companies

The complexity and scale of the marine plastic problem means that there are many possible solutions, and that an effective response will likely require a "solution set" that includes multiple efforts by different actors. Solutions can be adopted at a variety of levels, from individual choices to international agreements, and at various points along the chain from production to consumption to disposal. In general, solutions can be grouped into two basic types: mitigation, which seeks to reduce the flow of plastics into the environment, and remediation, which focuses on cleaning up the plastic that is already out there. Efforts are currently underway along both of these tracks, and at several different scales.

At the individual level, the "reduce, reuse, recycle" motto continues to guide consumers looking to cut down their plastic consumption. Reusable water bottles, coffee mugs, straws, and grocery bags are understood as personal commitments to avoid disposable plastic products. "Fast fashion" is increasingly criticized as wasteful and inefficient, especially given the growth and prevalence of synthetic fabrics that contain microplastic fibers.

Consumer awareness campaigns have a limited impact, however, because consumers are overwhelmed by the ubiquity of plastic, especially in packaging, at the stores they depend on. Although there are sometimes non-plastic versions of plastic products, these alternatives are almost always more expensive. And even when changes in demand cause companies to shift their offerings in one place, the effect is counteracted by rising ex-

ports of plastic-heavy products to new markets in developing countries, where consumers are less inclined, or less able, to make environmentally informed choices.

Multinational corporations are at the center of plastic production and consumption, and their decisions about product design, packaging, and marketing have consequences for the scale and persistence of the marine plastic problem. The governance of plastics is highly fragmented, and trade in products is thoroughly globalized, so manufacturers can easily shift to less restrictive jurisdictions. And in many cases, the industry has successfully fought against proposed bans on disposable plastic products.

Despite this reality, many believe that corporate social responsibility—the idea that companies will make decisions based on the public interest rather than profits—can help solve the problem of plastic pollution. Multinational corporations with global brands have increasingly touted "greening" efforts involving supply chain transparency, packaging changes, the use of recycled materials, and even the adoption of more degradable "bioplastics." But the underlying problem is that the goals that drive these corporations to adopt greener policies are ultimately profit-driven: deterring costly government restrictions, increasing brand value through marketing, and maximizing manufacturing efficiency. Corporations often reinvest the savings from these efforts into new plastic product lines and access to new markets. And plastics production continues to increase.

LIMITED ACTION

In the United States, state and municipal governments have taken action to require businesses to offer nonplastic alternatives to consumers. California has enacted several laws to restrict single-use plastic products. In 2015, the state voted to prohibit businesses from providing single-use plastic bags to customers. If a bag is provided, it must be paper, reusable, or compostable and sold to the customer for a minimum of 10 cents. Since 2016, single-use bags must be made of recycled material.

In 2019, San Francisco went farther and passed a law that requires businesses to make changes in two phases. First, single-use items like straws, utensils, and stirrers must be available only on request, and made of biodegradable or compostable materials. As of 2020, these items cannot be made of polylactic acid, which is not marine biodegradable and requires industrialized composting systems to break it down. Other coastal cities and states have enacted similar measures. But California is a relative outlier: in fact, more US state governments oppose regulations on disposable plastics than support new rules.

Although it is generally easier to pass mitigation-focused product prohibitions at the state and municipal levels, the US federal government has taken limited action in this area. The Marine Debris Research, Prevention, and Reduction Act of 2006 established a program, run by the National Oceanic and Atmospheric Administration (NOAA), to support collaboration among federal agencies, indigenous tribes, academia, and local agencies on projects including community education.

In 2018, the Save Our Seas Act reauthorized the NOAA Marine Debris Program through 2022, with an annual budget of $10 million. A proposed Save Our Seas Act 2.0 would provide more research funding, enhance international outreach and collaboration, and improve domestic waste and recycling infrastructure.

The Microbead-Free Waters Act of 2015 banned the use of microbeads in cosmetic products such as toothpaste, face wash, and makeup. Cosmetic microbeads are especially likely to flow into waterways because wastewater treatment plants are not designed to capture them.

These legislative responses have been matched or exceeded by many other countries. More than 120 countries have passed some type of plastic bag regulation, although these laws vary widely in their comprehensiveness and effectiveness. European and African countries have taken the lead in banning disposable plastic bags. By 2021, all European Union member states will be required to begin implementing single-use plastic restrictions and "extended producer responsibility," which requires companies that sell plastic products to pay into a fund for waste collection systems.

Recycling—long considered a central part of the solution to plastic waste—has come under increased scrutiny, and even criticism, as a feel-good but do-little alternative to reducing plastic consumption. A recent exposé by the Center for Public Integrity outlined a concerted and strategic effort by the plastics industry to promote recycling as the preferred "solution" to plastic pollution because it shifts responsibility from the industry to consumers and government-funded waste management systems. Overall, it is estimated that less than 10 percent of all plastic items are recycled, in

large part because recycling is rarely economical without subsidization, and many types of plastics are not recyclable with current technology. Single-stream recycling, in which all recyclable material is collected in the same bin, has combined with misinformation and confusion in the United States about what is recyclable, creating a situation where recycling is often mismanaged, contaminated, and of low value.

For many years, this lack of real recycling was hidden from consumers, as recyclables collected in developed countries like the United States were exported to China and Southeast Asia to be sorted and sometimes recycled by small and medium-size facilities. But in 2018, China prohibited the import of low-value "foreign waste," leading to a pileup of collected recyclables at facilities in the United States. Many cities have resorted to incinerating the amassed waste, which releases harmful air pollutants.

Even if consumers were able to reduce, reuse, and recycle enough to effectively mitigate flows of plastic into the marine environment, the millions of tons of plastic already in the oceans would continue to harm marine ecosystems and industries. In addition to beach cleanups, many high-profile remediation efforts have emerged in the past few years. The brilliant branding and technical success of Baltimore's "Mr. Trash Wheel" mobile collector led to an expansion of the program with two additional collectors. These solar-powered water wheels use an angled conveyor belt to collect garbage floating on the surface of Baltimore's harbor.

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More visible on the national and international scene is The Ocean Cleanup, a project founded by Dutch inventor Boyan Slat in 2013, which designed a passive system of floaters to collect debris on the high seas. The project's goal was to collect up to 50 percent of the marine debris in one of the world's several open-ocean gyres, the Great Pacific Garbage Patch, in five years, using a 600-meter-long group of connected floaters. The collected waste was to be recycled and sold to companies, with the resulting revenue feeding back into the project. But the initial voyage failed because of technical challenges, and critics of The Ocean Cleanup's approach are concerned about its impact on marine ecosystems and its durability. In 2019, the group switched its focus from the gyres to collecting marine debris from 1,000 of the world's most polluted rivers by 2025. Although such remediation efforts are valuable, an effective solution set ultimately must turn off the tap of plastic flowing into the ocean.

SOLUTIONS AT SCALE

The problem of marine plastic pollution shares many similarities with the challenge of climate change. Plastics are made from fossil fuels, and manufacturing them contributes to greenhouse gas emissions. Plastic pollution and climate change are both global issues, with multigenerational consequences. Their causes are decentralized, widely distributed, and difficult to trace with precision. The two problems result from modern industrial civilization, such that more globalization and economic development have tended to correlate with growth in both problems. And the products and conveniences that contribute to these global environmental problems—like imported produce, gasoline-powered cars, and Amazon's delivery service—are associated with a rising standard of living.

In both cases, questions of accountability and responsibility are difficult to answer. No single actor or small group can solve the problem alone. And the global population has a stake, because the negative impacts of climate change and marine plastic are broad, multifaceted, and incompletely understood.

Humans have not done enough to prevent the harmful impacts of climate change, and the same is true for marine plastic pollution. In many cases, there have been commitments without follow-through. For example, the 1982 United Nations Convention on the Law of the Sea, which 168 countries have ratified, includes a requirement that those countries take the necessary measures domestically, and establish global and regional rules, to "prevent, reduce, and control pollution of the marine environment from land-based sources." Clearly, these are unmet obligations.

More recent international agreements, like the UN Sustainable Development Goals and the 2011 Honolulu Commitment to reduce marine plastic debris, are nonbinding aspirations, meant to coordinate international action but not to enforce it. And the legislative actions taken at local, state, and national levels are not uniform enough, or strict

enough, to generate effective solutions from the bottom up. Many seem to be looking to the smallest possible scale—the level of the individual—for solutions. Consumers are increasingly expected to make lifestyle choices that reduce the consumption and disposal of plastic products. Meanwhile, the ultimate sources—the industries that produce, market, and export plastic products—have largely avoided regulation and accountability.

The differences between climate change and marine plastic debris suggest that the plastic waste problem should be easier to solve. Plastics are tangible, physical things that can be relatively easily collected, compared with atmospheric molecules of greenhouse gases. And it is difficult to explain why increasing numbers of wildfires or destructive hurricanes are a product of climate change, whereas it is easy to comprehend the cause and effect of a seal entangled in a net, a sperm whale with a belly full of plastic debris, or oysters containing microplastics.

But there is much we could be doing that has yet to be done. A thorough and effective solution set for marine plastic pollution would likely include government regulations on product design, international funding mechanisms for modernizing waste management systems, and investment by state and national governments in cleanup activities. A total solution is probably impossible, given the amount of plastic that is already in the oceans. But an effective set of responses can still reduce the magnitude and longevity of the problems caused by ocean plastic, and mitigate the eventual impact on ecosystems and human communities.

Marine plastic pollution is a grand challenge: it raises deep questions about the human relationship to the planet and broad international trends related to population growth, consumption, development, and sustainability. The best set of solutions is likely to span the scale from individual to international action, and to address different points along the chain of production, consumption, and disposal. Perhaps the most important response for now would be more education about this complex problem, to encourage consumers, voters, and ocean users to change their behavior—and pressure industries and governments to take decisive action. ■