Reckoning with the U.S. Role in Global Ocean Plastic Waste (2021)

DETAILS

250 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-45885-6 | DOI 10.17226/26132

CONTRIBUTORS

Committee on the United States Contributions to Global Ocean Plastic Waste; Ocean Studies Board; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2021. *Reckoning with the U.S. Role in Global Ocean Plastic Waste*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26132.

3

Plastic Waste and Its Management

Once produced, plastics are formed into a range of products that are used for a period of time. Some products, such as packaging, may have a very short use time while other more durable plastic products may remain in use for decades. There can be a short or long lag time between plastic production and its transformation into plastic waste. Plastic waste is created when, intentionally or unintentionally, plastics are taken out of use and enter a waste stream as part of a waste management process or are released into the environment.

This chapter first presents global estimates of plastic waste, followed by a detailed look into U.S. municipal solid waste (MSW) characterization, generation, and management. Other sources of U.S. plastic waste are explored. "Leaks" of plastic waste into the environment are discussed. Lastly, this chapter reviews the current regulatory framework of plastic waste management in the United States. Subsequent chapters identify transport, pathways, distribution, and fate of plastic waste that leak to the environment and ultimately to the ocean.

NATIONAL AND GLOBAL PLASTIC WASTE GENERATION

Plastic waste generation is directly related to the quantity of plastics produced and used. Understanding and estimating plastic waste generation can be challenging; there are a few different estimates from the past few years, which are summarized in Table 3.1. In terms of cumulative generation of plastic waste, Geyer, Jambeck, and Law (2017) estimate that from 1950 through 2015, 6.3 billion metric tons (BMT) of plastic waste were generated globally (Figure 3.1). In addition, Geyer, Jambeck, and Law (2017) estimated that in 2015, 302 million metric tons (MMT) of global plastic waste were generated. According to World Bank annual estimates, in 2016, the world generated 2.01 BMT of waste, of which 242 MMT was estimated to be plastic waste (Kaza et al. 2018). With cumulative quantities of plastic production projected to reach 34 BMT and plastic waste projected to reach 26 BMT by 2050, the total amount of plastics in the waste stream is projected to grow (Geyer, Jambeck, and Law 2017) (Figure 3.1).

Table 3.1 also indicates national estimates for U.S. plastic waste generation with estimates of 42 MMT in 2016 by Law et al. (2020) and 32 MMT in 2018 by the U.S. Environmental Protection Agency (U.S. EPA 2021b).

U.S. MANAGEMENT OF PLASTIC WASTE

Municipal Solid Waste

This chapter describes solid waste management and primarily focuses on MSW, what people throw away every day at home and on-the-go. It is typically measured in mass per person (per capita) generation rates. This chapter does not include intentional/permitted or unintentional land-based air, water (whether wastewater, stormwater, or other water), or sludge (e.g., from wastewater treatment plants) discharges that may also contain plastics (usually smaller particles such as pre-production plastics or microplastics from clothing) unless they are disposed of as solid

Reckoning with the U.S. Role in Global Ocean Plastic Waste

waste. It also does not apply to marine discharges (e.g., lost during shipping, lost or discarded fishing gear) unless recovered and deposited in a solid waste management system. Information on non-solid waste discharges and leakage is included in subsequent chapters.

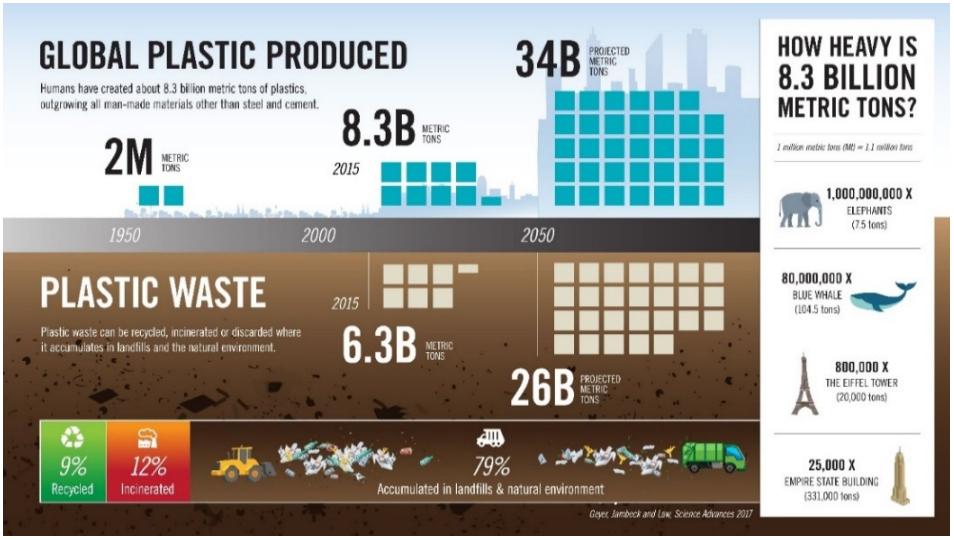

FIGURE 3.1 Global plastic production and waste generation infographic. SOURCE: Geyer, Jambeck, and Law (2017). Graphic credit: University of Georgia.

TABLE 3.1 Recent Estimates of Annual and Cumulative Generation of Plastic Waste in the United States and Globally

	Annual Plastic Waste Generation		Cumulative Waste Generation since ~1950	
Data Source	**USA**	**Global**	**USA**	**Global**
U.S. EPA 2021b	32 MMT in 2018	-	[1,000] MMT	-
Law et al. 2020	42 MMT in 2016	-	-	-
Geyer, Jambeck, and Law 2017	-	302 MMT in 2015	-	6,300 MMT in 2015
Kaza et al. 2018		242 MMT in 2016		

NOTE: Square brackets indicate "on the order of" or "approximately." These estimates were completed by the committee using available data.

Municipal Solid Waste Generation

The U.S. per person MSW generation rate ranges from 2.22 to 2.72 kg/person/day (4.9–6 lb/person/day) (EREF 2016, Powell and Chertow 2019, U.S. EPA 2021a). This is 2–8 times the waste generation rates of many other countries (Law et al. 2020). Figure 3.2 can be examined to see other countries' waste generation per capita. The United States generated about 321 MMT of waste in 2016, amounting to 16% of the world's waste (Kaza et al. 2018, Law et al. 2020). In 2016, the United States was the top generator of plastic waste (Law et al. 2020). This is despite containing 4.3% of the world's population (World Bank 2021) and being the third most populous country in the world.

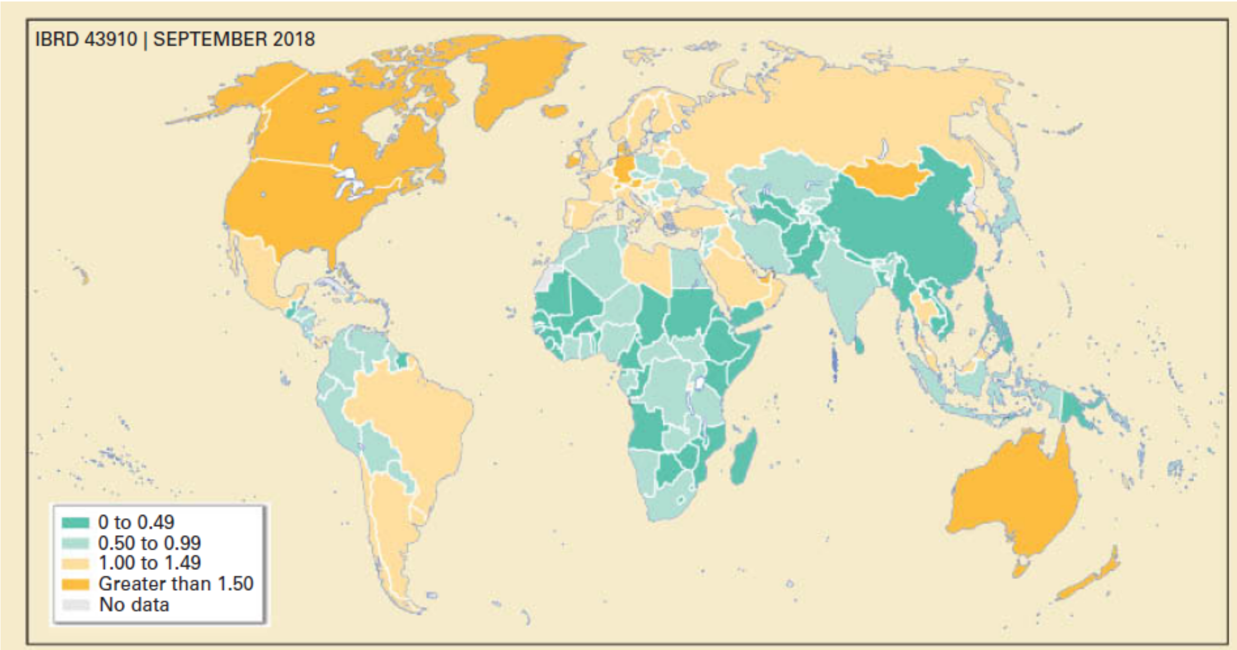

FIGURE 3.2 Waste generation per capita, illustrated in kilograms. SOURCE: Kaza et al. (2018).

In theory, managed solid waste in the United States should not contribute to ocean plastic waste as it is contained either by treatment and/or conversion into other products (recycling, composting, incineration) or contained in an engineered landfill environment. In practice, plastic waste still "leaks" from managed waste systems when blowing out of trash cans, trucks, and other managed scenarios. Waste not put into the management system, whether intentionally or unintentionally through actions like illegal dumping and littering, is considered unregulated and illegal waste in the United States.

Data on MSW are compiled by U.S. EPA through a materials flow analysis method. The quantities are estimations based on production, along with lifetimes for various products and sectors to estimate the quantity of waste generated in each sector and for particular products. Data are also measured by other industry and academic groups, states, and even cities to inform local waste management. The management of MSW typically takes place at the city or county level in the United States, and nearly every household is provided with a method to formally manage their waste. Other waste streams in the United States that may contain plastics also are described in this chapter, although little is known about their contribution to ocean plastic waste.

Municipal Solid Waste Characterization

U.S. EPA's Sustainable Materials Facts and Figures report, which calculates estimates as far back as 1960 and has been published periodically for more than 20 years, focuses on MSW. According to U.S. EPA, the MSW items include "packaging, food, grass clippings, sofas, computers, tires and refrigerators." However, U.S. EPA does not include in its analysis any materials disposed of in non-hazardous landfills that are not generally considered MSW such as construction and demolition debris, municipal wastewater treatment sludges, and non-hazardous industrial waste, some of which may be composed of plastics.

According to U.S. EPA, the generation of waste is the “weight of materials and products as they enter the waste management system from residential, commercial, and institutional sources and before recycling, composting, combustion or landfilling take place. Pre-consumer (industrial) scrap is not included in the waste generation estimate. Source reduction activities, such as backyard composting of yard trimmings, take place ahead of generation.” U.S. EPA’s materials flow methodology does not consider any “mismanagement” of waste within the United States, such as illegal dumping or littering.

The U.S. EPA MSW characterization describes waste both by material type—paper, plastics, metal, glass, etc.—and by products, which are separated into durable goods (typically stay in use more than 3 years), nondurable goods (stay in use less than 3 years), and containers and packaging (typically enter the waste stream the same year they are purchased). Examples of durable goods include appliances, furniture, casings of lead-acid batteries, and other products. Examples of nondurable goods include disposable diapers, trash bags, cups, utensils, medical devices, and household items such as shower curtains. U.S. EPA does not include plastics in transportation products, other than lead-acid batteries, in its management analysis (U.S. EPA 2021a).

U.S. EPA estimated that 12.2% of MSW (by mass) was plastics (32.4 MMT) in 2018. However, the estimate for annual generation of plastic solid waste has been as high as 42 MMT when using waste generation rates derived from waste disposal data from MSW management facilities (Law et al. 2020). Plastics are the third highest percentage of material (by mass) in MSW after paper and food waste, and are slightly higher than yard waste (Figure 3.3).

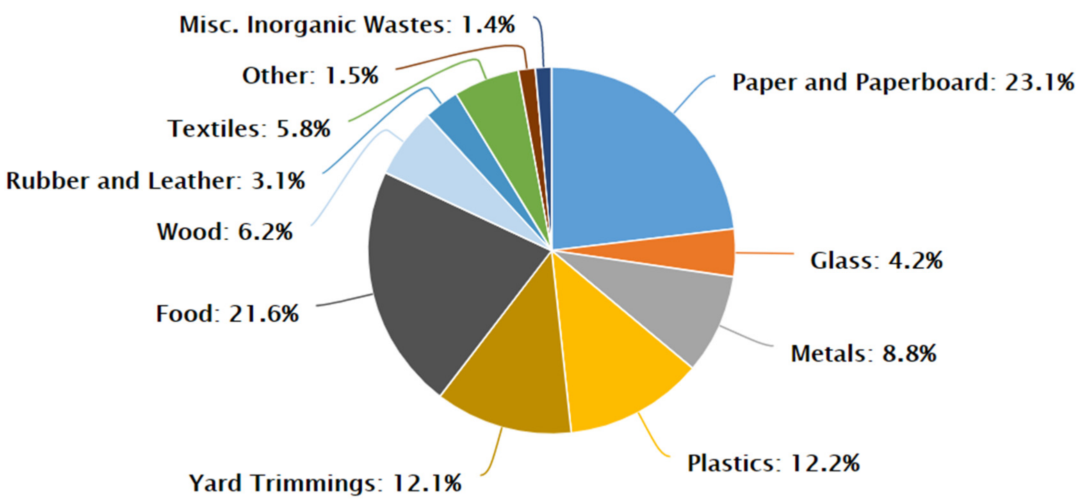

FIGURE 3.3 Municipal solid waste generation categorization by mass in the United States for 2018. SOURCE: U.S. EPA (2021a).

The steep increase in plastic production described in the previous chapter has been mirrored by an increase in the percent of plastics in U.S. MSW (by mass)—from 0.4% in 1960 to 12.2% in 2018, with a peak of 13.2% in 2017 (U.S. EPA 2020a). The mass of plastic waste generated has been increasing in the United States since 1960, with the fastest increase occurring from 1980 to 2000 (Figure 3.4).

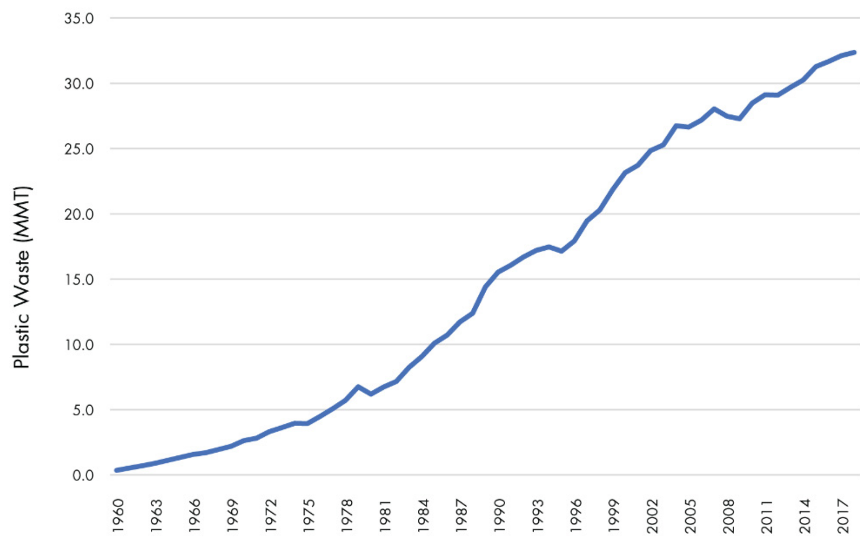

FIGURE 3.4 U.S. annual plastic waste generation from 1960 to 2018 in million metric tons. SOURCE: U.S. EPA (2020a).

Municipal Solid Waste Collection

Residential waste is a category of MSW. MSW is broader and includes waste from single-family homes to multi-family housing and waste from commercial and institutional locations, such as businesses, schools, and hospitals. Generally single-use plastics used in the home and packaging for any packed food items will end up in the residential waste stream, as will longer-lived durable goods, when disposed of. In the United States, the residential waste and recycle stream usually is picked up at people's homes by the local community (either paid through fees or taxes) or a private hauler (hired by the resident), or the resident takes the waste to a transfer station or directly to a management facility (e.g., landfill, or recycling facilities called material recovery facilities [MRFs]). Plastic waste generation at the residential level is not measured or monitored directly. Community members typically do not know how much or what kind of waste they generate. Residential waste and mass of items collected for recycling is recorded at the community level through landfill or MRF disposal. Garbage truck weight is measured at the landfill scale houses for the purpose of calculating tipping fees (e.g., a fee to pay for waste disposal). Outgoing trucks of baled materials (e.g., bales of plastics, such as polyethylene terephthalate [PET] or mixed plastics) that are shipped to processing facilities for recycling are also weighed.

Since solid waste is typically measured in mass (e.g., for solid waste audits, "tipping" fees at disposal facilities, etc.), but plastic bulk density is low, it weighs very little for how much space it takes up if uncompacted. The bulk density (the weight of the waste divided by the volume it occupies, including the space between waste items) of uncompacted mixed plastics is approximately 121 lb/yd^3 (72 kg/m^3). For example, trash may look like it is comprised mostly of plastics because film plastics spread out and look large owing to their surface area, and empty plastic containers still take up the space that held the product.

Waste collection methods are often determined by population density. For low population densities, curbside collection may not be economically feasible and residents may be required to take their own waste to a transfer station for drop-off, which puts an extra burden on residents. Rural areas not served by curbside collection may manage more MSW, including plastics, "at home" through open burning and dumping privately/illegally (Tunnell 2008). In Virginia, for

Reckoning with the U.S. Role in Global Ocean Plastic Waste

example, open burning is still allowed if there is no regular trash collection.[1] With population density as a driver for waste generation, higher density areas like urban and suburban areas generate more plastic waste per unit area than rural areas; however, urban areas have more developed waste management infrastructure (e.g., more curbside collection and recycling) than rural areas. This pattern occurs globally as well as in the United States (Schuyler et al. 2021, Youngblood et al. In Review).

Although plastic waste quantities generated in urban and rural areas differ and the proportion of plastic waste not collected or captured by waste management systems varies, both are sources of ocean plastic waste (see subsequent chapters). Regardless of population density or land use, coastal areas have greater connectivity to the ocean, placing any uncollected plastic waste from urban, suburban, rural, recreational, industrial, or other human activities at a higher risk of ending up in the ocean. Coastal areas might be subject to greater efforts to reduce, collect, and divert plastic waste sources, but inland areas, especially along waterways, should be managed to reduce plastic wastes moving toward the ocean.

Municipal Solid Waste Management

In 2018, to manage MSW, the United States landfilled 50%, recycled 24%, composted 8.5%, and combusted 12% of all MSW (U.S. EPA 2021a). Of plastics in MSW, 75.6% were landfilled (comprising 18.5% of all landfilled materials, by mass), 8.7% were recycled, and 15.8% were combusted with energy recovery. While both recycling and combustion capacity expanded in the 1980s and 1990s, these percentages have remained relatively consistent over the past 15 years (Figure 3.5).

Decisions about how waste, including plastic waste, is managed are made by state and local governments and other groups, who bear the growing costs and challenges of managing increasing amounts of waste. Plastic products disposed as waste (reported by U.S. EPA in durable goods, nondurable goods, and containers and packaging categories) consist of a wide variety of plastic polymers containing mixtures of chemical additives that allow for an array of properties (Deanin 1975). Thus, the composition of plastics in MSW is incredibly diverse, which creates challenges in waste management systems, especially when sorting materials for appropriate recycling or composting.

Landfilling

Since the Resource Conservation and Recovery Act (RCRA) passed in 1976, landfills are lined with composite liners to protect the soil and groundwater (e.g., geomembrane and 2 feet of compacted clay), and the liquid that permeates and seeps through the landfill waste is collected and removed. Landfills are sloped to one side with a drainage layer (e.g., sand) so the liquid can quickly run off the liner, collect, and then be pumped out of the landfill. Trucks deposit waste onto the working face of the landfill and bulldozers move the waste. Compacters compress the waste so the landfill is as dense as possible. Once the landfill has reached its fill height, gas wells are installed throughout the landfill to collect released gases (i.e., methane, carbon dioxide, nitrogen,

[1] § 10.1-1308 of the Code of Virginia; §§ 110, 111, 123, 129, 171, 172, and 182 of the Clean Air Act; 40 CFR Parts 51 and 60. "Open burning is permitted for the on-site destruction of household waste by homeowners or tenants, provided that no regularly scheduled collection service for such refuse is available at the adjacent street or public road."

and other trace gases). The landfill is then capped with an impermeable layer, which is similar to the bottom layer. Sometimes soil and grass are placed on top of the landfill. After the landfill is closed, it requires at least 30 years of monitoring.

None of the highest production plastics (PET, high-density polyethylene [HDPE], polyvinyl chloride [PVC], low-density polyethylene, polyethylene [PE], polystyrene [PS]) biodegrade in a landfill, and they are considered contamination in compost. Since plastic products also contain an array of additives (Deanin 1975), this diversity of plastic waste can challenge recovery and recycling. In addition, plastics can be mixed with food waste, most of which goes to landfills (only 6.3% of food waste is composted, as compared with 69.4% of yard waste, which is restricted from landfills).

With the vast majority (76%) of managed plastic waste disposed of in landfills, there are opportunities to reduce this amount and conserve non-renewable resources, increase energy efficiency, and provide economic and environmental benefits through effective source reduction, recycling, and composting. These options are in line with U.S. policy to prevent and reduce pollution at the source whenever feasible (Pollution Prevention Act). These principles are expressed in the RCRA, where the order of preference in managing materials is source reduction, reuse, recycling, and disposal.

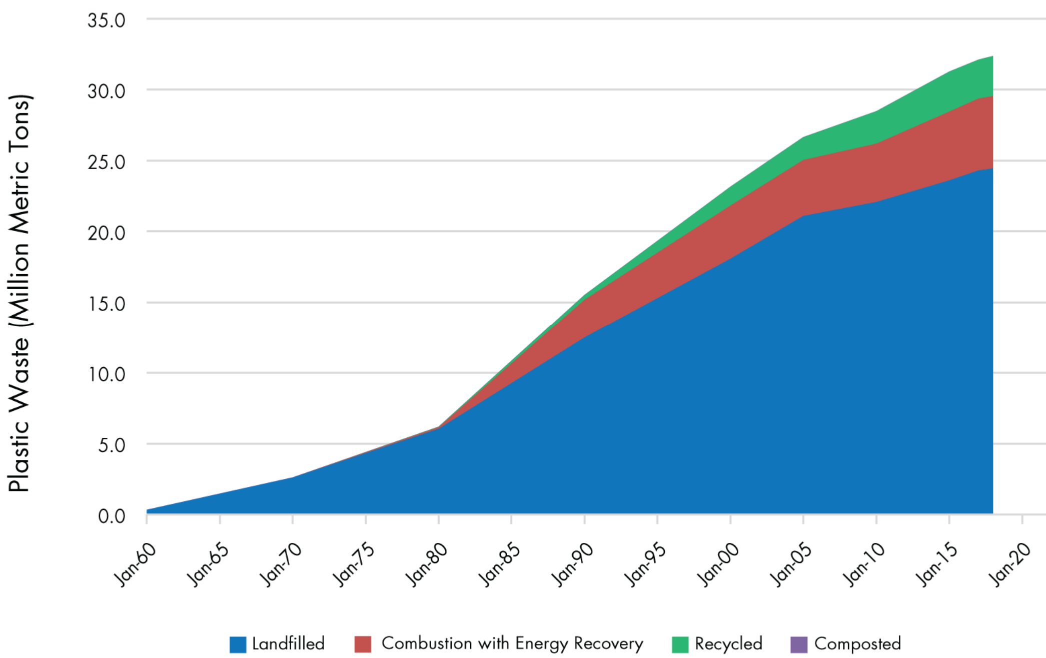

FIGURE 3.5 U.S. plastic waste management of municipal solid waste from 1960 to 2018 in million metric tons (MMT) per year. Composted levels are at zero during this period. SOURCE: U.S. EPA (2020a).

Recycling

The statistics reported by U.S. EPA on plastic recycling reflect the amount of plastic waste collected for reprocessing into a secondary raw material, primarily by mechanical recycling. Mechanical recycling requires waste items to first be sorted according to primary material type (polymer resin type), indicated on many household products by the numbered resin identification code ("chasing arrows" symbol). Products might be further sorted according to color, size, or

Reckoning with the U.S. Role in Global Ocean Plastic Waste

density before being washed of residues or contaminants, then shredded or chopped into smaller particles that can be remelted and formed into a reprocessed material (Ragaert, Delva, and Van Geem 2017).

The increasing diversity and complexity of material and product types present major challenges to recycling, especially when waste is collected in "single-stream" recycling programs, which require mechanical and manual separation at MRFs. Contamination of individual plastic items by food or product residues, and of entire loads by items that are not recyclable (often by people "wish-cycling," who place items in recycling collection in hopes they might be recycled), increases the difficulty and cost of separation (Damgacioglu et al. 2020). Furthermore, because plastics degrade throughout their life cycle and during reprocessing, recycled materials are frequently used in "downcycling" applications that do not require the same material quality standards as food grade applications, for example (Ragaert, Delva, and Van Geem 2017). For these reasons and others, such as the low cost of primary (usually fossil) feedstocks used to make virgin plastics and fluctuating market demand for recycled materials, the economics of recycling can be extremely challenging (Rogoff and Ross 2016). Further details on where plastic scrap can be exported is illustrated in Box 3.1.

A suite of chemical processes, many of which are under development, that aim to break plastic waste down into chemical constituents, which may include the monomer building blocks of the original plastic (total depolymerization) or other intermediates (partial depolymerization), are broadly referred to as "chemical recycling" or "advanced recycling". A major goal of chemical recycling is to produce secondary materials of the same or higher quality than the initial plastic waste itself ("upcycling"), ideally striving for many cycles of polymerization and depolymerization to maximize resource use (Coates and Getzler 2020). Presently, the only forms of chemical recycling utilized in the United States (and only at small scale) are energy-intensive pyrolysis and gasification processes, whose primary products are fuel and other chemical products rather than secondary polymers (Ragaert, Delva, and Van Geem 2017). Priority research opportunities have been identified to inform federal investment in research into new materials, together with the chemical processes to upcycle these materials once they become waste, in order to move toward a more circular life cycle for plastics (Britt et al. 2019).

Challenges include incompatibility of different plastic types and large differences in processing requirements (Closed Loop Partners 2020, Hopewell, Dvorak, and Kosior 2009, OECD 2018). Addressing these barriers to plastic recycling can produce co-benefits, including improving energy efficiency, environmental performance, and process efficiency, while creating economic opportunities for new products (U.S. Department of Energy 2021). A variety of prizes or challenge competitions have been designed to stimulate innovation in overcoming the barriers associated with plastic recycling or to minimize reliance upon these difficult-to-manage materials (e.g., Department of Energy Plastics Innovation Challenge, New Plastics Economy Innovation Prize, the REMADE Institute, or the Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment [BOTTLE] Consortium), and some of these efforts have already had results (Rorrer, Beckham, and Roman-Leshkov 2021, Shi et al. 2021).

Composting

High production plastics such as PE, polypropylene, PS, and PVC are strongly resistant to biodegradation in any environment, due to the strength of the carbon-carbon bond that constitutes the polymer backbone. Therefore, managed composting is not a suitable management strategy for the vast majority of today's plastic waste, which would be contaminants in composting environments. A variety of certified compostable plastics (with ester backbones) have been developed to completely biodegrade (defined by complete metabolism by microorganisms in a specified time period) in managed composting facilities that maintain the specific environmental conditions required for material breakdown. However, the benefits of these products are lost if they are not collected and transported to managed composting facilities. In most regions of the United States such facilities are not available. Even if there are nearby facilities, the consumer must recognize the item as compostable and place it in the correct collection bin, rather than in regular trash or in recycling collection, where it would contaminate the recycling stream (Law and Narayan 2021). Thus, the benefits of compostable plastics can only be realized if sizeable investments in composting infrastructure and consumer education occur.

Management of Plastic Containers and Packaging

Plastic containers and packaging comprise the largest fraction of the plastic waste stream (41%) and enter the waste stream most quickly after production in the year they are produced. Products in this category also commonly leak from the waste management system (see subsequent section on leakage). U.S. EPA defines plastic packaging as bags, sacks, and wraps; other packaging; PET bottles and jars; HDPE natural bottles; and other containers. It does not include single-service plates, cups, and trash bags, all of which are classified as nondurable goods. Plastic containers and packaging were the highest category within plastic materials in 2018 with an estimated 13.2 MMT generated, or approximately 5.0% of total MSW generation (U.S. EPA 2021b). In 2018, 1.8 MMT (13.6%) of plastic containers and packaging materials was recycled. However, this was lower than the quantity combusted with energy recovery, 16.9% (2.2 MMT), while the remainder (more than 69%) was landfilled (Figure 3.6). The two items most commonly recycled were PET bottles and jars at 29.1% (of total PET bottle waste generation) and HDPE natural bottles (e.g., milk and water bottles) at 29.3% (of total HDPE natural bottle generation). The higher rates of recycling are reflective of the product mass, with containers heavier than film plastics, and their more uniform design characteristics (monochromatic and with fewer additives), which makes these products easier to recycle and the recycled material more valuable.

Management by Designing for End of Life

The approach of designing products for end of life is embedded in the U.S. EPA's Sustainable Materials Strategy and related programs (U.S. EPA 2015). However, there are many barriers, including a substantial mismatch between the materials that are created and the ability of the waste management system to accept and transform these materials into a second use or beneficial product (U.S. GAO 2020), such as being effectively recyclable or biodegradable.

Part of the solution to this mismatch is to adopt an integrated, life-cycle perspective (Walls and Palmer 2001) in the design of plastic products, especially single-use products, that explicitly accounts for direct and indirect costs associated with the product's end-of-life disposal. This perspective would reduce the social cost of plastic disposal and waste leakage by pushing producers to design and use more easily biodegradable and recyclable/reusable materials, and by enabling consumers to choose products that permit low-impact disposal (Abbott and Sumaila 2019). Green Engineering principles (American Chemical Society 2021), if followed during material development and product design, can reduce the externalities associated with plastics. Circular Economy concepts, designed to promote "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops thanks to long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Geissdoerfer et al. 2017), may be helpful as well.

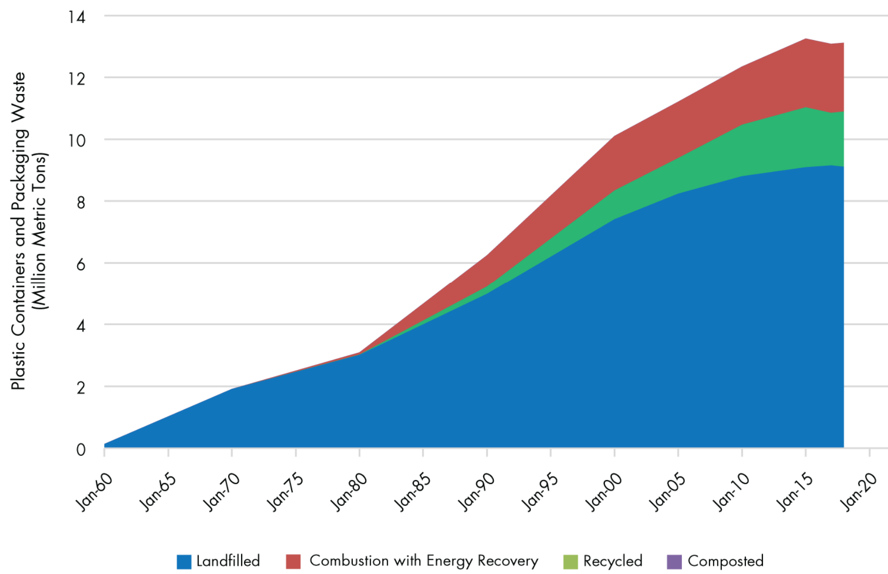

FIGURE 3.6 U.S. Environmental Protection Agency plastic containers and packaging waste management. Composted levels are at zero during this period. SOURCE: U.S. EPA (2021b).

BOX 3.1
Management Through Import and Export of Plastic Scrap

Some of the plastic materials sent to material recovery facilities in the United States are exported to other countries after processing. Prior to the import restrictions initially implemented by China at the end of 2017 (resulting in a relative import ban), the United States exported half of its plastic waste intended for recycling to China (Brooks, Wang, and Jambeck 2018). After 2018, plastic scrap previously destined for China was either re-routed to other countries (e.g., Cambodia, India, Indonesia, Malaysia, Pakistan, Vietnam, Thailand, and Turkey) or placed in domestic landfills (INTERPOL 2020). U.S. plastic scrap exports decreased by 37.4% in the first quarter of 2018, largely due to the 92.4% decline in plastic scrap exports to China (Mongelluzzo 2018). In the same time period, U.S. waste exported to Malaysia increased by 330%, to Thailand by 300%, to Vietnam by 277%, to Indonesia by 191%, and to India by 165% (INTERPOL 2020). In 2018, other Asian countries (e.g., Indonesia, Thailand, Malaysia, Vietnam, Taiwan, and India) started to regulate, and sometimes ban, plastic waste imports due to waste surpluses and illegally exported wastes (e.g., hazardous waste mixed in with plastic scrap) (INTERPOL 2020, Staub 2021, Upadhyaya 2019). In 2020, the United States' top six trade partners (Canada, Malaysia, Hong Kong, Mexico, Vietnam, and Indonesia) accounted for 75% of U.S. exports of plastic scrap (Brooks 2021).

Export destinations of U.S. plastic waste can be a source of plastics in the ocean. Recent amendments to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal placed new controls on exports of plastic waste. However, the United States is not a signatory and is therefore not subject to the stricter guidelines of plastic exports. As such, U.S. plastic waste exports have continued, though greatly decreased as described above. In addition, U.S. exports will be affected by decisions of the receiving countries that are parties to the Convention (U.S. EPA 2021h). In the absence of the Basel Convention, the United States could continue to record and document exports by the U.S. Trade Association and U.N. Comtrade.

Developing alternative materials or other product delivery systems can spark innovation and economic growth in the United States. There are several voluntary corporate commitments to change materials, use more recycled materials, and increase material circularity, so materials and infrastructure development to meet those demands are needed (U.S. Plastics Pact 2021). Efforts could include sustainable packaging associations (precompetitive collaborations) to develop alternative materials and agree on more homogenized packaging designs for end of life, packaging with more value (e.g., single, homogenous materials; design for recycling/end of life), and designing out problematic items/materials (e.g., certain colors, smaller caps/lids). For composting to be a part of an integrated management approach, there is a need for both biodegradable materials and further development and expansion of composting infrastructure in the United States. For a more detailed approach to materials design, please see the recent article by Law and Narayan (2021).

Municipal Solid Waste Management Disparities and Environmental Justice

U.S. EPA defines environmental justice as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations and policies." (U.S. EPA 2021g). Environmental justice is one of the top priorities of the current U.S. EPA Administrator, Michael S. Regan (U.S. EPA 2021g). Impacts to vulnerable populations occur all along the life cycle of plastics, starting from extraction of oil and natural gas as feedstocks of plastic production and including the production of plastic resins at refining and chemical processing facilities, the use of plastics from smaller or limited packaging choices, and management and leakage of plastic waste to the environment (CIEL 2019, UNEP 2021b).

Environmental justice efforts around waste began in the United States with communities (e.g., in Houston, Texas and Warren County, North Carolina) fighting landfills and hazardous waste management facilities in areas populated predominantly by African Americans (Bullard 1990, McGurty 2000). These impacts and concerns continued for years, with research similar to that done on hazardous waste landfills conducted on U.S. non-hazardous solid waste landfills in the contiguous 48 states finding that these landfills are also more likely to be located in counties with higher percentages of poverty and people of color (Cannon 2020). More recently in Houston and Dallas, Texas, studies show people of color are concentrated in neighborhoods closer to MSW landfill facilities where housing prices and median incomes are lower than those just 2 or 3 miles away (Erogunaiye 2019). This research also showed that the magnitude of disparity within 1–3 miles of a landfill had increased over the 15-year period from 2000 to 2015 (Erogunaiye 2019). Additionally, MSW incinerators are disproportionately located in communities with at least 25% people of color and/or impoverished people (Tishman Environment and Design Center 2019). Burning plastics releases toxic chemical pollutants, such as dioxins and furans (Verma et al. 2016), which can have serious health implications for community members (Tishman Environment and Design Center 2019, Verma et al. 2016, and see Box 1.3 for more information on health impacts).

U.S. EPA, in line with the Biden-Harris Administration's directive to all federal agencies to "embed equity into their programs and services to ensure the consistent and systematic fair, just, and impartial treatment of all individuals," announced in April 2021 that it was taking steps to address environmental justice across the agency. These steps include strengthening enforcement of violations, incorporating environmental justice across all its work, improving "early and more frequent engagement with pollution-burdened and underserved communities" and tribal officials, and considering and prioritizing "direct and indirect benefits to underserved communities in the development of requests for grant applications and in making grant award decisions as allowed by law" (U.S. EPA 2021g).

Municipal Solid Waste COVID-19 Impacts

The global COVID-19 pandemic has had extensive impacts on the generation and characterization of MSW in the United States. Within 1 week of various city, state, or national mandates for public areas to use and wear personal protective equipment, like masks, these items were reported as litter through the Marine Debris Tracker mobile app and to programs of the Ocean Conservancy (Ammendolia et al. 2021, Marine Debris Tracker 2020, Ocean Conservancy 2021b). In addition, waste collection companies reported decreases in commercial waste collection because people were not commuting to the office or conducting activities outside of home (Waste Advantage Magazine 2020). For the same reasons, residential waste increased by 5–35%, increasing logistical and economic strain on haulers and communities trying to manage MSW (Dzhanova 2020, Redling 2021).

Other Types of Plastic Waste (Non-MSW)

While some waste categories are included in the measurement of MSW, some other sources of plastic waste are identified below. Only some are measured or monitored under existing federal environmental law. The most consistent and well documented information on U.S. plastic waste comes from data on management of solid waste under RCRA or documentation of waste recovered from or measured in the environment (see Chapters 4 and 5). Because many leakage estimates rely only on MSW data, they are likely conservative estimates. Aside from the National Oceanic and Atmospheric Administration's (NOAA's) Marine Debris Monitoring and Assessment Program (Chapter 6), no federal monitoring programs document or monitor the amount of plastic waste contained in air or water discharges, though state and local governments have conducted specific monitoring studies, sometimes with federal support or assistance.

Construction and Demolition Debris

Starting in 2018, U.S. EPA included construction and demolition debris as a separate section outside of the MSW waste generation in its Sustainable Materials Facts and Figures report (U.S. EPA 2021a). In general, construction and demolition debris materials are durable goods and do not enter the waste stream quickly. However, they are sometimes illegally dumped or managed at unregulated construction sites or abandoned lots (Jambeck 2021), and it is unknown what quantity may be entering the ocean. Construction and demolition debris is also generated in catastrophic events (e.g., hurricanes, tsunamis, floods, etc.), which can generate debris, including plastics, that enters waterways and the ocean. The most prominent example of this occurred when the Tohoku Tsunami hit Japan. Of the 5 MMT of debris generated, 1.5 MMT floated and portions subsequently were transported to the shores of the United States (Murray, Maximenko, and Lippiatt 2018). It is currently unknown how much plastic waste may enter the ocean in U.S. waters from catastrophic events, such as floods.

Industrial

Industrial waste is any waste (including plastics) generated by manufacturing or industrial processes. As solid waste, it can be classified under RCRA as either hazardous or non-hazardous solid waste, and governed by assigned management requirements (see Appendix C: Legal Framework for more information). Industrial waste can include plastic pellets, also referred to as nurdles.

Industrial waste can also include sludge and liquid waste from industrial facilities regulated and permitted under other statutes, such as the Clean Water Act (U.S. EPA 2021c); however, the Clean Water Act does not identify plastics as a pollutant for discharge monitoring or limits (Appendix C). However, some chemicals used in plastics (and many other industrial applications) may be separately monitored or regulated. Under the Pollution Prevention Act, which promotes pollution prevention and production, U.S. EPA collects and publicly shares data on industrial facility releases of certain harmful chemicals (including unregulated chemicals) that it lists on the Toxics Release Inventory (TRI) (U.S. EPA 2021d). The TRI does not include plastics but does include a number of chemicals used in the manufacture of plastics (Wiesinger, Wang, and Hellweg 2021).

Plastic Waste in Wastewater and Stormwater

Some plastic waste enters wastewater infrastructure in sewage, sometimes combined with stormwater. Nearly all large plastic items entering sewers and arriving at wastewater treatment plants are removed by bar screens prior to treatment through biological and chemical processes. Most microplastics remain in the post-treatment sludge (managed typically through landfilling or land application) with a smaller amount discharged in treated wastewater, mostly as small fibers and fiber fragments (Carr, Liu, and Tesoro 2016). No federally mandated monitoring of plastic waste occurs at wastewater treatment plants. A 2021 U.S. EPA multisector stormwater general permit has been challenged in court for not sufficiently addressing plastic pollution from pre-production plastic pellets, flakes, and powders (Center for Biological Diversity 2021, U.S. EPA 2021c).

Transportation Infrastructure

Transportation systems are sources of plastic waste in the environment, including plastics shed from the operation of transportation systems (e.g., from tires, paints, brake linings), litter from passengers (considered MSW) and cargo, and litter from transportation systems themselves (e.g., plastics and chemicals from road paint and asphalts). Transportation systems also tend to be sources of plastics to stormwater and other drainage systems that transport plastic wastes to local waterways and as far as the ocean, with tire particles being a major source of microplastics (Werbowski et al. 2021), as described in Chapter 4. Some industrial plastics from transportation systems appear to have special forms of toxicity. For example, a tire-rubber derived chemical called 6PPD-quinone (also known as (*N*-(1,3-dimethylbutyl)-*N*′-phenyl-p-phenylenediamine quinone)) has been identified as a cause of mortality for salmon in the U.S. Pacific Northwest (Tian et al. 2021). Nonpoint source runoff from highways is subject to management guidance under the U.S. EPA Clean Water Act programs, as well as in coastal and Great Lakes areas through a joint program with NOAA under the Coastal Zone Management Act (U.S. EPA 2021e).

Reckoning with the U.S. Role in Global Ocean Plastic Waste

However, current federal law does not require monitoring of the sources of macroplastics or microplastics in transportation systems (Appendix C).

Marine Activities

The disposal of plastic waste from vessels and at-sea platforms into the ocean is prohibited by the 1988 international maritime regulations (MARPOL Annex V). The United States is a signatory to MARPOL Annex V (an optional, non-mandatory annex of MARPOL), which has been incorporated into U.S. law via the Act to Prevent Pollution from Ships (33 USC 1901 and 33 CFR 151). However, enforcement of MARPOL Annex V is challenging and compliance is difficult to assess. In addition, accidental loss of plastic waste at sea occurs, such as from abandoned vessels, lost ships and cargo, and release of plastic products or plastic "nurdles" from shipping containers. Some of these losses are recognized at the state legislative level, such as abandoned vessels, which are subjects of public concern, but are not well quantified in the United States or in U.S. waters.

One type of maritime-generated ocean plastic waste is abandoned, lost, or otherwise discarded fishing gear (ALDFG). No robust estimates of the total amount of ALDFG generated worldwide or by U.S. domestic fisheries are available (Richardson et al. 2021), though a recent global meta-analysis indicates 5–30% of fishing gear is lost annually worldwide depending on gear type (Richardson, Hardesty, and Wilcox 2019). Industrial trawl, purse-seine, and pelagic longline fisheries are estimated to lose a median of 48.4 kt (95% confidence interval: 28.4 to 99.5 kt) of gear each year during normal fishing operations, but this estimate does not include abandoned or discarded gear; other gears known to become derelict such as pots and traps, pole and line, and driftnets/gillnets; or nearshore and small-scale fisheries (Kuczenski et al. 2021). The role of illegal, unreported, and unregulated fisheries in the generation of ALDFG, or other plastic waste, is also unknown. Lastly, ALDFG resulting from U.S. recreational or subsistence fishing activities is also a source of ocean plastics that is little quantified or understood. There is also growing attention to the contribution of aquaculture activities to plastic waste at a global scale (Sandra et al. 2020), but U.S. contributions have not been assessed. A full description of the types of ALDFG generated in the United States or resulting from U.S.-based fisheries or aquaculture is beyond the scope of this report.

U.S. PLASTIC WASTE LEAKAGE

Quantities (Mass)

"Managed" plastic waste is contained by treatment and/or conversion into other products (recycling, composting, incineration) or contained in an engineered landfill. If not effectively "managed" in these ways it may have intentionally or unintentionally "leaked" into the environment. Plastic waste not making it into (e.g., illegal dumping, litter) or leaking out of (e.g., blowing litter or unregulated leaking or discharge) our management systems is categorized as "mismanaged" plastic waste. Figure 3.7 represents ways waste may leak, even from a solid waste management system reaching 100% of the population. Once in the environment, wastes are more difficult to recover for later treatment or disposal.

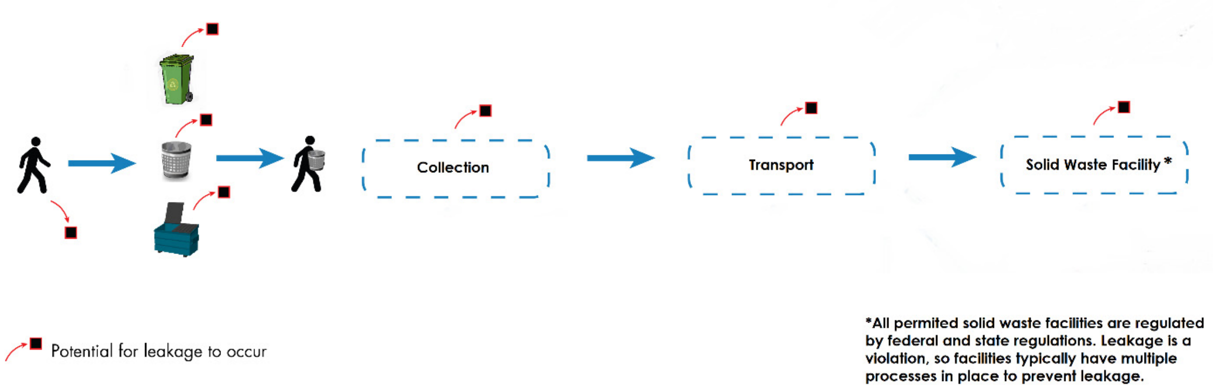

FIGURE 3.7 Points of plastic leakage for municipal solid waste in the United States. Black box with red outline denotes leakage potential.

Because U.S. EPA data on MSW do not quantify mismanaged solid waste that leaks into the environment, researchers have developed approaches to derive such estimates, drawing on U.S. EPA reported data and other data sources. Law et al. (2020) quantified the U.S. contribution of mismanaged plastic waste to the environment as 1.13–2.24 MMT in 2016. Mismanaged waste included a model estimate for litter, illegal dumping, and estimates of exported plastics collected for recycling that were inadequately managed in the importing country. Litter—solid waste that is intentionally or unintentionally disposed of into the environment despite the availability of waste management infrastructure—was coarsely estimated as 2% of plastic solid waste generation (owing to a lack of mass-based estimates of litter rates). For 2016, the quantity of plastic litter estimated annually in the United States was 0.84 MMT (Law et al. 2020). Law et al. (2020) estimated that 0.14 to 0.41 MMT of plastics were illegally dumped (i.e., disposed of in an unpermitted area) annually, despite the availability of waste management infrastructure. This estimate comes from assessment of illegal dumping in three U.S. cities (San Jose, California; Sacramento, California; and Columbus, Ohio).

The final component of mismanaged solid waste in the Law et al. (2020) analysis is exported plastic scrap collected for recycling that is inadequately managed in the importing country (see Box 3.1). Law et al. (2020) estimated that in 2016, 0.15–0.99 MMT of plastics exported by the United States in plastic scrap and paper scrap (in which plastics are included as contaminants) bales were disposed of during processing and likely entered the environment in the importing country (Law et al. 2020). The total quantity of plastic solid waste from the United States entering the environment in 2016 was estimated to be 1.13–2.24 MMT. Comparing mismanaged plastic waste from other countries, Law et al. (2020) concluded that the United States was the 3rd to 12th largest contributor of plastic waste into the coastal environment with 0.51–1.45 MMT in 2016.

High-Leakage Items

Similar to the waste management system categorizing the waste stream by material and products, varying plastic products and materials leak from the solid waste management system in different proportions evidenced by what does, and does not, end up in our environment. Litter surveys and community science efforts (at large scales, see Chapter 6) have shown that while plastics make up a large percentage (70–80%, see Table 3.2) of what is found in the environment as litter, the majority of plastic items are single-use, including packaging, as well as tobacco-

Reckoning with the U.S. Role in Global Ocean Plastic Waste

related (e.g., cigarette filters, product packaging, and e-cigarette cartridges) (Public Health Law Center 2020) and unidentified fragments from larger items. These large-scale surveys generally do not include the documenting of microplastic or pre-production resin pellets at a more local level (Tunnell et al. 2020).

TABLE 3.2 Top 10 Items Tallied from Each Data Set Compilation

Data Set	Date Range (n = number of litter items counted)	Top 10 in Rank Order
Ocean Conservancy's International Coastal Cleanup (USA only)	2015–July 2021 (n = 18,565,446), 82% plastic waste	Cigarette butts, food wrappers, plastic bottle caps, plastic beverage bottles, straws, stirrers, other trash, beverage cans, plastic grocery bags, glass beverage bottles, metal bottle caps, plastic lids
MDMAP Accumulation of items 2.5–30 cm	2009–2021 (n = 895,417), 84% plastic waste	Hard plastic fragments, foamed plastic fragments, plastic rope/net, bottle/container caps, filmed plastic fragments, plastic other, cigarettes, plastic beverage bottles, food wrappers
MDMAP Accumulation of items 30 cm or larger	2009–2021 (n = 5,561), 58% plastic waste	Lumber/building material, hard plastics, plastic rope/net, other plastics, cloth/fabric, foam plastics, film plastics, other metal, buoys and floats, other processed lumber, plastic bags
MDMAP 2.5 cm + standing stock and using MDMAP 2.0 protocol	2009–2021 (n = 71,306), 86% plastic waste	Hard plastic fragments, foamed plastic fragments, plastic bottle or container caps, plastic fragments film, plastic food wrappers, other plastics, cigarettes, plastic rope or net pieces, processed lumber–building material, plastic beverage bottles, processed lumber–paper and cardboard
Marine Debris Tracker (USA only)	2011–July 2021 (n = 2,333,337), 71% plastic waste	Plastic or foam fragments, cigarettes/cigars, plastic food wrappers, plastic caps or lids, other (trash), plastic bottle, plastic bags, paper and cardboard, aluminum or tin cans, foam or plastic cups or plates, straws
Mississippi River Plastic Pollution Initiative (MRPPI)	March 15–April 25, 2021 (n = 75,184), 74% plastic waste	Cigarette butts, food wrappers, plastic beverage bottles, foam fragments, aluminum cans, hard plastic fragments, plastic bags, plastic/foam cups, paper and cardboard, film fragments. Note: PPE was 1–2% of all litter found

NOTE: If an item labeled "Other" was in top 10, the 11th ranking item was also included since "Other" can include a wide array of items. MDMAP = Marine Debris Monitoring and Assessment Project, PPE = personal protective equipment.

While historically marine litter studies and land-based work have not always been consistent in terms of methods used (Browne et al. 2015), there has been consistent, even if opportunistic, data collection through a few community science-based initiatives. These include the International Coastal Cleanup, which has been collecting data annually for more than 35 years; NOAA's Marine Debris Monitoring and Assessment Project initiative; and opportunistic data from the mobile app Marine Debris Tracker (initially funded by NOAA) as well as a scientifically designed targeted data collection event in the Mississippi River corridor in 2021 (Youngblood, Finder, and Jambeck 2021). For more information about these programs, please see Chapter 6 on Tracking and Monitoring.

The Cost of Leakage

While the drivers for leakage of plastics into the environment are complex and varied (see previous section), the cost and burden are borne by communities, especially residents. The United States spends roughly $11.5 billion on cleanup from trash leakage into the environment (Keep America Beautiful Inc. 2010). States, cities, and counties together spend at least $1.3 billion. Cleanup is often a hidden cost within employee salaries or other projects, which makes it difficult to determine the actual cost to local governments. For example, the Georgia Department of Transportation spends more than $10 million on annual labor and equipment costs necessary for picking up and disposing of trash from state roadways (GDOT 2020). CalTrans costs have grown from $65 million in 2016–2017 to $102 million in 2018–2019 to keep trash off of transportation areas (CalTrans 2020).

CURRENT REGULATORY FRAMEWORK FOR U.S. MANAGEMENT OF PLASTIC WASTE

Starting in the 1970s, the United States created several legal frameworks designed to control and prevent the release of harmful, toxic, or hazardous substances, as well as manage transportation, treatment, and disposal of specific wastes. This body of law applies to many materials originally created for societal benefit that were later found to be harmful to human or environmental health, such as polychlorinated biphenyls or chlorofluorocarbons. These U.S. laws address waste disposal and pollution prevention, control, and cleanup across geographic boundaries (by air, water, and soil) by setting science-based criteria and technology-based limits at the federal level, and use command and control or more flexible compliance methods (e.g., cap and trade incentives). Various levels of delegations are shared with state and local authorities. In addition, states may have delegated or parallel requirements.

In 1976, in the wake of a national hazardous waste crisis, Congress fundamentally changed the way solid and hazardous waste is managed in the United States by enacting RCRA.[2] RCRA, implemented by U.S. EPA and the states, created a "cradle to grave" solid and hazardous waste management system. This hazardous waste management system prohibited the previous practice

[2] Resource Conservation and Recovery Act (RCRA) - Public Law 94-580, October 21, 1976, (42 U.S.C. 6901-6992; 90 Stat. 2795), as amended by P.L. 95-609 (92 Stat. 3081), P.L. 96-463 (94 Stat. 2055), P.L. 96-482 (94 Stat. 2334), P.L. 98-616 (98 Stat. 3224), P.L. 99-339 (100 Stat. 654), P.L. 99-499 (100 Stat. 1696), P.L. 100-556 (102 Stat. 2779).

of open dumping and replaced it with requirements to use engineered and regulated landfills, composting, and recovery systems like recycling.[3] RCRA has management requirements assigned to either "solid waste" or "hazardous waste" and currently treats plastic waste as a subset of "municipal solid waste" for disposal in landfills or by incineration.

Other U.S. environmental laws focus on preventing, controlling, and cleaning up discharges of pollutants, hazardous substances, and other contaminants to air and waters (including coastal and marine waters). These include laws enacted to control the discharge of pollutants or hazardous substances from certain facilities into the environment, such as the Clean Water Act, Clean Air Act, Ocean Dumping Act, and the Toxic Substances Control Act. In 1980, Congress assigned liability for cleanup and compensation for injury and contamination from historic contamination by enacting the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as Superfund). All of these laws are implemented by U.S. EPA as the lead agency. U.S. Coast Guard and NOAA have major roles for cleanup, removal, and damage assessment for injury in coastal and marine environments.

Neither the Clean Water Act nor the Clean Air Act controls or measures releases of plastic waste from littering, mismanaged waste, sewage outfalls, runoff, industrial emissions, or other sources. The legal or regulatory definitions of "pollutants" or "hazardous substances" do not include plastics or plastic pollution, though legal challenges are testing whether some may be included based on toxicity or other regulatory criteria. No specific plastic effluent limits for industrial wastewater, stormwater, and plastic production facilities exist unless established under a Clean Water Act regional protocol to protect certain receiving waters from specific discharges, such as from stormwater systems. These include Total Maximum Daily Load (TMDL) limits for "trash" in local water bodies in various locations. While these TMDLs are not specific to plastics, plastic waste is included in trash. The state of California has set plastic discharge limits to govern pre-production plastic discharges.

NOAA plays a leading federal role in plastic waste prevention, removal, cleanup, and restoration through a range of environmental authorities including the Clean Water Act and Ocean Dumping Act, which relates to ship-based disposal. Its most comprehensive role on ocean plastic waste is under the 2006 Marine Debris Research, Prevention, and Reduction Act, amended in 2012, 2018, and 2020 (Marine Debris Act), which specifies its role in cleanup, government coordination, grantmaking, and research. The Marine Debris Act does not provide specific authority for any federal agency to regulate the production, transportation, or release of plastic waste. The most specific legislative action around plastic pollution in aquatic and marine environments was the 2015 Microbead Free Waters Act, which prohibits the manufacturing, packaging, and distribution of rinse-off cosmetics and other products, like toothpaste, that contain plastic microbeads. U.S. EPA operates the non-regulatory Trash Free Waters program, which engages with states and communities on pilot prevention projects.

Most information available on U.S. plastic waste amounts, management, and leakage derives from solid waste data collected by U.S. EPA under RCRA, with other data from NOAA's Marine Debris Program, import or export data, and some state and local research, cleanup, or pilot projects.

[3] Code of Federal Regulations (CFR) Title 40, Parts 239–282.

CHAPTER SYNOPSIS

The potential for mismanaged waste starts at the generation of waste (discarded materials), although reused or donated materials are not categorized as waste. With the scale of U.S. waste generation, there is an opportunity to reduce the amount of waste produced, both for the environment as well as the economy, given that all waste management activities take effort, money, energy, and often transportation. As indicated in this chapter, there are multiple paths by which waste can enter into the environment. The next chapters describe how leaked plastic waste travels through the environment and the ocean.

PRIORITIZED KNOWLEDGE GAPS

As illustrated throughout this chapter, there are few data sources to understand sources, types, and relative scale of plastic waste generated and disposed or leaked to the environment beyond MSW in the United States. Specifically, there is a lack of plastic waste data on industrial wastes including pre-production plastics and fibers, nonpoint sources of waste like runoff, point sources, wastewater treatment outflows, and sludge applications.

Furthermore, direct measurements of plastic waste and leakage, in different geographic regions of the United States and urban/rural environments, are necessary to improve and better constrain source estimates from existing crude (order-of-magnitude) model-based estimates, as illustrated in the U.S. EPA data.

FINDINGS, CONCLUSIONS, AND RECOMMENDATION

Finding 4: The United States is the largest generator of plastic solid waste, by mass and per capita. Plastic product end-of-life disposal can be improved by enhancing the capability of municipal solid waste systems to collect, sort, and treat specific materials and products, and by considering end-of-life disposal in plastic material and product design and manufacture.

Finding 5: Although recycling is technically possible for some plastics, little plastic waste is recycled in the United States. Barriers to recycling include the wide range of materials (plastic resins plus additives) in the waste stream; increasingly complex products (e.g., multi-layer, multi-material items); the expense of sorting contaminated, single-stream recycling collections; and the low cost of virgin plastics paired with market volatility for reprocessed materials.

Finding 6: Chemical recycling processes that strive toward material circularity, such as depolymerization to monomers, are in early research and development stages. Such processes remain unproven to handle the current plastic waste stream and existing high production plastics.

Finding 7: Compostable plastics may replace some products currently made with unrecyclable materials. However, successful management of compostable plastics requires widely available managed composting facilities and consumer awareness on product disposal in dedicated compost collection, neither of which exists today.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Conclusion 2: Materials and products could be designed with a demonstrated end-of-life strategy that strives to retain resource value.

Conclusion 3: Effective and accessible solid waste management and infrastructure are fundamental for preventing plastic materials from leaking to the environment and becoming ocean plastic waste. Solid waste collection and management are particularly important for coastal and riparian areas where fugitive plastics have shorter and more direct paths to the ocean.

Conclusion 4: The United States has a need and opportunity to expand and evolve its historically decentralized municipal solid waste management systems, to improve management while ensuring the system serves communities and regions equitably, efficiently, and economically.

Conclusion 5: Although recycling will likely always be a component of the strategy to manage plastic waste, today's recycling processes and infrastructure are grossly insufficient to manage the diversity, complexity, and quantity of plastic waste in the United States.

Recommendation 1: The United States should substantially reduce solid waste generation (absolute and per person) to reduce plastic waste in the environment and the environmental, economic, aesthetic, and health costs of managing waste and litter.

Reckoning with the U.S. Role in Global Ocean Plastic Waste (2021)

DETAILS

250 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-45885-6 | DOI 10.17226/26132

CONTRIBUTORS

Committee on the United States Contributions to Global Ocean Plastic Waste; Ocean Studies Board; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2021. *Reckoning with the U.S. Role in Global Ocean Plastic Waste*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26132.

4

Physical Transport and Pathways to the Ocean

Plastic waste has a complex life cycle, moving from waste sources along a variety of long or short, direct or convoluted paths (Alimi et al. 2018, Bank and Hansson 2019, Eriksen et al. 2014, Hoellein and Rochman 2021). The ocean is the Earth's ultimate sink, lying downstream of all activities. Almost any plastic waste on land has the potential to eventually reach the ocean or the Laurentian Great Lakes. Major paths of plastics to the ocean are summarized in Figure 4.1. These include urban, coastal, and inland stormwater outfalls; treated wastewater discharges; atmospheric deposition; direct deposits from boats and ships; beach and shoreline wastes; and transport from inland areas by rivers and streams (Dris, Gasperi, and Tassin 2018). This chapter reviews the many pathways that plastic waste can take from land to enter the ocean.

In the course of transport, plastic waste may encounter mechanisms that sort particles by density, size, and other characteristics that, in turn, affect their subsequent transport, physical and chemical characteristics, and ultimate fate in the environment. These processes affect the storage, availability, and impact of plastic waste at locations in shoreline, nearshore, and offshore environments. Processes that sort particles and influence their transport along various pathways are described in this chapter. Transformations that affect their size, number, shape, chemical composition, and biological and physical reactivity are discussed further in Chapter 5.

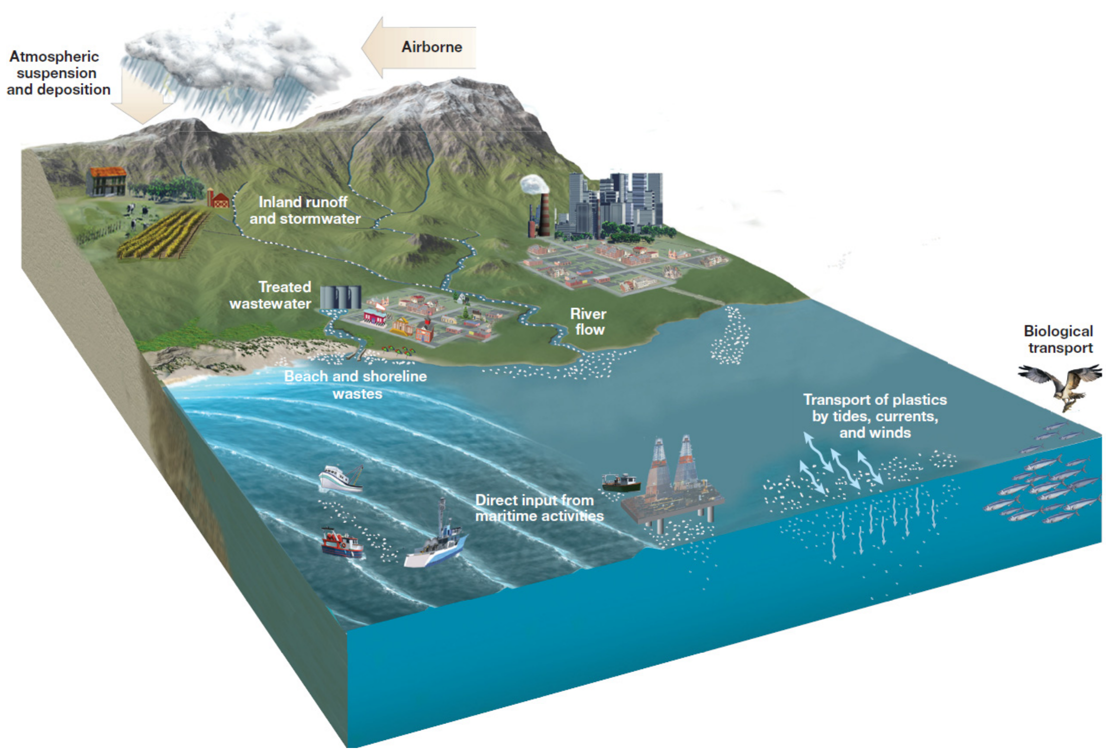

FIGURE 4.1 Major transport pathways for plastics from land to the ocean.

Figure 4.1 lists major pathways and mechanisms that move plastic waste to the ocean. The pathways are broadly categorized as waterborne, airborne, and direct deposit of plastic waste into the ocean. While the contributions of each pathway to the amount of plastic waste in the ocean are difficult to quantify, the following describes the state of knowledge about modes and patterns of transport, as well as examples of measurements or models of plastic waste transport along each pathway.

WATERBORNE PATHWAYS

Waterborne pathways of plastic waste include river flows, stormwater discharge, wastewater treatment plant effluent, and beach and shoreline wastes (see Figure 4.2). In the absence of a comprehensive U.S. national study, the presumptive pathway transporting the highest mass of plastic waste from both inland and coastal regions to the ocean is rivers and waterways. The mobilization of plastic waste along these pathways surges with floods and streamflow, as greater inundation gathers plastics from larger and more varied geographic areas and propels them seaward more energetically. These pathways also often bring about important transformations, delays, and barriers to the plastic waste they transport. Plastic particles' size, shape, and bulk density affect their waterborne transport (Haberstroh et al. 2021).

River Flow

Rivers and smaller waterways (e.g., streams, canals, channels) are major pathways for plastic waste entering the ocean from a variety of sources including littering (intentional or accidental), illegal dumping, and landfill leakage, as well as stormwater outfalls, combined sewer overflows, wastewater treatment plant effluent, and atmospheric deposition, which are described as pathways in more detail in subsequent sections (Williams and Simmons 1997, Windsor et al. 2019, Woodward et al. 2021). Once considered direct pipelines to the sea, rivers are dynamic drivers of plastic waste retention, burial, resuspension, and degradation as debris is transported downstream (Barrows et al. 2018, Hurley, Woodward, and Rothwell 2018, Nizzetto et al. 2016). Rivers, tributaries, and their floodplains are often "hotspots" of plastic accumulation (areas with the most marked and dramatic accumulation), with river and stream outlets also creating local hotspots in coastal marine areas (Windsor et al. 2019).

Plastic transport depends on the size, shape, and buoyancy of plastic items or particles, as well as river characteristics such as flow rate, velocity, and shoreline and waterway morphology (e.g., vegetation, rocks, etc.), which affect the time dependence of transport, including debris stranding and erosion (Balas et al. 2001, Hoellein and Rochman 2021). Variations in river discharge of plastics occur on a variety of time scales (Watkins et al. 2019), including those related to weather or climate variations (e.g., storm events, precipitation patterns) and source input (e.g., wastewater outflows or seasonal littering variability). For example, studies in the Los Angeles River (Moore, Lattin, and Zellers 2011) and Chesapeake Bay (Yonkos et al. 2014) found debris concentrations increased sharply after major rainstorms. In Delaware Bay, local concentrations of floating plastics were driven by ocean tides and winds (Cohen et al. 2019), and in the River Seine (France), the mass of floating plastics increased with river flow (Gasperi et al. 2014, Tramoy et al. 2019).

Robust estimation of spatially and temporally variable transport (or flux) of plastic debris is rare. Across the globe, including in locations across the United States, the abundance of large plastic and microplastic debris in river water and sediments has been measured using a variety of methods (e.g., Adomat and Grischek 2021, Campanale et al. 2020, González-Fernández and Hanke 2017, González-Fernández et al. 2021). However, most studies report abundance at discrete sampling stations in one-time or short-term studies, potentially underestimating variability in time. For example, McCormick et al. (2016) measured the accumulation and export of anthropogenic litter from the riparian zone (up to 10 m from the water's edge) of rivers near Chicago, Illinois at biweekly and seasonal scales (McCormick et al. 2016). This riparian litter was highly mobile, a factor not captured in one-time "snapshot" sampling. Net accumulation rates depended on sampling frequency, where more frequent sampling gave higher accumulation rates. Also, they found that mobility varies with different debris characteristics. For example, because of their pliability, lightweight plastic films (wrappers and bags) were more likely to be retained on natural debris or vegetation than heavier, but more rigid, metal cans and glass bottles, which were transported farther. In some studies, microplastic loads increased after storm events (Yonkos et al. 2014) or periods of increased river discharge, and in one case the increase was attributed to combined sewer overflows (Wagner et al. 2019).

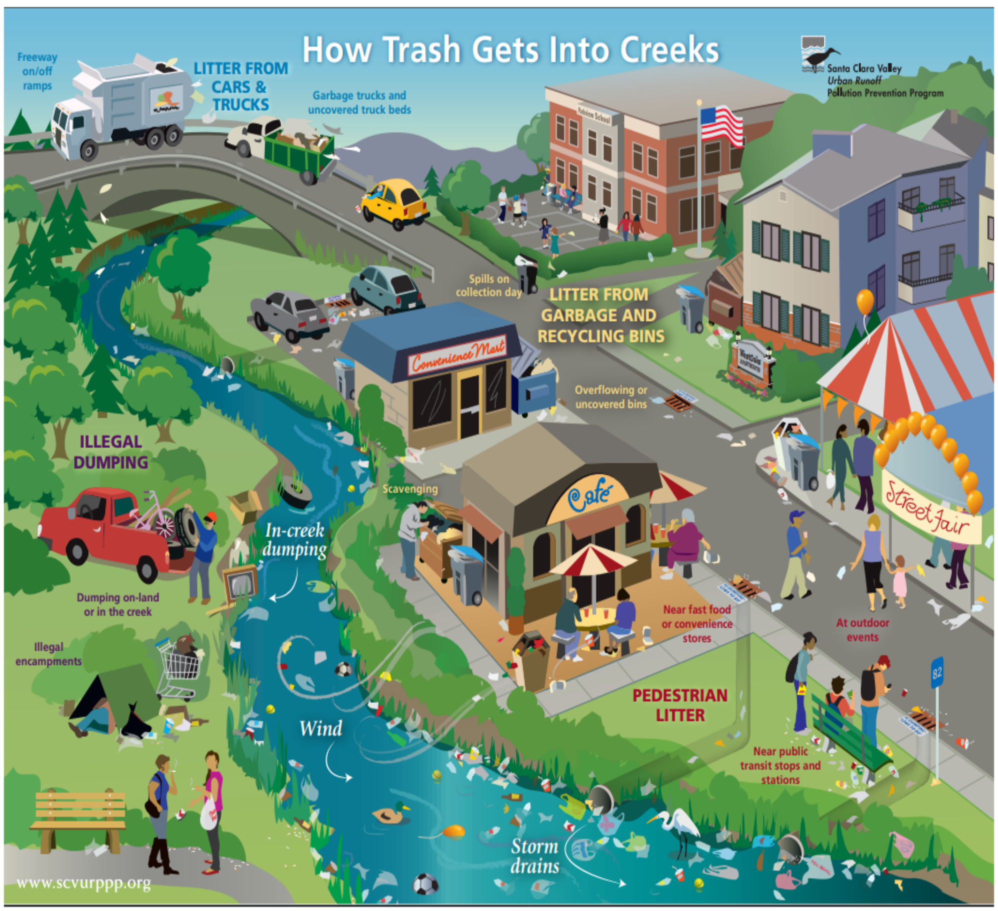

FIGURE 4.2 Sources and pathways of plastics in waterways. SOURCE: SCVURPPP (2021).

Quantitative global estimates of transport of plastic debris by rivers to the ocean come from modeling studies that use proxies including population density and mismanaged plastic waste generation rates to predict debris fluxes, which were then evaluated against available published data from a small number of individual rivers (Lebreton et al. 2017, Schmidt, Krauth, and Wagner 2017). At least one field study found poor agreement between estimates based on field measurements and the previously modeled predicted outflow of plastics, in this case in six Chinese rivers (Mai et al. 2020). Meijer et al. (2021) added probabilistic modeling to account for the likelihood of land debris to enter a waterway as a function of distance from the shoreline, land use, wind, and precipitation. This study estimated 0.8–2.7 million metric tons (MMT) of plastic waste enter the ocean globally per year from riverine sources, with 80% entering from more than 1,000 rivers. However, another study taking a similar modeling approach, but with slightly different model construction and calibration methods, estimated much smaller global plastic outflows from rivers (0.057–0.265 MMT [Mai et al. 2020]). There continue to be large uncertainties in the global estimation of riverine transport of plastic waste to the ocean, highlighting the importance of local field studies to more directly measure these fluxes and their variability. Such information will be valuable not only to better understand local sources and transport dynamics but also to build and validate models used for process studies and for regional or global budgeting studies.

Stormwater Runoff

Urban and suburban stormwater can be substantial and important contributors of plastic waste, especially microplastics from land to rivers and nearshore areas (Sutton et al. 2019). Stormwater runoff occurs when precipitation (e.g., rain and snowmelt) "flows over land or impervious surfaces, such as paved streets, parking lots, and building rooftops, and is not absorbed into the ground"(U.S. EPA 2021). This runoff gathers debris and chemical pollutants, including plastic waste, from the land and streambanks (see Figure 4.3) and propels them to rivers, streams, lakes, and coastal waters, where they can harm humans and ecosystems (U.S. EPA 2020b).

Recent regulations on the amount of trash allowed in receiving water bodies in California have resulted in initial studies that estimate the total amount of trash, including plastic waste, generated and loaded in California's San Francisco Bay Area stormwater system (Werbowski et al. 2021). This study (discussed in greater detail later in the chapter) confirmed findings of an earlier study in Los Angeles County, California, showing that trash loads could be roughly estimated by land use in the drainage area (EOA 2014). Researchers typically use land use as a proxy for stormwater trash loading in urban areas (Marais, Armitage, and Wise 2004).

The highest rates of plastic waste generation and loading found in California were from industrial, retail, and residential areas, as well as highways and expressways (EOA 2014). Other factors associated with higher plastic loading from urban areas include combinations of lower income, higher population density, and other demographic factors. However, significant correlations were not observed between generation rates and any individual factor. These results are similar to those for a study completed near Leipzig, Germany (Wagner et al. 2019).

FIGURE 4.3 Mixed stormwater debris. Photo credit: K.L. Law.

Wastewater Discharges

Wastewater entering treatment plants can be highly contaminated with quantities of mostly fine microplastics, particularly fibers shed from clothing and other textiles (Carr, Liu, and Tesoro 2016). In wastewater treatment plants, most microplastics are removed and concentrated in wastewater sludges (Carr, Liu, and Tesoro 2016, Werbowski et al. 2021). These wastewater sludges are usually landfilled (buried), but some are applied to forest or agricultural land or are incinerated. Primary, secondary, and tertiary wastewater treatment removes cumulatively higher proportions and smaller sizes of plastic particles, with the remaining plastics discharged in liquid effluent, which may enter estuaries or the ocean directly, or rivers and streams leading to the ocean. Most microplastic removal occurs in primary treatment by surface skimming and sludge settling (Carr, Liu, and Tesoro 2016). Plastics in treated wastewater effluent tend to be much smaller in size and density and tend to be textile fibers or fiber fragments (Carr, Liu, and Tesoro 2016, Werbowski et al. 2021). Small amounts of these plastics can escape the wastewater collection system before they can arrive at wastewater treatment plants (e.g., during big storms which cause sewer overflows).

The role of onsite sewage disposal systems (e.g., septic tanks and cesspools) in the transport of microplastics to groundwater, and possibly to the ocean via groundwater discharge, is little studied. There is some preliminary evidence of the presence of microplastics in groundwater (Panno et al. 2019). Waterborne pollution delivery via submarine groundwater discharge to the ocean from onsite sewage disposal systems is known for other pollutants (e.g., Amato et al. 2020, and see Mezzacapo et al. 2021 for a state of Hawaii review). Coastal inundation events from storms, tides, or related to climate-induced sea level rise are expected to increase with attendant vulnerabilities to coastal- or waterway-adjacent onsite sewage disposal systems (Habel et al. 2017), potentially increasing the frequency of this type of microplastic transport. The importance of onsite sewage disposal systems as microplastic sources, and associated groundwater discharge of microplastics to waterways and the ocean, is presently uncertain.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Beach and Shoreline Waste

Beach and shoreline waste may be deposited as locally generated litter (accidental or intentional), or may be waste that was generated elsewhere and washed ashore (i.e., “beached”). The hydrodynamic processes that transport shoreline debris and determine its residence time before entering or returning to the ocean are complex. These processes are largely determined by local winds, waves, and tides, which are influenced by the shape of the coastline and seafloor bathymetry (van Sebille et al. 2015). The turbulence generated by wave breaking, especially in shallow areas such as the surf zone, can cause particles on the seabed or in sediments to be resuspended, and interaction of plastic waste with beach or seafloor sediments creates stresses that may enhance their fragmentation into smaller particles (Chubarenko et al. 2020, Efimova et al. 2018).

Delays and Barriers on the Way to the Ocean

Whether plastic waste entering inland streams is likely to arrive at the ocean depends on interceptions or transformations that occur along the way. This section examines processes that filter, sort, and delay plastics on the way to the ocean. Chapter 5 expands the discussion of chemical, physical, and biological transformations to plastic particles.

Sortings

Plastic particles transported by waterborne pathways often become sorted by density and size, much like natural sediments (Lenaker et al. 2019). Denser waterborne plastics tend to settle to the bottom, where they are transported as bedload sediment by river, storm, and tidal currents, and tend to deposit in bays, canyons, and nearshore areas (Barnes et al. 2009, Galgani, Souplet, and Cadiou 1996, Schwarz et al. 2019). Larger denser particles tend to accumulate locally near river and stormwater outfalls, as stream velocities diminish in open water. However, very tiny (micron-sized) and more fibrous plastics tend to remain in suspension by fluid turbulence (Carr, Liu, and Tesoro 2016), causing them to move more readily in water flows (Liro et al. 2020, van Emmerik et al. 2018). For an individual plastic item or particle, this might lead to a cycle of transport, settling, and flood remobilization that prolongs its path to the sea for years (Liro et al. 2020).

In the nearshore region, highly periodic tidal currents are important in moving and sorting plastic particles. Plastic particles denser than seawater, such as tire particles, tend to settle but may continue to move under the influence of tidal and flood currents and may become resuspended by waves in shallower water (Chubarenko and Stepanova 2017, Sutton et al. 2019). Floating plastic particles, which are less dense than seawater, will tend to accumulate near the water surface and be moved by tidal and wind-driven currents. Particles near the density of seawater are expected to be suspended more evenly throughout the water column and be carried by ambient three-dimensional currents. The processes that affect the sorting, transport, and retention of plastic particles in coastal areas are complex and, thus far, little-studied (Sutton et al. 2019, van Sebille et al. 2015).

Filtration and Adsorption

Plastics can become stuck or filtered in ways that detain or retain them before reaching the ocean (see Figure 4.4). In particular, plastics are subject to contact with stream and river banks or floodplains, including vegetation, where they can become attached or deposited for a time or quasi-permanently (Ivar do Sul et al. 2014).

FIGURE 4.4 Mixed debris experiencing a delay during low flows on the Pearl River between Mississippi and Louisiana. SOURCE: U.S. Fish and Wildlife.

Biological Transport

Biological transport of inland plastic waste to the ocean or lakes, and vice versa, occurs by birds, fish, and other animals. Although the amount of transport by these means is likely small relative to the overall transport of ocean plastic waste, it can be meaningful from an ecological, community, or individual organism's perspective. The interaction of plastic waste and living organisms can result in negative impacts on organisms or ecosystems (Bucci, Tulio, and Rochman 2020). The nexus between biological transport of plastic waste and its distribution and fate is addressed in Chapter 5.

Microbial and other colonization of plastic waste in aquatic environments, also known as biofouling, can lead to the vertical transport of plastic waste in the water column (Tibbetts et al. 2018). Biofouling may alter the bulk density of plastic items, causing them to sink and affecting their settling.

AIRBORNE PATHWAYS: WIND

As with waterways, the atmosphere is both a transport mechanism and a reservoir for environmental plastics. Plastic waste from shed microplastics, to everyday litter (e.g., bags and wrappers), to large debris mobilized in severe wind storms can be suspended in the atmosphere and transported as a function of item size, density, and aerodynamic shape, as well as wind strength, turbulence, wind duration, and pathway obstructions. Figure 4.5 illustrates the familiar "Christmas tree effect" resulting from the snagging of plastic bags borne by wind in tree branches.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Microplastics in soil, on roads, and at the ocean surface that are large enough to be entrained into the atmosphere and small enough to be elevated into the atmospheric planetary boundary layer can be subject to long-range transport and may have residence times up to 1 week (Brahney et al. 2021). Cycles of suspension, deposition, and resuspension (or emission and re-emission) of microplastics result in sizable reservoirs of atmospheric plastics. For example, the estimated average atmospheric load of microplastics (4–250 um in size) over the land regions of the western United States is 0.001 MMT (Brahney et al. 2021). In analyses of particle pathways, research has demonstrated that microplastic transport can occur on regional scales (>100 km; see Allen et al. 2019) or can be dominated by large-scale (1,000 km) atmospheric patterns, resulting in deposition far from the emissions source (Brahney et al. 2021). Airborne pathways also carry a small proportion of microplastics resuspended from the ocean by sea spray for deposition on land (Allen et al. 2020, Brahney et al. 2021).

FIGURE 4.5 Plastic bags caught in tree branches in Southport, Merseyside, UK. SOURCE: Shutterstock Stock Photo**.**

DIRECT INPUT

Plastic waste is also disposed, either intentionally or unintentionally, directly into the ocean. These discharges include losses of fishing and aquaculture gear, recreational gear (e.g., during boating or scuba diving), over-board litter or intentional dumping, and cargo lost from ships and barges. Additionally, major storm events such as floods, hurricanes, and tsunamis can deposit massive amounts of debris of all types from land into the ocean in a relatively short time period. For example, the 2011 Tohoku earthquake and tsunami in Japan deposited an estimated 5 MMT of debris into the ocean (Murray, Maximenko, and Lippiatt 2018).

Finally, plastic particles that are shed during normal product use can directly enter the ocean. Examples include marine paints, coatings, and anti-fouling systems (International Maritime Organization 2019); shedding of textile fibers from synthetic clothing worn at sea; and shedding of particles from fishing gear (e.g., lines, nets).

CASE STUDY ON SAN FRANCISCO BAY AREA

San Francisco Bay is one of the most well-studied environments in the United States in regards to the transport and loading of plastic waste. Work discussed earlier on microplastic transport in the San Francisco Bay area provides some insight into quantification of flows into the ocean, in this case, from stormwater runoff and wastewater outflows (Sutton et al. 2019). The San Francisco Bay region also has a lengthy history of collecting trash data from beaches and inland shorelines during volunteer beach cleanups. An overview of the takeaways from these studies is provided below.

Despite being well-investigated relative to other areas of the United States, the San Francisco Bay has important gaps in understanding of plastic waste transport and loading. Specifically, atmospheric deposition of microplastics has not been well studied.

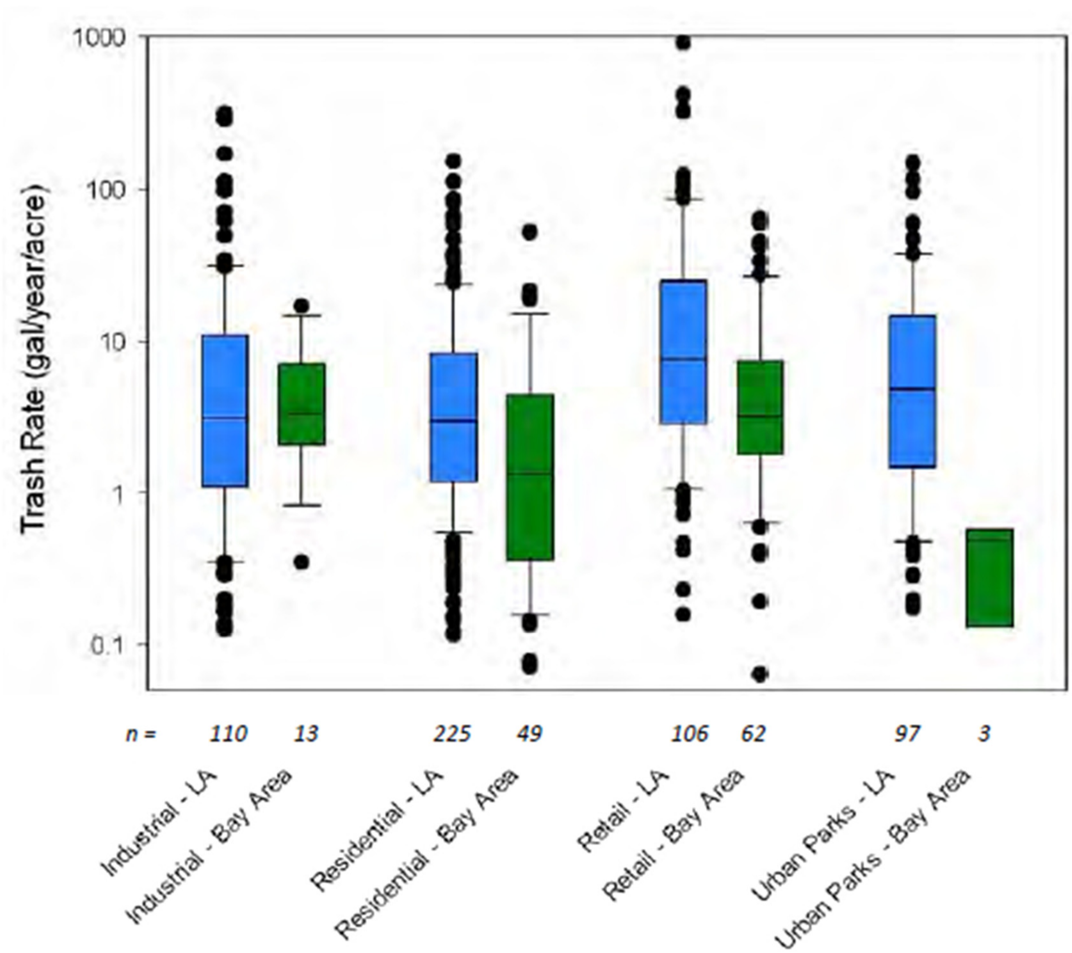

FIGURE 4.6 Ranges and median loading rates for all trash by land-use class for the San Francisco Bay Area and Los Angeles regions. The statistical minimum (lower whisker) and maximum (upper whisker), 25th percentile (lower box), median (horizontal line), and 75th percentile (upper box) are presented. Circles are statistical outliers as designated by the study. SOURCE: EOA (2014).

Trash (All Types) Loading

A study focusing on the San Francisco Bay Area and Los Angeles examined debris that is captured in stormwater systems. The vast majority of collected debris was composed of organic material (e.g., vegetation), sand, and sediment. Trash (the debris composed of human-made materials) was 17% by volume and 4% by weight of all debris collected. Of the trash, plastics were roughly 70% by volume and 50% by weight (EOA 2014).

This study examined annual trash generation (all materials, not just plastics) and how loading to stormwater systems varies with land use, population density, and income (Figure 4.6; EOA 2014). As illustrated in Figure 4.6, trash loading rates vary up to three orders of magnitude between land-use classes, indicating that other factors must also be considered (EOA 2014). The reported units (gallons/year/acre) also illustrate the difficulty of standardizing units for reporting and analysis in this field.

The San Francisco Bay Region study was prompted by efforts to regulate trash in stormwater systems in California. These efforts are now being promulgated across the state due to recent amendments to statewide stormwater permits that require municipalities and other entities to achieve zero discharge of trash into receiving water bodies. Recognizing that achieving this goal will require effective monitoring methods by which to measure progress, the California State Water Resources Control Board and San Francisco Estuary Institute recently published the *California Trash Monitoring Playbook* in an attempt to help standardize data collection (Moore et al. 2021a).

Microplastic Loading

Stormwater runoff of microplastics and microfibers is also an important contributor of plastic waste to coastal and near-coastal environments (Werbowski et al. 2021). While the volume or mass input may not be large due to the inherently small nature of the particles, the number of particles entering the marine ecosystem each year is extremely high. According to a recent study conducted by the San Francisco Estuary Institute and 5 Gyres, more than 7 trillion plastic microparticles and fibers enter the San Francisco Bay each year via stormwater runoff, which was approximately 300 times greater than the number of particles discharged by wastewater treatment facilities around San Francisco Bay (Sutton et al. 2019). Tire and road wear particles are a substantial component of synthetic microparticles to San Francisco Bay. This work can be used as a guide for interventions that target these sources.

Shoreline Debris from Community Science

In addition to the studies discussed above, the San Francisco Bay region has a decades-long record of community science efforts to capture data on beach and inland shoreline debris through volunteer beach cleanup efforts. Although the volunteer cleanups do not identify the ultimate paths of individual trash items, they indicate the types of items most frequently found in the environment, especially given the long-term data consistency. During the most recent year in which cleanups were held (e.g., not disrupted by COVID-19), 8 of the top 10 items found during cleanup activities were identified as plastics, comprising 67.3% of the total amount of debris collected (Ocean Conservancy and International Coastal Cleanup 2019). These beach cleanups identify common litter items (plastic and non-plastic) and can be used to inform litter prevention or mitigation efforts.

THE CHALLENGE OF ESTIMATING FLOWS OF PLASTICS ENTERING THE OCEAN

Although there is some understanding of the major mechanisms that transport plastic waste to the ocean, it is difficult to make quantitative estimates. Plastic waste inflows from each transport mechanism are very difficult to measure in the field. Inflows involve many large and small pathways and transport a very wide range of particle sizes, shapes, and densities, the smallest of which are often difficult to distinguish from natural fibers and materials. Furthermore, the fluxes vary over orders of magnitude with seasons, weather conditions, and location.

Another important challenge in assessing major paths and quantitative transport of plastic waste to the ocean is the lack of standard methods and data reporting within the scientific community. Each research team must decide what size debris to measure (micro-macro), the number of samples to collect and sampling area, the number of replicate samples to collect, and the timespan between repeated sampling campaigns (if any) at the same site. In addition, studies report findings in variable units including mass (kilograms), particle counts (number of particles), and volume (gallons). For analysis of microplastics, specifically, one must select an extraction protocol to remove particles from tissues, organic matter, or sediment, as well as a method for chemical identification of some or all suspected plastic particles (Hidalgo-Ruz et al. 2012). Ideally, researchers make these decisions to best address their research objective, but cost, available resources, and other practical considerations are important. Researchers routinely call for standardization or harmonization of methods to ensure high-quality data and reproducibility between studies, and for reporting standards to allow robust comparability across local, regional, and global scales (Cowger et al. 2020, Rochman, Regan, and Thompson 2017). This is a priority for hypothesis-driven research and also for assessment and monitoring objectives. This lack of standardization in plastic waste studies has hindered the effective synthesis of current knowledge and is also discussed in Chapter 6 on Tracking and Monitoring.

KNOWLEDGE GAPS

A comprehensive understanding of the contribution of various transport pathways to plastic waste in the ocean is hindered by the complexity of the transport processes and thus the data needed to measure and model variability in fluxes over space and time. Improved understanding of the absolute and relative contributions of each pathway to plastic waste in the ocean could inform and prioritize actions to reduce the transport of plastics to the ocean. The committee identified the following research gaps needed to better understand transport of plastic waste to the ocean:

1. A lack of standardized or harmonized methods for measuring plastic and microplastic concentrations and fluxes hinders comparisons between data sets that are needed to make robust estimates at regional or global scales.
2. Without systematic field, laboratory, and modeling studies on processes influencing plastic and microplastic transport in water, in air, and on shorelines, flux estimates are necessarily crude, based upon limited field data that cannot fully capture variability associated with these complex processes. Such flux estimates are critical to both designing and implementing measures to reduce these fluxes, and to understanding the impacts of these fluxes. For example, identifying large mass inputs of plastic waste is important to inform design of interventions to prevent transport into the ocean, whereas quantifying the

Reckoning with the U.S. Role in Global Ocean Plastic Waste

abundance and potential toxicity of different microplastics transported to the ocean is critical to understanding the risk to marine organisms.

FINDINGS AND CONCLUSION

Finding 8: Although the transport of plastic waste to the ocean in the United States cannot be comprehensively estimated from available data, individual studies show a sizeable transport of microplastics and macroplastic wastes along a variety of waterborne and airborne paths as well as direct inputs from shorelines and maritime activities.

Finding 9: Plastic waste discharge to the ocean varies greatly with location and in time, reflecting variability in plastic waste generation by source, effectiveness of waste collection, and variability in transport processes such as river and stream flows; ocean waves, currents, and tides; and winds.

Conclusion 6: Regular, standardized, and systematic data collection is critical to understanding the extent and patterns of plastic waste inputs to the environment, including the ocean, and how they change in time.

Reckoning with the U.S. Role in Global Ocean Plastic Waste (2021)

DETAILS

250 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-45885-6 | DOI 10.17226/26132

CONTRIBUTORS

Committee on the United States Contributions to Global Ocean Plastic Waste; Ocean Studies Board; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2021. *Reckoning with the U.S. Role in Global Ocean Plastic Waste*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26132.

5

Distribution and Fate of Plastic Waste in the Ocean

The distribution and fate of plastic waste in the ocean is a reflection of the amount and type of plastic waste that enters the environment from a diversity of sources, the efficiency of its transport from upstream locations to the ocean, and the transport and transformation of the material once it is in the ocean. For the purposes of this report, the "distribution" of plastic waste is the concentration or abundance of plastics contained in a particular component of the ocean or the Laurentian Great Lakes, including coastal boundaries (Browne et al. 2015, Gray et al. 2018, Wessel et al. 2016), the water column (Choy et al. 2019, van Sebille et al. 2020, Woodall et al. 2015), the seafloor (Goldberg 1997, Williams, Simmons, and Fricker 1993), and within marine biota (e.g., Lusher et al. 2016). The "fate" is the final form of the plastic waste after undergoing physical and chemical transformations, and the permanent or semi-permanent location in the ocean dependent on this physical and chemical fate. Thus, the concepts overlap in defining the location of plastics within the ocean, though distribution may be a reflection of both short- and long-term storage occurring at any given time.

Transformation of plastic waste resulting from physical- (abrasive), photo-, chemical-, or bio-degradation will inform plastic waste life cycles, transport, and environmental sinks. This alteration of plastic waste is known to contribute to the generation of micro- and possibly nanoplastics as larger items are transformed ever smaller. The size of plastic waste greatly affects where it will be distributed in the ocean. Quantifying the rate of these transformations is a challenge described in this chapter.

In what form and where plastic waste resides determines its effects on natural, cultural, industrial, and recreational resources at local, regional, national, and global scales. Furthermore, understanding the distribution and fate of plastic waste is critical to informing mitigation strategies (described further in Chapter 7) such as cleanup and recovery options, understanding of global ocean plastic waste sources to achieve prevention, economic policies and other rulemaking, and citizen and consumer interest and engagement.

This chapter presents, synthesizes, and evaluates key information, where available, on the distribution and fate of plastic waste in the marine environment and Laurentian Great Lakes. It also identifies associated knowledge gaps and research opportunities, and reports associated findings. The chapter begins by examining estimates of plastic waste flows to the environment, which includes land, aquatic ecosystems, coastlines, and the ocean. It then describes the various reservoirs of plastic waste in coastlines and estuaries, the water column, seafloor, and aquatic life. Next, it explains the mechanisms involved in the transformation and ultimate fate of plastics in the marine environment. The final two sections present prioritized knowledge gaps and the committee's findings.

ESTIMATED PLASTIC WASTE INPUTS TO THE ENVIRONMENT

Table 5.1 summarizes estimates of plastic waste inputs to the environment, including land, aquatic ecosystems, coastlines, and the ocean, in the United States and globally. All estimates follow the basic modeling framework first presented in Jambeck et al. (2015), in which data on

Reckoning with the U.S. Role in Global Ocean Plastic Waste

plastic waste generation and management are used to first estimate the amount of plastic municipal solid waste not collected in formal infrastructure (Jambeck et al. 2015). Nearly all studies, with the exception of Lebreton and Andrady (2019) and Meijer et al. (2021), primarily used global municipal solid waste data compiled and reported by the World Bank. While Jambeck et al. (2015) estimated mismanaged plastic waste generated by coastal populations that entered the ocean, subsequent studies considered waste generated by populations living in inland watersheds, where mismanaged waste could enter and contaminate rivers and other waterways and ultimately reach the ocean. Studies focused on riverine input of plastic waste to the ocean included available (albeit limited) field data to calibrate and test their models (Lebreton et al. 2017, Meijer et al. 2021, Schmidt, Krauth, and Wagner 2017). Later models included additional pathways of plastic waste to the environment, including flows of microplastics (Lau et al. 2020) and export of plastic waste for reprocessing (Law et al. 2020), and Lau et al. (2020) also estimated the impact of the informal sector of waste collectors on the recovery of plastics with market value.

Estimates of global input of plastic waste to the environment vary by orders of magnitude, although few are directly comparable because of differences in modeling approaches, and none are grounded in extensive empirical measurements of plastic waste abundance or transport into the environment. However, these estimates do convey the scale of the problem, with up to 100 million metric tons (MMT) of plastic waste generated in a single year estimated to be uncollected in formal waste management systems globally. In the United States, despite a well-developed formal waste management system, approximately 1 to 2 MMT of plastic waste generated domestically was estimated to enter the environment at home and abroad (after export for recycling) in 2016 (Law et al. 2020).

ENVIRONMENTAL RESERVOIRS OF AQUATIC PLASTIC WASTE

There is an incomplete understanding of the distribution of plastic waste in aquatic (freshwater and seawater) environments, though the question is much investigated. For example, a recent scholarly review of the transport and associated distribution of floating ocean plastic waste cites 400 reference sources or studies (van Sebille et al. 2020). Since the ocean is a large and complex environment, it can be helpful to break it down in smaller components to better study and address plastic pollution at various spatial and temporal scales. These smaller scales can be considered reservoirs because they are regions where plastics are being held. Reservoirs considered in this report include coastlines and estuaries, ocean water column, seafloor, and marine life (Figure 5.1). This conceptualization necessarily involves some imprecision: for example, at the water column-seafloor interface and across stratified but contiguous water column depths. Furthermore, a comprehensive assessment of the amount of plastic waste in any particular environmental reservoir has yet to be achieved.

This section reviews a selection of the scholarly literature to illustrate and explore some of these reservoirs. Information and criteria related to each reservoir reflect its unique nature, as well as available data. This section does not present a comprehensive review of the literature, which continues to grow at a staggering rate. Chapter 4 describes inland reservoirs of plastic waste, which may remain in those areas and are thus not treated in this chapter.

TABLE 5.1 Estimates of Plastic Waste Inputs to the Environment, Including Land, Aquatic Ecosystems, Coastlines, and the Ocean, in the United States and Globally

Study	Estimate of plastics entering environment (land, aquatic ecosystems, coastline, ocean)	Receiving environment	USA	Global	Year of estimate	MSW not collected in formal infrastructure	Illegal dumping (USA only)	Littering	Microplastics input	Informal sector	Export of waste	Entire population	Population in inland watersheds (via rivers)	Coastal population (50 km buffer)	# countries included (global estimates only)	Primary data source for plastic waste *(MSW)* estimation
Jambeck et al. 2015	4.8 - 12.7 MMT	Ocean		✓	2010	✓		✓						✓	192 countries	World Bank (Hoornweg and Bhada-Tata 2012)
	31.9 MMT	Coastline (50 km buffer)		✓	2010	✓		✓						✓		
	0.04 - 0.11 MMT	Ocean	✓		2010	✓		✓						✓		
	0.28 MMT	Coastline (50 km buffer)	✓		2010	✓		✓						✓		
Lebreton et al. 2017	1.15 - 2.41 MMT	Ocean		✓	2010	✓		Unknown					✓		182 countries	World Bank (Hoornweg and Bhada-Tata 2012)
Schmidt, Krauth, and Wagner et al. 2017	0.47 - 2.75 MMT	Ocean		✓	2010	✓		✓					✓		233 countries	World Bank (Hoornweg and Bhada-Tata 2012) Also Jambeck et al. 2015
	76 MMT	Land		✓	2010	✓		✓					✓			
Lebreton and Andrady 2019	60 - 99 MMT	Land		✓	2015	✓		✓					✓		160 countries	Waste Atlas 2016; Hoornweg and Bhada-Tata 2012 Also Jambeck et al. 2015
	0.0029 - 0.29 MMT	Land	✓		2015	✓		✓					✓			
Borrelle et al. 2020	19 - 23 MMT	Aquatic ecosystems		✓	2016	✓		✓					✓		173 countries	World Bank (Kaza et al. 2018); Also Jambeck et al. 2015, Lebreton and Andrady 2019
	0.20 - 0.24 MMT	Aquatic ecosystems	✓		2016	✓		✓					✓			
Lau et al. 2020	9.0 - 14 MMT	Aquatic ecosystems		✓	2016	✓			✓	✓	✓		✓		Unknown number of countries	World Bank (Kaza et al. 2018)
	13 - 25 MMT	Land		✓	2016	✓			✓	✓	✓		✓			

(Continued)

Continued

Study	Estimate of plastics entering environment (land, aquatic ecosystems, coastline, ocean)	Receiving environment	USA	Global	Year of estimate	MSW not collected in formal infrastructure	Illegal dumping (USA only)	Littering	Microplastics input	Informal sector	Export of waste	Entire population	Population in inland watersheds (via rivers)	Coastal population (50 km buffer)	# countries included (global estimates only)	Primary data source for plastic waste *(MSW)* estimation
Law et al. 2020	1.13 - 2.24 MMT	Land	☑		2016	☑	☑	☑			☑	☑				World Bank Bank (Kaza et al. 2018); Also USA-specific data
	0.51 - 1.45 MMT	Coastline (50 km buffer)	☑		2016	☑	☑	☑			☑			☑		
Meijer et al. 2021	0.80 - 2.7 MMT	Ocean		☑	2015	☑		☑					☑		160 countries	Lebreton and Andrady 2019
	67.5 MMT	Land		☑	2015	☑		☑					☑			
	0.0024 MMT	Ocean	☑		2015	☑		☑					☑			
	0.27 MMT	Land	☑		2015	☑		☑					☑			

NOTE: This table represents best available estimates, which were made using data, methods, and assumptions that vary by study or source. Gray highlighted lines indicate estimates for the United States. MMT = million metric tons, MSW = municipal solid waste.

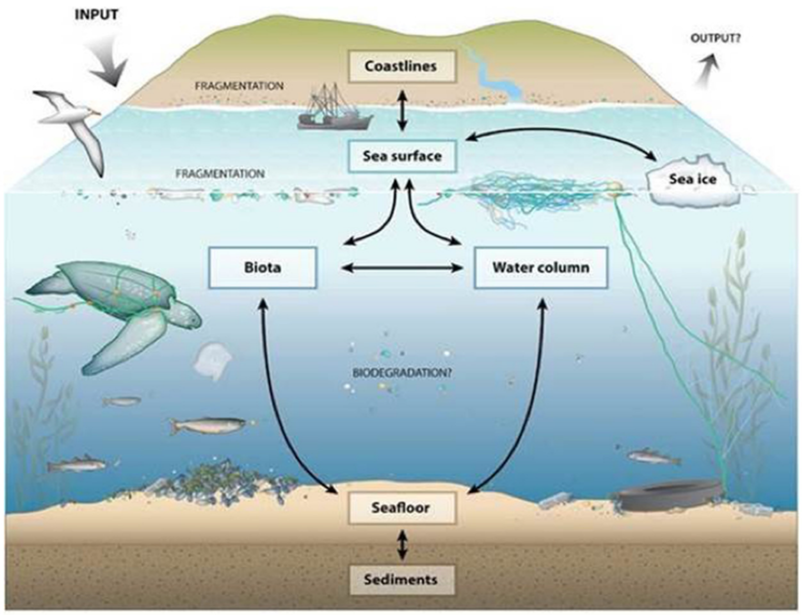

FIGURE 5.1 Schematic of plastic waste in the ocean and interactions that can occur from land to sea and from surface to seafloor. SOURCE: Law (2017) .

The varying methods and units used across these studies make it difficult to understand the distribution of plastic waste in the ocean. The abundance of plastic waste is typically reported either as mass (weight) of items or as item count. Both measures are important and useful to inform strategies on ocean plastic waste. Mass budgeting is a tool used to assess stocks and flows of waste, and is a sensible metric to assess the outcome of source reduction activities. On the other hand, item count is more suitable for impact assessments, especially for microplastics, when the objective is to understand exposure to microplastics relative to natural prey during feeding, for example. Furthermore, abundance may be reported per unit area (e.g., mass or count per square meter, or per square kilometer) or per unit volume (e.g., mass or count per liter, or per cubic meter). In the absence of standardized field sampling protocols, each investigator appropriately determines the reporting unit(s) for their specific study. However, this creates difficulty when comparing results from different studies that followed different protocols and reported numerical data in different units.

The need for, and challenge of, defining standardized or harmonized (i.e., comparable) sampling and analysis protocols is commonly asserted in the scientific literature (e.g., GESAMP 2019, Hung et al. 2021), and researchers are working to evaluate existing methods (e.g., Hanvey et al. 2017, Löder and Gerdts 2015, Wang and Wang 2018) and to define guiding frameworks to collect data that would better inform risk assessments, for example (Connors, Dyer, and Belanger 2017). Until a time when such protocols may exist, researchers stress the importance of proper sampling design to address the stated scientific objective, strict quality assurance and quality control measures, and comprehensive reporting of methods utilized in studies quantifying plastic waste (especially microplastics) in the environment (Hermsen et al. 2018, Hung et al. 2021).

Throughout this chapter, the terms “abundance” and “amount” are used to describe quantitative measurements without specifying a particular unit. Interested readers should refer to original studies for further information about reported quantities.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Shorelines and Estuaries

Coastlines, including sandy beaches, rocky shorelines, and estuarine and wetland environments, are the recipients of plastic waste that may be generated locally, carried from inland sources (e.g., rivers, as described in Chapter 4), or brought ashore by storms, tides, or other nearshore processes. Microplastic and macroplastic waste, including litter and abandoned, lost, or otherwise discarded fishing gear (ALDFG), have been reported along coastlines worldwide, including in the United States. Historically, attention has been focused on litter found on sandy beaches (Browne et al. 2015), in part because of the decades-long International Coastal Cleanup (ICC) coordinated by Ocean Conservancy. Since the mid-1980s, when the first cleanup was carried out in Texas, citizen volunteers have participated in a 1-day annual beach cleanup on shores spanning the U.S. states and territories and more than 100 countries worldwide. In 2019, more than 32 million individual items were collected and categorized from more than 24,000 miles of beaches around the globe (International Coastal Cleanup 2020). The Top 10 list (highest number of items collected) has included the same familiar consumer products year after year, including cigarette filters, food wrappers, beverage bottles and cans, bags, bottle caps, and straws. In 2017, for the first time all items on the Top 10 list were composed of plastics (International Coastal Cleanup 2018). In 2013, in response to increasing attention to smaller debris, including microplastics, the category "Tiny Trash (less than 2.5 cm)" was added to the ICC data card.

The National Marine Debris Monitoring Program, which ran from 1996 through 2007 (and continued later under the National Oceanic and Atmospheric Administration's (NOAA's) Marine Debris Monitoring and Assessment Project, described in Chapter 6), was a federal beach monitoring program designed by the U.S. Environmental Protection Agency with support from other federal agencies and implemented by Ocean Conservancy, with goals to identify major sources of coastline debris and trends in the amount of debris over time (Ribic et al. 2010). Regionally coordinated monthly surveys were conducted by trained volunteers to assess the net accumulation of indicator items on beaches across the contiguous United States, Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands (U.S. EPA 2002). An analysis of survey data (see Ribic et al. 2010, Ribic, Sheavly, and Klavitter 2012)identified regional differences in amounts and trends of land-based, ocean-based, and general-source debris that were, in some cases, related to presumed drivers of debris sources including population size, land use, and fishing activity. The complexity of the results of these scientific surveys is indicative of the challenges inherent in assessing the amounts, sources, and trends of plastic waste in any environmental reservoir.

More recently, Hardesty et al. (2017) reported an estimated 20 million to 1.8 billion pieces of plastic debris along the shoreline of the United States, based on a statistical analysis of beach data (average mass per mile of shoreline) from the NOAA Marine Debris Monitoring and Assessment Project, ICC data, and additional survey data collected for the project. In this analysis several states were identified as national "hot spots" for marine debris (see Figure 5.2), possibly related to coastal population density, urbanization (mid-Atlantic states), transport by coastal currents and wind patterns (Texas), and contributions from inland waterways.

The state of Hawaii is also particularly well-known to suffer a disproportionately heavy marine debris burden, not only from locally based marine litter (Carson et al. 2013) but also due to the state's mid-Pacific Ocean location and associated exposure to widely circulated plastic pollution originating throughout the Pacific Rim (Donohue 2005, Ebbesmeyer et al. 2012, Ingraham Jr and Ebbesmeyer 2001, Kubota 1994, Matsumura and Nasu 1997, McDermid and McMullen 2004, Moy et al. 2018). As a result of oceanic convergence zones, aggregated debris of all types regularly intersects the archipelago, including the Northwestern Hawaiian Islands that comprise the uninhabited and remote Papahānaumokuākea Marine National Monument, an area of conservation and cultural importance (Dameron et al. 2007, Donohue et al. 2001, McDermid and McMullen 2004, Morishige et al. 2007, and see Howell et al. 2012).

The aggregation of plastic ALDFG in the nearshore waters and coastlines of the Hawaiian archipelago is particularly destructive as these "ghost" gears and nets entangle marine life of commercial, cultural, and environmental concern (Boland and Donohue 2003, Dameron et al. 2007, Donohue et al. 2001, Donohue and Foley 2007, Henderson 2001). Fishing gear becomes abandoned, lost, or otherwise discarded for many reasons such as adverse weather; gear conflicts; "operational fishing factors including the cost of gear retrieval; illegal, unreported, and unregulated fishing; vandalism/theft; and access to and cost and availability of shoreside collection facilities" that may incentivize deliberate at-sea disposal (Macfayden, Huntington, and Cappell 2009). Worldwide, industrial trawl, purse-seine, and pelagic longline fisheries are estimated to lose a median of 48.4 kt (95% confidence interval: 28.4 to 99.5 kt) of gear during normal fishing operations annually (Kuczenski et al. 2021). This estimate, based on fishing activity in 2018, did not include abandoned or discarded gear; other gears known to become derelict such as pots and traps, pole and line, and driftnets/gillnets; or nearshore and small-scale fisheries (Kuczenski et al. 2021). By percentage, a separate study estimated annual ALDFG worldwide at 5.7% of all fishing nets, 8.6% of all traps, and 29% of all lines (Richardson, Hardesty, and Wilcox 2019).

At least 46% of the debris (by mass) in the Great Pacific Garbage Patch, an area of ocean plastic accumulation in waters between California and Hawaii, is estimated to be ghost gears and nets (Kuczenski et al. 2021, Lebreton et al. 2018). In 2007, it was estimated that 52 metric tons of ALDFG accumulate each year in the Northwestern Hawaiian Islands alone (Dameron et al. 2007); more current estimates are unavailable. Furthermore, plastic debris is known to increase the susceptibility of reef-building corals to disease (Lamb et al. 2018) and was recognized at least as early as 2001 as a threat to Hawaiian coral reef ecosystems (Donohue et al. 2001).

Marine debris on Hawaii's coastlines is not limited to ALDFG. A 16-year study from 1990 to 2006 on one small atoll islet at French Frigate Shoals in the Papahānaumokuākea Marine National Monument documented more than 50,000 marine debris items with an annual deposition ranging from 1,116 to 5,195 items per year (Morishige et al. 2007). Morishige et al. (2007) reported that more than 70% of these items were composed of plastics. Smaller plastics, including microplastics, are also increasingly known to be found on the coastline and nearshore Hawaiian Island environments with potentially dire effects (Gove et al. 2019, McDermid and McMullen 2004, Morishige et al. 2007). On Hawaii's most visited and populous island, Oahu, microplastic beach densities of up to 1,700 particles per square meter have been documented—among the highest worldwide on remote island beaches (Rey, Franklin, and Rey 2021).

Alaska coastlines are also a known reservoir for significant amounts of plastic debris (Merrell 1980, Polasek et al. 2017). As early as 1974, 349 kg of plastic litter per kilometer of beach was recorded on Amchitka Island in the Aleutian Island chain (Merrell 1980). In one study, 80 km of coastline in five national park service units in Alaska was cleaned of more than 10,000 kg of debris, the majority of which was composed of plastics (Polasek et al. 2017), a finding consistent with earlier seabed studies offshore Kodiak Island, Alaska (Hess, Ribic, and Vining 1999). Plastic waste on Alaska beaches is often characterized by large, buoyant objects of maritime origin such as lines, buoys, and fishing nets that are likely wind- and current-driven to shore (Pallister 2012).

Reckoning with the U.S. Role in Global Ocean Plastic Waste

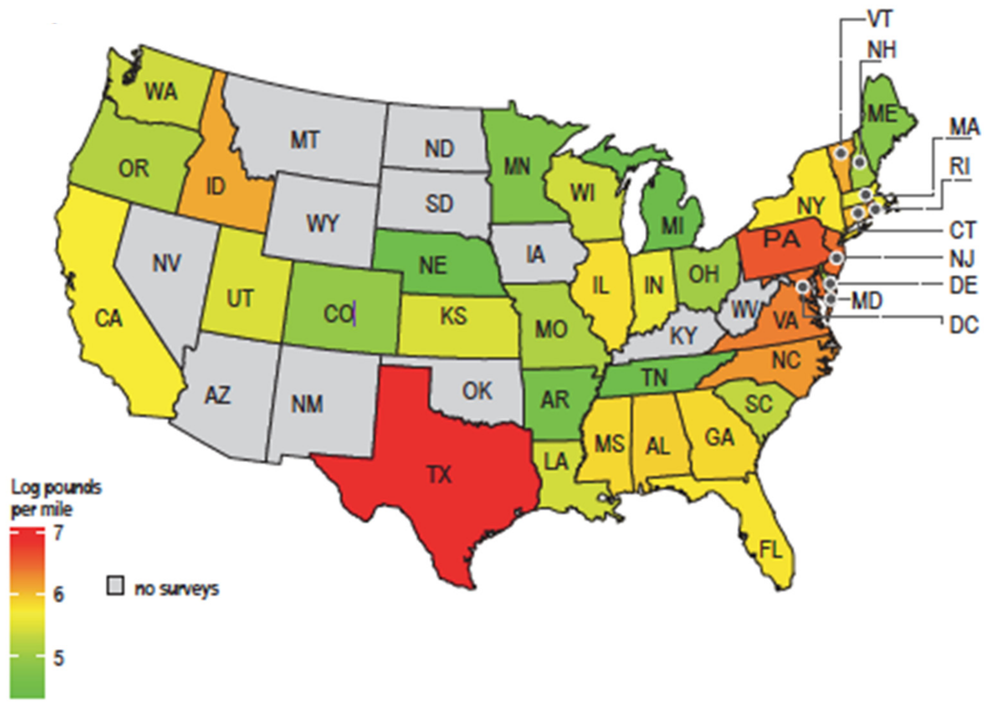

FIGURE 5.2 Assessment of debris load based on beach cleanup (International Coastal Cleanup) data for contiguous U.S. states (not including Alaska or Hawaii). Values represent the average weight of debris (including, but not limited to, plastics) per mile of shoreline for all coastal cleanup surveys across each state. SOURCE: Hardesty et al. (2017, Figure 2).

Several major estuaries and inland freshwater waterways in the United States have been surveyed for plastic debris, especially microplastics in the water column or buried in sediments (studies and their results detailed in Appendix D). These studies are widespread geographically—carried out in California (Los Angeles, San Francisco), the Pacific Northwest, and along the eastern seaboard from New York to Florida, as well as in regions far from the ocean (Illinois, Montana, Wyoming, Wisconsin, western Virginia). While these are a small number of studies relative to the number of estuaries and rivers in the United States, they have found microplastics to be ubiquitous.

In two estuary studies, particle concentrations were higher after rainfall or storm events (for San Francisco Bay, seeSutton et al. 2019; for Chesapeake Bay, see Yonkos et al. 2014), whereas in a study of the inland Gallatin River basin (Montana and Wyoming), microplastic concentration was inversely related to discharge, suggesting that microplastic sources are decoupled from discharge sources (Barrows et al. 2018). Studies in the metropolitan Chicago area found, at most sites, a higher microplastic abundance downstream of wastewater treatment plant outfalls than upstream, although no change in concentration was detected with increasing distance downstream (Hoellein et al. 2017, McCormick et al. 2016). A wide range of particle types, or forms, were reported across studies, with the proportion of fibers, fragments, pellets, films, and foams variable in each study. Some studies reported an abundance of polyethylene, polypropylene, and/or polystyrene, which are all polymers used extensively in packaging and other single-use applications. Direct comparison of results across studies is made difficult by differences in sampling methods, including particle sizes collected (dependent on net mesh size), sediment volumes or masses collected, and number of samples collected at a location (one-time versus repeated samples over time).

Plastic debris has also been well documented in the Laurentian Great Lakes, including in major Great Lakes tributaries, on shorelines, in surface water, and in benthic sediment (see systematic review by Earn, Bucci, and Rochman 2021). Individual studies reported plastic abundances comparable to or higher than those in ocean environments, with similarly large variation within studies due to environmental variability, and between studies due to different sampling and analysis methods (Earn, Bucci, and Rochman 2021). In one study, following similar methods to those estimating plastic input to the ocean (see Table 5.1), an estimated 10,000 metric tons of plastic debris from mismanaged solid waste entered the Great Lakes from the United States and Canada in 2010 (Hoffman and Hittinger 2017). In the same study, using a hydrodynamic model calibrated with field data, the authors identified likely accumulation zones across the Great Lakes and predicted the highest mass of floating plastic debris in Lake Erie (4.41 metric tons), followed by Lake Huron (1.44 metric tons) and Lake Superior (0.0211 metric tons).

Ocean Water Column

Floating Plastics

Some of the earliest reports of plastic debris in the ocean described small particles floating at the sea surface in estuarine (Kartar, Milne, and Sainsbury 1973), nearshore (Buchanan 1971, Carpenter and Smith 1972), and offshore waters of the North Atlantic Ocean (Carpenter et al. 1972); and large, identifiable objects (plastic bottles, balloon, sandal) floating in the open ocean of the North Pacific (Venrick et al. 1973). A more recent reanalysis of data from the North Atlantic Ocean and adjacent seas found that plastic contamination by large, entangling debris occurred as early as the 1950s, with significant increases observed in subsequent decades (Ostle et al. 2019). Since the 1970s, the majority of studies of the abundance and distribution of plastic marine debris have sampled the sea surface using plankton nets of varying types (van Sebille et al. 2015). The longest continuous data sets have been collected by undergraduate Sea Education Association Semester students sailing in the western North Atlantic since the mid-1980s (Law et al. 2010) and in the eastern North Pacific Ocean since 2001 (Law et al. 2014). The widespread coverage of surface plankton net data reported by a multitude of international research groups has allowed scientists to assess the large-scale accumulation of floating debris across ocean basins, which occurs in subtropical convergence zones centered around 30° latitude in ocean gyres in both the northern and southern hemispheres. These accumulation zones, commonly referred to as "garbage patches," are mainly composed of microplastics that have broken apart from larger items, although large floating debris (especially derelict fishing gear, including nets, floats, and buoys) is also found in these regions. The origin of these debris items (especially microplastics) typically cannot be determined except in rare instances, such as after the 2011 Tohoku earthquake and tsunami in Japan. Debris from this event, such as docks, vessels, and buoys, was identified for many years afterward, floating on the sea surface and washing ashore in Hawaii and North America (Carlton et al. 2017).

Contrary to common misperceptions of "garbage patches," floating plastic debris is not aggregated together in a single large mass in the subtropical gyres but instead is dispersed across an area estimated to be millions of square kilometers in size (Lebreton et al. 2018). Even within the accumulation zones, particle concentrations (measured using plankton nets) can vary by orders of magnitude across spatial scales of tens of kilometers or less (Goldstein, Titmus, and Ford 2013), driven, at least in part, by physical transport processes creating small-scale convergences that are difficult to predict (see Figure 5.3).

Reckoning with the U.S. Role in Global Ocean Plastic Waste

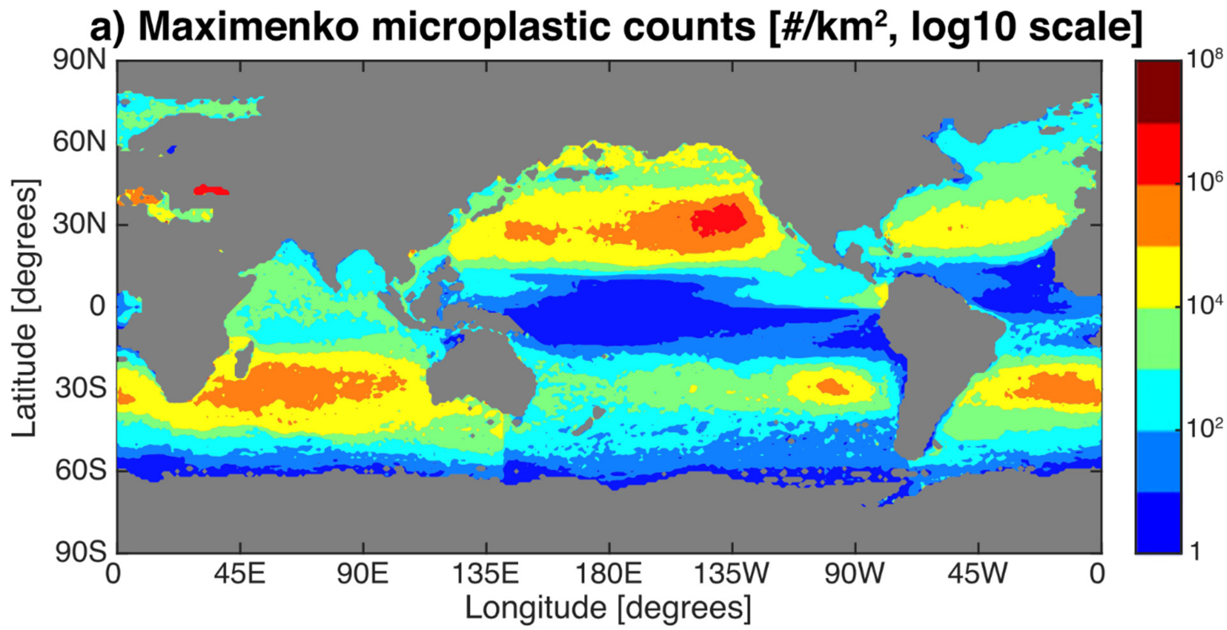

FIGURE 5.3 Map illustrates model prediction of microplastic abundance at the ocean surface. The highest abundances (warm colors) are in the ocean subtropical convergence zones (bands ~30 degrees latitude in the North and South Atlantic, North and South Pacific, and Indian Oceans), where ocean surface currents weaken and converge, causing floating material carried by the currents to accumulate. SOURCE: van Sebille et al. (2015).

Global estimates of the mass of floating plastics at the ocean surface have been made by synthesizing and extrapolating field data (Cozar et al. 2014), and with field data in combination with models of wind-driven ocean circulation to account for dispersal and variability across the ocean (Eriksen et al. 2014, van Sebille et al. 2015). Estimates vary depending on the data set used and data analysis methodologies, and range from 7,000–35,000 tons (Cozar et al. 2014) to 93,000–236,000 metric tons of microplastics (van Sebille et al. 2015), to 268,940 tons of microplastics and larger items (Eriksen et al. 2014) at the global ocean surface. All estimates of the mass of plastic waste in this sea surface “reservoir” have been only a small fraction of the estimated input of plastic waste to the ocean in a single year (Jambeck et al. 2015). There are many possible explanations for this discrepancy. One explanation is the incomplete measurement of the size spectrum of floating plastic waste using plankton nets (which typically sample items from ~0.33 to 1 m) compared to visual observations by observers on ships or in aircraft, in which case only larger debris is detected because detection is dependent on the distance from observer to object. Furthermore, visual surveys are very resource intensive and typically cover only small areas over short time periods. Bulk water samples filtered on very fine mesh filters have identified particles as small as 10 um in size (Enders et al. 2015); however, sample volumes are very small and relatively few samples of this kind have been collected. Thus, the abundance and distribution of floating plastics across the known size spectrum (microns, and possibly nanometers, to many meters in size) is a major knowledge gap.

Suspended Plastics in the Water Column

Microplastics and occasional larger items, such as plastic bags, have also been detected in the water column between the sea surface and the seafloor. Vertical mixing of the water column driven by wind energy can distribute buoyant plastics to depths of tens of meters or greater (Kukulka et al. 2012, Reisser et al. 2015), and interactions with organic matter and biota may also cause initially buoyant particles to become dense enough to sink. A study in the nearshore environment of Santa Monica Bay, California (depths up to 15 m) found plastics larger than 0.333 mm at all depths sampled (Lattin et al. 2004), whereas a coastal survey off the U.S. west coast only measured subsurface plastics (sampling to 212 m depth with plankton nets) in one out of four seasonal surveys (winter survey) (Doyle et al. 2011). Discrete water samples collected from remotely operated vehicles in Monterey Bay, California collected microplastics at 10 depths between 5 m and 1,000 m, with the highest concentrations (up to 15 particles per m^3) found between 200 and 600 m depth (Choy et al. 2019). In this study, the majority of microplastics were composed of polyethylene terephthalate (PET) and polyamide, polymers denser than seawater. Furthermore, eight discarded mucus feeding structures ("sinkers") of filter-feeding giant larvaceans and the gastrointestinal tracts of 24 pelagic red crabs examined in this study all contained microplastics. The known distribution and feeding behaviors of these animals are consistent with intake of microplastics between 100 and 200 m depth, indicating important interactions with organisms in pelagic ecosystems and a potential mechanism for vertical transport of microplastics to the seafloor (e.g., in sinkers).

Seafloor

Macroplastics and microplastics have been found in benthic environments around the world. Observed concentrations vary greatly, suggesting that proximity to sources, and water currents and seafloor topography acting as concentrating mechanisms, may play important roles in determining benthic loading.

Kuroda et al. (2020) conducted 63 surveys for seafloor marine debris in three areas of the waters off Japan between 2017 and 2019, using bottom trawls with 60 to 70 mm mesh nets at depths ranging from 67 to 830 m. The surveys identified debris concentrations averaging 2,962 items (53 kg) per km^2 in Hidaka Bay to 81 items (9 kg) in the East China Sea. Of all debris items, plastics accounted for 89% in Hidaka Bay, 69% off Joban, and 34% in the East China Sea. Based on information from labels on several debris items, Kuroda et al. (2020) estimated that about 30 years had elapsed between their manufacture and their retrieval from the seafloor. Comparison by Kuroda et al. (2020) to other studies in Japan and in Europe confirmed that plastics frequently account for the largest percentage of debris on the seafloor, though the percentage varies by location, from 22.2% (Hakata Bay, see Fujieda 2007) to up to 95% (eastern Mediterranean, see Ioakeimidis et al. 2014).

Peng et al. (2020) reviewed studies of the concentration of microplastics in seawater, beach sands and marine sediments, and marine biota. Abundance measurements varied greatly, which may provide a rough understanding of geographic variation, though they did not reflect standardized sampling methodologies, analyses, or units of measure. Smaller quantities have been detected in marine sediments in the Arctic (Kanhai et al. 2019) and Antarctic (Reed et al. 2018). Not surprisingly, higher, though variable, abundances are found near more populated areas (for Mediterranean Sea, see Guven, Gökdağ, and Kideys 2016; for North Sea, see Lorenz et al. 2019; for Plymouth, UK, see Thompson et al. 2004). Some studies that have measured microplastics in

Reckoning with the U.S. Role in Global Ocean Plastic Waste

the water column and sediment have found higher abundances in sediments, suggesting the sediment is a significant sink for microplastics as they deposit over time (Kanhai et al. 2019, Song et al. 2019; however, see Zheng et al. 2019 for a reverse situation).

Nanoplastics have been identified in sea water using the presence of chemical markers (Ter Halle et al. 2016), but their concentration and distribution have not been well resolved (Piccardo, Renzi, and Terlizzi 2020) as methods do not yet exist to directly detect and identify nanoplastics in the environment.

Benthic organisms may be impacted by exposure to deposited plastics and to toxic additives to the plastics. For example, hexabromocyclododecanes (HBCDs) are flame retardants commonly used as additives with expanded polystyrene and extruded polystyrene foam insulation, and with textile coatings. HBCD has been found in marine sediments (de la Torre et al. 2021, Klosterhaus et al. 2012, Sutton et al. 2019) and Laurentian Great Lakes sediments (Yang et al. 2012).

Marine Life

The intersection of the distribution of aquatic plastic waste, as well as its abundance, and freshwater and marine wildlife habitat use necessarily informs how and to what extent organisms encounter and entrain this pollution. The nexus of marine life and the distribution and fate of aquatic plastic waste has been illustrated through two primary mechanisms: ingestion-egestion of and entanglement in plastic waste by living organisms (Gall and Thompson 2015, Gregory 2009, Kühn, Bravo Rebolledo, and Van Franeker 2015, Kuhn and van Franeker 2020, Laist 1997, Shomura and Yoshida 1985). Ingestion is the taking in or consuming of food or other substances into the mouth or body. Egestion is discharging or voiding undigested food or other material, such as through feces or vomiting. One review by Kuhn and van Franeker (2020) found documented cases of entanglement or ingestion by marine biota in 914 species from 747 studies—701 species having experienced ingestion and 354 species having experienced entanglement. When ocean or lake borne plastic waste becomes bioavailable to and is ingested by living organisms, they themselves may serve as de facto vectors. As vectors, they could potentially distribute plastics through complex ecological mechanisms, such as foraging strategies, diurnal or seasonal movements, or via trophic transfer. The distribution and fate of ocean plastic waste thus both affects and is affected by the marine lifescape in ways not fully understood.

Ingestion of Plastics

The ingestion of plastic waste by aquatic life has been documented for hundreds of species (e.g., Figure 5.4, Kühn, Bravo Rebolledo, and Van Franeker 2015, Kuhn and van Franeker 2020). It occurs at spatial scales ranging from the planktonic ingestion of microplastics and nanoplastics (Botterell et al. 2019, Desforges, Galbraith, and Ross 2015, Lee et al. 2013, Sun et al. 2018) to the ingestion of all sizes of plastic debris by whales (Alzugaray et al. 2020, Baulch and Perry 2014, Besseling et al. 2015, de Stephanis et al. 2013, Im et al. 2020, Jacobsen, Massey, and Gulland 2010, Lusher et al. 2017, Unger et al. 2016). Nearly 60% of all whale and dolphin species have been shown to ingest debris with associated fatal results in up to 22% of stranded animals (Baulch and Perry 2014, de Stephanis et al. 2013, Jacobsen, Massey, and Gulland 2010). Figure 5.4 shows one global estimate of plastic ingestion by terrestrial, freshwater, and marine animals.

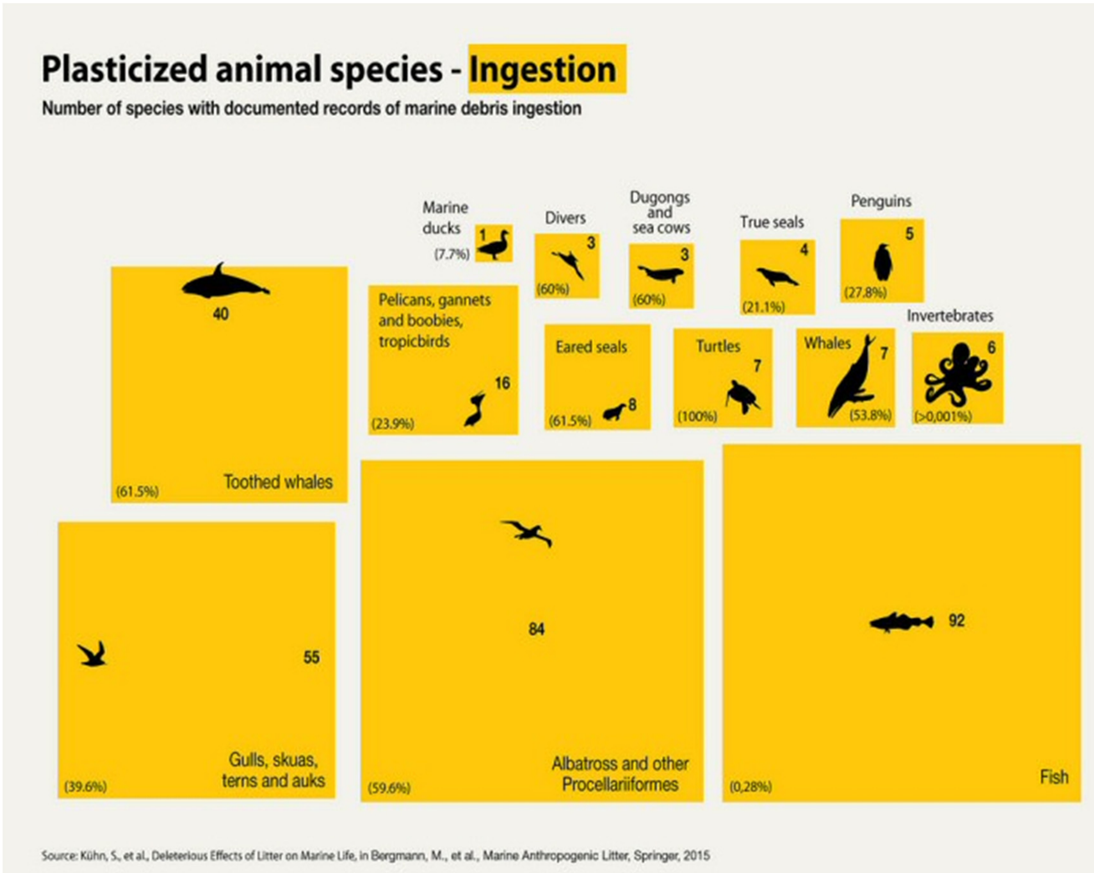

FIGURE 5.4 Visualization of the number of species with documented records of ingestion of plastics, based on a review of studies through December 2014. SOURCE: Maphoto/Riccardo Pravettoni, based on data from Kühn, Bravo Rebolledo, and Van Franeker (2015).

Entry of plastics into the ocean food web can occur when environmental plastics are consumed by organisms as a putative food source (Cadée 2002, Campani et al. 2013, Carr 1987, Lutz 1990, Mrosovsky, Ryan, and James 2009, Provencher et al. 2010, Ryan 1987, Schuyler et al. 2012, Schuyler et al. 2014, Tourinho, Ivar do Sul, and Fillmann 2010), via plastic contaminated prey (Bourne and Imber 1982, Cole et al. 2016, Ryan 1987, Ryan and Fraser 1988), or indirectly through ambient seawater or sediments during foraging or other encounters (Beck and Barros 1991, Bravo Rebolledo et al. 2013, Di Beneditto and Ramos 2014, Murray and Cowie 2011). The interaction among such variables as availability of plastics in the environment, prey resemblance to plastics, prey selection, and the nutritional state of an organism has been hypothesized to increase the risk of plastic ingestion by individual organisms, a hypothesis largely supported by studies to date (reviewed by reviewed by Santos, Machovsky-Capuska, and Andrades 2021). The preferential ingestion of plastics by some organisms has been shown to result from plastics' size, color, shape, age, abundance, or a combination of these factors (e.g., Botterell et al. 2019, Lavers et al. 2020, Lee et al. 2013). In certain seabirds, and perhaps other marine wildlife, plastic ingestion has been hypothesized to be facilitated by an olfactory signal—emanating from a complex biofilm that develops on aquatic plastic particles—that attracts birds to floating plastics (Savoca et al. 2016), though questions remain (Dell'Ariccia et al. 2017). When an organism's traits or behaviors become maladaptive in the face of environmental change it is termed an evolutionary trap; plastic ingestion has been identified as an evolutionary trap as a result of the availability of environmental plastics, plastics' mimicking of food options, and the proclivity of organisms to ingest plastics (Santos, Machovsky-Capuska, and Andrades 2021).

High concentrations of both microplastics and microscopic larval fish and invertebrates have been found in oceanographic features known as surface slicks, which are "lines of smooth water on the ocean surface" (Gove et al. 2019, Whitney et al. 2021). This discovery raises concerns regarding the trophic transfer of these plastics and associated toxins within the food web and ultimately to humans (Gove et al. 2019). The presence of plastics in the excrement of secondary and tertiary marine predators has been offered as empirical evidence of trophic transfer both in captive (Nelms et al. 2018) and wild marine mammals (Donohue et al. 2019, Eriksson and Burton 2003, Le Guen et al. 2020, Perez-Venegas et al. 2018, and see Perez-Guevara, Kutralam-Muniasamy, and Shruti 2021 for a recent review of microplastics in fecal matter).

Plastic ingestion has been documented in the Laurentian Great Lakes, though a recent systematic review of the scientific literature demonstrates that the body of knowledge on plastics' effects on freshwater biota lags that which is known for the marine environment (Earn, Bucci, and Rochman 2021). Studies of the effects of plastics on freshwater biota have been predominantly laboratory-based and hence not readily applied or extrapolated to the complexity of real-world conditions, among other caveats (Earn, Bucci, and Rochman 2021). Nonetheless, Earn, Bucci, and Rochman (2021) report that 60% of studies reviewed detected effects of plastics on freshwater biota (Earn, Bucci, and Rochman 2021). Notably, a recent study of fish in Lake Superior and Lake Ontario documented some of the highest abundances of microplastics and other anthropogenic particles in bony fish (marine or freshwater) reported to date (Munno et al. 2021). Of the two lakes, Lake Ontario fish had the greatest mean number of anthropogenic microparticles at 59 ± 104 standard deviations per fish and the greatest number to date in a single fish at 915 microparticles (Munno et al. 2021). Plastics in seafood being sold for human consumption have also been documented both in the United States (Rochman et al. 2015) and abroad (Naji, Nuri, and Vethaak 2018, Rochman et al. 2015, Van Cauwenberghe and Janssen 2014), highlighting a potential route of plastic contaminant trophic transfer to humans (Smith et al. 2018). Microplastics in particular have been identified as an emerging permanent contaminant of increasing concern in seafood (Farady 2019), though understanding of the relevance of this pollution to human health via seafood consumption is presently limited (Dawson et al. 2021).

Once entrained in aquatic food webs, within the bodies and tissues of living organisms across diverse taxa, plastic waste is subject to a diversity of spatio-temporal distribution mechanisms. An example is the transport of ingested plastic vertically in the water column through the diurnal vertical migration of zooplankton and fish, termed the "plastic pump." This plastic pump is also postulated as a mechanism by which plastics are delivered from shallower waters to the deep ocean including through fecal pellets (Choy and Drazen 2013, Cole et al. 2016, Katija et al. 2017, Lusher et al. 2016, van Sebille et al. 2020, Wright, Thompson, and Galloway 2013). As such, zooplankton have been postulated as a reservoir for microplastics (Sun et al. 2018), as have the water column and animals of the deep sea (Choy et al. 2019, Hamilton et al. 2021).

Animals that demonstrate high site fidelity to particular geographic locations, such as nesting or birthing sites, but ingest plastics during distant foraging may transport and distribute ingested plastics long distances upon their return (Buxton et al. 2013, Le Guen et al. 2020). The intergenerational transfer of plastics in seabirds that regurgitate ingested plastics to feed chicks has been known since the 1980s (Pettit, Grant, and Whittow 1981, Ryan 1988, Ryan and Fraser 1988). An additional example is the transport and distribution of microplastics by northern fur seals

(*Callorhinus ursinus*) in the eastern north Pacific Ocean (Donohue et al. 2019). These seals forage offshore, returning to land in repeating cycles to rest, breed, or attend to their pups (Gentry and Kooyman 1986) and distribute microplastics ingested during foraging to novel locations, as feces containing microplastics are deposited on land (Donohue et al. 2019).

The biotic distribution of microplastics can also occur at smaller geographic scales, for example, through the sedimentary ingestion and subsequent concentrated egestion of microplastics by the sea cucumber (*Holothuria tubulosa)* (Bulleri et al. 2021). Bulleri et al. (2021) show that microplastic resuspension rates to the water column are greater from sea cucumber fecal material than surface sediments, facilitating microplastic bioavailability (Bulleri et al. 2021). While not an exhaustive treatment, the above examples demonstrate the diversity of taxa that may serve as reservoirs of ocean plastic waste and highlight the importance of considering marine life when addressing the distribution and fate of environmental plastic waste.

Entanglement in Plastics

The prevalence and distribution of ocean plastic waste is reflected in the ever-increasing number of species with plastic entanglement records—354 species by 2019, including birds, marine mammals, turtles, sea snakes, fish, and invertebrates (Kuhn and van Franeker 2020, Kühn, Bravo Rebolledo, and Van Franeker 2015; see also Figure 5.5). As with ingestion of plastics, studies of entanglement and other impacts of environmental plastics in freshwater systems have lagged those in marine systems, with assertions that freshwater impacts have been both underestimated and understudied (Blettler and Wantzen 2019). Entanglement in plastics, primarily derelict and operational/active fishing gear, has been identified as a primary threat to the endangered Hawaiian monk seal (*Neomonachus schauinslandi*) (Boland and Donohue 2003, Donohue et al. 2001, Henderson 2001) and North Atlantic right whale (Johnson et al. 2005, Knowlton and Kraus 2001, Moore et al. 2021b, Myers and Moore 2020).

Entanglement of marine life in ocean plastic waste may distribute this pollution via the active or passive movement of living or dead entangled organisms across aquatic habitats, though the frequency and ramifications of this mode of plastic waste distribution and transport are essentially unstudied. Scholarship has, understandably, focused primarily on understanding or documenting the effects of marine debris parameters (e.g., distribution, density) on individual species and biodiversity (e.g., Woods, Rødder, and Verones 2019). Seals entangled in derelict fishing gear are routinely observed returning to land with associated injuries such as deep and advanced wounds (Allen et al. 2012, Boren et al. 2006), suggesting they have been entangled for some time transporting the entangling net, line, rope, or other plastic waste with them. Individual North Atlantic right whales entangled in fishing gear are known to have carried the entangling debris on average at least 10 months and it is speculated that as the animals starve, lose body fat, and become denser, they sink at death, both concealing this marine debris-mediated mortality and distributing plastic debris to depth (Moore et al. 2006). In addition to the grave animal welfare issue entanglement presents (Butterworth, Clegg, and Bass 2012, Knowlton and Kraus 2001, Moore et al. 2006), the movement of ocean plastic waste by entangled organisms may also transport and distribute any living organisms present on the plastic waste, such as potentially invasive species (Kiessling, Gutow, and Thiel 2015, Miralles et al. 2018, Rech et al. 2018, Vegter et al. 2014) and novel viral or bacterial assemblages (Amaral-Zettler et al. 2016, Barnes 2002, Keswani et al. 2016, Kirstein et al. 2016, Masó et al. 2003, Zettler, Mincer, and Amaral-Zettler 2013).

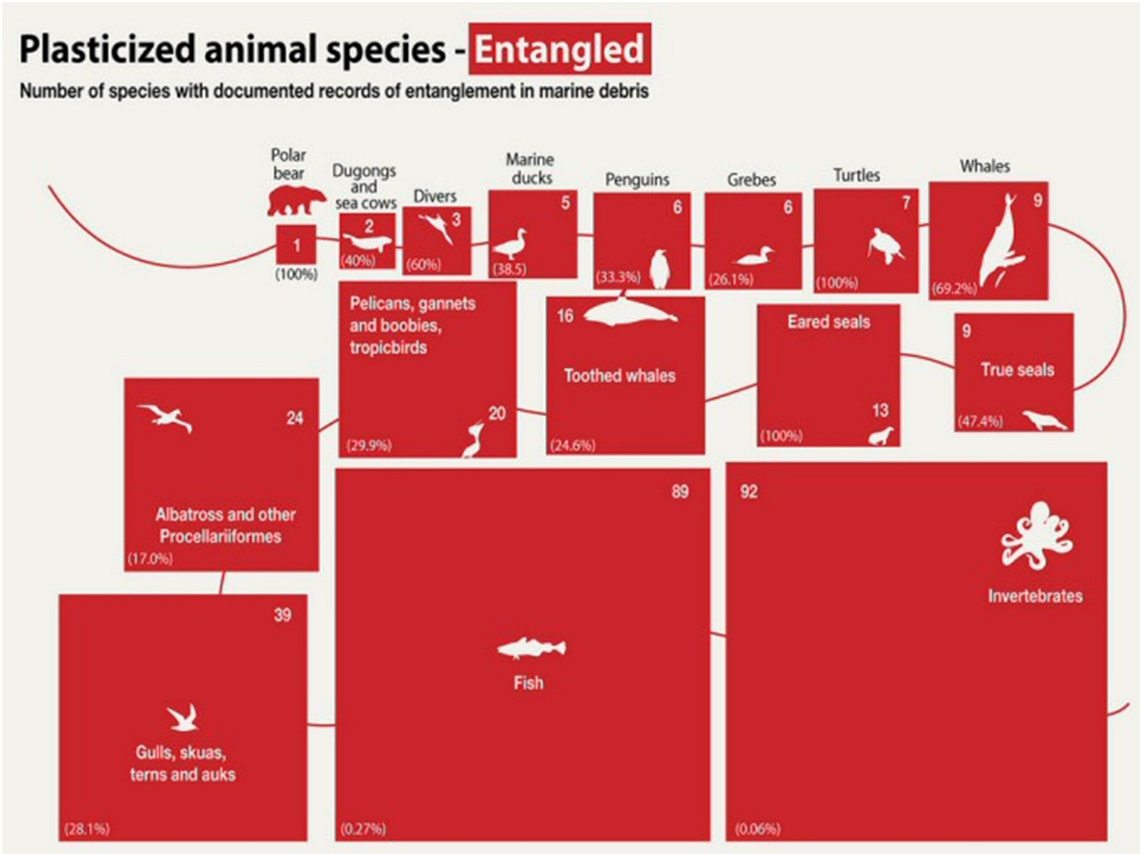

FIGURE 5.5 Visualization of the number of species with documented records of entanglement in plastics, based on a review of studies through December 2014. SOURCE: Maphoto/Riccardo Pravettoni, based on data from Kühn, Bravo Rebolledo, and Van Franeker (2015).

Technical and design solutions to reduce entanglement threats to marine life have largely focused on reducing by-catch in actively fished (rather than derelict) gear (Hamilton and Baker 2019). Successful design advances include pingers (acoustic deterrent devices) for small cetaceans; exclusion devices for pinnipeds and turtles; and guard-type designs to reduce marine mammal entrapment in pots and traps (Hamilton and Baker 2019), though the effectiveness of these mitigation measures once gears become derelict is uncertain. Biodegradable panels on traps and pots have demonstrated success in reducing threats to marine life when traps and pots become derelict (Bilkovic et al. 2012). Some designs envisioned or proposed may ultimately reduce derelict fishing gear and associated entanglements, such as advances in gear marking (He and Suuronen 2018), ropeless trap and pot fishing (Myers et al. 2019), and biodegradable trap and pot panels (Bilkovic et al. 2012).

The Plastic Microbiome

Plastic litter can harbor unique microbial assemblages and may even facilitate the spread of antibiotic resistance across aquatic systems (Arias-Andres et al. 2018, Liu et al. 2021, Zettler, Mincer, and Amaral-Zettler 2013). Plastic microbial communities have been shown to be distinct and more variable than those in the surrounding water and serve as effective disease vectors (Bryant et al. 2016, Kirstein et al. 2016, Lamb et al. 2018, Zettler, Mincer, and Amaral-Zettler

2013). Environmental DNA methods show the plastic microbiome may contain human and wildlife pathogens (Pham, Clark, and Li 2021). Most types of flotsam can serve as a vector of diseases and pollutants; however, the persistence of plastic litter and its transport and distribution exceed that of organic materials (Harrison et al. 2011). Multiple taxa associated with human gastrointestinal infections have been identified on microplastics downstream of wastewater treatments—but not in the surrounding water or organic matter—suggesting certain microbes may have an affinity for plastics (McCormick et al. 2016), though a recent comparative review of the science failed to confirm this (Oberbeckmann and Labrenz 2020). Members of the bacterial genus *Vibrio* are common in the plastic microbiome; many are harmless, but some are pathogens to humans and corals, and they frequently plague aquaculture facilities (Amaral-Zettler, Zettler, and Mincer 2020, Ben-Haim et al. 2003, Curren and Leong 2019, Lamb et al. 2018, Zettler, Mincer, and Amaral-Zettler 2013). Though understanding of the plastic microbiome remains incomplete, its role in microbial ecology underscores the diversity of impacts of ocean plastic waste.

Microbes may affect the distribution and fate of ocean plastic waste through colonization. Functioning as a microhabitat sometimes termed the "plastisphere," microbial colonization of aquatic plastic litter begins within hours and develops an amalgamated, crowded, complex three-dimensional structure of prokaryotes, archaea, protists, and detritus (Amaral-Zettler, Zettler, and Mincer 2020, Andrady 2011, Wright et al. 2020, Zhao et al. 2021). As this biofilm develops it can decrease the buoyancy of a microplastic particle forcing it to sink, thus enhancing its bioavailability (Andrady 2011, Eriksen et al. 2014, van Sebille et al. 2020). As mentioned previously, chemical signatures associated with biofilms on plastic waste may also serve as an attractant to foraging wildlife (Savoca et al. 2016). Microbial colonization, then, joins entanglement and ingestion-egestion as a biotic distribution mechanism for plastic aquatic waste.

TRANSFORMATION OF PLASTICS IN THE OCEAN

Two mechanisms are involved in the transformation and ultimate fate of plastics in the ocean: chemical and physical degradation, and potential for biodegradation.

Chemical and Physical Degradation

In the ocean, plastics are subject to wave and wind forces and solar radiation. Under these conditions, these plastics weaken and fragment into smaller and smaller particles (MacLeod et al. 2021). Physical degradation involves the breakage of bulk pieces of plastic into smaller fragments. Chemical degradation involves the breakage of chemical bonds in the plastic structure and may be accelerated by exposure to ultraviolet (UV) radiation, high temperatures, and elevated humidity (Chamas et al. 2020). This typically results in the creation of more microplastics and potentially nanoplastics that can accumulate in the ocean and be transported up the food chain through ingestion by fish, birds, and other aquatic species. Fragmentation into microplastics and nanoplastics increases the particle surface area, which facilitates the release of toxic additives into the environment (Arp et al. 2021). Despite the tendency to break into smaller pieces, plastics are known to have long half-lives, though specific degradation rates under various conditions are not well known (Chamas et al. 2020). The potential to degrade is dependent on both the plastic polymer type and the environmental conditions, which are most favorable at the ocean surface due to exposure to UV radiation, higher temperatures, and energetic waves.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Potential for Biodegradation

Non-Microbial Marine Biota Transformation

As described in Chapter 2, both fossil-based and biobased plastics can have carbon-carbon bonds that require substantial energy to break apart. Degradation and, specifically, biodegradation depend on the chemical and physical structure of the plastics and the receiving environment, not where the carbon originates from. Therefore, biobased plastics are not necessarily more readily biodegradable than fossil-based plastics (Law and Narayan 2021).

While there are numerous records of ingestion of plastics by marine biota (described earlier in the chapter), there is a nascent understanding of the role marine biota may play in the transformation and ultimate fate of ocean plastic waste. In one study, microplastic particle size was not altered through the sedimentary bioturbation process (ingestion and egestion) of the sea cucumber (Bulleri et al. 2021). However, size reductions in ocean plastic debris have been observed in Antarctic krill (Dawson et al. 2018) and attributed to grinding of ingested plastics in the muscular gizzard of fulmarine petrel seabirds, followed by egestion (van Franeker and Law 2015).

Microbial Interaction with Plastics

Microbial utilization of plastics as a carbon (energy) source, possibly resulting in complete biodegradation (and removal) of the material, has been proposed. Recent work on ocean microbes has focused on characterizing the microbial communities found on ocean plastics compared to those on natural substrates and in free-living communities in seawater, and on understanding the interactions between colonizing marine microbes and specific polymers. As described in an earlier section, some of the first studies on marine microbes reported different microbial communities on plastics than on natural substrates or in seawater (e.g., Zettler, Mincer, and Amaral-Zettler 2013). However, in a recent critical review and comparative analysis of the scientific literature, Oberbeckmann and Labrenz (2020) found little evidence of polymer-specific microbial communities or of an increased affinity of pathogenic species for plastic substrates. Instead, they concluded that microbial communities on plastics tend to be opportunists that will readily colonize both synthetic and natural surfaces.

The vast majority of studies examining potential biodegradation of plastics in the marine environment (i.e., complete assimilation of plastic carbon by microbes and remineralization to CO_2, H_2O, and inorganic molecules) have focused on weathering (mainly photochemical degradation) and fragmentation (reduction in particle size) processes, which are necessary precursors to microbial assimilation and mineralization, particularly in the ocean (see Figure 5.6). However, relatively few studies have addressed microbial assimilation of carbon in traditional plastics to complete mineralization (removal) (Wang et al. 2018). Plastics with hydrolysable chemical backbones (e.g., PET and polyurethanes) may be more susceptible to enzymatic degradation and eventual biodegradation than those with carbon-carbon backbones (Amaral-Zettler, Zettler, and Mincer 2020), as illustrated by the discovery of PET-degrading bacteria isolated from a bottle recycling plant (Yoshida et al. 2016). However, Oberbeckmann and Labrenz (2020) argue, based upon Alexander's (1975) paradigm on microbial metabolism of a substrate, that the very low bioavailability and relatively low concentration of plastics in the ocean together with their chemical stability render these molecules very unlikely candidates for biodegradation by marine microbes, despite their potential as an energy and carbon source. Whether marine microbes have the evolutionary potential to adapt to plastic biodegradation in the future, especially if the concentration of plastics increases substantially in the ocean or in localized hotspots, remains an open question.

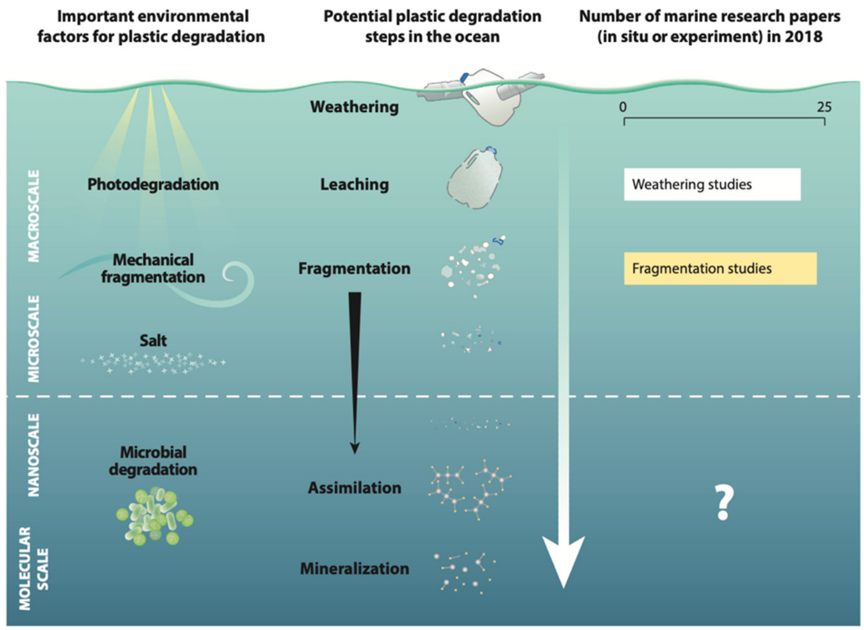

FIGURE 5.6 Schematic illustrating plastic degradation processes in the ocean and studied components. Vertical depth in this schematic indicates smaller sizes. The three columns across the schematic, from left to right, illustrate (1) factors for plastic degradation; (2) potential steps for degradation as particles become smaller; and (3) the available evidence to support each step across, from the year 2018. Steps underneath the white dashed line indicate processes that have not yet been validated in the marine environment. SOURCE: Oberbeckmann and Labrenz (2020).

CHAPTER SYNOPSIS

A large and rapidly growing body of research documents the presence and characteristics of plastic waste throughout the marine environment, from the sea surface to seafloor sediments, coastlines to the open ocean, and in marine biota. The scale of plastic waste flows to the environment and the ocean has been estimated based on plastic waste generation rates and leakage outside of waste management systems, in the United States and globally. However, challenges remain in refining these global estimates and in identifying accumulation hotspots because of limited environmental data that are not readily comparable due to a lack of standardized methods, combined with large variability in ocean plastic concentrations in time and space. Addressing these knowledge gaps will improve estimates of plastic waste flows to the ocean from the United States and globally as a baseline from which to assess the impact of mitigation actions. Based on existing polymer chemistry and microbiology research, plastics (mainly carbon-carbon backbone polymers) are persistent in the marine environment, experiencing little to no biodegradation, and thus accumulate over time scales of decades or more.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

KNOWLEDGE GAPS

There is insufficient information to create a robust (gross) mass budget for marine plastic waste and its distribution in ocean reservoirs. Measurements to date of plastic concentrations in individual locations over short time periods are difficult to extrapolate to larger areas and in time. In order to improve understanding of the fate of plastics in the ocean, research is needed on the following issues:

1. The rate at which plastics physically and chemically degrade into smaller particles at various depths in the ocean, and how this varies by polymer type.
2. The fate of plastics in marine biota, including residence time, digestive degradation, and excretion rates.
3. The physical, chemical, and biological consequences of marine microbial interaction with different plastics.

FINDINGS AND CONCLUSION

Finding 10: Plastics are found as contaminants throughout the marine environment, including in marine life, but plastic amounts and volume in specific reservoirs or in the ocean as a whole cannot currently be accurately quantified from existing environmental data.

Finding 11: Research to date suggests that the distribution and concentrations of plastic waste in the ocean and Laurentian Great Lakes reservoirs can vary substantially across multiple spatial and temporal scales.

Finding 12: Plastics, especially those with carbon-carbon polymer backbones, are persistent and accumulating in the ocean. Even though plastics are chemically and physically transformed into smaller particles in the environment (e.g., through weathering-induced fragmentation and by interaction with biota), evidence suggests that biodegradation (complete carbon utilization by microbes) does not readily occur in the marine environment.

Conclusion 7: Without modifications to current practices in the United States and worldwide, plastics will continue to accumulate in the environment, particularly the ocean, with adverse consequences for ecosystems and society.

Reckoning with the U.S. Role in Global Ocean Plastic Waste (2021)

DETAILS

250 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-45885-6 | DOI 10.17226/26132

CONTRIBUTORS

Committee on the United States Contributions to Global Ocean Plastic Waste; Ocean Studies Board; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2021. *Reckoning with the U.S. Role in Global Ocean Plastic Waste*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26132.

6

Tracking and Monitoring Systems for Ocean Plastic Waste

This report illustrates the limited, or absent, data from which to inform and implement effective plastic intervention actions. To inform source reduction strategies and policies, a national-scale tracking and monitoring program (or system of systems) is needed that spans the plastic life cycle—that is, from plastic production to leakage into the ocean (Figure 6.1). Tracking and monitoring plastic waste in the environment are essential to understanding and subsequently addressing the problem, but no comprehensive life-cycle tracking and monitoring of ocean plastic waste presently exists. Tracking and monitoring systems currently in place focus on solid waste management inputs and plastic waste items detected in the environment and ocean (Figure 6.1). This chapter explores tracking and monitoring systems currently in use and their limitations, and offers recommendations to inform the design, implementation, and benefits of a system or a system of systems to comprehensively track and monitor ocean plastic waste. Optimal systems will contribute to identifying and understanding the sources, transport pathways, distribution, and fate of ocean plastic waste, including legacy waste, to inform source reduction strategies or policies at multiple, if not all, intervention stages.

FIGURE 6.1 Flow diagram of potential plastic waste interventions from plastic production to direct input into the ocean. SOURCE: Modified from Jambeck et al. (2018).

As noted in previous chapters, there are still immense gaps in understanding these processes, and there is an opportunity to utilize and expand tracking and monitoring programs to fill these gaps. Observational data are particularly valuable to inform scholarly modeling of plastic waste, such as mass-balance models that integrate and assess plastic material entering and leaving a system, as well as the fate of discarded plastics (Borrelle et al. 2020, Geyer, Jambeck, and Law 2017, Jambeck et al. 2015, Lau et al. 2020). Tracking and monitoring are two tightly related methods; in this report, tracking means following the transport of marine debris over time, whereas monitoring typically involves detection and measurement of plastic waste in the environment at various temporal and spatial scales. Most existing activities qualify as monitoring efforts. However, throughout the chapter, the committee refers to the value of both approaches.

Documentation of the extent and character of plastic waste and potential sources or hotspots (reservoirs and sinks) informs prevention, management, removal, and cleanup strategies (UNEP 2020). Moreover, it plays a critical role in evaluating the effectiveness of any interventions or mitigation actions, such as source reduction strategies or policies (described further in Chapter 7). Thus, information obtained through tracking and monitoring efforts is critical to share with the public and decision makers involved in motivating and designing intervention strategies.

There is no national-scale monitoring system, or “system of systems,” to provide a baseline to track important sources, pathways, and sinks at the current scale of public or governmental concern. Under U.S. environmental management and protection law, monitoring systems are designed to achieve specific authorized purposes: legal compliance (e.g., waste generation or discharge monitoring), source detection (e.g., drinking water monitoring), and assessment of status and trends (e.g., ambient or in situ monitoring). The U.S. Environmental Protection Agency, the states, and other agencies operate a range of monitoring systems to meet such requirements, including those that monitor point and nonpoint sources and waste streams for pollutants or hazardous substances. These systems do not track or monitor plastic waste because it is not classified as a pollutant or constituent of concern. Much of the data on plastic waste are derived from data on municipal solid waste and, in a few cases, from nonpoint source trash monitoring, or from the efforts of research and community-based initiatives.

Part of the charge to the committee is to assess the value of a national marine debris tracking and monitoring system and how it could be designed and implemented. As specified in the task, this chapter considers how such a system may help in identifying priorities for source reduction and cleanup and assessing progress in reducing U.S. contributions to global plastic waste, and specifies existing systems and technologies that would be effective. The chapter gives particular attention to the National Oceanic and Atmospheric Administration's (NOAA's) Marine Debris Monitoring and Assessment Project (MDMAP), part of the NOAA Marine Debris Program (MDP), and potential improvements.

The chapter first explains existing tracking and monitoring strategies and programs. The following section describes considerations, enhancements, and opportunities for tracking and monitoring in the United States. The third section delves into the potential value of a national tracking and monitoring system. The final two sections outline priority knowledge gaps and present the committee's findings and recommendations.

EXISTING TRACKING AND MONITORING STRATEGIES AND PROGRAMS

Due to the lack of federal regulation of plastics as a pollutant in the United States and with the attendant lack of tracking and monitoring requirements, approaches to ocean plastic waste tracking and monitoring, including by the federal government, have been grounded in either research-based efforts or community science-based approaches.

Research-based Approaches

Research-based monitoring for ocean plastic waste is often driven by government initiatives at various levels and geographic scales: local, regional, state, national, and tribal. One example is NOAA's MDP, which is directed by Congress to maintain an inventory of marine debris and its impacts. To help achieve this directive, NOAA's MDP offers several nationwide, competitive, short-term (< 3 years) funding opportunities. Funds support "original, hypothesis-driven research projects focused on ecological risk assessment, exposure studies, and the fate and transport of marine debris" (NOAA Marine Debris Program 2021). These projects may be conducted by government agencies, industry, or academic institutions.

Many local and regional research-based programs design their programs around concerns specific to that region. For example, plastic pollution is a central concern for the state of California insofar as it is a leading state in the United States in terms of the size of the plastic industry (NOAA Marine Debris Program 2020a,b). Among western U.S. regions, Southern California holds the greatest assemblage of plastic processors (Moore 2008), and California is the nation's most populous state with approximately 40 million citizens (U.S. Census Bureau 2019). As a microcosm of the national (and global) plastic pollution problem, California is leading research, removal, and prevention efforts. While other U.S. states may not have the same focus and funding profile, lessons learned in California and other states can inform state and national efforts through research, removal, and prevention experiences.

Discrete, competitive *ad hoc* funding is appropriately employed to identify and fund hypothesis-driven research on aquatic plastic pollution but does not operate as a plastic waste tracking and monitoring system. While the information gained from this research can inform such a system, *ad hoc* research funding results in a disjointed monitoring record when individual projects end. This can contribute to a mosaic of plastic waste tracking and monitoring data collected using a diversity of methods, making it difficult to synthesize and interpret at meaningful spatial and temporal scales.

Community Science-based Approaches

Community science-based approaches often include citizen-science activities or other experiential activities that also build public awareness and engagement. Experiential activities engage individuals through active participation, such as beach cleanups conducted through a variety of entities (often nonprofit organizations). Here, the term “community science-based” rather than “citizen science-based” is used to more accurately reflect the diversity of individuals engaging in the broader plastic waste tracking and monitoring enterprise. Community science-based efforts therefore may encompass citizen-science while recognizing diversity, seeking equity, and promoting inclusion.

A wide variety of community-based approaches are used to gather data on plastic pollution in the environment. Most approaches are focused on coastal areas, but a multitude of electronic mobile applications (apps) do not limit data gathering to coastal regions. This enhanced accessibility by a broader demographic has increased the transparency and availability of litter and other debris data along inland waterways and urban areas. The majority of these apps gather data and are not designed to answer specific research questions. The interpretation of those data to answer specific questions occurs *a posteriori*; therefore, the available data may not always be suitable to the questions. Furthermore, community science-based approaches do not routinely select locations in a scientifically rigorous manner, and thus the data collected may not be representative of plastic pollution at regional or national scales. Despite these limitations, several of these systems have been consistently gathering data on plastic waste for many years at various temporal and spatial scales.

A recent river basin-scale community science-based project illustrates the integration of community-based data collection with targeted research data collection in three pilot communities along the Mississippi River (Youngblood, Finder, and Jambeck 2021). Researchers engaged the public in data collection using consistent transect-based methods so that the data could be compared with data from other research-based work in urban and riverine systems. The distinction between research- and community-based approaches is often blurred, and there is increasing interest in integrating research- and community-based science approaches (e.g., Earp and Liconti 2020, Liboiron et al. 2016). As with the Mississippi River project (Youngblood, Finder, and Jambeck 2021, NOAA Marine Debris Program 2021a), tracking and monitoring efforts may provide volunteers with specific research question-derived protocols that are distinct from cleanup-type protocols or opportunistic debris sightings used in other cases.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Selected Examples of Tracking and Monitoring Efforts

The following examples of plastic waste tracking and monitoring efforts are not intended to be comprehensive. Rather, they illustrate various approaches at assorted spatial and temporal resolutions. They may also potentially be integrated into a national-scale marine debris tracking and monitoring network or system of systems.

NOAA's Marine Debris Monitoring and Assessment Project

NOAA's MDP operates the MDMAP, a federal marine debris (plastics and other waste) inventory called for under the Marine Debris Act. MDMAP is the flagship community-science initiative of the MDP, engaging partner organizations and volunteers in a national shoreline monitoring program. The program has met many important national goals, including raising the issue to the public and decision makers, informing understanding of the risk and extent of marine debris in coastal and ocean areas, and identifying cleanup and mitigation priorities. Data collected and shared through the MDMAP are also intended to foster capacity at the local level in developing marine debris mitigation strategies to reduce impacts (NOAA Marine Debris Program. 2020b).

The foundation of MDMAP surveys is the NOAA-developed set of shoreline monitoring protocols (Lippiatt, Opfer, and Arthur 2013, Opfer, Arthur, and Lippiatt 2012) that standardize marine debris monitoring for consistent assessment of marine debris status and trends. The MDMAP surveys occur every 28 days (+/- 3 days), as close to low tide as possible for shoreline sites that meet NOAA's criteria (i.e., sandy beach or pebble substrate, year-round access, no breakwaters or other structures that may affect coastal circulation, and no known regular cleanup activities). In 100-m long sections, shoreline sites are surveyed for debris larger than 2.5 cm. Monitoring protocols include two shoreline survey types: standing stock and accumulation. Standing stock surveys are rapid visual assessments of debris concentration at a shoreline site. Accumulation surveys are tactile assessments that provide estimates of the flux, or accumulation rate, of debris at a shoreline site. For standing stock surveys, the 100-m long sections are divided into 20 five-meter length transects that extend from the back shoreline barrier to the water's edge. Surveyors identify and record debris items within four replicate, randomly selected transects. For accumulation surveys, debris is identified and removed from the entire 100-m site. To date, there are 9,055 surveys at 443 sites that span 21 U.S. states and territories and nine countries.

Studies, such as Uhrin et al. (2020), have demonstrated the utility of MDMAP data to estimate marine debris abundance and temporal trends, while also identifying associated limitations. The most extensive study on the benefits and challenges of existing marine debris monitoring programs, including MDMAP, is provided by Hardesty et al. (2017). The study was a collaborative project among Australia's Commonwealth and Industrial Research Organization, the Ocean Conservancy, and NOAA's MDP to better understand marine debris within the United States. Example issues identified include the following:

1. **Survey spatial sampling**. Most of the United States is not covered by existing data. Accumulation data are adequate for the West Coast, but standing stock is limited to concentrated efforts (Hardesty et al. 2017).
2. **Survey temporal sampling**. Accumulation rates are driven by regional/local biogeophysical forcing as well as debris type, such that the 28-day (+/- 3 days) sampling window might be insufficient (Hardesty et al. 2017, Smith and Markic 2013, Uhrin et al. 2020).

3. **Survey site selection**. Environmental and anthropogenic factors impact debris counts (e.g., distance to the nearest town, freshwater outfall, nearest river) but were not strategized/prioritized when designing a long-term monitoring program (Uhrin et al. 2020).
4. **Substrate type selection criteria**. Shoreline debris monitoring methods are not analogous for rocky shores, and thus limited data exist for these environments (McWilliams, Liboiron, and Wiersma 2018, Thiel et al. 2013).
5. **Number of survey participants**. A linear relationship exists between debris counts and the number of participants, such that some surveys could be severely underestimated if the volunteer threshold is not met (Hardesty et al. 2017, Uhrin et al. 2020).
6. **Characteristics of survey participants**. The quality of the data collected by community scientists can be equivalent to that collected by professional researchers, though variability may exist, for one example, younger primary school students detecting more debris than secondary students (van der Velde et al. 2017).

A key shortcoming of MDMAP identified by Hardesty et al. (2017) was the lack of a comprehensive national baseline for debris densities along the coast. This hinders the ability to monitor change in general, as well as change in association with the implementation of new policies and other interventions. In addition to a nationwide baseline survey, Hardesty et al. (2017) suggested regular surveys be conducted every 5 to 10 years at strategically selected sites in addition to continued citizen science efforts at self-selected sites. Aspects of these recommendations (i.e., one protocol, two approaches—community science and a national survey) appear in the NOAA MDP 2021–2025 Strategic Plan.

The International Coastal Cleanup

Developed and launched in 1986 by the nonprofit organization The Center for Marine Conservation (now known as Ocean Conservancy), the International Coastal Cleanup (ICC) volunteer effort grew from a small local cleanup in Texas to an annual international effort, engaging with people in more than 100 countries. The Ocean Conservancy leveraged its partnerships with volunteer organizations and individuals worldwide to expand toward The Ocean Conservancy's Trash Free Seas initiative.[1] A pioneer in citizen-science, the ICC was notable from inception insofar as it asked participants not only to collect coastal litter but also to document it using a standardized data card.

The ICC is the longest-running and most consistent community science data set, proving itself useful in both research and discussions around decision making. The ICC has been collecting largely the same data set since 1988, with comparable data available on local, regional, state-, and nationwide perspectives. This data set has been used to track the effectiveness of regulations on plastic pollution. For example, the data set was used to evaluate the impacts of beverage deposit return schemes in the United States and Australia, finding that states that have a beverage container deposit result in 40% fewer containers littered (Schuyler et al. 2018). Data for the ICC are typically collected on a paper data card; however, an app (Clean Swell) is now available that mimics the paper data card, albeit with limited items. The full ICC data card is also integrated into the mobile app Marine Debris Tracker (described below), and the Ocean Conservancy and University of

[1] See https://oceanconservancy.org/trash-free-seas/.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Georgia are now coordinating on data collection and management. Both apps allow for more widespread collection of plastic pollution data through the engagement of a broader public demographic.

Marine Debris Tracker

Launched in 2011, the mobile app Marine Debris Tracker was the first litter or debris tracking app developed and has the longest history of electronic data collection (Jambeck and Johnsen 2015). In addition, it is one of few applications and programs to allow complete open access to all data ever collected. The Marine Debris Tracker was originally sponsored by a grant award from NOAA to the University of Georgia. NOAA subsequently sponsored research work with the app, with other partners contributing over time. The app has been used for various community science-based projects, as well as education and research initiatives (Ammendolia et al. 2021, Martin et al. 2019, National Geographic 2021, Thiel et al. 2017, Youngblood, Finder, and Jambeck 2021, Youngblood et al. In Review). In 2019, the app became sponsored by the global financial services company Morgan Stanley to professionalize it in partnership with the National Geographic Society, but the University of Georgia independently maintains science and data management for the app.

The Marine Debris Tracker database provides insights on managing, compiling, harmonizing, and visualizing plastic pollution data because it is a harmonized background database that allows for the creation of customized litter lists for individual organizations that vary in individual items cataloged. The app's harmonization allows for combined data compilation and statistics to be completed on the entire data set. To date, approximately 4 million items have been catalogued with the Marine Debris Tracker, with 2.33 million items originating in the United States. For example, The Mississippi River Plastic Pollution Initiative collected data on more than 75,000 debris items by both researchers and community members over 3 weeks in April 2021. Marine Debris Tracker was an early example of the successful application and acceptance of app use in community science, and remains the foremost and most comprehensive extant plastic pollution app.

Supporting Plastic Waste Mitigation with Monitoring Data

Data integration between electronically collected databases can provide a more complete picture of plastic waste and marine debris in the United States. While integrating these databases is not trivial, it is possible. The current three largest electronic research and community science-based data sets in the United States—the ICC, Marine Debris Tracker, and NOAA's MDMAP—are not well integrated.

Growing online and wireless connectivity nationwide and worldwide is making community science-based tracking and monitoring of plastic waste in the environment increasingly accessible. Many existing data collection efforts already allow the data to be visualized in map form.[2] Increased accessibility of plastic waste data through visualization tools has the potential to engage a larger, more diverse sector of society in community science-based activities—such as data crowdsourcing—toward awareness of and solutions to the ocean plastic waste problem.

[2] See https://mdmap.orr.noaa.gov/.

Example Efforts

California established its Water Quality Monitoring Council's Trash Monitoring Workgroup "to support current practices and advances in trash monitoring" (California Trash Monitoring Methods Projects 2021). This Trash Monitoring Workgroup is "developing data analysis and visualization tools aimed at assessing the effectiveness of policies and practices for limiting the amounts of trash in the environment" (California Trash Monitoring Methods Projects 2021). One outcome was the 2021 publication of the *California Trash Monitoring Methods and Assessment Playbook*, which provides an overview of the methods in use to monitor trash in the environment (Moore et al. 2021b).

Monitoring waste transport through watersheds (i.e., waste transported from the source via freshwater rivers and other waterways to the ocean) offers a more comprehensive understanding of plastic waste sources to guide targeted interventions. A recent research-based effort in Japan has quantified plastic emissions into the ocean using microplastic and macroplastic observations, correlations between microplastic concentrations in rivers and basins, and a water balance analysis (Nihei et al. 2020). This analysis estimated plastic input from Japanese land to the ocean as 210–4,776 tons per year. This work has also produced a plastic emissions map (Figure 6.2), which allows more efficient and effective deployment of plastic interventions throughout the country with a scale of 1-km grid cells. However, Nihei et al. (2020) did not include higher flow conditions or wastewater treatment plant outputs in the analysis.

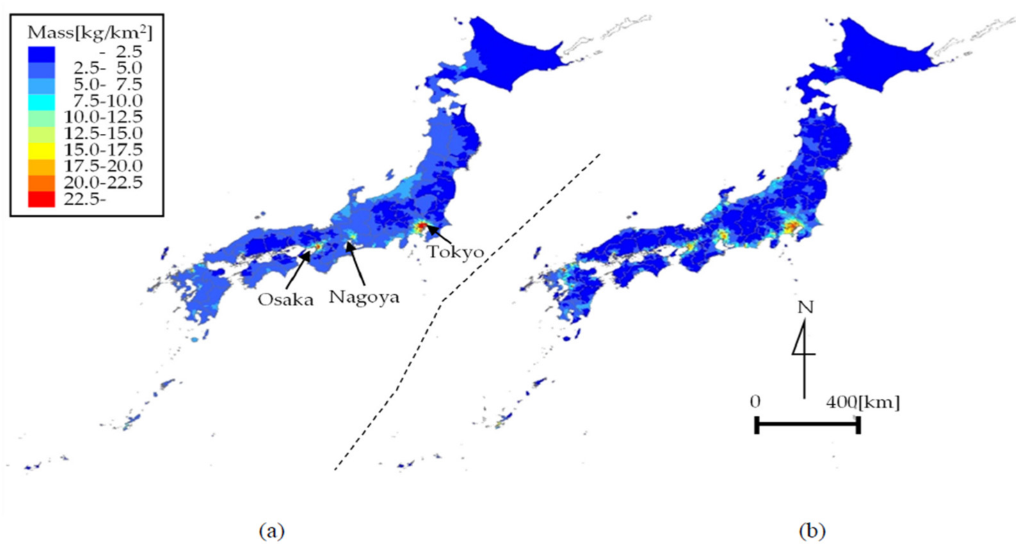

FIGURE 6.2 These maps indicate microplastic mass concentrations across 1-km grids in Japan for (a) population density and (b) urban area ratio. These estimated concentrations were found by use of linear approximation and a ratio of macroplastics/microplastics of 3.13. Hotter colors illustrate higher levels of microplastics, and cooler colors represent lower emissions. SOURCE: Nihei et al. (2020).

The United Nations' Economic and Social Commission for Asia and the Pacific's Closing the Loop program[3] seeks to reduce plastic waste entering the ocean. This program has four main components: a plastic pollution calculator, a digital mapping tool informed by monitoring efforts, local action plans, and resource sharing. The International Solid Waste Association and the

[3] See https://www.unescap.org/projects/ctl.

University of Leeds have worked with the Closing the Loop program to use the Plastic Pollution Calculator to look at four cities to determine how plastics move from land to rivers and eventually to the ocean. The calculator provides information on sources, pathways, hotspots, and sinks of plastic waste to inform interventions to reduce ocean plastics. A digital mapping tool can examine images to determine the presence of plastic waste that could enter the ocean. This method can utilize images from a variety of sources, therefore reducing costs. The third component is creating a local action plan from the data gained from the plastic pollution calculator and the digital mapping tool. These plans are in process in Da Nang, Vietnam; Kuala Lumpur, Malaysia; Surabaya, Indonesia; and Nakhon Si Thammarat, Thailand. Last, a resource platform is being created along with an eLearning course to share information with stakeholders.

An additional program focused on Asia and the Pacific is CounterMEASURE,[4] conducted by the United Nations' Environment Programme's Regional Office for Asia and the Pacific, which works alongside a variety of local and international partners. This work is funded by the Government of Japan. CounterMEASURE focuses on rivers as a source and transport mechanism of plastic pollution. CounterMEASURE has completed Phase I, which included the development of a conceptual framework for monitoring plastic pollution in rivers and a geographic information system data visualization platform, and is now expanding to Phase II to reduce plastic pollution in rivers regionally and globally. A description of CounterMEASURE Phase II, the "theory of change" to reduce plastic waste in rivers, is provided in Figure 6.3 and shows the interconnected nature of understanding the distribution of plastics and developing tools, policies, technologies, and innovate financial mechanisms to reduce marine plastic pollution.

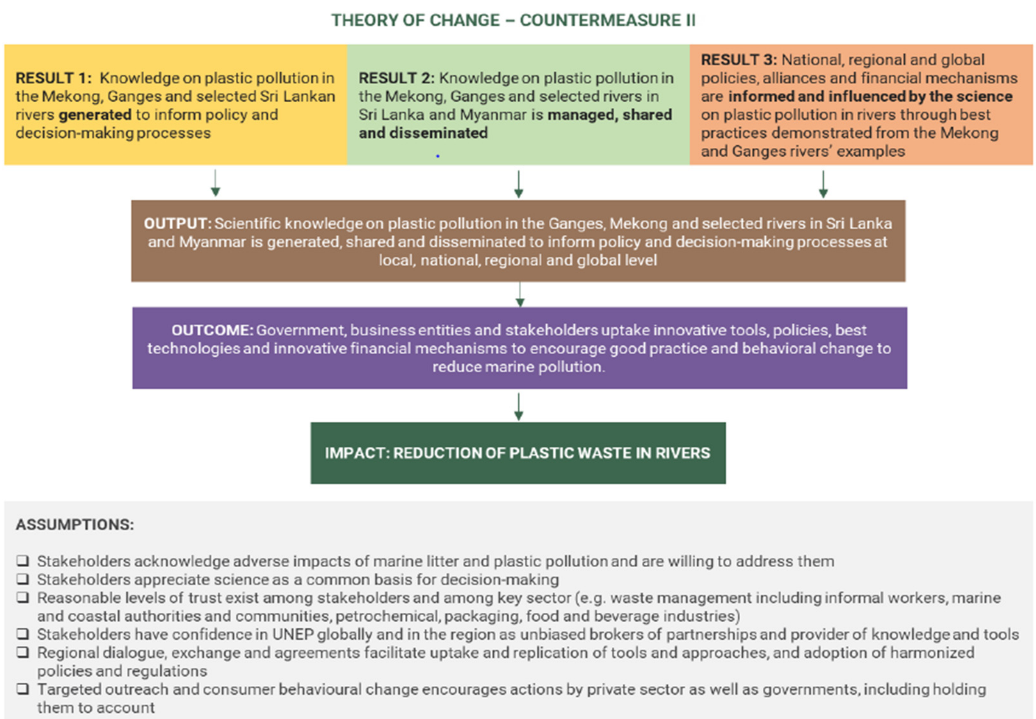

FIGURE 6.3 Theory of change for the United Nations Environment Programme's CounterMEASURES II program. SOURCE: CounterMEASURE (2021).

---

[4] See https://countermeasure.asia/.

CONSIDERATIONS, ENHANCEMENTS, AND OPPORTUNITIES FOR TRACKING AND MONITORING IN THE UNITED STATES

Spatial and Temporal Scales

The spatial and temporal scales of plastic waste data collection are very important because they will define the nature of the information gleaned from tracking and monitoring, as well as its potential usefulness in answering key questions. Data collected on marine debris items during coastal cleanups may illustrate waste management issues at local, regional, or national scales (Ribic, Johnson, and Cole 1997, Ribic, Sheavly, and Klavitter 2012, Ryan and Moloney 1993, Schuyler et al. 2018, Sheavly 2007, and see Ryan et al. 2009) but have been less effectively synthesized and interpreted at a global scale (Browne et al. 2015). Spatial monitoring of plastic waste is also commonly informed by elements of human geography such as the built environment, population density, and land use (Jambeck et al. 2015). Emerging technologies, described below, can expand our ability to collect data on plastic waste at a larger scale.

The timing of tracking and monitoring efforts will also shape the resulting findings. Widespread geographic monitoring at a "single" point in time can provide a static "snapshot" of aquatic plastic waste at various spatial or temporal scales; this type of monitoring is also known as standing stock sampling or standing stock surveys (Opfer, Arthur, and Lippiatt 2012, Ryan et al. 2009). Longitudinal sampling of locations at defined time intervals—ideally after initial cleanup—can provide dynamic information on plastic waste accumulation or reduction (Boland and Donohue 2003, Dameron et al. 2007, Morishige et al. 2007, Opfer, Arthur, and Lippiatt 2012, Ribic, Johnson, and Cole 1997, Ribic, Sheavly, and Klavitter 2012, Ryan et al. 2009), though sampling frequency may bias results from such factors as beach litter turnover or litter burial (Ryan et al. 2014).

A multitude of temporal factors may inform repeated sampling designs such as seasonality and the frequency and patterns of resource use such as beach attendance and fishing effort, among others (Jambeck et al. 2015). Opportunistic tracking and monitoring of ocean plastic waste associated with episodic or pulsed events such as tsunamis (e.g., Murray, Maximenko, and Lippiatt 2018), hurricanes/tropical cyclones (e.g., Lo et al. 2020), floods and precipitation events (e.g., Pasternak et al. 2021, Yu et al. 2002), or the capture of these events within established monitoring programs is also informative. When tracking and monitoring programs use standardized protocols, regional and site-specific comparisons are possible, greatly improving the ability of monitoring data to set priorities for source reduction and evaluate the success of intervention measures. In an effort to support site-specific and regional comparisons, NOAA developed standardized protocols and data collection for shoreline sampling (Opfer, Arthur, and Lippiatt 2012). Last, the scale of ocean plastic waste tracking and monitoring both in space and time is determined by the capital, including human capital, available and invested in such efforts.

Standardized Methods

Historically, data collection methods have been inconsistent among plastic waste tracking and monitoring efforts, resulting in detailed place-based studies but failing to form a body of research that can be compared geographically or temporally (Browne et al. 2015). Consistent methods used across geographic scales do allow for geographic comparisons, trend analyses, and data compilations. This has been possible through U.S. federal programs such as the National

Reckoning with the U.S. Role in Global Ocean Plastic Waste

Marine Debris Monitoring Program, which ran from 1996 through 2007 (Ribic et al. 2010), and currently via the NOAA MDMAP (Hardesty et al. 2017).

Consistent, scientifically robust methods such as the use of randomized transects in cities, villages, and communities, often considered geographic sources of litter and leakage, are being used for projects to obtain data comparable across locations, over time, and in regional settings such as river basins (National Geographic 2021, Youngblood, Finder, and Jambeck 2021). In some cases, these methods are only applied by researchers. In other instances, community scientists with some level of training in the use of guiding tools such as mobile apps can meaningfully contribute to robust tracking and monitoring data collection. Participatory sensing of litter data can be opportunistic or led by research protocols. The latter improve data quality and facilitate the answering of specific research questions (Ammendolia et al. 2021, Jambeck and Johnsen 2015, Martin et al. 2019, Youngblood, Finder, and Jambeck 2021, Youngblood et al. In Review).

Development of standardized or harmonized (i.e., comparable) sampling and analysis protocols is a commonly asserted need, with known challenges, (GESAMP 2019, Hartmann et al. 2019, Hung et al. 2021) that is gaining attention both in the United States and internationally. For example, an International Standards Organization (ISO) subcommittee on environmental aspects of plastics is currently working on standards to be used in a regulatory structure.[5] In the United States, U.S. EPA Region 9 is focusing on water quality monitoring methods and ASTM standards for sampling microplastics, which would enable microplastics to be included in the National Coastal Condition Reports and monitored in support of Clean Water Act 303d impairment monitoring in states like Hawaii and California; it could also be used in remediation and cleanup (Allen 2021). The state of California has already adopted a formal definition of microplastics for use in developing standards for drinking water, and is anticipated to have developed standardized methodology, a sampling and analysis plan, health effects, and accreditation for drinking water by Fall of 2021 (California Water Boards 2021). Such standardization will allow for multiple tracking and monitoring efforts by researchers, communities, and industrial entities to be interpreted in aggregate.

Study Design

The *a priori* definition of the purpose of a tracking or monitoring program is essential to effective program design. For example, monitoring for the quantity of plastics entering *the environment* differs from monitoring for the quantity of plastics entering *the ocean*. A first step in designing a monitoring system is often to articulate the questions to be answered through the establishment of the monitoring program. These questions guide the appropriate development and implementation of the monitoring program. In considering a design to address the entire life cycle of plastics (Figure 6.1), tracking and monitoring could occur from the production of resin polymers (the ultimate source of the material) through manufacturing, distribution, use, and disposal.

However, most often plastic monitoring is done at the waste management intervention stage and environment stages (Figure 6.1). This is often considered the *de facto* source of pollution because a majority of macroplastic pollution stems from mismanaged municipal waste. However, other pathways into the ocean exist, such as derelict fishing gear and direct input of microplastics from sources such as direct discharge, stormwater runoff, and tire wear, among others. Monitoring for leakage of waste can be used to pinpoint where the materials management system is disjointed

---

[5] See ISO/CD 24187.2: Principles for the Analysis of Plastic and Microplastic Present in the Environment.

or broken. Monitoring leakage of plastic waste could include measuring litter in cities, or along riverbanks or coastlines; capturing floating debris in rivers and waterways; or documenting plastics in the ocean. While leakage of plastic waste into the environment can be an indicator of a system that is not working properly, data further upstream in the plastic life cycle (e.g., production) can inform interventions that might have the most impact and be most cost-effective (Figure 6.1). In this role, tracking and monitoring can provide a more holistic understanding of the plastic materials management system toward enhanced and more informed policy making and decision making.

Some challenges related to designing a tracking and monitoring system include the following:

- inaccessible data, including proprietary data, which is why open, accessible data are so important;
- difficulty in collecting data over time for a large area such as the entire United States and its territories;
- limited data collection and analysis speed (which is improving with near-real-time data available from sites such as the Marine Debris Tracker);
- rapid and episodic changes in plastic use for which it is difficult to predict and plan monitoring—as one example, increased single-use plastic consumption and waste during the COVID-19 pandemic; and
- the ongoing degradation of larger plastic items or fragments into ever smaller pieces in the environment.

Given the degradation of plastics in the environment (see Chapters 4 and 5), there is a clear need for the identification, adaptation, or development of technologies to detect ever-smaller plastics. Current analytical practices are insufficient to detect environmental plastics at nanoscale sizes.

Available and Emerging Technologies

Intergovernmental agencies, environmental groups, and the research community have begun to assess all existing and emerging technologies for tracking and monitoring marine plastic debris, including *in situ* sensing, remote sensing, and numerical modeling, toward the goal of an integrated marine debris observing system (Maximenko et al. 2019 and depicted in Figure 6.4). These *in situ* sensing, remote sensing, and modeling initiatives could be integrated into already existing surface, inland, and coastal observing systems (e.g., NOAA's Integrated Ocean Observing System and state or federal water monitoring systems) and could form the basis for nationwide coordination around monitoring among different groups and using multiple technologies (similar to NOAA's National Mesonet Program for weather prediction). To do this effectively would require coordination between emerging technology programs and existing monitoring programs. Such coordination would focus on expanding collection measurements and protocols to allow remote sensing to measure plastic information already collected, GPS coordinates, photos, and, optimally, plastic spectra.

Remote sensing has been emphasized as an underutilized and viable option for near-surface tracking and monitoring of plastic debris on land and at sea, and from land to sea (Figure 6.4) given the following: (1) the variety of available platforms (unmanned aerial vehicles or UAVs, aircraft, and satellites) and sensors; (2) its ability to provide spatially coherent coverage and consistent surveillance in time across scales—local to global (see also Martínez-Vicente et al.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

2019); (3) its ability to access difficult to reach areas (Candela et al. 2021, Lavers and Bond 2017); and (4) its possibility to design a national monitoring program and illustrate where marine plastic debris is found (Candela et al. 2021).

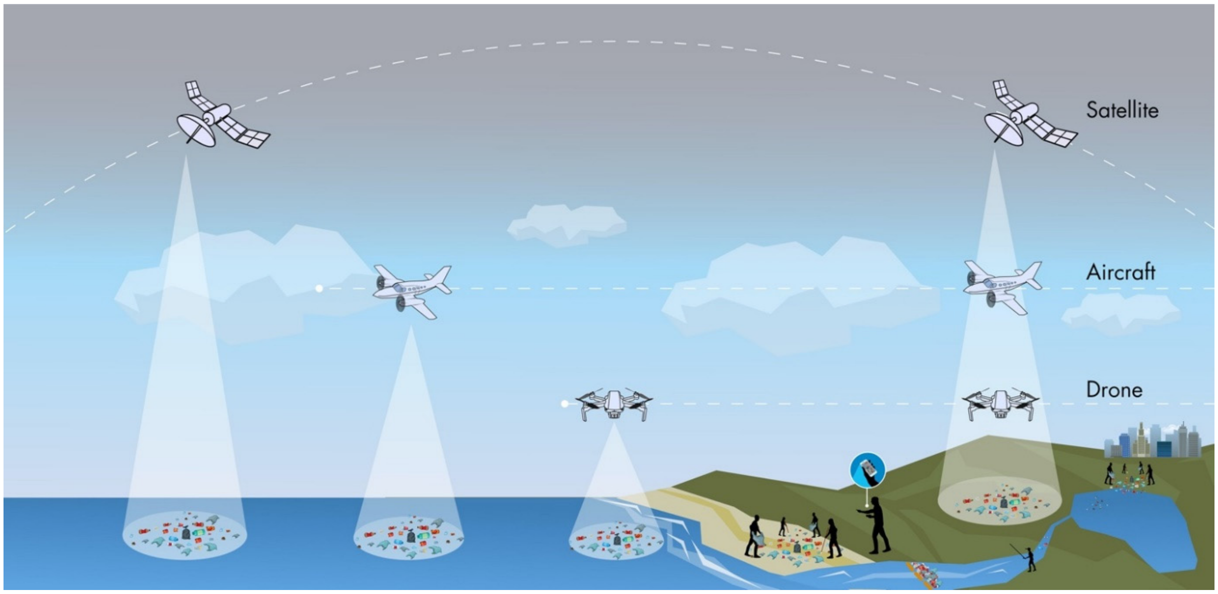

FIGURE 6.4 Depiction of a network of monitoring platforms that can be utilized as part of a marine debris observing system, collecting data at various scales.

Current remote sensing approaches under investigation with potential for marine debris detection include Synthetic Aperture Radar (Arii, Koiwa, and Aoki 2014, Matthews et al. 2017), bistatic radar (Evans and Ruf 2021), LIght Detection And Ranging (LIDAR) systems (Ge et al. 2016, Pichel et al. 2012), polarimeters, thermal infrared sensors (Garaba, Acuña-Ruz, and Mattar 2020, Goddijn-Murphy and Williamson 2019), and passive optical remote sensing (e.g., Acuña-Ruz et al. 2018, Biermann et al. 2020, Ciappa 2021, Garaba and Dierssen 2018, Goncalves et al. 2020, Kikaki et al. 2020, Topouzelis et al. 2020, Topouzelis, Papakonstantinou, and Garaba 2019). Assessment of the capabilities and limitations of remote sensing techniques are the subjects of active research (see Hu 2021, International Ocean Colour Coordination Group 2022, Martínez-Vicente et al. 2019, Maximenko et al. 2019). However, certain technologies have shown success in detection and thus could already be utilized as part of a tracking and monitoring system. Specifically, passive optical remote sensing is the most explored option with demonstrated potential in literature for inland, coastal, and open ocean marine debris detection (see International Ocean Colour Coordination Group 2022, Martínez-Vicente et al. 2019, Maximenko et al. 2019 for more information on all techniques).

Passive optical remote sensing includes red-green-blue (RGB) cameras, multispectral imagers, and hyperspectral imagers on various platforms (UAVs, aircraft, and satellites) with different spatial resolutions (on the order of submeter to hundreds of meters). RGB cameras simulate human eyesight, focusing on three bands within the visible portion (400–700 nm) of the spectrum. Multispectral imagers collect measurements in a limited number of wavelength bands (typically less than 10–15). Hyperspectral imagers (otherwise referred to as imaging spectroscopy) provide narrow, contiguous sampling across the spectrum (spectral sampling typically less than 10 nm translating to hundreds of wavelength bands). The spectral range covered by multispectral imagers and imaging spectroscopy is sensor-dependent but can span the visible, near-infrared (NIR), and shortwave infrared (SWIR) spectral range (700–2500 nm).

RGB cameras on UAVs have been used extensively for indirect detection of marine litter on beaches and shorelines (e.g., Bao et al. 2018, Deidun et al. 2018, Fallati et al. 2019, Goncalves et al. 2020, Martin et al. 2018, Moy et al. 2018) with some application in coastal waters (e.g., Themistocleous et al. 2020, Topouzelis et al. 2020, Topouzelis, Papakonstantinou, and Garaba 2019), providing a cost-effective solution for localized image acquisitions at very high spatial resolution (on the order of centimeters). However, the practicality of RGB detection degrades as the platform changes to those at higher elevations, such as aircraft or satellite for regional to global coverage, wherein individual plastic targets will become less distinct with respect to their environment such that more wavelength bands are necessary to ensure accuracy between plastic debris and radiometric properties.

Recent laboratory studies revealed that marine plastic debris has unique spectral features in the NIR and SWIR spectrum (e.g., Garaba and Dierssen 2018, Hu et al. 2015, Knaeps et al. 2021, Moshtaghi et al. 2021, Tasseron et al. 2021). Therefore, passive methods that include the NIR and SWIR offer the greatest potential for direct plastic debris detection (Martínez-Vicente et al. 2019). Several recent papers have used NIR and SWIR spectral information from airborne imaging spectroscopy (Garaba and Dierssen 2018) and multispectral satellite imagery (e.g., Acuña-Ruz et al. 2018, Biermann et al. 2020, Ciappa 2021, Kikaki et al. 2020, Topouzelis et al. 2020, Topouzelis, Papakonstantinou, and Garaba 2019) to detect marine plastic debris in inland, coastal, and open ocean environments. Optical passive sensors provide an opportunity to identify and monitor leakage sources and accumulation regions (or hotspots), guide removal efforts, aid with design or refinement of a national monitoring program (areas where field collection are a priority), and enable trend assessment over time with repeat observations.

Passive optical remote sensing has the potential to detect marine macroplastics at the ocean surface but likely not microplastics (from aircraft and satellite) and especially not at depth. For detection of microplastics, *in situ* methods have been applied to various environments, including marine and freshwater environments (e.g., Choy et al. 2019, Enders et al. 2015, Ghosal et al. 2018, Koelmans et al. 2019, Lenz et al. 2015, Tagg et al. 2015, van Cauwenberghe et al. 2013, Wolff et al. 2019, Zhang et al. 2017). Typically, water is sampled using bulk collection for small volumes or using plankton nets to filter large volumes, and samples are analyzed for potential plastic particles that must be identified via various techniques. Methods currently recommended for monitoring by GESAMP (2019) include optical identification (naked-eye detection, visual and fluorescence microscopy, and flow cytometry) and chemical identification/quantification methods (Fourier Transform InfraRed [FTIR], Raman spectroscopy, pyrolysis-gas chromatography-mass spectrometry [py-GC-MS], and thermo-extraction and desorption gas chromatography-mass spectrometry [TED-GC-MS]). See literature reviews from Araujo et al. (2018, Table 1), Mai et al. (2018), Primpke et al. (2020), Silva et al. (2018), and Zarfl (2019) for detailed information on all approaches and additional techniques (e.g., hyperspectral imaging, scanning electron microscopy, etc.), as well as sampling and sample extraction.

FTIR and Raman spectroscopic techniques (e.g., Araujo et al. 2018, Elert et al. 2017, Kappler et al. 2016) are the two most commonly used techniques to characterize microplastics and their polymers. The European Union expert group on marine litter recommended that all suspected microplastics in the 1–100 mm size range should have their polymer identity confirmed by spectroscopic analysis (Gago et al. 2016, MSFD Technical Subgroup on Marine Litter 2013). Within the literature, FTIR and Raman techniques have been used for analytical identification of microplastics ranging from biota, sediment, seawater, freshwater, and wastewater, to food, beverage, and cosmetics (see Table 1 of Araujo et al. 2018 for a comprehensive list of Raman literature up to January 2018, and Primpke et al. 2020 for FTIR literature up to May 2019). The current limitation of Raman and FTIR imaging is the resource-intensive, both in time and dollars, nature of singular particle characterization.

Agency Coordination

Numerous agencies within the U.S. federal government have mandates or programs that directly or indirectly intersect with the issue of ocean plastic waste (U.S. GAO 2019). The value of interagency coordination has long been recognized, if not yet exhaustively achieved. The Marine Plastic Pollution Research and Control Act of 1987 (33 U.S.C. § 1914) (amending the Act to Prevent Pollution from Ships) provided for an "Interagency Committee," later amended by the Marine Debris Research, Prevention, and Reduction Act of 2006 (Marine Debris Act; 33 U.S.C. § 1954, as amended), to establish the Interagency Marine Debris Coordinating Committee (IMDCC). With the reauthorization and amendment of the Marine Debris Act by the 2020 Save Our Seas 2.0 Act (Public Law Number 115-265), the IMDCC remains a primary vehicle for enhanced interagency connectivity. Members include NOAA (which chairs the committee), U.S. EPA, U.S. Coast Guard, U.S. Navy, U.S. Department of State, U.S. Department of Interior, U.S. Agency for International Development, Marine Mammal Commission, and the National Science Foundation.

The IMDCC serves as a legislated foundation for interagency coordination, including with regard to tracking and monitoring, but has unrealized potential in several areas in part stemming from a lack of clarity on IMDCC membership (U.S. GAO 2019). The IMDCC has predominantly focused on its information-sharing role, citing the challenges of interagency collaboration such as mandate, mission, and budgetary appropriations variability among NOAA and other IMDCC members as barriers to expanded member coordination (U.S. GAO 2019). Research and technology development and coordination were among topics identified by experts in an audit report by the Government Accountability Office (GAO) of the IMDCC as areas of suggested action (U.S. GAO 2019). GAO suggested enhanced coordination among federal, local, state, and international governments and other nonfederal partners to address marine debris, as well as research on sources, pathways, and location of marine debris, inclusive of upstream elements such as rivers and stormwater. Tracking and monitoring of environmental plastic waste is foundational to such efforts.

A national approach to tracking and monitoring mismanaged plastic waste that includes "upstream" source areas in the watershed has the potential to identify and inform intervention opportunities earlier, eliminating or reducing the time plastic waste is present in the environment. This necessitates enhanced collaboration and coordination with entities, including local, state, federal, and tribal agencies that have jurisdiction or other interests in the watersheds and waterways upstream of the coastal deposition of plastic waste. For example, the U.S. Geological Survey (USGS) maintains 27 regional Water Science Centers with core capabilities in hydrologic data collection, research and assessments, and information services. Their inland river and streamflow measurements, as well as flood forecasts, could inform aquatic plastic waste tracking and monitoring and potentially be co-located with plastic debris sensors as part of a monitoring network. USGS scientists have contributed to research-based monitoring and analysis efforts for microplastics (Baldwin, Corsi, and Mason 2016). A national approach may constitute a "system of systems," where programs and data collection efforts by various agencies, as well as research and community-based initiatives, are coordinated.

Effective Approaches to Tracking and Monitoring to Reduce Plastic Waste in the Ocean

Using their own experience and expertise, open session presentations from speakers, and research illustrated in this report, committee members created a list of tracking and monitoring program attributes expected to have the greatest efficacy in informing strategies to reduce plastic waste inputs to aquatic systems. Figure 6.5 illustrates a conceptualized approach to designing, implementing, evaluating, and adapting tracking and monitoring systems for plastic waste.

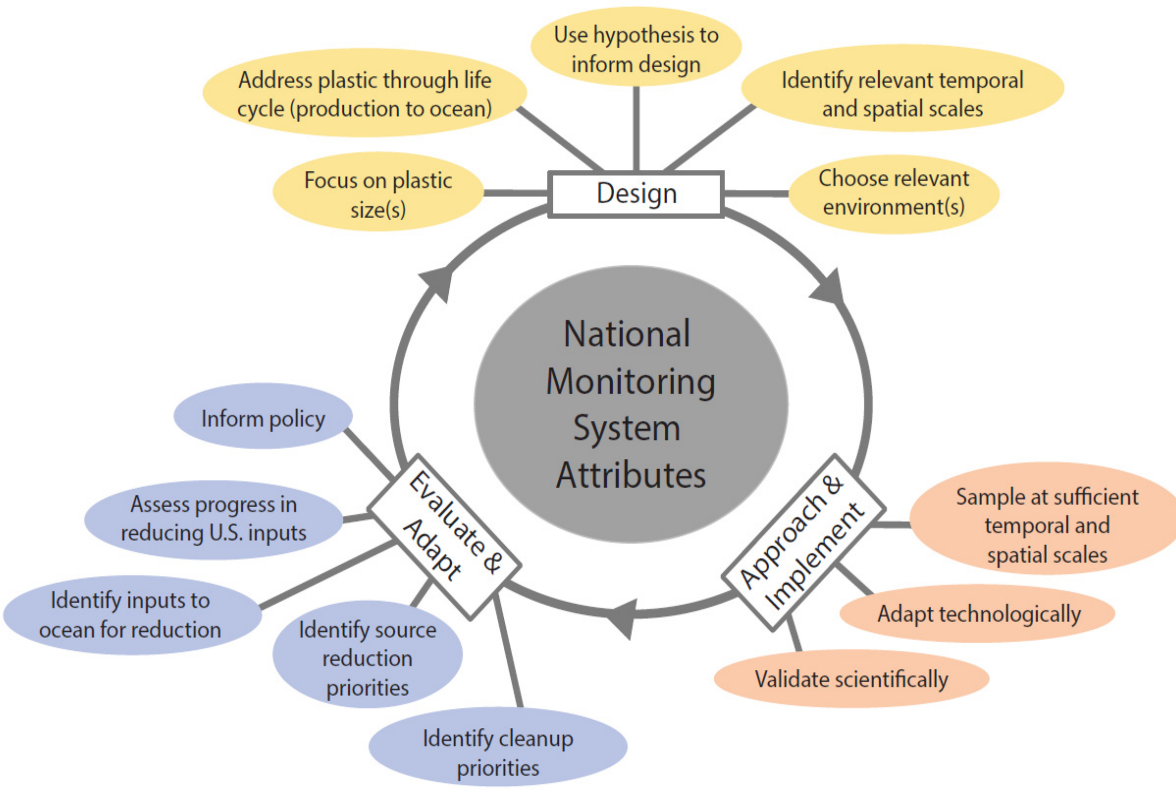

FIGURE 6.5 A conceptualization of the attributes of effective tracking and monitoring systems for marine plastic waste and other aquatic plastic waste. Even if all elements illustrated are not included, tracking and monitoring systems can still provide significant value based on specific needs, knowledge gaps, or other circumstances and are critical for the prioritization, design, and evaluation of interventions to reduce mismanaged plastic waste. Temporal and spatial scales are important to consider at the design stage and the approach and implementation stage. At the design stage, the focus may be on statistical power whereas the approach may have to include sampling changes in the field dependent on environmental conditions (e.g., weather).

The following describes tracking and monitoring systems of plastic waste items expected to have the greatest efficacy in ultimately reducing plastic waste inputs to aquatic systems. The specific type or types of plastic waste addressed by any system, including polymer types, associated chemicals, or other characteristics or parameters of interest, will necessarily reflect the aims and drivers of those entities establishing the tracking and monitoring system.

- Tracking and monitoring systems that are **scientifically robust, hypothesis-driven, and conceptualized *a priori* to answer critical knowledge gaps,** rather than approaches applied post-hoc to plastic waste tracking and monitoring questions.
- **Technologically adaptive tracking and monitoring systems** that are able to incorporate and utilize current and emerging technologies to improve the spatial and temporal resolution of mismanaged plastic waste including the application of
    - remote sensing, autonomous underwater/remotely operated vehicles, sensor advances, passive samplers, and others;
    - crowdsourcing apps;
    - barcode tracking for recyclability and traceability;
    - biochemical markers and tracers that provide information on organismal exposure to environmental plastics, including legacy exposure and that which relates to organismal, including human, health; and
    - other current or emergent technologies.
- Tracking and monitoring systems that are **applied with sufficient spatial and temporal resolution** to capture meaningful data concerning knowledge and policy needs. For example, monitoring from a watershed perspective or including pre- and **post-intervention tracking and monitoring to assess progress.**
- Tracking and monitoring systems that **collect data that are comparable and, when scientifically robust, compatible with prior efforts. Examples including using standardized** measurement units or experimental design.
- Tracking and monitoring systems that **leverage, rather than separate, U.S. federal investment** in the reduction of mismanaged plastic waste among government departments and create synergies in the federal response to such waste.
- Tracking and monitoring systems that **encompass the full life cycle of plastics**, thereby achieving an understanding of the "upstream" plastic waste compartments and associated leakages.

POTENTIAL VALUE OF A NATIONAL MARINE DEBRIS TRACKING AND MONITORING SYSTEM

A single, national marine debris (or plastic waste) tracking and monitoring system does not exist in the United States, nor does such a system appear to be feasible given the complexity of plastic production, use, and disposal and the diversity of environments through which plastics are transported and distributed. A summary of marine debris/aquatic plastic waste tracking and monitoring systems and the intersection of such systems in addressing key aquatic plastic waste mitigation aims is provided in Table 6.1. This table illustrates that no single system or component serves as a comprehensive, stand-alone, national marine debris tracking and monitoring system. Furthermore, the specific aims of local, regional, national, and international efforts require the application of tracking and monitoring tools and technologies effective at particular spatial and temporal scales.

However, the use of multiple, complementary tracking and monitoring systems (depicted in Figure 6.6) in a synergistic approach implemented at sufficient spatial and temporal scales would contribute to (1) understanding the scale of the plastic waste problem and (2) the identification of priorities for source reduction, management, and cleanup and the assessment of progress in reducing U.S. contribution to global ocean plastic waste. For example, an optimal monitoring system design for first flush events would be useful to inform cleanup sites, track their progress, and reduce inputs to the ocean. The design could encompass community science cleanups, capture devices, trash booms, and remote sensing approaches.

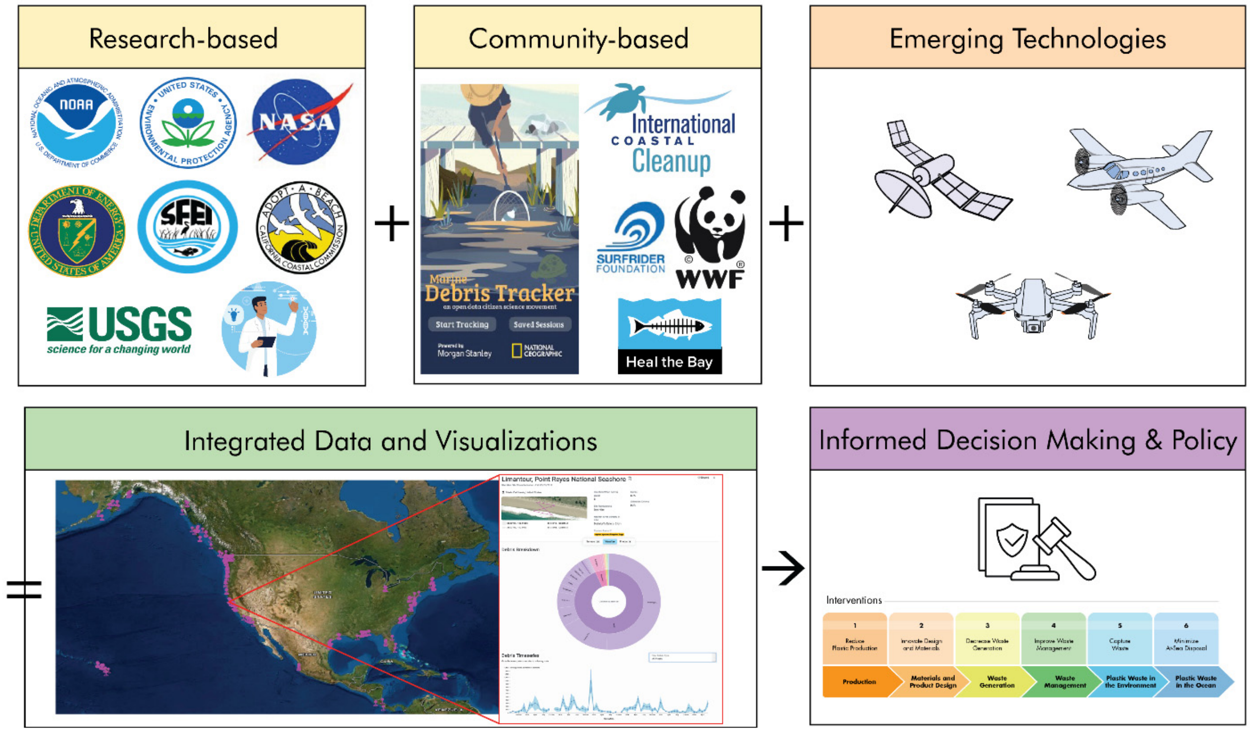

FIGURE 6.6 Depiction of the components of a national marine debris tracking and monitoring network, consisting of research and community-based initiatives, supplemented and supported by large-scale monitoring by remote sensing methods. Integrated data and associated visualizations would provide comprehensive understanding of plastic pollution in the United States, critical to informing actions toward plastic pollution reduction.

KNOWLEDGE GAPS

Currently, data collected by various monitoring efforts are not well integrated. There would be significant value in developing a data and information portal by which existing and emerging marine debris/aquatic plastic waste data sets could be integrated to provide a more complete picture of the efforts currently tracking plastic pollution across the nation. Such a portal would need to be supported by (1) standardized methods of data collection and (2) support for long-term data infrastructure. The ability to visualize the data contained in the portal would greatly enhance its utility for the public and decision makers to inform and assess the progress of plastic waste reduction efforts.

Reckoning with the U.S. Role in Global Ocean Plastic Waste

TABLE 6.1 A Summary of Marine Debris/Aquatic Plastic Waste Tracking and Monitoring Systems, Components, or Technologies and Their Intersection in Addressing Key Aquatic Plastic Waste Mitigation Aims

Marine Debris/Aquatic Plastic Waste Tracking and Monitoring						
		Mitigation Aims				
System, Component, or Technology	**Size class sampled or tracked**	**Identify source reduction priorities**	**Identify cleanup priorities**	**Assess progress in reducing U.S. inputs**	**Reduce inputs to ocean**	**Inform policy**
Community/Citizen-Science/ Traditional and Indigenous Community Cleanups	Micro Meso Macro					
Community/Citizen-Science/ Traditional and Indigenous Community Data Collection and Surveys	Meso Macro					
Industry/Corporate efforts[a]	Micro Macro					
Municipal Solid Waste Organizations and Entities	Micro Macro					
Derelict Fishing Gear Surveys	Macro					
Passive or Static Capture Systems[b]	Macro					
Remote Sensing Applications	Macro					
Government/Agency Efforts[c]	Meso Macro					
Opportunistic Systems or Surveys of Opportunity[d]	Macro					
Opportunistic and Episodic Events[e]	Micro Meso Macro					
Research-based Systems[f]	Micro Meso Macro					

[a] e.g., reporting of plastic production data and use by sector.
[b] e.g., Mr. Trashwheel, retention booms, capture devices, stormwater, outflow pipe of wastewater treatment plant.
[c] e.g., National Oceanic and Atmospheric Administration's Marine Debris Monitoring and Assessment Project, National Aeronautics and Space Administration, U.S. Environmental Protection Agency, the U.S. Geological Survey, government point and nonpoint source monitoring.
[d] e.g., submersible missions, vessels of opportunities.
[e] e.g., hurricanes/tropical cyclones, animal strandings, first-flush precipitation events.
[f] e.g., institutes, colleges, think tanks.
NOTE: The degree of shading indicates the existing or potential value of the system, component, or technology in achieving a mitigation aim, with darker shading representing greater value. The size class of plastic waste customarily addressed by each system, component, or technology are categorized as microplastics, mesoplastics, or macroplastics. Tracking and monitoring systems, components, or technologies are not presently available for environmental detection of nanoplastics (<100 nm in size) and are thus not included in this table. SOURCES: Koelmans, Besseling, and Shim (2015) and Mattsson et al. (2018).

FINDINGS AND RECOMMENDATIONS

Finding 13: No national-scale monitoring system, or "system of systems" exists to track important sources, pathways, and sinks of plastic waste to the ocean at the current scale of public or governmental concern. Presently, no baseline exists nor does a monitoring system to track changes from such a baseline.

Finding 14: The complexity of plastic production, use, and disposal, and the diversity of environments (inland to ocean) through which plastics are transported and distributed, requires the use of an expanded suite or network of tracking and monitoring systems to set priorities to reduce global ocean plastic waste.

Recommendation 2: The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Monitoring and Assessment Project, led by the NOAA Marine Debris Program, should conduct a scientifically designed national marine debris shoreline survey every 5 years using standardized protocols adapted for relevant substrates. The survey should be designed by an ad hoc committee of experts convened by NOAA in consultation with the Interagency Marine Debris Coordinating Committee, including the identification of strategic shoreline monitoring sites.

Recommendation 3: Federal agencies with mandates over coastal and inland waters should establish new or enhance existing plastic pollution monitoring programs for environments within their programs and coordinate across agencies, using standard protocols. Features of a coordinated monitoring system include the following:

- Enhanced interagency coordination at the federal level (e.g., the Interagency Marine Debris Coordinating Committee and beyond) to include broader engagement of agencies with mandates that allow them to address environmental plastic waste from a watershed perspective—from inland to coastal and marine environments.
- Increased investment in emerging technologies, including remote sensing, for environmental plastic waste to improve spatial and temporal coverage at local to national scales. This will aid in identifying and monitoring leakage points and accumulation regions, which will guide removal and prevention efforts and enable assessments of trends.