Plastic Marine Pollution in the Gulf of Maine

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Abstract

Plastic pollution is a leading environmental issue because of its demonstrated and potential harms to wildlife, as well as to ecosystem and human health. The Gulf of Maine has already suffered ecological shifts due to recent unprecedented warming of ocean waters, with consequences to coastal economies that rely on ecosystem services. Here, we explore the prevalence of plastic pollution as a potential compounding threat to Gulf of Maine ecosystems by analyzing microplastics and plastic debris collected in surface-towed plankton nets since 1987. Although we find low concentrations of small floating plastic particles, 20 years of coastal and remote-island shoreline cleanup activities demonstrate the continued accumulation of large plastic debris. Policies to address plastic pollution in the Gulf of Maine could strive to minimize littering or at-sea disposal, while also supporting environmental cleanup.

INTRODUCTION

Pollution, including plastic pollution, is recognized as one of three global environmental issues facing modern society. Together with climate change and biodiversity loss, these have been dubbed the *triple planetary crisis* by the United Nations (UN). Since the 1960s, scientists have documented plastic debris in the marine environment, including on beaches, in seabirds and other marine life, and floating far offshore in the open ocean (Ryan 2015a). More recent public and scientific attention to this problem culminated in a 2022 agreement by UN Member States to negotiate, by the end of 2024, an international legally binding agreement to address global plastic pollution, including in the marine environment.[1]

Plastic items, ranging in size from large masses of fishing nets to everyday consumer items to tiny particles called microplastics, contaminate the farthest reaches of the planet, even in remote areas far from human populations (e.g., Napper et al. 2020; Pinheiro et al. 2023). Larger plastic debris—especially looping and entangling items—clearly harms wildlife (Bucci et al. 2020). Yet, recent scientific concern is mainly focused on the risk of microplastics, not only to animals who encounter them in the environment, but also to human health if particles are inhaled or ingested (Nor et al. 2021). Because microplastics are an incredibly diverse class of contaminants—in size, shape, polymer type, and chemical content—characterizing their risk to human and ocean health is extremely challenging. Developing robust risk assessment frameworks for microplastics is a rapidly growing field of scientific research (Mehinto et al. 2022), which not only requires information on the biological effects of interaction with specific types of microplastics, but also knowledge of environmental exposure levels.

Recent scientific and public attention has also turned to the Gulf of Maine because of unprecedented levels of ocean surface warming, which are among the highest observed in the global ocean (Pershing et al. 2015). The warming appears to be related to northward shifts in the position of the Gulf Stream (Gonçalves Neto et al. 2021), carrying warmer water to the Gulf of Maine and displacing colder slope waters offshore (Seidov et al. 2021), as well as an increase in the frequency of Gulf Stream warm core ring formation (Gangopadhyay et al. 2019). These shifts, which may be linked to anthropogenic warming driven by greenhouse gas emissions, affect the water masses entering the Gulf of Maine and, therefore, its temperature, salinity and nutrient concentrations (Townsend et al. 2023). The Gulf of Maine is both ecologically and economically important to populations of the three US states (Maine, Massachusetts, and New Hampshire) and two Canadian provinces (Nova Scotia and New Brunswick), whose coastlines, together with several offshore banks and shoals, define the boundaries of this regional sea of the North Atlantic Ocean.

The Gulf of Maine is a biologically productive region, in part due to deep waters rich in dissolved inorganic nutrients

(Zang et al. 2022). These nutrients are mixed upwards into surface waters, where they fuel an annual spring phytoplankton bloom (Thomas et al. 2003). The seasonal bloom stimulates secondary production and growth at higher trophic levels, including in fishes, marine mammals, and seabirds (Staudinger et al. 2019). This biological productivity fuels commercial fisheries in the Gulf of Maine, including for American lobster, elver, soft shell clam, menhaden, and other species. The value of commercially harvested marine resources to the state of Maine alone in 2022 was $574 million, most of which was attributed to the lobster fishery ($388.6 million).[2]

Ecological shifts associated with the rapid warming of the Gulf of Maine have led to serious economic impacts on commercial fisheries. In 2012, a marine heat wave led to an earlier-than-usual onshore migration of American lobster in the Gulf of Maine, spurring increased fishery catch rates that ultimately caused a major economic disruption to both the US and Canadian lobster fisheries (Mills et al. 2013). And rapid ocean warming from 2004 to 2013 was associated with increased mortality in the Atlantic cod stock in the Gulf of Maine, leading to a collapse of the fishery despite increasing management restrictions to address chronic overfishing (Pershing et al. 2015).

Given the well-documented impacts of ocean warming to the Gulf of Maine ecosystem and ecosystem services, we investigated the abundance of floating microplastics at the sea surface of the Gulf of Maine as a potential compounding risk to marine life. Since 1987, scientists at Sea Education Association[3] have led research by undergraduate and high school students to measure plastic particles larger than ~0.3 mm in size in the western North Atlantic Ocean (Law et al. 2010). Here, we report the abundance and distribution of microplastics collected by towing a plankton net at the sea surface in the Gulf of Maine from 1987 to 2022. We compare these patterns to data on the abundance of larger plastic marine debris collected along coastal and remote-island shorelines of the Gulf of Maine from 2011 to 2020.

METHODS

Since 1971, SEA has offered academic, semester-long programs for undergraduate students (SEA Semester) and summer programs for high school students, which include up to six weeks onboard a tall sailing ship serving as an oceanographic research vessel. Cruises in the Gulf of Maine typically occur from May to October. Routine oceanographic sampling includes twice-daily plankton net tows, nominally at noon and midnight, to sample the neuston (surface) layer of the ocean in support of student-designed research projects. Originally deployed to collect plankton and macroalgae, the emergence of tar balls (Joyce 1998) and plastic particles (Wilber 1987) in neuston net tows as early as the late 1970s sparked scientific interest and ultimately led to decades-long time series measuring these ocean surface contaminants.

Plastic particles collected with the neuston net[4] are typically between 0.5 mm and 10 mm in size (Morét-Ferguson et al. 2010). To confirm that the particles archived from net tows are indeed plastic, we have used visual analysis followed by Raman spectroscopy to chemically identify 4,578 particles from 258 tows spanning decades of sample collection in the Atlantic and Pacific Oceans and Caribbean Sea, including eight tows from the Gulf of Maine. More than 98 percent of particles whose composition was identified are composed of plastics, primarily polyethylene, polypropylene, and expanded polystyrene, all of which initially float in seawater (unpublished data).

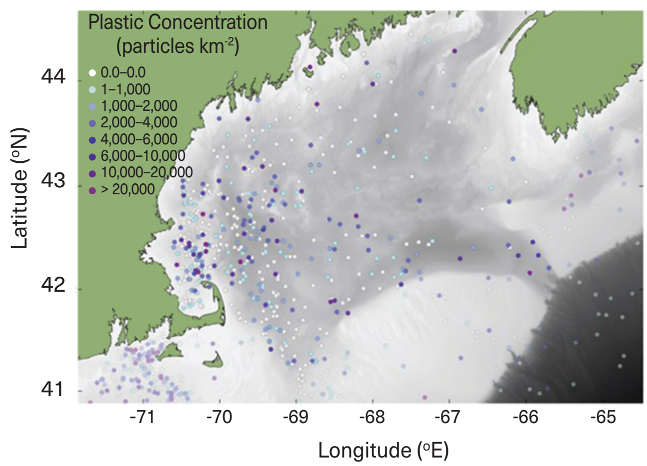
We characterized all available particles collected from tows in the Gulf of Maine between 2017 and 2021 (27 tows, 80 particles), and all particles from selected tows in the subtropical gyre during the same time period (5 tows, 111 particles). Each particle was first classified by morphology as fragment (irregularly shaped), film (very thin, sheet-like particles), foam (embedded air pockets), line (quasi-two-dimensional linear particles of very small diameter), pellet (spherical or cylindrical particles, likely the primary product of plastic resin), or other. For gyre samples and 81 percent of Gulf of Maine samples, we measured particle size using a high-resolution scanner to obtain a digital image, which we then analyzed using image analysis software to measure a suite of two-dimensional size metrics.[5] For the remaining Gulf of Maine samples, we used hand calipers to measure maximum caliper length. For all samples we also recorded particle color.

RESULTS AND DISCUSSION

Microplastic Abundance and Distribution

Between June 1987 and July 2022, SEA carried out 517 neuston net tows at the sea surface of the Gulf of Maine (Figure 1). The majority of tows were conducted in

FIGURE 1: **Locations of Plankton Net Tows in the Gulf of Maine (Bright Colors) and Surrounding Area (Faded Colors), 1987–2022**



Note: Symbol color indicates measured plastic concentration, green shading indicates land (Office of the Geographer and Global, US Department of State, Large Scale International Boundaries) and gray shading indicates ocean depth (General Bathymetric Chart of the Oceans).

the southwestern portion of the basin, to the north and east of Cape Cod, and 70 percent took place in the 1990s and 2000s.

In total, we collected 1,341 plastic particles in the Gulf of Maine within the 35-year time period. More than 50 percent of tows (266/517) contained no visible plastic particles, which we interpret as concentrations below the limit of detection.[6] For net tows in which at least one plastic particle was detected, the range in measured concentrations was 336 to 49,120 particles per square kilometer. The mean concentration, including from tows that didn't detect any plastic, was 1,510 particles per square kilometer, which is equivalent to fewer than three plastic particles in a single tow. There are no clear geographic patterns in the relatively low plastic concentrations measured in the Gulf of Maine.[7]

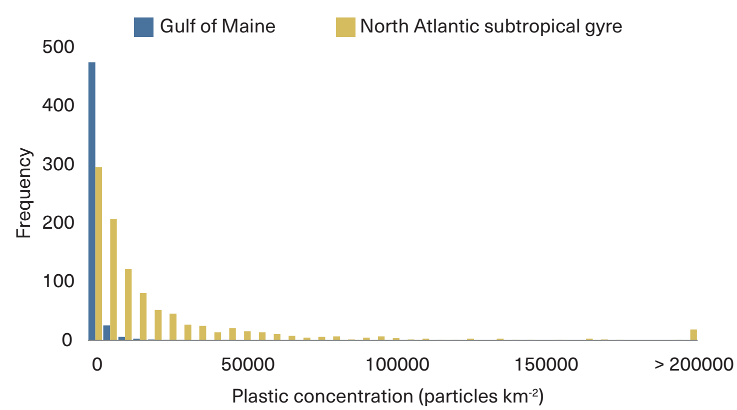
For comparison, in the North Atlantic subtropical gyre, commonly referred to as a "garbage patch" because of the converging surface currents that accumulate and retain floating debris in this region (Law et al. 2010), only 7 percent of 1,022 tows collected in the same time period contained no visible plastic particles. The highest measured concentration in this region was more than 1.3 million particles per square kilometer and the mean concentration was 28,400 particles per square kilometer (Figure 2).

Microplastic Particle Characteristics

The particles we collected are mainly fragments from once-larger objects, a consequence of plastics weakening and fragmenting when exposed to sunlight and physical forces (Andrady 2022). We found clear differences in particle characteristics between the Gulf of Maine and the subtropical gyre. In the gyre, 95 percent of particles collected were fragments, with very few lines, one pellet, and no film or foam. In the Gulf of Maine, particle morphology was more diverse, with 31 percent fragments, 23 percent line, 19 percent film, 15 percent foam, and 13 percent other (Figure 3). Other morphologies included typically larger, sometimes identifiable objects (e.g., alcohol prep pad in its wrapper, lobster claw band). In both regions, the majority of particles (60 percent) were white or translucent in color. However, the Gulf of Maine samples had a much higher proportion of brightly colored (i.e., dyed or pigmented) particles (33 percent vs 15 percent in the gyre), and a lower proportion of yellowed particles (8 percent vs 17 percent in the gyre), where yellowing is a consequence of environmental exposure and weathering (Andrady et al. 1998).

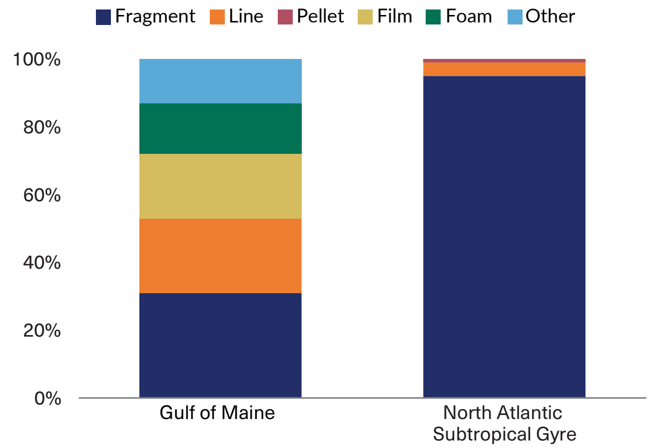
Although the particle size range is similar in the Gulf of Maine and the gyre (0.88–94.01 mm collectively), the size

FIGURE 2: **Frequency of Net Tows Binned by Plastic Concentration, Gulf of Maine vs North Atlantic Subtropical Gyre**



Note: More than 50 percent of tows in the Gulf of Maine collected zero plastics, indicating plastic concentrations below the limit of detection. In contrast, only 7 percent of tows in the gyre collected zero plastics.

FIGURE 3: **Microplastic Particles in Six Morphology Categories in the Gulf of Maine and the North Atlantic Subtropical Gyre**



Note: Particle morphologies are much more diverse in the Gulf of Maine than in the gyre, which is strongly dominated by fragments.

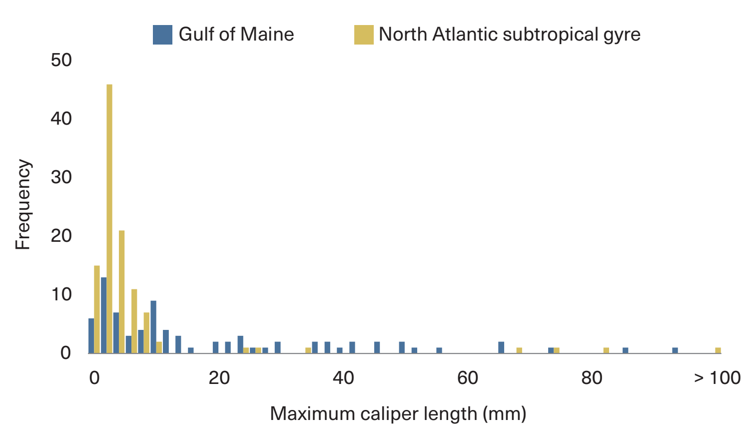
distribution in the Gulf of Maine is fairly uniform, whereas in the gyre, 71 percent of particles collected are smaller than 5 mm (Figure 4). In fact, 71 percent of particles collected in the Gulf of Maine are larger than 5 mm and not considered microplastics. Consequently, the mean and median particle sizes in the Gulf of Maine (19.38 mm and 11.35 mm, respectively) are larger than in the gyre (5.89 mm and 3.58 mm, respectively). The largest particles in the Gulf of Maine consist mainly of line, film, and other morphologies, which are largely absent in the gyre.

The source (geographic or parent item) and age (time since entering the environment) of microplastics usually cannot be determined from the particles themselves; however, the characteristics we observed suggest that microplastics collected in the subtropical gyre have been in the ocean for longer than those in the Gulf of Maine. Brightly colored plastics may contain soluble dyes, which are not chemically bonded and therefore have a high migration potential out of the polymer (Hahladakis et al. 2018). The abundance of colored particles in Gulf of Maine samples suggests the leaching of dyes or colorants has not yet occurred, in contrast to the higher abundance of yellowed, more weathered particles in the gyre. The dominance of smaller particles in the gyre also suggests a longer environmental exposure.

Further, experimental studies have demonstrated that initially buoyant plastics may become dense enough to sink from the sea surface when colonized by marine microbes and other attached organisms, especially in biologically productive regions (e.g., Liu et al. 2022; Van Melkebeke et al. 2020). Ryan (2015b) argued that the surface area to volume ratio is a key factor in determining the rate of biofouling and subsequent time for a particle to sink; thus, films might sink more readily than other debris morphologies. A study of the abyssal seafloor (5,700 to 5,800 m depth) offshore of Japan found the dominant type of identifiable debris was "fragments of plastic bags, and other films and packages" (Nakajima et al. 2021). Relatively rapid sinking of plastic films close to their source could explain the lower proportion of film particles collected at the sea surface of the gyre compared to the Gulf of Maine.

Foam particles, which we observed in the Gulf of Maine but not in the gyre samples, are typically composed of expanded polystyrene (EPS), which readily breaks apart into constituent air-encapsulated beads upon agitation (Efimova et al. 2018). Further, upon exposure to sunlight polystyrene can be partially or completely removed by chemical processes triggered by ultraviolet radiation (Ward et al. 2019). We hypothesize that together these processes fragment or remove EPS from surface waters before they reach the gyre.

FIGURE 4: **Frequency of Plastic Particles Binned by Particle Size, Gulf of Maine vs North Atlantic Subtropical Gyre**



Note: The Gulf of Maine has a more uniform particle size distribution than the gyre, which is dominated by particles smaller than 5 mm

The very low concentration of floating microplastics in the Gulf of Maine may be surprising given the proximity to the coast and the variety of maritime activities (e.g., fishing, aquaculture, recreation, shipping) that take place in its waters. In fact, line was the second most abundant particle morphology in the Gulf of Maine (23 percent, compared to 5 percent in the gyre). The majority of line particles are likely shed from ropes used in the fishing industry, which are typically composed of polypropylene or polyethylene. While proximity to likely sources may partially account for the abundance of line, as well as the less weathered nature of the plastic particles in the Gulf of Maine, ocean currents may explain why floating debris does not remain in the Gulf of Maine long enough to generate many more and smaller microplastics.

The Gulf of Maine mostly receives water from the Scotian Shelf to the northeast, whose coastal boundary (Canadian Maritimes) has a relatively small human population. The Maine Coastal Current flows west along the coast as a relatively strong and coherent feature, but loses strength and becomes more variable as it flows towards Cape Cod (Li et al. 2014). From surface drifter measurements, the mean transit time from the Bay of Fundy to the Great South Channel in this current was less than two months (Manning et al. 2009), suggesting the retention time in near-coastal waters in the basin may be quite short. Across the rest of the basin, the mean circulation consists of a cyclonic (counterclockwise) circulation, with smaller features defined by the complex bathymetry of several deep basins and shallow banks. In addition, the basin is strongly influenced by tides, and the currents exhibit large seasonal and interannual variability (Townsend et al. 2023), which makes predicting floating debris pathways difficult.

Plastic Debris on Coastal and Remote-Island Shorelines

While we found relatively low concentrations of floating microplastics in offshore waters of the Gulf of Maine, this is only one component of plastic marine pollution. Since 2011, the nonprofit organization Rozalia Project for a Clean Ocean has conducted marine debris removal and data collection along coastal and remote-island shorelines in the Gulf of Maine, primarily between Kittery and Bar Harbor, Maine. Rozalia Project volunteers typically clean the entire length of the shoreline, from the water's edge to the tree line or farthest wrack line. All visible debris is relocated to a central area where it is hand-sorted, and item counts are recorded using printed data cards or the Debris Tracker app. In 10 years, Rozalia Project has systematically removed and catalogued more than 100,000 items of shoreline debris.[8]

TABLE 1: **Plastic Waste Collected in Coastal and Remote-Island Shoreline Cleanups in Maine between 2011 and 2020.**

Plastic waste category	Item count	% of total
Foam fragments	11,578	23.1
Plastic fragments	8,351	16.6
Plastic food ware: cups/plates/utensils/ containers/lids/caps	7,793	15.5
Plastic drink bottles	6,140	12.2
Foam food ware: cups/plates/containers	3,685	7.3
Food wrappers	2,989	6.0
Strapping bands/zip-ties	2,427	4.8
Plastic sheeting/tape	2,302	4.6
Cigarettes/cigar tips	1,236	2.5
Balloons	1,075	2.1
Bleach/cleaner bottles	834	1.7
Plastic bags	747	1.5
Straws/stirrers	577	1.2
Shotgun shells/wadding	399	0.8
Oil/lube bottles	390	0.8

Note: Plastic waste items account for 59 percent of total debris items collected.

Item count data collected between 2011 and 2020 indicate that shoreline debris larger than 5 mm in size is primarily composed of plastic waste (59 percent) and separately counted fishing-related debris (30 percent), much of which is also composed of plastic. The most frequently collected plastic waste items include foam and plastic fragments, as well as single-use food packaging and food-related items (Table 1), while fishing debris is largely composed of rope, buoys and floats, and filament from nets and fishing line (Table 2). Perhaps not surprisingly, these results are remarkably similar to data collected on a remote, uninhabited Maine island (Cross Island) more than 30 years earlier. Podolsky (1989) found 67 percent of items collected along the entire island shoreline were composed of plastic, with unidentified fragments, bottles, caps/lids/utensils and polypropylene line dominating the plastic category. An

TABLE 2: **Fishing-Related Debris Collected in Coastal and Remote-Island Shoreline Cleanups in Maine between 2011 and 2020.**

Debris category	Item count	% of total
Rope	13,248	45.6
Buoys/floats	5,716	19.7
Filament from nets and fishing line	4,860	16.7
Traps/trap pieces	2,598	8.9
Lobster claw bands	1,542	5.3
Bait containers/crates	984	3.4
Fishing nets	60	0.2
Lures and light sticks	23	0.1

Note: Fishing-related items account for 30 percent of total debris items collected, most of which are composed entirely or partially of plastic.

additional 28 percent of debris was composed of plastic foam fragments, cups, buoys and food containers/cartons. In both studies, bleach, cleaner and motor oil bottles had notably high frequencies of occurrence. Similarly, balloons accounted for 1.3 percent of debris collected on Cross Island in 1988, and for 1.2 percent of total items in the Rozalia Project dataset.

All debris on uninhabited islands and most of the debris collected on the lightly populated islands cleaned by Rozalia Project was likely generated elsewhere and carried ashore by winds and ocean currents. Podolsky (1989) found twice as much debris per length of shoreline on western Cross Island shores compared to eastern shores. This, together with the high windage profile of many of the objects found (e.g., bottles, buoys, larger foam objects), suggests that large debris is primarily transported to island shores by prevailing westerly winds. Debris becomes trapped by the coastal islands acting as a sieve, potentially preventing it from further drift at sea where it might escape the Gulf of Maine or ultimately fragment into microplastics.

SUMMARY AND POLICY IMPLICATIONS

From samples collected using surface-towing plankton nets between 1987 and 2022, we found very low concentrations of microplastics (0.3 to 5 mm in size) in the surface waters of the Gulf of Maine compared to most of the western North Atlantic Ocean and Caribbean Sea. The physical characteristics of Gulf of Maine plastic particles suggest they have spent less time in the environment than those found in the accumulation zone of the North Atlantic subtropical gyre (garbage patch). It is important to note that the abundance of microplastics smaller than 0.33 mm in size, including plastic microfibers and potentially nanoplastics, could not be assessed in this study.

Although microplastic concentrations are low in the Gulf of Maine, macroplastic debris (> 5 mm in size) is abundant on Maine coast and remote-island shorelines. The most commonly collected identifiable items in shoreline cleanups are associated with food and food packaging and fishing activities, especially rope, buoys/floats, and filament from nets and fishing line. Maine islands may act as sieves, trapping wind-blown, large buoyant plastic items onshore before they can drift farther out to sea and break apart into large fragments and microplastics. The ocean circulation in the Gulf of Maine is fairly complex and varies seasonally and interannually, but does not appear to trap or accumulate floating debris over long time periods.

Despite being unable to determine the origin of large plastic items, or microplastics, that contaminate the marine environment in the Gulf of Maine, the prevalence of consumer and fishing-related items suggests losses occur during coastal and maritime activities, whether accidentally or intentionally. Public policy measures to address plastic marine pollution could strive to minimize intentional losses, as well as provide support for environmental cleanup activities.

Several state policies enacted in the state of Maine since 2019 are intended to reduce use of problematic single-use plastic items and their loss to the environment. These include bans on thin carry-out plastic bags and expanded polystyrene foam used in food service ware. Additionally, in a bill amending the state's litter law, balloons released or abandoned outdoors are considered litter and subject to penalty. These restrictions should theoretically reduce the number of these specific plastic items lost to the marine environment in Maine.

More than 45 years ago, Maine enacted the Returnable Beverage Container Law (bottle bill) requiring most beverages in containers four liters or smaller to carry a $0.05 or $0.15 deposit, paid at time of purchase and redeemable after use. The bill's purpose was to create incentives for recycling and reuse and to reduce solid waste generation and litter.[9] Despite strong evidence that beverage containers are less frequently littered in states with bottle bills, including Maine (Register 2020), plastic beverage bottles were the fifth most collected item (12.2 percent of all items) in shoreline cleanup data presented here. It is impossible to know if that proportion would be higher if there were no bottle bill.

Finally, management of fishing-related plastic debris includes approaches such as improving access to, and lowering the cost of, proper disposal onshore, and subsidized "Fishing for Litter" programs to incentivize collection of fishing debris at sea.[10] However, Maine statute (MRSA Title 12, § 6434(1)) prohibits the removal of derelict or abandoned fishing gear by anyone but a marine patrol officer, the licensed owner, or a person with written permission to do so. Feasible and effective management strategies to prevent or recover fishing-related debris are an important area of active study (Bowling 2016).

Although the data presented here do not indicate a substantial reservoir of microplastics floating in the Gulf of Maine, larger plastic debris has contaminated Maine's coastal environment for decades. There is strong evidence that looping or entangling items—such as ropes, lines, fishing nets, and balloon string—can inflict serious harm on individuals (Bucci et al. 2020), and thereby pose a risk to marine life in the Gulf of Maine. Other larger plastic items, such as consumer items collected on Maine shorelines, have less well-documented impacts, although they serve as parents of future microplastics, which may pose risks upon ingestion or inhalation. Therefore, long-term plastic pollution could pose a compounding risk to ecological changes already occurring in the Gulf of Maine. Efforts to prevent or mitigate this contamination are warranted. Evidence-based policies that include metrics to assess effectiveness, paired with improved awareness by consumers and fishers alike, must work in tandem to reduce preventable losses of plastics to the environment, where they can harm wildlife and ecosystem health, and threaten ecosystem services upon which Gulf of Maine economies rely.

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NOTES

1 https://unfccc.int/blog/what-is-the-triple-planetary-crisis; https://www.unep.org/inc-plastic-pollution

2 https://www.maine.gov/dmr/news/fri-03032023-1200-2022-commercial-fisheries-value-returns-levels-more-line-recent-years

3 https://sea.edu/

4 The neuston net has a 1.0 x 0.5-meter rectangular frame trailing a 0.335 µm (micrometer) mesh net with a collecting jar secured to the end. The net is towed at the air-sea interface (sampling to 0.25 m depth) for 30 minutes at a nominal ship speed of 2 knots (3.7 km h^{-1}). Tow distance was historically measured using a mechanical speed log deployed off the ship's stern, which measures distance traveled through water, and later using GPS positions recorded during the tow (Law et al. 2014). Upon retrieving the net, its contents are sieved and processed by students and scientists, who hand-pick all plastic particles visible to the naked eye, record particle counts and tow distance, and archive the particles for future analysis. Plastic concentration is calculated as the number of particles collected divided by the surface area sampled (net width * tow length), reported in units of particles km^{-2}.

5 Epson GT-20000 scanner, and Image Pro-Premier software

6 For a typical tow distance of 1.85 km, the detection limit is equal to 540 particles km^{-2}. Actual tow distances ranged from 0.185 to 4.630 km.

7 To our knowledge, the data we report here are the only offshore measurements of floating microplastics in the Gulf of Maine. Barrows et al. (2018) measured microplastics by filtering small volume (1 L) water samples onto 0.45 µm filters, finding an average concentration of 7.6 +/- 2.4 particles L^{-1} from six samples collected in nearshore waters of the Gulf of Maine. Similarly, Woods et al. (2018) measured the concentration of microplastic fibers, finding comparable concentrations (10.16 +/- 0.54 fibers L-1). Because of the difference in sampling protocols, these results cannot be directly compared to plankton net data because their methods are optimized to measure much smaller particles.

8 https://www.rozaliaproject.org/data-cleanups

9 https://www.bottlebill.org/index.php/current-and-proposed-laws/usa/maine

10 https://marinedebris.noaa.gov/prevention/fishing-energy

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