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Review

Plastic debris in the Laurentian Great Lakes: A review

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ABSTRACT

Pollution by plastic debris is an increasing environmental concern in the Laurentian Great Lakes where it affects open-water, shoreline, and benthic environments. Open-water surveys reveal that, in certain areas of the Great Lakes, surface water densities of plastics are as high as those reported for areas of litter accumulation within oceanic gyres. Data from volunteer beach cleanups show that typically more than 80% of anthropogenic litter along the shorelines of the Great Lakes is comprised of plastics. The distribution of plastics in bottom sediments of the Great Lakes is essentially unknown. Sources of plastic debris to the Great Lakes include microplastic beads from consumer products, pellets from the plastic manufacturing industry, and waste from beach-goers, shipping, and fishing activities. Many plastics degrade slowly in the environment and may have long-term adverse ecological and economic impacts, including the dispersal of persistent organic pollutants. Plans to combat and curtail plastic debris pollution in the Great Lakes will come at a significant economic cost, likely in excess of $400 million annually. Here, we review the current state of knowledge on plastic pollution in the Great Lakes, identify knowledge gaps, and suggest future research directions.

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Introduction

Plastic litter is found in marine and freshwater ecosystems all around the globe. The Laurentian Great Lakes are no exception; plastic debris is present in each of the lakes (Eriksen et al., 2013a; Hoellein et al., 2014; Zbyszewski and Corcoran, 2011; Zbyszewski et al., 2014). The durability and persistence of plastics, combined with their rising production and low rates of recovery (US EPA, 2014), are likely causing a net accumulation of plastic debris along shorelines, in surface waters, throughout the water column, and in bottom sediments (Barnes et al., 2009; Ryan and Moloney, 1993).

Plastic debris is variably classified according to size, origin, shape, and composition. While there are no internationally agreed upon size classes, ‘microplastic debris’ generally refers to plastic particles smaller than 5 mm (Arthur et al., 2009). Furthermore, the term microplastic

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debris is often restricted to particles larger than 333 μm because in most open-water studies neuston nets with a mesh size of 333 μm are used to collect debris (Andrady, 2011; Barnes et al., 2009). The term ‘microscopic plastic debris’ is reserved for plastic particles smaller than 333 μm that are retained on a 0.45 μm pore size filter (Andrady, 2011). Plastic debris larger than 5 mm is referred to as ‘macroplastic debris’. Plastic debris exhibits a wide range of shapes; in addition to recognizable plastic objects, the most common shapes are fragments, films, pellets, lines, fibers, filaments, and granules.

Plastic debris is often classified as either primary or secondary. Primary plastics are in their original or close-to-original form when collected, such as bottle caps, cigarette butts, microbeads or resin pellets. Secondary plastic debris encompasses the smaller pieces of plastic resulting from the breakdown of primary debris through various environmental degradation processes (Wagner et al., 2014). The composition of plastic refers to the polymer type, which in turn determines the density of debris. Low-density plastics, such as polypropylene and polyethylene, produce debris that is less dense than water and therefore likely to remain afloat. Plastics that are denser than water and thus tend to sink include polyethylene terephthalate, polystyrene, and cellulose acetate. The densities of plastics found in the Great Lakes are listed in Table 1.

Plastic debris can have wide-ranging ecological and economic impacts in both freshwater and marine environments. Macroplastics pose a health risk to aquatic animals, including fish, turtles, and birds, because of possible entanglement and ingestion (Boerger et al., 2010; Codina-García et al., 2013; Gregory, 2009; Sheavly and Register, 2007). Ingestion of plastic may cause internal bleeding, abrasion and ulcers, as well as blockage of the digestive tract (Wright et al., 2013). Plastic debris may act as a vector for contaminants, including persistent organic pollutants (POPs) and heavy metals (Ashton et al., 2010; Holmes et al., 2012; Mato et al., 2001; Rios et al., 2010; Zarfl and Matthies, 2010). Sorption to plastics has been shown to limit the biodegradation of organic contaminants, increasing their persistence in the environment (Teuten et al., 2009). Plastic debris can also transport non-native species (Barnes et al., 2009; Gregory, 2009) and be colonized by microbes including possible pathogens (Wagner et al., 2014; Zettler et al., 2013). In littoral zones, the accumulation of sinking plastic debris and the dragging of fishing nets may disrupt bottom sediments, displace or smother infauna, and affect the structure and functioning of benthic microbial communities (Goldberg, 1994).

Accumulation of plastic debris in coastal areas can deter recreational usage, pose a hazard to swimmers and divers, and carry a risk of minor cuts or abrasion injuries to beach-goers (Sheavly and Register, 2007). Plastic debris can reduce revenue generated from tourism due to forced beach closures, but also because tourists use beach cleanliness as a dominant factor in selecting recreational destinations (Jeftic et al., 2009). Macroplastic debris represents a navigational and structural hazard to shipping vessels and smaller marine vehicles, including burnt out water pumps and entangled propellers (Mouat et al., 2010). Derelict fish nets and other lost plastic gear may trap commercial fish accidentally, hence removing them from the pool available for harvest (Gregory, 2009).

Plastic debris in the environment will break down through a combination of photo- and thermal-oxidative degradation by ultraviolet (UV) radiation, mechanical weathering, and biodegradation, but complete mineralization may not be possible, or then only after hundreds or thousands of years (Andrady, 2011; Corcoran et al., 2009; Gregory and Andrady, 2003; Shah et al., 2008). The breakdown products, including microplastic and microscopic plastic debris, create additional challenges. As plastics degrade they can release toxic chemicals that were initially incorporated during their manufacturing or sorbed to their surfaces in the environment. These chemicals include phthalates, nonylphenols, bisphenol A (BPA), heavy metals, and polybrominated diphenyl ethers (PBDEs) (Bittner et al., 2014; Cheng et al., 2010; Nakashima et al., 2011; Teuten et al., 2007), which can disrupt endocrine functions and cause harmful reproductive and developmental effects in aquatic animals (Meeker et al., 2009). Smaller plastic debris is also more bioavailable—several aquatic species have been found to ingest microplastics—and the trophic transfer of plastics along aquatic food webs has been verified, hence posing a health threat to aquatic ecosystems (Andrady, 2011; Boerger et al., 2010; Fossi et al., 2012; Teuten et al., 2009). The direct transfer of plastic-sorbed toxins to organisms through oral ingestion represents an additional hazard (Rochman et al., 2013; Ryan et al., 1988). While the possible transfer of plastic-sorbed toxins to humans through consumption of aquatic species is of concern, it has yet to be demonstrated.

The Great Lakes have likely been polluted with plastic debris since the mid-twentieth century when mass production of plastics began in North America (Thompson et al., 2009). However, while numerous studies have focused on plastic debris in marine systems (e.g. Cole et al., 2011; Cózar et al., 2014; Eriksen et al., 2013b; Law et al., 2010; Moore et al., 2001), few have explored the distribution and fate of plastics in freshwater systems. The reason is not entirely clear, but may have been exacerbated by the use of ambiguous terminology (the term ‘marine debris’ is well-established and its application to lentic environments may be a cause for confusion), and a lack of communication between freshwater and marine researchers. Nonetheless, plastic pollution may represent an equal, if not greater, threat to lakes compared to the oceans. In this context, the present paper (1) reviews the current state of research about plastic pollution in the Great Lakes, (2) identifies knowledge gaps, and (3) proposes future research directions.

Table 1

Densities and common uses of plastics that have been identified, or are highly likely to be present in the Great Lakes (density values at room temperature, compiled from Teegarden (2004), and common uses compiled from various sources). In principle, plastics with densities greater than 1 g/cm^3 should sink in water.

Plastic type	Abbreviation	Density (g/cm^3)	Common uses
Expanded polystyrene	EPS	0.01–0.04[a]	Foam cups, plates, trays, clamshell containers
Polypropylene	PP	0.85–0.92	Auto parts, food containers, dishware, bottle caps, straws
Low-density polyethylene	LDPE	0.89–0.93	Container lids, six-pack holders, squeeze bottles, tubing, diapers, shotgun shells
High-density polyethylene	HDPE	0.94–0.98	Detergent and household cleaner bottles, milk jugs, grocery bags, recycling bins, playground equipment, buoys
Acrylonitrile-butadiene-styrene	ABS	1.04–1.06	Electronic equipment casing, pipes
Polystyrene	PS	1.04–1.08	Plates, cutlery, optical disk cases, toys
Polyamide (nylon)	PA	1.13–1.16	Toothbrush bristles, fishing line and nets, rope
Polymethyl methacrylate (acrylic)	PMMA	1.16–1.20	Optical lenses, paint, shatterproof windows
Polycarbonate	PC	1.20–1.22	Optical disks
Cellulose acetate	CA	1.30[b]	Cigarette filters
Polyethylene terephthalate (polyester)	PET	1.38–1.41	Textiles, soft drink and water bottles, strapping
Polyvinyl chloride	PVC	1.38–1.41	Pipes, fencing, shower curtains, flooring, plastic wrap, tampon applicators
Polytetrafluoroethylene	PTFE	2.10–2.30	Wires, cables, bearings, gears

Alternate sources:
[a] Winterling and Sonntag (2011).
[b] http://www.goodfellow.com/E/Cellulose-Acetate.html (accessed 11.17.14).

Plastics in the Great Lakes

Data availability

Only a limited number of peer-reviewed papers present quantitative data on the abundance and distribution of plastic debris in the Great Lakes (Table 2). Eriksen et al. (2013a) collected debris in Lakes Superior, Huron, and Erie using a manta trawl lined with a 333 μm mesh size net. The surface water concentrations of microplastics extrapolated from the debris counts varied between 0 and 0.4663 items/m^2. Plastic debris included pellets, fragments, foam pieces, film, and line. Additional expeditions by Mason and colleagues in 2013 confirmed the presence of pelagic microplastics in Lakes Michigan and Ontario (Dr. Sherri Mason, State University of New York at Fredonia, unpublished data).

Debris counts by Hoellein et al. (2014), Zbyszewski and Corcoran (2011), and Zbyszewski et al. (2014) yielded concentrations of micro- and macroplastic debris along the shorelines of Lakes Michigan, Huron, St. Clair, and Erie, between 0 and 34 items/m^2. However, whereas in Lake Huron 93% of plastic debris were comprised of pellets, in Lakes Erie and St. Clair fragments were more abundant (Zbyszewski et al., 2014). In Lake Michigan, cigarette filters were found to be a major source of shoreline accumulation of macroplastic debris (Hoellein et al., 2014). The surface textures of plastic debris samples from Lakes Huron, St. Clair, and Erie have been examined by scanning electron microscopy (SEM): 78% and 37% of samples showed signs of mechanical and oxidative weathering, respectively (Zbyszewski et al., 2014). Hoellein et al. (2014) also reported data on anthropogenic debris >1 cm in the North Branch of the Chicago River. The average concentration of plastic debris was found to be greater in the riparian zones than in bottom sediments of the river.

Volunteer-led cleanups of beaches and coastal areas organized by non-governmental organizations (NGOs) have gathered a wealth of information on the abundance and distribution of plastic debris along the Great Lakes shorelines. These cleanup activities engage individuals, schools, marinas, civic associations, businesses, and governmental agencies. Since 1991, the Alliance for the Great Lakes has run the Adopt-a-Beach™ (AAB) program whose volunteers not only conduct debris removal but also test water quality and assess general beach health (Alliance for the Great Lakes, 2014). The number and type of anthropogenic debris items collected are reported in AAB's online information system: litter data from 2002 onwards are accessible through the website www.greatlakes.org/adoptabeach. In 2012, 12,618 AAB volunteers cleaned roughly 1240 km of Great Lakes shoreline, removing nearly 20,000 kg of anthropogenic debris. The AAB program is part of the Ocean Conservancy's broader International Coastal Cleanup, a global initiative promoting trash-free waters.

In Canada, the Vancouver Aquarium and World Wildlife Fund run the Great Canadian Shoreline Cleanup (GCSC), which includes activities in the Great Lakes region. Based on the cleanup data reported on GCSC's website (www.shorelinecleanup.ca), we estimate that, in 2012, 2925 GCSC volunteers cleaned roughly 280 km of Great Lakes beaches and removed around 9300 kg of anthropogenic debris. Note that, as with the AAB program, the cleanup activities of GCSC primarily target visible litter and, thus, mainly provide information on the abundance and distribution of macroplastic debris.

Sources of plastics

Eriksen et al. (2013a) found high abundances of plastic pellets <1 mm in the surface waters of Lakes Superior, Huron, and Erie. A major fraction of these pellets are most likely microbeads that are used as abrasive agents in a range of consumer products, including exfoliating creams, soaps, toothpastes, shampoos, lip gloss, eye liner, sunscreens, and deodorants. Microbeads that are flushed down sink and shower drains enter the wastewater collection system. Canadian and American wastewater treatment regulations, however, make no

Table 2
Summary of plastic debris concentrations in the Great Lakes region reported in the literature or calculated from beach cleanup data. Note the differences of units in which the plastic debris concentrations are reported.

	River				Lake										
Zone	Riparian		Benthic		Open-water			Shoreline							
Reference(s)	Hoellein et al., 2014[1]		Hoellein et al., 2014[1]		Eriksen et al., 2013a,b[2]			Zbyszewski and Corcoran, 2011[3]; Zbyszewski et al., 2014[3]			Hoellein et al., 2014[1]		AAB & GCSC 2012 data[4] AAB/GCSC		
	# Sites	PDC	# Sites	PDC	# Tows	PDC		# Sites	PDC		# Sites	PDC	# Sites	PDC**	
		Avg.		Avg.		Range	Avg.		Range	Avg.		Avg.		Range	Avg.
Lake Superior	0	-	0	-	5	0.0013–0.0126	0.0054	0	-	-	0	-	19/10	0.0101–7.2015/0.0155–1.0540	0.6591/0.4992
Lake Michigan	0	-	0	-	0	-	-	0	-	-	3	0.0005	223/0	0–23.0972/–	1.1053/–
Chicago River*	3	0.0385	3	0.0180	0	-	-	0	-	-	0	-	0/0	–/–	–/–
Lake Huron	0	-	0	-	8	0–0.0065	0.0028	7	0–34	5.4300	0	-	12/27	0.0250–3.8960/0.0942–5.4280	1.1162/0.8601
Lake St. Clair*	0	-	0	-	0	-	-	9	0.1800–8.3800	1.7256	0	-	0/0	–/–	–/–
Lake Erie	0	-	0	-	8	0.0047–0.4663	0.1055	10	0.3600–3.7000	1.5410	0	-	32/10	0.0460–3.5240/0.0185–0.8820	1.0617/0.2786
Lake Ontario	0	-	0	-	0	-	-	0	-	-	0	-	5/108	0.1160–1.2385/0.0163–14.2740	0.6941/0.9991

* Not a Great Lake.
PDC = plastic debris concentration (items/m^2), ** (items/m).
Smallest size of debris counted: [1]100 mm, [2]0.355 mm, [3]~1 mm, [4]~100 mm.

provision for microplastic debris, including microbeads; wastewater treatment plants (WWTPs) are currently not required to monitor microplastics in influent or effluent streams. For a WWTP to effectively remove microbeads, a form of advanced filtration is probably required, for example, fine- or micro-screens, microfiltration, sand filtration, or mixed media filtration (Nalbone, 2014). Many WWTPs in the Great Lakes region are not equiped with such treatment systems. For example, in the state of New York, which borders sections of Lakes Ontario and Erie, 66% of WWTPs do not use advanced treatment methods. Also, preliminary research conducted at the State University of New York at Fredonia positively identified microbeads in the effluent of six out of seven WWTPs sampled in New York state (Nalbone, 2014).

Plastic fibers are also suspected to contribute to the microplastic loadings of the Great Lakes, although no conclusive data on their presence in the Great Lakes exist to date. Polyester and acrylic fibers have been widely observed in marine sediments (Browne et al., 2011). Small plastic fibers are released from synthetic fabrics in washing machines. Households and textile laundering facilities may therefore represent a significant source of plastic fibers (Eriksen et al., 2013a). The fibers can be transferred to surface water bodies directly via the effluent discharges of WWTPs, or indirectly via their solid residues. When the latter are used as fertilizers and compost material on crop fields, the fibers may be remobilized and ultimately reach natural or man-made waterways (Browne et al., 2011; Habib et al., 1998; Zubris and Richards, 2005).

Further research should include a thorough review of the current microplastic removal efficiencies of WWTPs surrounding the Great Lakes region, as well as an assessment of the plant upgrades and associated costs required to effectively prevent the discharge of microbeads and other microplastics from water treatment systems. Equally important, the fate of microplastics in solid residues of WWTPs should be investigated because they could represent a significant, but unknown, source of environmental plastic pollution.

Plastic resin pellets, a raw material used in the manufacturing of plastic products are a common pollutant along Great Lakes shorelines (Zbyszewski et al., 2014). Spillage during transport and subsequent rain events can cause the entry of resin pellets into streams and storm sewers. In urban areas with combined sewer systems, pellets and other plastic debris in stormwater may be discharged directly into streams and rivers, and ultimately reach the Great Lakes. Hoellein et al.'s (2014) analysis of anthropogenic debris in the Chicago River, although limited to only one tributary waterway, implies that rivers could represent a major transport pathway of plastic debris to the Great Lakes.

To help delineate the sources of plastic debris to beaches along the Great Lakes, we sorted the cleanup data from AAB and GCSC according to activity class (Fig. 1; for details on the activity classes, see Appendix A). The 'shoreline and recreational' and 'smoking-related' classes contain the vast majority of debris. The most commonly reported items in the AAB and GCSC surveys are cigarette filters followed by plastic food wrappers and containers. Fishing gear comprises only a small amount of shoreline anthropogenic debris in the Great Lakes (~1%). In 2012, plastic anthropogenic debris items made up between 77% and 90% of the total shoreline debris collected during AAB and GCSC cleanups. Because intact or near-intact debris, such as cigarette filters and food-related items, mostly represent in situ litter, beach-goers appear to be a major source of macroplastic debris along Great Lakes shorelines. However, some of this debris may also be transported from urban areas by wind or stormwater and ultimately end up on the beaches. In addition, because volunteer cleanups preferentially target beaches used for recreational purposes, they tend to introduce a site sampling bias.

For comparison, in the marine environment on average between 60% and 80% of shoreline debris items consist of plastics (Gregory and Andrady, 2003). Land-based sources account for up to 80% of the total debris input to the oceans with offshore sources making up the remainder (Allsopp et al., 2006). Land-based sources of plastic debris to the oceans include riverine outflow, landfills, stormwater drains, textile laundering facilities, petrochemical plants, and WWTPs, as well as direct inputs in coastal areas, for example trash left by recreational beach users (Browne et al., 2011; Wright et al., 2013). The primary offshore source of plastic debris in the oceans is derelict fishing gear (nets, lines, traps). In six separate studies, fishing gear was found to represent on average more than 3% of the total number of debris items collected along marine shorelines (Santos et al., 2009). Other offshore sources include illegal dumping of plastic waste from ships and the release of plastic resin pellets and products when shipping containers are lost at sea (Andrady, 2011).

Distribution of plastics

Existing survey data indicate that areas in the Great Lakes region with greater human and industrial activity are generally associated with higher concentrations of plastic debris in the adjacent Great Lakes basin(s). Among Lakes Superior, Huron and Erie, Eriksen et al. (2013a) found the highest concentrations of pelagic microplastics in Lake Erie, with an average of 0.1055 plastic items/m^2. This observation is in line with the higher population density and greater industrial

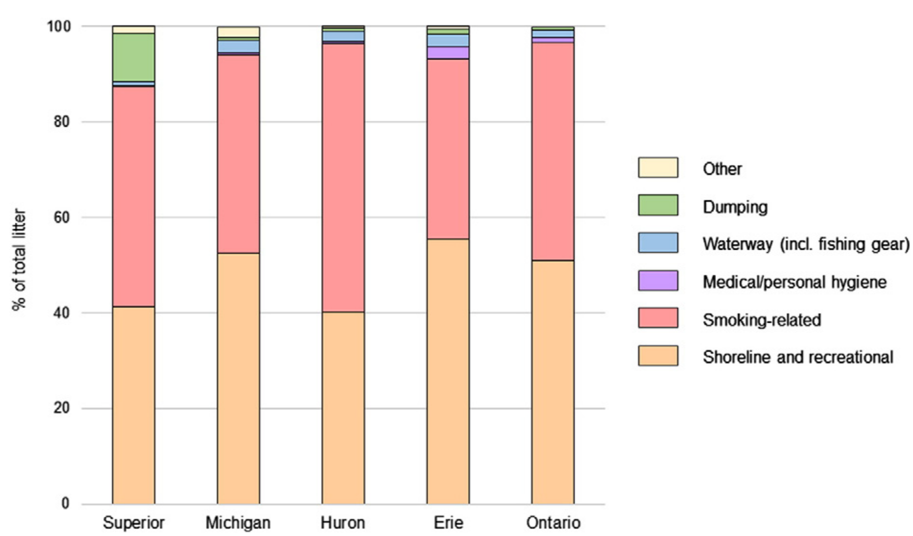

Fig. 1. Percentages of litter items in the Great Lakes grouped according to activity on an item-by-item basis (see Appendix A for details). All data are from Adopt-a-Beach™ and Great Canadian Shoreline Cleanup for the year 2012.

activity characterizing Lake Erie's catchment. The higher reported microplastic density in Lake Superior compared to Lake Huron is more surprising (Eriksen et al., 2013a). However, the surface water samples in Lake Superior were collected closer to shore than in Lake Huron, and thus closer to the land-based sources of plastic debris. Among the shoreline locations surveyed in Lake Huron by Zbyszewski and Corcoran (2011), and in Lakes Erie and St. Clair by Zbyszewski et al. (2014), the highest concentration of plastics (34 items/m^2) was observed at Sarnia Beach, which is located along the southern shore of Lake Huron in relatively close proximity to petrochemical plants that produce plastic resin pellets. The same authors also found high concentrations of plastic debris on Lake Erie beaches that receive high numbers of visitors each year.

Shoreline debris counts in or near urban centers may be affected by grooming of public beaches. For example, the two largest cities along the Great Lakes, Toronto and Chicago, have their beaches groomed daily from mid-spring to late summer, that is, during peak use (Chicago Park District, 2014; City of Toronto, 2009). This may explain why Hoellein et al. (2014) found relatively little plastic debris (0.0005 items/m^2) on Lake Michigan beaches surveyed near Chicago. In addition, volunteer beach cleanups often target urban shorelines because of greater accessibility and impact. Microplastics and microscopic plastic debris in urban areas are probably not greatly affected by volunteer cleanups or grooming activities. Manual litter removal and mechanical grooming equipment are mostly ineffective at removing the smallest plastic debris, including cigarette filters.

The existing AAB and GCSC survey data indicate that the vast majority of anthropogenic debris along the Great Lakes shoreline consists of plastics. On an item-by-item basis, plastics comprise the greatest proportion of anthropogenic debris in Lake Erie and Lake Huron and the lowest in Lake Superior. The percentages of debris items that were found to be plastics at the AAB and GCSC cleanup locations in 2012 are shown in Fig. 2 (for details on the items classified as plastics, see Appendix B). Although historically AAB and GCSC cleanups have only yielded information on macroplastic debris, in 2013 GCSC volunteers also began to collect and report plastic debris <2.5 cm, hence producing data that could potentially provide insights into the distribution of microplastic debris on the beaches of the Great Lakes.

The variable number and expertise of the volunteers, as well as the irregularly distributed temporal and spatial occurrences of cleanups, introduce uncertainties and sampling biases in beach cleanup data that may be difficult to fully account for. For instance, cleanup activities tend to be more frequent near urban areas and during the summer months. Comparison between shoreline survey data is also complicated by the use of different metrics; AAB and GCSC cleanups report linear debris densities, i.e., debris counts per meter of shoreline, while Zbyszewski et al. (2014) and Hoellein et al. (2014) report surface-normalized debris densities, i.e., counts/m^2 of beach. Furthermore, the AAB and GCSC cleanup databases do not report the weights of individual debris classes, only the total weight of debris collected per cleanup, hence limiting the extent to which quantitative analyses of plastic debris distributions can be carried out. Overall, there is much scope for a closer dialogue between cleanup organizers, beach groomers, and the Great Lakes science community to streamline the reporting and optimize the utilization of shoreline plastic debris distribution data.

Surface current patterns undoubtedly influence where plastic debris concentrate in the Lakes. For instance, the highest reported concentrations of pelagic plastic particles in Lake Erie are located in the eastern basin, in areas of converging surface currents (Eriksen et al., 2013a). Similarly, dominant surface currents help explain the spatial distribution of plastic debris along Lake Huron's shoreline (Zbyszewski and Corcoran, 2011). However, to our knowledge, there has been no systematic research linking the spatial and temporal distributions of plastic debris to water circulation in the Great Lakes.

In addition to circulation, the density of plastic debris is expected to be an important factor controlling their distribution. Given their low densities, it is not surprising that polyethylene, polypropylene, and expanded polystyrene (e.g. Styrofoam) are the most commonly

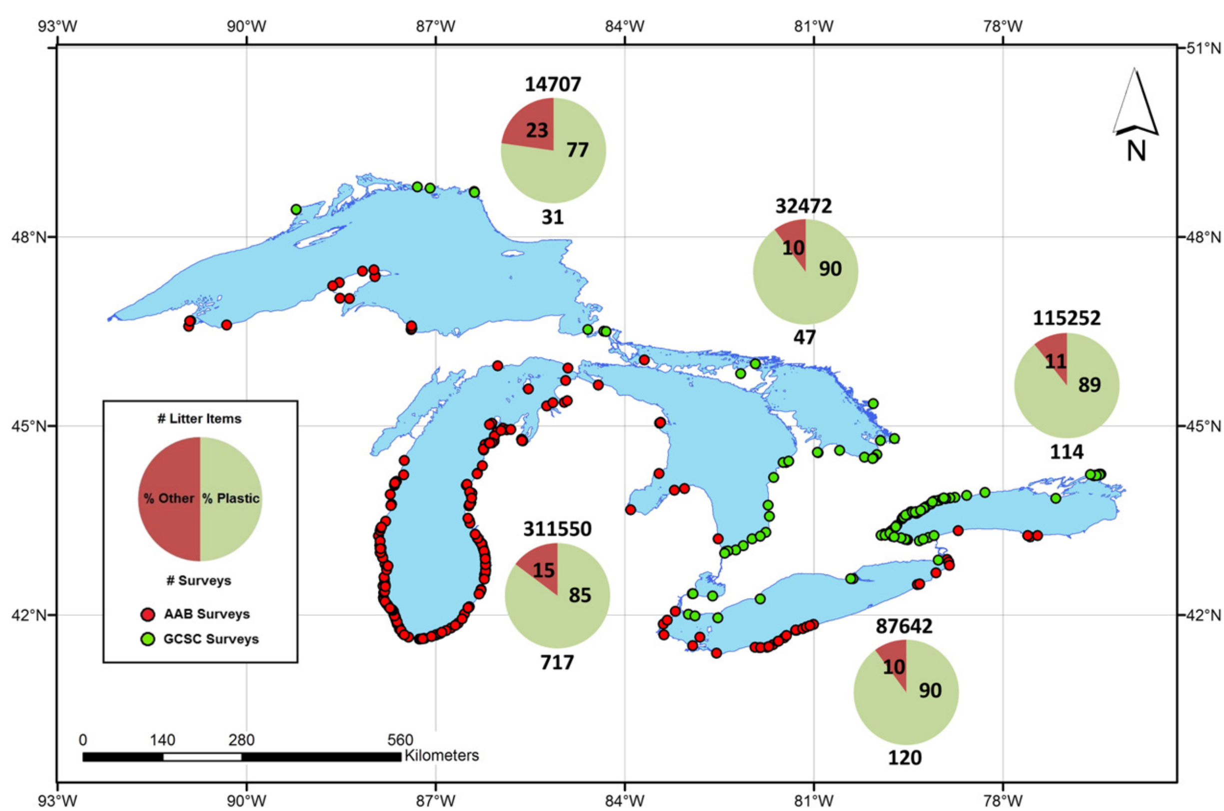

Fig. 2. Great Lakes beach cleanup surveys. The figure shows the locations of beach cleanup surveys, the number of surveys conducted, and the percentages of anthropogenic debris comprised of plastic for each of the Great Lakes. The data used in the figure were collected by Adopt-a-Beach™ (AAB) and Great Canadian Shoreline Cleanup (GCSC) volunteers in 2012.

observed plastics in Great Lakes surface waters and shorelines (Eriksen et al., 2013a; Zbyszewski et al., 2014). The density of plastic debris may be altered by biofilm growth, which may cause otherwise buoyant debris to sink (Andrady, 2011; Wright et al., 2013). According to one estimate, 70% of plastic debris entering the oceans ultimately sink (Oceaneye, 2013). Vertical distributions of plastics in the water column of the Great Lakes have, to our knowledge, not been determined. Similarly, little is known about plastic debris deposited at the bottom of the lakes. Preliminary analyses of bottom sediments from a near-shore region of Lake Superior have shown the presence of plastic debris (Dr. Lorena Rios Mendoza, University of Wisconsin Superior, unpublished data). Thus, future research should include surveys of the abundance, size, composition, and extent of degradation of plastic debris in the water column and sediments of the Great Lakes.

Comparison to other aquatic environments

Data on plastic debris are available for the surface waters and sediments of Lake Geneva, Switzerland (Faure et al., 2012) and Lake Hovsgol, Mongolia (Free et al., 2014), as well as for shoreline sediments of Lake Garda, Italy (Imhof et al., 2013). Compared to these lakes, Lake Erie exhibits the highest average concentration of pelagic microplastics (0.1055 items/m^2, compared with the next highest value of 0.0516 items/m^2 for Lake Geneva). The population of Lake Geneva's watershed, normalized to the lake's surface area (1627 people per km^2) is significantly greater than for Lake Erie (483 people per km^2). Thus, population density alone cannot account for the differences in the concentrations of pelagic microplastic debris. This remains true even if we factor in the populations living in the watersheds of Lakes Superior, Michigan, and Huron, which ultimately drain into Lake Erie. At this point, we can only speculate that Lake Geneva receives lower inputs of plastics, possibly because of higher plastics recycling rates and WWTP retention efficiencies. In a similar vein, the average abundance of pelagic microplastic debris in Lake Hovsgol is considerably higher than in Lakes Superior and Huron, even though the population densities of the watersheds of Lakes Superior and Huron are 4 and 25 times greater than Lake Hovsgol's, respectively (when normalized to the corresponding lake surface areas). Possibly, the greater level of pelagic microplastic pollution of Lake Hovsgol reflects the relatively long water residence time of the lake and the lack of a modern waste management system (Free et al., 2014).

Comparison between the concentrations of pelagic microplastic debris in the Great Lakes and those in ocean surface waters is complicated by the different ways in which marine plastic debris concentrations are reported. While in some studies concentrations are expressed in number of plastic debris per unit ocean surface area (Goldstein et al., 2013; Law et al., 2010; Moore et al., 2001), other authors express the number of items per unit volume of water (Doyle et al., 2011; Lattin et al., 2004; Moore et al., 2002), while others use units of mass of plastic per unit area or volume of water (Cózar et al., 2014; Day and Shaw, 1987). Nonetheless, based on the average concentration of pelagic microplastic debris in Lakes Superior, Huron and Erie (0.0425 items/m^2), it would appear that the Great Lakes are as polluted with plastic debris as known areas of litter accumulation within ocean gyres. For comparison, average concentrations of plastic debris reported in the South Pacific Gyre, the North Atlantic Gyre and the North Pacific Gyre are 0.0269 (Eriksen et al., 2013b), 0.0203 (Law et al., 2010) and 0.3343 items/m^2 (Moore et al., 2001), respectively.

Although sizes of pelagic plastic debris in the oceans have been examined by a number of authors (Doyle et al., 2011; Morét-Ferguson et al., 2010; Shaw and Day, 1994; Yamashita and Tanimura, 2007), only the studies of Lattin et al. (2004), Moore et al. (2002, 2001) and Eriksen et al. (2013b) report size distributions over the same range as those of Eriksen et al. (2013a) for the Great Lakes. Similarly, Free et al.'s (2014) analysis of plastic debris in Lake Hovsgol can be directly compared to the size data of Eriksen et al. (2013a). The comparison reveals a much greater percentage of microplastic debris <1 mm in the surface waters of the Great Lakes (81%) relative to the five other marine and freshwater studies (Fig. 3).

Another difference with marine environments is the much larger proportion of pellets in <1 mm pelagic plastic debris of the Great Lakes (58%), relative to fragments and other shaped debris (Eriksen et al., 2013a). In contrast, pellets make up less than 1% of the <1 mm debris in the North and South Pacific Gyres, while fragments represent 73% and 94%, respectively (Eriksen et al., 2013b; Moore et al., 2001). As pellets in consumer products are often intentionally <1 mm, the available data suggest a greater relative contribution of microbeads to open water plastic debris in the Great Lakes than in the oceanic gyres. Fragments resulting from the breakdown of larger plastic objects appear to preferentially accumulate in the oceanic gyres.

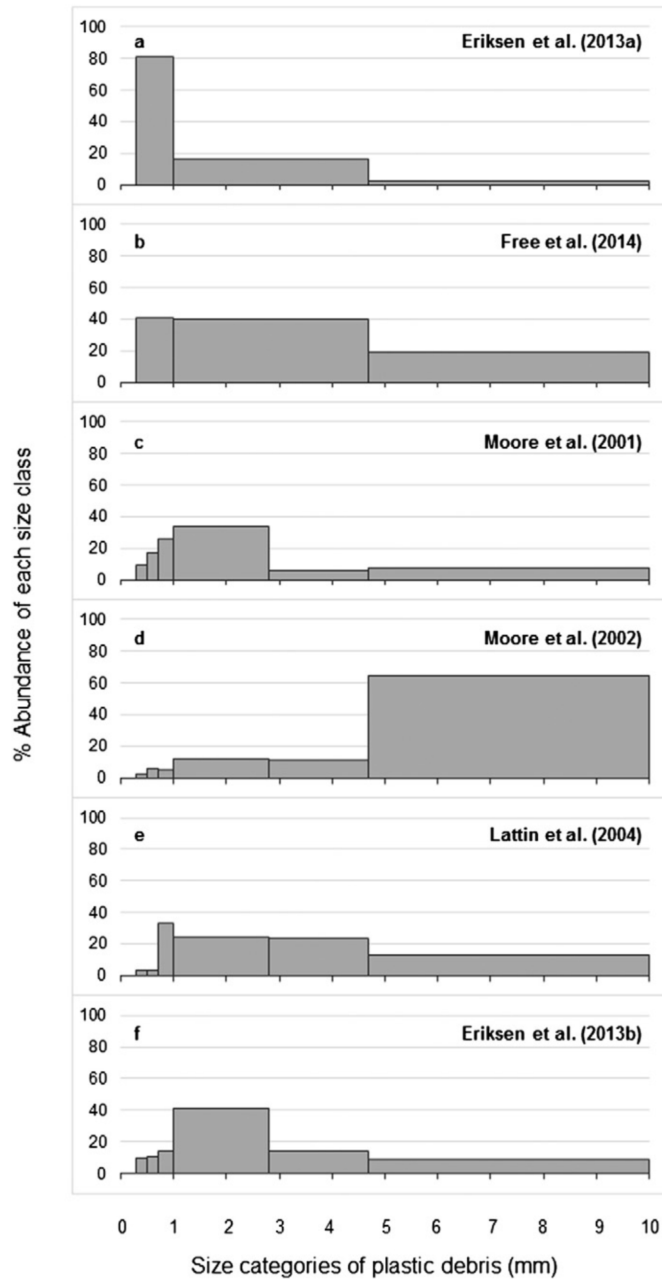

Fig. 3. Comparison of pelagic microplastic debris size distributions. Freshwater studies: (a) Laurentian Great Lakes, (b) Lake Hovsgol, Mongolia. Marine studies: (c) North Pacific Central Gyre, (d–e) Southern California Coastal Waters, (f) South Pacific Subtropical Gyre. The 10 mm upper limit is arbitrary; the studies cited reported >4.75 mm as their top size class. Note that the results shown are from studies that reported size data over a range comparable to Eriksen et al. (2013a).

The smaller sizes of pelagic plastics in the Great Lakes, compared to the debris found in oceanic gyres, could possibly also reflect differences in degradation. Unlike the fairly steady surface currents that permanently trap plastic debris within the oceanic gyres, the surface currents in the Great Lakes lack persistence and are driven more by short-term atmospheric forcing because of the Lakes' much smaller sizes (Beletsky et al., 1999). This, combined with the Great Lakes' greater shoreline to surface area ratio, would tend to intensify the interactions of the plastic debris with the shoreline. Along and near the shore, plastic debris are subject to more intense mechanical and (photo-) oxidative degradation, thus accelerating the breakdown into smaller pieces (Andrady, 2011).

The presence of plastic debris in nearshore marine sediments has been documented in several studies (Browne et al., 2010, 2011; Ribic, 1998; Santos et al., 2009). Although data as a function of depth below the sediment surface are available for a number of cases, most studies are limited to plastic debris in the very surface layer of sediment surface. The reported microplastic debris abundances within the upper 5 cm of marine sediments range from 0.21 to more than 77,000 items/m^2 (Hidalgo-Ruz et al., 2012). These values are much higher than those of Zbyszewski et al. (2014), who found between 0 and 34 plastic items/m^2 in sediments along the shorelines of Lakes Huron, St. Clair, and Erie. It should be noted, however, that, in contrast to the marine studies, synthetic fibers and other microplastics and microscopic plastic debris were not included in the survey by Zbyszewski and coworkers.

Hoellein et al. (2014) compared the abundance and mass of anthropogenic debris on Lake Michigan beaches with data from four marine beaches located in New Jersey (USA), Costa dos Coqueiros (Brazil), Darsait (Oman), and the Transkei Coast (South Africa) (Ribic, 1998; Santos et al., 2009). All of the marine beaches had significantly higher plastic debris counts than the Lake Michigan beaches, possibly due to the systematic grooming of the latter (see above). The river bottom sediments and riparian zones of the Chicago River, however, exhibited comparable counts of anthropogenic debris as the marine beaches. Based on the available data, it would seem that beaches, nearshore sediments, riparian zones, and possibly other transitional environments may represent preferential sites of accumulation of plastic debris. This hypothesis will require more data to be confirmed. An important step forward would be the development of internally consistent sampling protocols and metrics to compare data from different studies.

Contaminants

Preliminary work by Dr. Lorena Rios Mendoza at University of Wisconsin Superior (unpublished results) have shown that a portion of plastic debris collected in the surface waters of Lake Erie carry polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), both of which are capable of causing cancer and birth defects. Concerns are also being voiced about plastic fibers detected in the guts of Great Lakes fish, which may carry similar contaminants (Schwartz, 2013). Little definitive information is available about the potential bioavailability and bioaccumulation of contaminants from plastic debris in the Great Lakes, however. The possible transfer of plastic-associated toxins to humans through consumption of freshwater organisms remains to be demonstrated.

Economic impacts

With over 60 million people visiting the 98 state parks, 39 provincial parks, and 12 national parks bordering the Great Lakes each year (US EPA, 2012), and millions more visiting public beaches, the indirect costs of plastic debris on the tourism industry are undoubtedly significant, but have yet to be quantified. The indirect costs of plastic debris on other industrial activities, for example commercial fisheries, are also unknown. In addition, litter, including plastic debris, may negatively affect the quality of life in coastal communities and depress coastal property values. Thus, beach cleanup activities enjoy broad public support and mobilize large volunteer groups. According to the Alliance for the Great Lakes, in 2012, the monetary value of the hours spent by volunteers cleaning up beaches around the Great Lakes represented over US $250,000 (Alliance for the Great Lakes, 2013).

We are not aware of any study estimating the direct cost of combating and curtailing plastic debris pollution in the Great Lakes region. However, a study prepared for the US Environmental Protection Agency analyzed the direct cost of marine litter management in the states of California, Oregon and Washington (Stickel et al., 2012). Data received from a random sample of West Coast communities in those states revealed that approximately US $13 per inhabitant is spent annually on beach and waterway cleanup, street sweeping, installation of storm-water capture devices, storm drain cleaning and maintenance, manual cleanup of litter, and public anti-littering campaigns. If we apply the same per capita $13 to the 36 million people who live within 50 km of the shoreline of a Great Lake (estimated using 2012 LandScan data), the direct cost of combating plastic debris pollution in the Great Lakes region would amount to $468,000,000 annually.

A study conducted by Industrial Economics Inc. for the US National Oceanic and Atmospheric Administration (NOAA) Marine Debris Division (Leggett et al., 2014) examined the direct cost of littered beaches for residents of Orange County, California. The study found that the residents consider beach cleanliness a top criterion for deciding which beaches to visit: they are willing to travel further to cleaner beaches at a cost. A travel cost model calculated that Orange County residents would save a combined US $148 million annually if all nearby beaches were completely litter-free. By extrapolation, we expect that littered beaches in the Great Lakes region similarly cost residents millions of dollars annually due to increased travel expenditures.

The growing number of media reports on plastics ingested by commercial fish, crustaceans, and shellfish could potentially lead to reduced consumer spending on these food items. The uncertainties surrounding the abundance, ecological effects, and human health risks of plastics could ultimately have a greater economic impact on the fishing industry in the Great Lakes than the revenue losses resulting from damage to vessels by plastic debris or lower catches due to the presence of litter in hauls. However, further research will be needed to determine to what extent the fishing industry in the Great Lakes region could be affected by plastic pollution.

Policy

Public awareness of plastic debris in the Great Lakes is on the rise as a result of new research findings, increased media exposure, NGO-led cleanup activities, and governmental initiatives, including NOAA's Marine Debris Program and Canada's National Marine Debris Surveillance Program (the latter ran between 1998 and 2002). NOAA's Great Lakes Land-Based Marine Debris Action Plan (2014–2019) aims to identify knowledge gaps, guide relevant policy and management decisions, and reduce debris input by educating and engaging stakeholders, as well as to lessen plastic debris impacts through tracking and removal efforts. The plan represents a collaborative effort between federal agencies, states, tribal nations, researchers, business leaders, and NGOs in the Great Lakes region (NOAA Marine Debris Program, 2014).

At the municipal level, the Great Lakes and St. Lawrence Cities Initiative (GLSLCI), a binational coalition of mayors and municipal officials that seeks to advance the protection and restoration of the Great Lakes and the St. Lawrence River, has identified microplastics as a key environmental threat. GLSLCI has adopted a resolution that calls on industry to phase out microbeads from consumer products, including personal care products. The resolution further calls on provincial, state, and federal governments to establish legislation banning the use of microbeads in consumer products (Great Lakes and St. Lawerence Cities Initiative, 2014). Several companies have already committed to voluntarily phase out microbeads from their products over the next several years

(Plastic Soup Foundation et al., 2014). A ban on the manufacture and sale of personal care products containing microbeads has become law in Illinois. Similar legislation has been introduced in New York, California, Michigan, and Ohio (but not yet adopted), and is being considered in Wisconsin, Pennsylvania, Ontario, and Québec. Minnesota has passed a bill requiring a study on the issue (Olga Lyandres and Jared Teutsch, Alliance for the Great Lakes, 2014, personal communication).

Dumping of plastics in the oceans has been illegal since 1988, following the adoption of Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL) by the International Maritime Organization. Similarly, Annex V of the Great Lakes Water Quality Agreement (GLWQA) prohibits vessels from discharging garbage into the Lakes, including all plastic waste. However, the GLWQA does not regulate the input of plastic debris into the Great Lakes from land-based sources. A number of municipalities bordering the Great Lakes have enacted by-laws prohibiting littering on beaches, while some municipalities have also banned smoking on public beaches and charge fees for plastic grocery bags. These initiatives may help limit plastic input to the Great Lakes. Nonetheless, it may require incorporation of new regulations in the GLWQA in order to explicitly address the issue of pollution by microplastics and microscopic plastic debris.

Survey methods

At present, open-water and shoreline surveys designed to assess the distributions of plastic debris in oceans and lakes are time-consuming, costly, and provide limited areal coverage and temporal resolution. Remote sensing and field-deployable sensors have the potential to overcome these limitations. However, to our knowledge, these approaches have not been widely deployed for the detection and tracking of plastic debris in aquatic environments.

Plastics have characteristic absorbance and reflectance spectra in the near-infrared (NIR) domain (~750–2500 nm) (Masoumi et al., 2012). Thus, in principle, NIR spectrometers could be used to detect and identify plastics by matching spectra obtained on environmental samples to those of reference materials. NIR spectroscopy is currently used in related applications including the sorting of plastic debris in recycling facilities (Hopewell et al., 2009). In collaboration with P&P Optica (http://www.ppo.ca/), a spectrometer manufacturer, the authors of this study successfully used NIR reflectance spectrometry (spectral range 890–2500 nm) to detect common plastic debris in beach sand (unpublished results).

A significant limitation for the direct detection of plastics in aquatic systems with NIR spectroscopy is the strong absorption of infrared radiation by water (Mace, 2012). Raman spectroscopy offers an alternative method to identify plastics in environmental samples (Allen et al., 1999; Tsuchida et al., 2009). As Raman scattering from water is weak, Raman spectroscopy could be used to identify plastics in aqueous samples and, ultimately, directly in the aquatic environment. One avenue that deserves to be explored further is the development of portable and field-deployable Raman spectrometers. One could envision applications ranging from fast shipboard screening of samples to the deployment on buoys or remote controlled vehicles.

Remote sensing is another tool that could prove useful for monitoring plastic debris in marine and lentic settings. Identification of larger plastic debris (>1 m) in terrestrial environments using hyperspectral imaging sensors mounted on unmanned aerial vehicles (UAVs) has been demonstrated (Hörig et al., 2001). Most hyperspectral sensors operate in the NIR spectrum and have sufficient spectral resolution to identify plastics in the same way that NIR spectrometers do. However, the small size of much of the plastic debris found in lakes and oceans presents a major obstacle, as the pixel area, that is, the spatial resolution of the sensor, is limited in part by the sensor's proximity to the target. Furthermore, when imaging aquatic environments, hyperspectral sensors are subjected to lower reflected light levels, high absorption of NIR energy, and possible interference from wave action and sun glint, all of which restrict the detection of plastic debris (Veenstra and Churnside, 2012).

Remote sensing could be used indirectly to determine where plastic debris is likely to accumulate. In the ocean, plastic debris has been shown to concentrate in anticyclonic eddies, along frontal boundaries and in other areas of surface convergence (Eriksen et al., 2013b; Howell et al., 2012; Pichel et al., 2007). These convergent areas can be assessed from satellite imagery and hydrodynamic models that forecast the speed and direction of surface flow. Pichel et al. (2007), for example, derived a Debris Estimated Likelihood Index (DELI) for a section of the ocean within the North Pacific Subtropical Convergence Zone, based on sea surface temperature and chlorophyll absorption data obtained from multispectral satellite imagery. It would therefore be worthwhile to assess the relationship between surface flow convergence and plastics abundance in the surface waters of the Great Lakes: the development of tools similar to Pichel et al.'s (2007) DELI would greatly help in identifying open-water and coastline hot spots prone to debris accumulation. This information would provide welcome support to monitoring programs, scientific research on plastics, and cleanup efforts in the Great Lakes.

Concluding remarks

The review of the available data and information suggests that plastic debris represents a major environmental challenge for the Great Lakes. However, many uncertainties surround the nature and magnitudes of the ecosystem impacts of pollution by plastics in the Great Lakes, primarily because of a lack of targeted scientific research into the sources, transport, breakdown, and ecological plus human health implications of plastic debris. The following are some of the essential research questions that require attention.

1. What are the annual inputs of plastic debris to each of the Great Lakes basins? How do the inputs vary throughout the year? What is the breakdown of the inputs in terms of size and composition of the plastic debris?
2. What are the rates and mechanisms at which different types of plastic debris degrade in the Great Lakes? What proportion of plastics is ultimately preserved in bottom sediments?
3. How widely are microplastics and microscopic plastic debris distributed in the Great Lakes? How do their sources and environmental fate differ from that of larger plastic debris?
4. How much plastic debris accumulates along the Great Lakes shoreline, both in beach and non-beach environments (e.g., wetlands, harbors, rocky shores)? Do plastics interact differently with organisms in the different shoreline habitats?
5. What is the extent of bioaccumulation of plastics and associated contaminants along the food webs of the Great Lakes? What are the ecotoxicological consequences? Are there potential risks to human health?

Answers to these and other related questions are crucial to assess the current state of pollution of the Great Lakes by plastics, but also to develop a predictive understanding of the fate of plastic debris within the lakes. The latter is needed to interpret the distributions of plastics in the different environmental compartments of the Great Lakes, and to develop the necessary tools to forecast the effectiveness of proposed actions, regulations, and policies.

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Appendix A

Anthropogenic debris items sorted by activity class as used in Fig. 1, based on Alliance for the Great Lake's classification of anthropogenic debris items on their Adopt-a-Beach™ Litter Monitoring Form.

Shoreline and recreational	Smoking-related	Medical/personal hygiene	Waterway	Dumping	Other
Six-pack holders	Cigar tips	Condoms	Bait containers	55-gal drums	Discarded food
Bags (paper)	Cigarette lighters	Diapers	Bleach/cleaner bottles	Appliances (refrigerators, washers, etc.)	Drug paraphernalia (crack pipes, bags, etc.)
Bags (plastic)	Cigarettes/cigarette filters	Syringes	Buoys/floats	Batteries	Fireworks debris
Balloons	Tobacco packaging/wrappers	Tampons/tampon applicators	Crates	Building materials	
Beverage bottles (glass)			Fish traps	Car/car parts	
Beverage bottles (plastic) 2 L or less			Fishing line	Tires	
Beverage cans			Fishing lures/light sticks		
Caps, lids			Fishing nets		
Clothing, shoes			Light bulbs/tubes		
Cups, plates, forks, knives, spoons			Oil/lube bottles		
Food wrappers/containers			Pallets		
Pull tabs			Plastic sheeting/tarps		
Shotgun shells/wadding			Rope		
Straws, stirrers			Strapping bands		
Toys					

Appendix B

Anthropogenic debris items classified as plastic or non-plastic (other) as used in Fig. 2, based on the European Environmental Agency's (EEA) classification of anthropogenic debris items in their Marine LitterWatch App.

Plastic	Other
Six-pack holders	55-gal drums
Bags (plastic)	Appliances (refrigerators, washers, etc.)
Bait containers	Bags (paper)
Beverage bottles (plastic) 2 L or less	Balloons
Bleach/cleaner bottles	Batteries
Buoys/floats	Beverage bottles (glass)
Caps, lids	Beverage cans
Car/car parts	Building materials
Cigar tips	Clothing, shoes
Cigarette lighters	Condoms
Cigarettes/cigarette filters	Crates
Cups, plates, forks, knives, spoons	Discarded food
Diapers	Fireworks debris
Drug paraphernalia (crack pipes, bags, etc.)	Fish traps
Fishing line	Light bulbs/tubes
Fishing lures/light sticks	Pallets
Fishing nets	Pull tabs
Food wrappers/containers	Tires
Oil/lube bottles	
Plastic sheeting/tarps	
Rope	
Shotgun shells/wadding	
Strapping bands	
Straws, stirrers	
Syringes	
Tampons/tampon applicators	
Tobacco packaging/wrappers	
Toys	

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