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Pelagic plastic pollution within the surface waters of Lake Michigan, USA

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ABSTRACT

During the summer of 2013, a total of 59 surface water samples were collected across Lake Michigan making it the best surveyed for pelagic plastics of all the Laurentian Great Lakes. Consistent with other studies within the Great Lakes, Mantra-trawl samples were dominated by particles less than 1 mm in size. Enumeration of collected plastics under a microscope found fragments to be the most common anthropogenic particle type, followed by fibers, with more minor contributions from pellets, films and foams. The majority of these pelagic plastic particles were found to be polyethylene, with polypropylene being the second most common polymeric type, which is consistent with manufacturing trends and beach survey results. The pelagic plastic was found to be fairly evenly distributed across the entire Lake Michigan surface, despite the formation of a seasonal gyre at the southern end of the lake. We found that an average plastic abundance of ~17,000 particles/km^2, which when multiplied by the total surface area, gives on the order of 1 billion plastic particles floating on the surface of Lake Michigan. As the majority of these particles are extremely small, less than 1 mm in size, which allows for easy ingestion, these results highlight the need for additional studies with regard to the possible impacts upon aquatic organisms.

Introduction

Global plastic production exceeded 300 million tonnes per year in 2014 (Plastics Europe, 2015). Estimates vary as to how much plastic ultimately reaches the oceans (Thompson, 2006; Eriksen et al., 2014; Jambeck et al., 2015), but without proper waste management and products designed for recovery or environmental degradation, the amount is expected to continue to grow over the next few decades as production continues to increase. While the presence of plastic debris in marine ecosystems has been well documented (Colton et al., 1974; Law et al., 2010; Moore et al., 2001; Thompson et al., 2004; Cózar et al., 2014), freshwater ecosystems, such as rivers and lakes, have only recently begun to be investigated (Eriksen et al., 2013; Hollein et al., 2014; Free et al., 2014; Corcoran et al., 2015; Dris et al., 2015; Eerkes-Medrano et al., 2015). The Laurentian Great Lakes are the largest surface freshwater ecosystem in the world, containing nearly 20% of the world supply of surface freshwater. The water from the lakes and the channels that connect them eventually flows to the Atlantic Ocean; and thus the presence, transport and fate of microplastics in the Laurentian Great Lakes are of concern not only for freshwater systems, but also for the marine environment. Recent shoreline, stream and open-water surveys of the Great Lakes have found densities of plastics as high as those reported in oceanic gyres (Eriksen et al., 2013; Zbyszewski and Corcoran, 2011; McCormick et al., 2014; Zbyszewski et al., 2014).

Microplastics are defined as plastic particles less than 5 mm in size (Thompson et al., 2009). Given their small size, mobility and widespread distribution, microplastics have a high potential to be ingested by aquatic organisms (Browne et al., 2008; Graham and Thompson, 2009; Murray and Cowie, 2011; Lusher et al., 2013). Direct effects of ingestion, such as abrasions or blockages and subsequent starvation, are likely to be less pronounced with micro- as compared to macroplastics. Of more concern for microplastics are the potential secondary effects, such as the ability of the plastic to transfer inherent or adsorbed persistent organic pollutants (POPs) into the organism. Studies have shown that POPs will preferentially partition onto plastic reaching concentrations up to a million times greater than in the surrounding aqueous environment (Mato et al., 2001; Hirai et al., 2011). Once ingested, these chemicals can desorb, leading to a variety of negative impacts (Browne et al., 2013; Rochman et al., 2013; Wright et al., 2013; Chua et al., 2014; Rochman et al., 2014; de Sa et al., 2015; Tanaka et al., 2015). The longer the particles remain within the organism the greater the potential for this desorption and transfer of toxins (Andrady, 2011). While this study was not focused on the impacts of plastic pollution, understanding the implications of such marine debris on aquatic organisms does provide context for its results.

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Relative to oceans there is limited research on the distribution and abundance of plastic debris in the Great Lakes (Drieger et al., 2015) and only one other open-water study of pelagic plastics (Eriksen et al., 2013). In this study, we conducted the first open-water survey for plastic pollution in Lake Michigan in order to examine the abundance, composition, distribution and potential sources of plastic debris. This study is the most comprehensive single-lake, open-water study conducted in the Great Lakes to date.

Materials and methods

Sample collection

During the summer of 2013, a total of 59 open-water samples were obtained across the surface of Lake Michigan (Fig. 1). All samples were collected with the use of a manta trawl, which consists of an aluminum frame with a rectangular opening 16 cm high by 61 cm wide attached to a 3 m long, 333 μm-mesh net with a 30 × 10 cm^2 collecting bag. The trawl was towed along the lake surface and was positioned with the towline sitting outside of the ship's wake. The sea state for all sample sites was fairly calm with values between 1 and 3 on the Beaufort Wind Scale. While the sample sites were not equidistant from one another nor were the transects of equal length, all samples were collected for 30 min (timed using a stopwatch) and the tow speed was kept under 2.0 knots. The tow length was determined by three independent measures (utilizing GPS coordinates, a flowmeter suspended within the mouth of the trawl net and via an onboard knotmeter) and averaged. The surface area sampled could then be calculated by multiplying the tow length by the width of the trawl mouth opening. All samples were rinsed from the collection bag into a sample container and immediately preserved in 70% isopropyl alcohol for later laboratory processing and analysis.

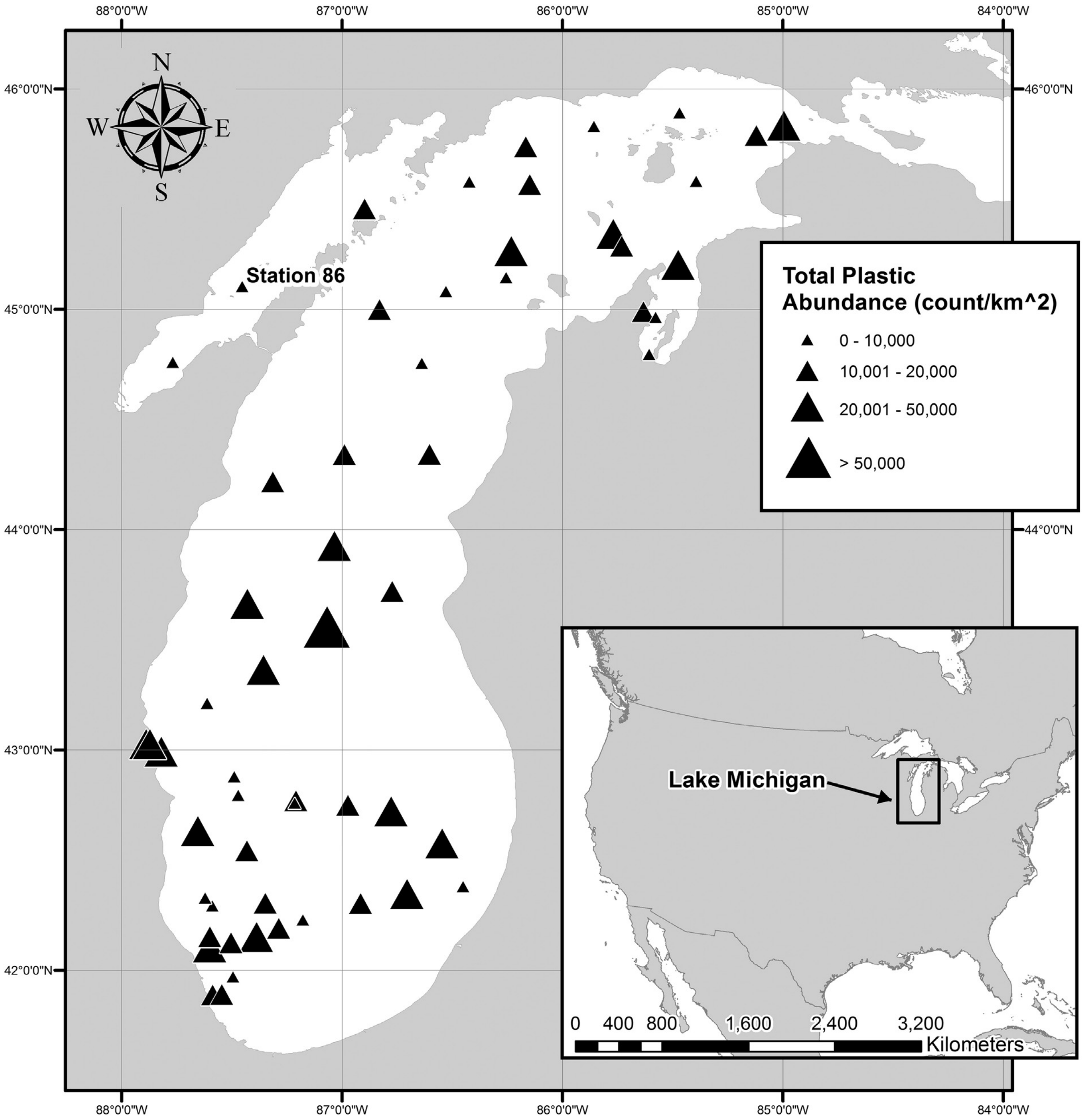

Fig. 1. Distribution of plastic abundance (particles/km^2) for the 59 open-water surface samples obtained across Lake Michigan during the summer 2013. All but one sample– station 86, indicated in the figure– contained plastic.

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Sample processing

Open-water samples were processed in a laboratory for isolation of plastic debris using a modified National Oceanic and Atmospheric Administration marine debris protocol (Masura et al., 2015), briefly described here. Each sample is filtered through a series of 8 in. diameter Tyler sieves of 4.75 mm, 1.00 mm and 0.355 mm stainless steel mesh, which separates the solid material into 3 size classifications (0.355–0.999 mm, 1.00–4.749 mm and ≥4.75 mm). Solids within the largest size fraction (≥4.75 mm) were manually sorted to remove visible plastic debris from organic material. In order to collect any microplastics initially stuck to the labile organic material, all were rinsed with DI water with rinse water running through the stacked sieves. The solids in the smaller two size classifications (0.355–0.999 mm and 1.00–4.749 mm) were subjected to a wet peroxide oxidation (WPO), which digests labile organic material using 30% hydrogen peroxide in the presence of an iron (II) catalyst. Plastic debris is resistant to this wet peroxide oxidation (WPO) processing (Masura et al., 2015). After processing, samples were once again filtered through a stacked sieve set (1.00 mm and 0.355 mm). Within each size classification (0.355–0.999 mm and 1.00–4.749 mm)

Table 1
Locations, counts and abundances of pelagic plastic for all 59 Lake Michigan samples.

				Particle counts							
Sample ID	Date	Latitude	Longitude	Fragments	Pellets	Fibers/lines	Films	Foams	Total	Tow length (km)	Abundance (count/km^2)
GL13 #23	17-Jun-2013	44.99	−85.63	10	–	6	–	–	16	1.54	17,082
GL13 #24	18-Jun-2013	44.96	−85.58	6	–	–	1	–	7	2.05	5593
GL13 #25	26-Jun-2013	44.79	−85.61	10	–	–	1	–	11	2.36	7657
GL13 #26	8-Jul-2013	45.29	−85.73	5	1	7	1	–	14	2.01	11,414
GL13 #27	8-Jul-2013	45.42	−86.25	108	–	23	6	–	137	2.25	100,016
GL13 #28	24-Jul-2013	45.34	−85.77	21	–	4	5	–	30	2.29	21,474
GL13 #29	25-Jul-2013	45.20	−85.48	32	2	17	–	–	51	2.33	35,811
GL13 #40	2-Aug-2013	45.83	−85.00	31	–	23	–	–	53	2.26	38,773
GL13 #41	2-Aug-2013	45.79	−85.12	18	–	4	–	–	22	2.69	13,430
GL13 #42	2-Aug-2013	45.58	−85.39	6	1	2	–	–	9	2.08	7084
GL13 #43	3-Aug-2013	45.57	−86.15	20	–	–	–	–	20	2.09	15,670
GL13 #44	3-Aug-2013	45.26	−86.23	33	3	5	1	–	42	2.51	27,457
GL13 #45	3-Aug-2013	45.14	−86.25	2	5	–	–	–	7	2.28	5023
GL13 #46	3-Aug-2013	45.08	−86.53	5	1	–	1	–	7	2.59	4433
GL13 #47	3-Aug-2013	45.00	−86.83	14	–	7	–	–	21	2.90	11,853
GL13 #48	4-Aug-2013	44.75	−86.64	4	–	–	–	–	4	4.66	1407
GL13 #49	4-Aug-2013	44.34	−86.60	15	–	1	–	–	16	1.57	16,662
GL13 #50	4-Aug-2013	44.34	−86.99	11	–	2	–	–	14	1.92	11,629
GL13 #51	4-Aug-2013	44.22	−87.31	14	–	–	1	2	17	1.92	14,523
GL13 #52	4-Aug-2013	43.92	−87.04	31	–	1	–	–	32	2.40	21,890
GL13 #53	4-Aug-2013	43.72	−86.77	18	–	2	2	–	22	2.19	16,449
GL13 #54	4-Aug-2013	43.56	−87.07	84	4	7	–	–	95	2.04	76,284
GL13 #55	5-Aug-2013	43.66	−87.43	25	2	7	–	–	34	2.15	25,869
GL13 #56	5-Aug-2013	43.36	−87.36	48	14	3	1	–	66	2.17	49,838
GL13 #57	5-Aug-2013	43.21	−87.61	5	1	5	–	–	11	2.11	8553
GL13 #58	5-Aug-2013	43.03	−87.87	36	–	3	–	–	39	2.41	26,516
GL13 #59	6-Aug-2013	43.03	−87.89	33	–	4	–	–	37	2.07	29,241
GL13 #60	6-Aug-2013	42.99	−87.82	29	3	4	1	–	37	2.09	29,072
GL13 #61	6-Aug-2013	42.88	−87.49	4	2	–	–	–	6	2.28	4315
GL13 #62	6-Aug-2013	42.76	−87.21	3	–	–	–	–	3	2.30	2138
GL13 #63	6-Aug-2013	42.54	−87.43	10	–	–	1	2	13	1.92	11,109
GL13 #64	7-Aug-2013	42.33	−87.62	4	–	–	1	–	5	2.51	3261
GL13 #65	7-Aug-2013	42.30	−87.35	12	1	–	–	–	13	1.76	12,113
GL13 #66	7-Aug-2013	41.97	−87.49	9	1	–	–	–	9	2.11	7311
GL13 #67	7-Aug-2013	41.89	−87.55	21	–	3	–	–	24	2.04	18,968
GL13 #68	7-Aug-2013	41.89	−87.59	20	2	4	–	–	26	2.21	19,321
GL13 #69	8-Aug-2013	42.15	−87.60	12	–	3	–	–	15	1.98	12,441
GL13 #70	8-Aug-2013	42.29	−87.59	4	–	3	–	–	7	1.57	7290
GL13 #71	9-Aug-2013	42.63	−87.65	20	–	3	–	–	23	1.74	21,613
GL13 #72	9-Aug-2013	42.79	−87.47	8	1	–	–	–	9	1.79	8264
GL13 #73	9-Aug-2013	42.77	−87.21	12	–	6	–	–	18	1.62	18,215
GL13 #74	9-Aug-2013	42.75	−86.97	11	1	1	–	1	13	1.29	16,877
GL13 #75	9-Aug-2013	42.72	−86.78	25	–	–	–	–	25	1.91	21,465
GL13 #76	9-Aug-2013	42.57	−86.55	11	4	4	–	5	24	1.89	20,821
GL13 #77	10-Aug-2013	42.38	−86.45	7	–	–	1	–	8	2.14	6133
GL13 #78	10-Aug-2013	42.34	−86.71	17	–	2	1	–	20	1.62	20,228
GL13 #79	10-Aug-2013	42.30	−86.92	14	–	–	1	–	15	1.81	13,618
GL13 #80	10-Aug-2013	42.23	−87.18	10	–	–	–	–	10	1.77	9656
GL13 #81	10-Aug-2013	42.19	−87.29	13	2	1	–	–	16	1.81	14,496
GL13 #82	10-Aug-2013	42.15	−87.39	24	4	8	–	–	36	2.45	24,052
GL13 #83	10-Aug-2013	42.12	−87.50	15	–	–	–	–	15	2.13	11,528
GL13 #84	10-Aug-2013	42.10	−87.60	27	–	6	–	–	33	2.05	26,403
GL13 #85	19-Aug-2013	44.76	−87.77	7	–	1	1	–	9	3.28	4504
GL13 #86	19-Aug-2013	45.10	−87.45	–	–	–	–	–	0	2.79	0
GL13 #87	20-Aug-2013	45.45	−86.90	14	–	2	–	–	16	2.41	10,894
GL13 #88	20-Aug-2013	45.58	−86.42	7	–	–	–	–	7	3.66	3136
GL13 #89	20-Aug-2013	45.74	−86.17	14	–	1	–	–	15	2.33	10,561
GL13 #90	20-Aug-2013	45.83	−85.86	7	–	1	–	–	8	2.48	5282
GL13 #91	20-Aug-2013	45.89	−85.47	4	–	–	–	–	4	2.53	2592

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Table 2
Plastic abundances (count/km^2) averaged over all 59 samples, distinguished by size and particle type.

	0.355–0.999 mm	1.000–4.749 mm	>4.75 mm	% of total
Fragment	8381.3	4418.4	866.3	79%
Pellet	540.8	141.9	23.8	4%
Fiber/line	1006.3	858.9	549.6	14%
Film	105.3	97.0	139.0	2%
Foam	118.7	29.0	0.0	1%
Count/km^2	10,152.5	5545.2	1578.8	
% of total	59%	32%	9%	

all microplastic particles were removed, enumerated and categorized as fragment, pellet, line/fiber, film or foam with a dissection microscope (Free et al., 2014) and later archived. Six blank samples in which DI water was stored within sample containers for periods of 1–14 days were processed concurrently with the open-water samples and none were found to have any microplastic particulate indicating that the risk of sample contamination from the containers, lab or processing was negligible.

Spectroscopic analysis

A scanning electron microscope with an elemental detection system (SEM/EDS) was used to analyze the pelagic plastic particles within the smallest size fraction (i.e., 0.355–0.999 mm) in order to distinguish between organic and inorganic materials owing to the more reflective nature of minerals as compared to carbon-based materials (Eriksen et al., 2013). Based upon availabilities at the time of analysis, particles within this size range were not amendable to other spectroscopic techniques (namely FTIR discussed below). Additionally, the SEM can provide detailed images of the particle surface, which are not available via other analytical techniques. Of the 59 samples, 52 contained particles within this smallest size classification. Of these 52 sites, a 20% random selection of sites (11 sites total) was chosen for analysis. For these 11 sites, all particles within the smallest size classification were analyzed using the SEM/EDS system. Samples were prepared for SEM/EDS analysis by securing the particles onto double-sided carbon tape prior to imaging using a Phenom ProX desktop SEM/EDS system operating at 15 keV in backscatter mode.

Fourier transform infrared (FTIR) analysis was used to determine the polymeric composition of retrieved pelagic particles whose diameter (or longest particle edge) was greater than (or equal to) 4.75 mm. Of the 59 sampled sites, 30 sites contained a total of 122 particles within this largest size classification. A total of 72 particles (59%) were analyzed. For this analysis, particles were dissolved in a small amount of dichlorobenzene (~1 mL), which usually necessitated the use of some heat (100 °C). A small amount of this solution was then transferred and allowed to dry on a Real Crystal (NaCl) IR Card (International Crystal Laboratories). Samples were analyzed using a Matteson Polaris FTIR operating at 32 scans and 4 cm^{-1} resolution. Background scans using a Real Crystal IR Card with only dichlorobenzene dried to its surface were obtained every fifth spectra or each new day, whichever came first. Background spectra are automatically subtracted from each raw spectrum to yield sample spectra. A library of spectra from known polymers was created by using in-house polymer samples or from common consumer products, such as plastic bottles, containers and cigarette filters. Sample spectra were compared to this library for polymeric composition identification to support visual interpretation.

As the instrumental equipment available at the time of analysis are both 'destructive' techniques (e.g., dissolution to form films for FTIR and bound to carbon tape for SEM/EDS), retrieved pelagic plastic particles within the middle size classification (1.00–4.749 mm) were not analyzed by either technique. Rather these particles were archived for future research endeavors.

Results and discussion

During the summer of 2013, a total of 59 surface water samples were collected across Lake Michigan (Fig. 1). As the only previous pelagic plastic survey in the Great Lakes collected at most 8 samples in each of Lakes Superior, Huron, and Erie (Eriksen et al., 2013), our collection effort on Lake Michigan constitutes the most intensive such survey in the Laurentian Great Lakes to-date. Plastic particles extracted from the samples were categorized and counted (Table 1). Of the 59 samples, all but one contained plastic (station 86, indicated in Fig. 1). Using these counts and the surface area sampled (tow length × trawl net width), the plastic abundance (no. of particles per square kilometer, particles/km^2) for each sample was determined (Table 1; Fig. 1) in order to standardize the data due to the varying tow lengths. Aside from the one sample which did not contain any plastic, abundances varied from ~1400 to 100,000 particles/km^2.

Plastic particle distribution

Numerical modeling of circulation currents in Lake Michigan notes the creation of an anticyclonic gyre within the southern basin, which develops over the course of the summer and is especially prominent in August (Beletsky et al., 2006). As a result of this seasonal gyre, we expected that we might find greater particle abundances within the southern end of Lake Michigan as compared to the northern end during our August 2013 expedition. Our results, however, do not indicate any particular aggregation of plastic particles as a result of this temporary gyre formation (Fig. 1). Rather, our results show a fairly even distribution of plastic particles across the lake surface. We reason that the fairly even distribution may be a consequence of: (1) the long residence time of waters within Lake Michigan, (2) the high variability of circulation currents, especially within the southern end of the lake, and/or (3) the wind acting to move any debris with an above-surface profile differently than surface currents carrying subsurface debris. Such 'windage' effects were noted in the movement of debris after the Japanese tsunami (Desforges et al., 2013). Beletsky et al. (2006, 2007) both note a strong interannual variability within the circulation currents within Lake Michigan with warmer years exhibiting anticyclonic currents, which would aggregate particles, but colder years demonstrating cyclonic currents, which would act to transport plastic particles downward. NOAA NowCast data (http://www.glerl.noaa.gov/res/glcfs/) indicates that August 2013 was a cyclonic year, rather than anticyclonic, which would help explain the lack of aggregation. Additionally, of the Great

Table 3
Comparison of results of this study to a previous Laurentian Great Lakes study in percentages by size and particle type.

	Size classification			Particle type				
	0.355–0.999 mm	1.000–4.749 mm	>4.75 mm	Fragment	Pellet	Fiber/line	Film	Foam
Eriksen et al., 2013	81%	17%	2%	42%	48%	0%	1%	8%
This study	59%	32%	9%	79%	4%	14%	2%	1%

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Lakes, Lake Michigan is second only to Lake Superior in terms of residence time (99 years) owing to its cul-de-sac formation and equal surface elevation to its sister Great Lake, Lake Huron. Water entering the lake circulates slowly and tends to remain for nearly a hundred years (Beletsky et al., 2006) before discharging to Lake Huron, which can also allow for a more even distribution of plastic pollution across the lake surface.

Plastic particle abundances averaged 17,276 particles/km^2 across the Lake Michigan surface, with the 95% confidence interval of the mean ranging from 12,898 to 21,655 particles/km^2. Extrapolating across the surface area of Lake Michigan, our data suggest that there are on the order of one billion particles across the surface of just this one Great Lake, with 95% confidence values ranging from nearly 750 million up to 1.26 billion particles.

Consistent with the 2012 Great Lakes survey (Eriksen et al., 2013), the vast majority of plastic particles are found within the smallest size classification (0.355–0.999 mm; 59%; Table 2). However, the distribution of plastic particles differed substantially between these two studies (Table 3). While pellets were the dominant particle type in the 2012 study, fragments dominate the pelagic plastic obtained from Lake Michigan (79%), with pellets making a more minor contribution (4%; Table 3). Interestingly, fibers were the second most abundant type (14%; Table 2), which stands in contrast to the other Great Lakes study, in which they were only a minor component (Table 3; Eriksen et al., 2013).

This difference in the distribution of pelagic plastic particle types could be attributed simply to spatio-temporal variations or may be a factor of differences in methodology. The sources of microplastics are diverse and include both primary and secondary sources. Primary sources include preproduction pellets and powders (Mato et al., 2001), as well as polyethylene and polypropylene microbeads used in many personal care products, such as facial scrubs and toothpastes (Gregory, 1996, Fendall and Sewell, 2009). Secondary sources are produced by mechanical and photo-oxidative degradation (Singh and Sharma, 2008) of plastic bags, bottles, fishing line and nets, and other litter types into smaller fragments (Browne et al., 2007; Cole et al., 2011). The prominence of fragments within the Lake Michigan samples as compared to pellets seems to indicate that secondary sources outweigh primary in this waterbody. This could be affiliated with the longer residence time of waters within Lake Michigan, which allow for longer exposure of primary plastics to UV light and freeze–thaw cycles that lead to brittleness, as well as the mechanical abrasion of wind and waves. The prominence of pellets within the Eriksen et al. 2012 study, largely due to Lake Erie samples, as compared to these Lake Michigan samples, could also be owing to a greater concentration of primary sources (pellet producers and consumers) in the Sarnia area of Lake Huron and around Lake Erie (Zbyszewski and Corcoran, 2011; Zbyszewski et al., 2014) as compared to the Lake Michigan watershed.

Table 4
Summary of SEM/EDS analysis on retrieved particles in smallest size classification (0.355–0.999 mm).

Sample ID	Number of particles 0.355–0.999 mm	Percent of total	
		Plastic	Mineral
GL13 #24	7	100%	0%
GL13 #40	37	93%	7%
GL13 #45	7	100%	0%
GL13 #49	3	67%	33%
GL13 #50	16	73%	27%
GL13 #56	23	67%	33%
GL13 #60	30	100%	0%
GL13 #66	8	60%	40%
GL13 #67	20	93%	7%
GL13 #74	15	75%	25%
GL13 #80	8	80%	20%
Total/Average	174	84%	16%

Table 5
Summary of FTIR results on retrieved pelagic plastic particles in largest size classification (≥4.75 mm). PE = polyethylene; PP = polypropylene.

Sample ID	Number of particles: >4.75 mm	Type of polymer			
		PE	PP	Copolymer	Unknown
GL13 #23	1	0	1	0	0
GL13 #26	1	0	1	0	0
GL13 #27	6	3	1	1	1
GL13 #28	3	1	2	0	0
GL13 #29	2	1	1	0	0
GL13 #40	1	1	0	0	0
GL13 #44	2	0	1	1	0
GL13 #49	3	0	1	0	2
GL13 #51	1	0	0	0	1
GL13 #54	5	1	1	3	0
GL13 #55	3	3	0	0	0
GL13 #56	15	12	3	0	0
GL13 #59	4	2	1	0	1
GL13 #60	2	0	1	0	1
GL13 #62	3	2	1	0	0
GL13 #65	2	1	1	0	0
GL13 #67	2	0	2	0	0
GL13 #68	3	0	0	3	0
GL13 #75	2	2	0	0	0
GL13 #76	3	0	3	0	0
GL13 #83	3	2	1	0	0
GL13 #85	2	2	0	0	0
GL13 #88	3	0	2	1	0
Total	72	33	24	9	6
Percentage	100%	46%	33%	13%	8%

In addition to these possible spatio-temporal variations, the sample processing methodology in the 2012 study differed from that employed here. Eriksen et al. (2013) separated plastic from the associated seston via density-flotation separation using salt-water (a common technique in oceanic studies), but here we utilized the wet peroxide oxidation technique. Fibers are typically composed of more negatively buoyant polymeric materials, such as polyamides, polyethylene terephthalate and polyester. Plastic fragments and pellets, however, are typically composed of polyethylene and polypropylene, which are positively buoyant polymers. Because of this difference in density, plastic fragments and pellets may be more easily separated via the density-flotation method as compared to the fibers causing the fibers to not be as prominent in the 2012 samples as compared to the Lake Michigan samples.

Plastic composition analysis

Several studies have confirmed the need to analyze suspected particulates obtained in environmental sampling in order to confirm their identification as plastic as compared to natural materials (Fillela, 2015; Eerkes-Medrano et al., 2015; Eriksen et al., 2013). Similar to the results from Eriksen et al. (2013), an average of 16% of the particles within the 0.355–0.999 mm size class were found to be misidentified as plastic when they were really of mineral origin based upon SEM/EDS analysis (Table 4). All counts within this size class were adjusted accordingly (Table 1). FTIR results of the 72 particles (59%) analyzed within the largest size classification (Table 5) found thirty-three (46%) to be polyethylene, with high-density polyethylene being more prevalent (84%) as compared to low-density. Polypropylene was found to be the second most abundant polymeric type (33%) within these samples. These findings are consistent with global trends in the mass production of plastics, with polyethylene, followed by polypropylene, being the most widely manufactured polymers (Plastics — The Facts, 2015) and with the findings of beach surveys conducted along the shores of the Laurentian Great Lakes (Zbyszewski and Corcoran, 2011).

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The remaining 20% of plastic particles analyzed are believed to be either copolymers (13%) or could not be identified (8%) given our instrumentation and polymer libraries (Table 5).

Conclusions

Open-water sampling of Lake Michigan revealed a fairly even distribution of pelagic plastic particles across the lake surface, despite the usual formation of a summer seasonal gyre at the southern end of the lake. This seasonal gyre formation is, however, highly variable, depending largely on water temperatures, with warmer years leading to the anticyclonic currents that would be associated with particle aggregation. As August 2013 was a cooler year, which resulted in cyclonic current formation that is associated with downward mobility of water and dispersal of surface particles, this may explain the lack of a plastic particulate 'hot spot' during this sampling expedition. Long residence time (99 years) of waters within Lake Michigan and 'windage' effects may also be factors in the surface distribution. Consistent with previous studies within the Laurentian Great Lakes, plastic particles less than 1 mm were the dominant size classification. This size class could have significant consequences for aquatic organisms as these smaller particles have greater surface area for possible adsorption of persistent organic pollutants, which are of concern in the Great Lakes, and are more easily ingested whether intentionally or not. Fragments were the most abundant type of plastic particle, indicating secondary sources being more significant than primary. Ultimately, understanding the sources, spatio-temporal trends, eventual sinks and possible food web impacts of this pelagic plastic pollution will require additional study.

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