



Review

A systematic review of the literature on plastic pollution in the Laurentian Great Lakes and its effects on freshwater biota



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ARTICLE INFO

Article history:

Received 20 June 2020

Accepted 24 October 2020

Available online 1 December 2020

Communicated by Tim B. Johnson

Keywords:

Great Lakes

Plastic pollution

Microplastics

Effects

Microfibrer

ABSTRACT

Plastic pollution is ubiquitous in freshwater systems worldwide, and the Laurentian Great Lakes are no exception. We conducted a systematic review to synthesize the current state of the literature on plastic pollution, including macroplastics (>5 mm) and microplastics (<5 mm), in the Great Lakes. Thirty-four publications were used in our systematic review. We found ubiquitous contamination of microplastics in surface water, with maximum abundances exceeding those in ocean gyres. There are also high levels of plastic contamination reported across benthic sediments and shorelines of the Great Lakes. Citizen science data reveals macroplastic across Great Lakes shorelines, with more than three million pieces of plastic litter recorded over a span of three years. We completed a second systematic review of plastic pollution and its impact on freshwater ecosystems in general to inform how plastic in the Great Lakes may impact wildlife. Among studies published in the literature, we found 390 tested effects, 234 (60%) of which were detected and 156 (40%) of which were not; almost all of the freshwater effects (>98%) were tested on microplastics. Based on a subset of these papers, we found that the shape and size of a particle likely affects whether an effect is detected, e.g., more effects are detected for smaller particles. Finally, we identify gaps in scientific knowledge that need to be addressed and discuss how the state of the science can inform management strategies.

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Introduction

The Laurentian Great Lakes, hereinafter referred to as the Great Lakes, are a vital resource, containing 84% of the available freshwater in North America and 21% of the available freshwater on Earth (Environment and Climate Change Canada [ECCC], 2019). Comprised of five lakes, the Great Lakes span an area of > 200,000 km² and cross the borders of the United States and Canada. It is estimated that 30% of US and Canadian economies are linked to the Great Lakes through fisheries, industry, tourism, and recreation (Great Lakes Commission, 2017). Overall, the Great Lakes support a population of approximately 30 million people (US EPA, 2019) and 4,000 species of wildlife (Environment and Climate Change Canada [ECCC], 2019). Among other anthropogenic stressors, plastic waste has become a major concern in the Great Lakes as scientists have begun to understand the ubiquity and implications of plastic pollution in aquatic ecosystems (Burgess et al., 2017).

For decades, researchers focused on plastic pollution in the oceans while largely ignoring freshwater environments. This oversight is particularly striking given that freshwater lakes and rivers are often the first receivers of urban and industrial pollution, including plastic debris (Alimi et al., 2018). Sources of and/or pathways for plastic debris to aquatic environments include wastewater treatment plants, landfill leakage, litter, agricultural runoff, stormwater runoff, tributaries, and industrial effluent or spills (Alimi et al., 2018; Raju et al., 2018; Ziajahromi et al., 2016). From litter alone, due to mismanaged solid waste, an estimated 10,000 tonnes of plastic debris is estimated to enter the Great Lakes annually (Hoffman and Hittinger, 2017). Today, we know that the plastic entering the Great Lakes from diverse sources has led to ubiquitous contamination (Ballent et al., 2016; Corcoran et al., 2015; Dean et al., 2018; Eriksen et al., 2013; Hendrickson et al., 2018; Mason et al., 2016). In recent years, studies focusing on freshwater ecosystems have reported concentrations of plastic debris similar to those found in marine ecosystems (Dris et al., 2015).

Despite the ubiquity of freshwater plastic pollution and associated chemicals (Anderson et al., 2008; Colborn et al., 1998; Guo et al., 2016; Ivleva et al., 2017), few studies have explored the risks of macroplastics (>5mm) and microplastics (<5mm) in freshwater ecosystems (Blettler et al., 2017). In the marine environment, macroplastics are reported to lead to entanglement, laceration, suffocation, and starvation of biota. For microplastics, reported effects include changes to gene expression, changes to reproductive output, and increased mortality (Alimba and Faggio, 2019). Several laboratory studies have investigated the effects of microplastics on freshwater organisms; many of which are standard species used in toxicity testing. Effects on freshwater organisms include increased mortality, changes in reproduction, and reduced locomotion (e.g. Cui et al., 2017; De Felice et al., 2019). Still, the risks associated with plastics and their associated chemicals within freshwater ecosystems remain largely unknown. Further work must be done to better understand the fate and effects of plastic pollution in freshwater organisms.

The Great Lakes provide an opportune case study to increase our understanding of the sources, fate, and effects of plastic pollu-

tion in freshwater ecosystems. In 2015, Driedger et al. reviewed the state of knowledge on plastic pollution in the Great Lakes. In their study, they highlighted the major knowledge gaps in the field of plastic pollution within the Great Lakes specifically and described the need for preservation of these freshwater resources. In this study, we conducted a systematic review of the literature to synthesize what is known about plastic pollution in the Great Lakes, and measure how the state of the science has advanced since the Driedger et al. (2015) review. The objective of this study is to gain a better understanding of the state of the science regarding plastic pollution in the Great Lakes, highlight research gaps, and identify relevant policy options. In addition, we conducted a second systematic review, expanding our original search to include the literature on the effects of plastic pollution to freshwater biota in general, to inform hypotheses about how plastic pollution may impact wildlife in Great Lakes ecosystems.

Methods

Plastic pollution in the Great Lakes

We searched the literature for research regarding plastic pollution in the Great Lakes from 1943 (oldest date accessible) to June 25th, 2019 using the keywords “Great Lake and plastic” and “Great Lake and microplastic” (Web of Science, All Databases). Our search resulted in papers from a broad range of disciplines, including policy, toxicology, chemistry, ecology, limnology, agriculture, and social science. Additional papers that did not appear in the initial literature search, but were known by the authors to be relevant, were also included. Only peer-reviewed literature was included. The title and abstract of each paper were assessed to determine if the paper was relevant for our systematic review. A paper was determined to be relevant if it discussed plastic pollution in Great Lakes watersheds specifically. These papers reported on a range of topics including: 1) the concentrations of plastics on shorelines, in water and in sediment of the Great Lakes; 2) the sources, transport, distribution, and/or the fate of plastics in the Great Lakes; and 3) the contamination of plastics in local wildlife. See Fig. 1 for a flow chart describing this process and Electronic Supplementary Material (ESM) Table S1 for a list of all studies classified as relevant for our systematic review.

Concentrations of plastic pollution in the Great Lakes

To determine the concentrations of plastics found in the Great Lakes, we extracted data from studies that reported concentrations of plastics in various environmental matrices. Additionally, we collected data from a number of papers that reported the concentrations of plastic pollution in small and large tributaries of the Great Lakes. We extracted the following information: the lake(s) or tributary in which the study was performed, the matrix the plastic was collected from (surface water, sediment, shoreline), the location of sampling (tributary, nearshore, open water, etc.), the method of sampling used (manta trawl, sediment grab, trowel, etc.), the mesh size of the equipment, the number of sites sampled in each study, the total number of samples collected, the dominant category of plastic found (including whether or not they counted microfibers),

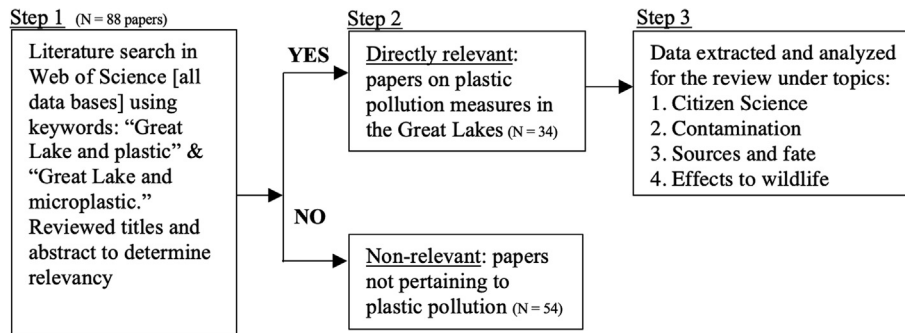


Fig. 1. A flow chart showing the methods for our systematic review on plastic pollution in the Great Lakes.

the size of the debris, the method of chemical identification, and the method of quality assurance/quality control (e.g. sample blanks). Finally, the mean, median, minimum, and maximum concentration of plastic found in each study was recorded (See ESM Table S2). In some cases, we subtracted the number of microfibers found in a study from the total concentration reported to facilitate comparing these concentrations with other studies that excluded microfibers from their analysis (see ESM Figs. S1 and S2 for this comparison). The detailed data extracted about sampling and analysis allowed us to assess whether certain parameters informed the results and conclusions within each study.

To supplement the data obtained in our systematic review, we included citizen science data. This dataset, provided by Ocean Conservancy, was from community cleanups in the Great Lakes region as part of the International Coastal Cleanup. Although we recognize that these data were not collected using systematic or peer-reviewed methods, it provides a broad overview of the (mostly macroscopic) plastic debris present along the shorelines of the Great Lakes.

Effects of plastic on freshwater biota

To better understand the potential impacts of plastic pollution on wildlife in the Great Lakes region, we conducted a second systematic review to identify research studying the impacts of plastic pollution on freshwater organisms in general. For this literature search, we updated the dataset provided by Bucci et al. (2020) using the same keywords ("marine debris", "plastic debris", and "microplastic"). Our updated dataset includes studies published through 7 June 2019. Only papers pertaining to the effects of plastic on freshwater biota were included in our analysis; marine and terrestrial studies were excluded. For visualization of these methods see Fig. 1 from Bucci et al. (2020) and ESM Table S3 for a list of studies that report the effects of plastic pollution in freshwater ecosystems.

Each additional paper was assessed by reading the title and abstract to determine its relevance to effects on biota in freshwater exclusively. Only peer-reviewed primary literature was included. As in Bucci et al. (2020), the following data were extracted from each additional study: the taxonomic group, the organism studied, the characterization of the plastic (polymer type, chemicals included, shape, colour, size), the effect tested, the level of biological organization of the tested effect, the type of study (i.e. field experiment, laboratory experiment), the experimental design (i.e. use of controls, dose, length of exposure), and whether or not the effect was detected (see ESM Table S4). We then classified the data according to the level of biological organization tested (subatomic, atom, small molecule, macromolecule, molecular assemblage, organelle, cell, tissue, organ, organ system, organism, population, assemblage, or ecosystem), and ordered the effects by ecological

relevance using an established framework for pollutants (Adams et al., 1989). We considered a study's endpoints to be ecologically relevant when they targeted endpoints to an organism (mortality, behaviour, growth), a population (change in population growth rate or shifts in reproductive output), an assemblage (change in structure or composition), or an ecosystem (change in structure or function; e.g., changes in nutrient cycling, primary productivity).

To visualize the current state of the knowledge, we plotted the data on a matrix organized by the level of biological organization targeted (14 levels) and the size of the debris tested (from 1 nm to 1 km). In studies that tested multiple levels of biological organization and/or tested more than one effect, each level and effect was plotted individually (Bucci et al., 2020; Rochman et al., 2016). Finally, we used studies that reported dose in particles per unit volume to explore whether plastic type, size, and shape influence whether or not an effect was detected, and visualized the results with dotplots.

Results

From the 88 papers found in our initial literature search, 34 papers were classified as relevant to plastic pollution in the Great Lakes and thus included in our systematic review. This is a large increase since the Driedger et al. (2015) review, where only 15 papers on plastic pollution in the Great Lakes were cited (Fig. 2). Eleven of the 34 studies in our systematic review quantified and characterized plastic pollution in the Great Lakes and their water-

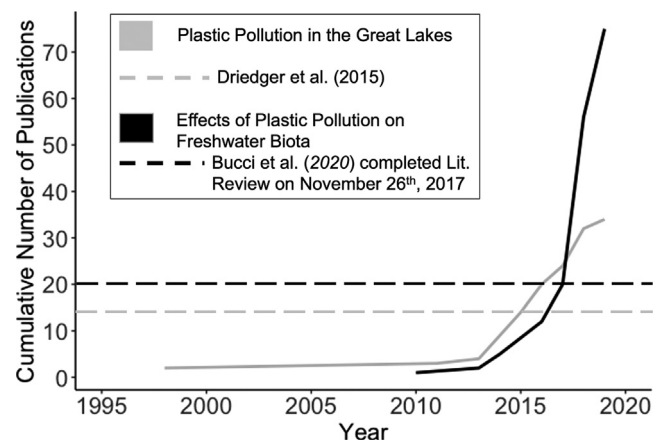


Fig. 2. Each solid line represents the cumulative number of publications found for the two systematic reviews discussed in this paper: The grey line represents all papers published on plastic pollution in the Great Lakes, and the black line represents all papers published on the effects of plastic on freshwater biota. Each dotted line represents the sum of all papers when the last literature review on each topic was completed.

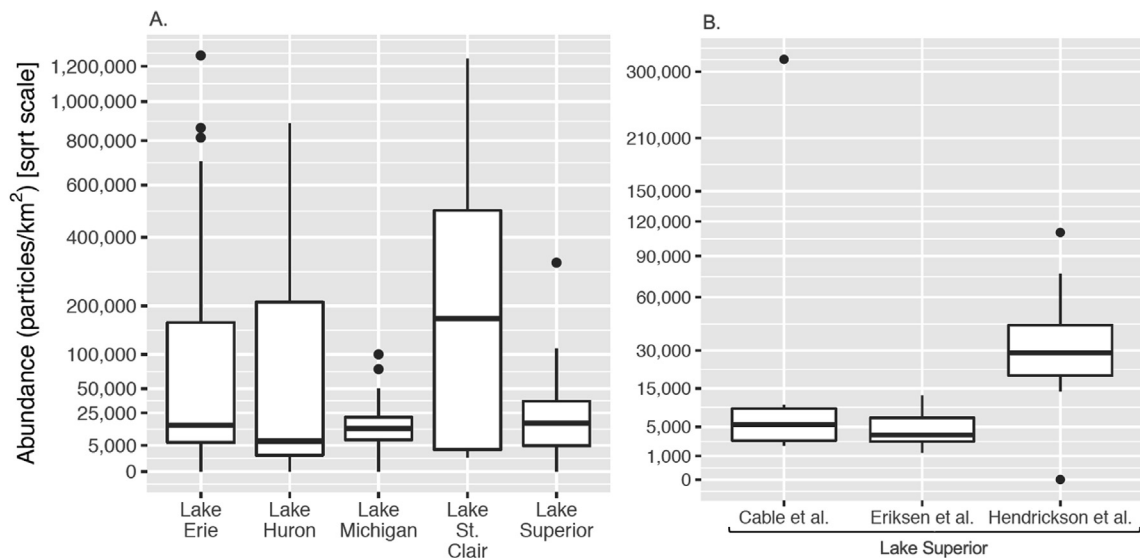


Fig. 3. Reported concentrations of microplastics within the surface waters of the Great Lakes (A). Three studies report microplastics concentrations within Lake Superior (B). Note change of scale on Y-axis between (A) and (B).

sheds. Ten studies characterized the sources, transport, distribution, and fate of plastics across the Great Lakes. Six reported contamination and effects of microplastics in local wildlife. Finally, nine studies (including three reviews) reported on a range of topics that contribute to informing the current state of knowledge on plastic pollution in the Great Lakes.

Concentrations of plastic pollution in the Great Lakes and their tributaries

Of the eleven studies that reported concentrations of plastic pollution in the Great Lakes, four reported concentrations in surface water (Cable et al., 2017; Eriksen et al., 2013; Hendrickson et al., 2018; Mason et al., 2016), three on shorelines (Corcoran et al., 2015; Zbyszewski et al., 2014; Zbyszewski and Corcoran, 2011), three in benthic sediment (Ballent et al., 2016; Dean et al., 2018; Corcoran et al., 2015) and three in the major Great Lakes tributaries (Baldwin et al., 2016, Cable et al., 2017, Castaneda et al., 2014).

Four studies reported microplastic concentrations in the surface waters of four of the Great Lakes: Lake Superior, Lake Huron, Lake Michigan, and Lake Erie. Here, we also include concentrations reported in Lake St. Clair. None of the studies in our systematic review reported surface water concentrations in Lake Ontario. Surface water concentrations ranged from 0 to 318,241 particles/km² in Lake Superior (Cable et al., 2017; Eriksen et al., 2013; Hendrickson et al., 2018), 0 to 885,599 particles/km² in Lake Huron (Cable et al., 2017; Eriksen et al., 2013), 0 to 100,016 particles/km² in Lake Michigan (Mason et al., 2016), 0 to 1,243,636 particles/km² in Lake St. Clair (Cable et al., 2017) and 0 to 1,264,293 particles/km² in Lake Erie (Cable et al., 2017; Eriksen et al., 2013) (Fig. 3). The average microplastic concentrations ranked, from highest to lowest, are Lake St. Clair (355,120 particles/km²), Lake Erie (161,702 particles/km²), Lake Huron (111,231 particles/km²), Lake Superior (35,327 particles/km²), and Lake Michigan (17,276 particles/km²) (Fig. 3A). To assess the variability across studies, we compared the microplastic concentrations reported in Lake Superior in three separate studies (Cable et al., 2017; Hendrickson et al., 2018; Eriksen et al., 2013; Fig. 3B). The three studies demonstrated a difference in average microplastic concentrations of ~ 52,000 particles/km². Cable et al. (2017) reports an average

microplastic concentration in Lake Superior of ~ 57,300 and collected 6 samples from 2 sites and counted microfibers in their samples. Similarly, Hendrickson et al. (2018), which reports an average concentration of ~ 55,700 particles/km², collected 15 samples from 12 sites and included microfibers in their final particle count, while Eriksen et al. (2013) reported an average concentration of ~ 5,400 particles/km², and collected only 5 samples from 5 sites and did not include microfibers in their final particle count. The difference between these three studies tells us that there is high variation among studies, likely based on sampling sites, sampling methods, and analytical methods.

Four studies reported plastic concentrations on the shorelines of Lake Erie, Lake St. Clair, Lake Huron, and Lake Ontario (Ballent et al., 2016; Corcoran et al., 2015; Zbyszewski et al., 2014; Zbyszewski and Corcoran, 2011). However, only two studies report concentrations using the same units (pieces/m²), and from those studies we extracted data to show the distribution of macroplastics across the shorelines of Lakes Huron, Erie and St. Clair (Zbyszewski and Corcoran, 2011; Zbyszewski et al., 2014; Fig. 4A). Concentrations across these three lakes range from 0 to 34 pieces/m². Lake Huron had both the most polluted shores as well as the most pristine shores, with concentrations ranging from 0 to 34 pieces/m²; this may be explained by Lake Huron having very remote regions in addition to larger population centers on its shorelines (Zbyszewski and Corcoran, 2011). Lake St. Clair and Lake Erie had plastic abundances ranging from 0.36 to 3.7 and 0.17 to 8.38 pieces/m², respectively (Zbyszewski et al., 2014). Corcoran et al., 2015 reports high abundances of expanded polystyrene and plastic pellets on the shorelines of Lake Ontario, however their total counts are reported in mass therefore they are not included in Fig. 4A. These three studies provide the only data published on the abundance of macroplastic from any environment of the Great Lakes. Finally, sediment cores from Lake Ontario shorelines have high concentrations, ranging from 20 to 470 particles/kg dry sediment (Ballent et al., 2016; See Fig. 4B).

To better understand the distribution and abundance of macroplastic pollution on the shorelines of the Great Lakes, we supplemented the primary literature from our systematic review with citizen science data from Ocean Conservancy's International Coastal Cleanup from 2016 to 2018 (Fig. 5). By isolating the cleanups that occurred in districts and counties bordering the Great

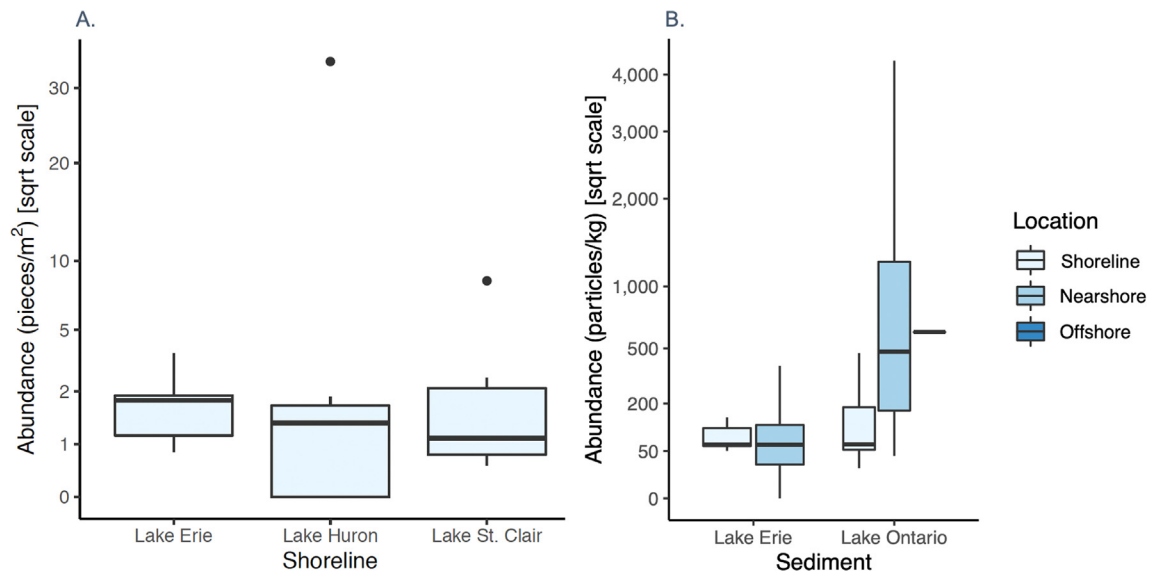


Fig. 4. Reported abundances of microplastics (<5mm industrial pellets) and macroplastics on the shorelines of two Great Lakes and Lake St. Clair (A). Reported concentrations of microplastics (particles per kilogram of dried sediment) found within various locations of sediment from Lake Erie and Lake Ontario (B). Data for Offshore sediment were collected only for Lake Ontario, and in only one sample from one study (yielding a flat box plot). Note change of scale and units of measurement on Y-axis between (A) and (B).

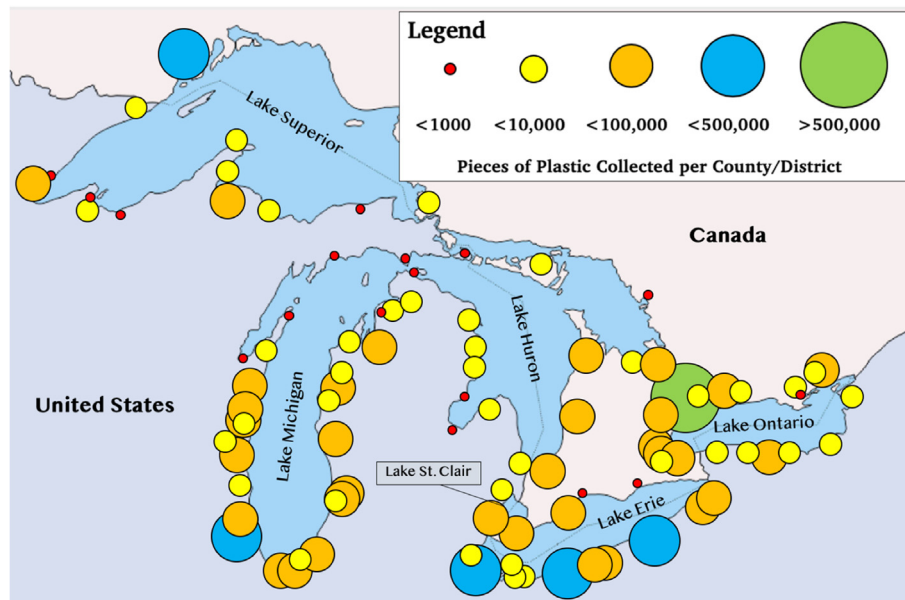


Fig. 5. Abundance of plastic litter collected through citizen science per district (in Canada) or per county (in the United States) which border the Great Lakes from International Coastal Cleanup data over a three-year period (from 2016 to 2018).

Lakes, we were able to determine the distribution and abundance of plastic pollution along the shorelines. Over the three-year period, 3,591,967 pieces of plastic were collected along the shorelines of all five of the Great Lakes. The great majority of items by count were single-use plastic items, including: 1,198,461 cigarette butts (33% of the total litter), 240,457 food wrappers (7%), 189,175 bottle caps (5%), 102,456 plastic bottles (3%), 103,303 plastic bags (3%), 97,995 straws/stirrers (3%), and 30,747 drink lids (0.9%). Only plastic litter was included in this data extraction and synthesis; see Table S5 for more information.

Three of the eleven studies from our literature search reported concentrations of microplastics in benthic sediment from two of the Great Lakes: Lake Erie (Dean et al., 2018) and Lake Ontario

(Ballent et al., 2016; Corcoran et al., 2015; Fig. 4B). Concentrations from these three studies ranged from 0 to 4,270 particles/kg of dry sediment. In Lake Erie sediment, the concentrations ranged from 0 to 391 particles/kg with a mean abundance of ~89 particles/kg. In Lake Ontario sediment, the concentrations ranged from 40 to 4,270 particles/kg with a mean abundance of ~941 particles/kg. However, Lake Ontario shoreline data in Fig. 4B is not included in these ranges or averages, as those samples are discussed in the shoreline section above. For Lake Erie, the shoreline samples are included because they are benthic shoreline samples (rather than beach cores as is the case for Lake Ontario shoreline samples). On average Lake Ontario samples had ten times more microplastic particles than those from Lake Erie. Two of the studies included microfibers

in their particle counts and sampled microplastic particles down to 63 μm (Ballent et al., 2016; Dean et al., 2018).

Five papers from the literature report abundances of plastic pollution in the surface waters or sediment of Great Lakes tributaries: the Detroit River (Cable et al., 2017) which flows out of Lake St. Clair to Lake Erie, the Niagara River (Cable et al., 2017) connecting Lake Erie to Lake Ontario, the St. Lawrence River (Castaneda et al., 2014), which flows out of Lake Ontario to the Atlantic Ocean, 29 small tributaries across all five of the Great Lakes (Baldwin et al., 2016), and a few smaller tributaries of Lake Ontario and Lake Erie (Ballent et al., 2016; Dean et al., 2018). In the surface water of the Niagara River and the Detroit River, a range of 0 to 1,993,808 particles/ km^2 was reported (Cable et al., 2017). In the surface water of 29 Great Lakes tributaries across the Great Lakes, researchers reported a range of microplastics from 0.05 to 32 particles/ m^2 (Baldwin et al., 2016). In the sediment of the St. Lawrence river, researchers reported a range of microplastics from 0 to 398,000 microbeads/ m^2 , with a mean of 13,759 microbeads/ m^2 (Castaneda et al., 2014). Although this study only quantified microbeads, they were found to be abundant across all sediment samples in the St. Lawrence River. Across all Lake Erie sediment samples, the highest concentrations were found in tributary sediment samples, ranging from 10 to 462 particles/kg (Dean et al., 2018). Lake Ontario tributary sediment samples ranged from 40 to 1740 particles/kg (Ballent et al., 2016). We removed an extreme outlier (27,830 particles/kg) from the Lake Ontario tributary samples at the recommendation of the authors due to the large algal component of the sample. This was because they measured samples based on dry weight, and algae is heavy when wet, but light when it dries. Therefore, the concentration of plastic was disproportionately high in this one outlier because the dry weight of the sample was so low. Overall, tributaries of the Great Lakes have high concentrations of microplastics in their surface waters and sediment.

Sources of and pathways for plastic pollution to the Great Lakes

Scientists estimate that ~ 10,000 tonnes of plastic waste enter the Great Lakes annually (Hoffman and Hittinger, 2017). The primary source of this plastic waste comes from large population centers, such as Chicago, Toronto, Cleveland, and Detroit (Cable et al., 2017; Hoffman and Hittinger, 2017). In our systematic review, we found ten papers that discuss known sources of plastic pollution to the Great Lakes. Although there are likely many sources (e.g., tire and road wear particles, microfibers from washing machines, litter) and pathways (e.g., wastewater, stormwater, agricultural runoff, industrial spillage), we only discuss the ones highlighted in papers found during our literature search.

Two papers from our systematic review investigate shipping and boating as sources of plastic pollution to the Great Lakes. In 1993, scientists used multibeam sonar detection to look at the pattern of anthropogenic debris on the bottom of Lake Ontario (Lewis et al., 2000). They also took grab samples and found a combination of anthropogenic particles including plastics, coal, oil, fly ash, and other chemicals. The researchers determined that the shipping industry was a source of historic pollution to the Great Lakes (Lewis et al., 2000). Five years later, Baasel-Tillis and Tucker-Carver (1998) surveyed boaters from the Great Lakes to better understand their contribution to plastic pollution; 90% of the boaters self-reported as never having dumped plastic waste (or other anthropogenic debris) into the lakes. This suggests that, while historical shipping routes have left traces of plastic contamination in the Great Lakes sediment, modern-day boating may not be a source of plastic pollution into the Great Lakes.

We found three papers reporting on beach visitation as a source of plastic litter on Great Lakes beaches. Plastic has been reported to

accumulate on Great Lakes beaches at rates similar to the accumulation on marine beaches (Vincent and Hoellein, 2017). The authors report their maximum density of anthropogenic litter, ~1 item/ m^2 , to be very close to the average of ~ 1.83 items/ m^2 found on marine beaches (Vincent and Hoellein, 2017). Given that the plastic found on Great Lakes beaches is primarily food and smoking related, increasing population sizes and beach visitations have been identified as a major source of beach pollution (Hoellein et al., 2015; Vincent et al., 2017; Vincent and Hoellein, 2017). Further research done on the beaches of Lake Michigan demonstrated lower pollution in the summer as a result of municipal beach cleaning throughout the summer, and an increase in plastic litter as cleaning was reduced/halted in the autumn and spring (Hoellein et al., 2015; Vincent et al., 2017; Vincent and Hoellein, 2017).

One paper from the literature investigated wastewater treatment plants (WWTP) as a source of plastic pollution by sampling downstream of WWTP effluent within the Great Lakes and their tributaries. Cable et al. (2017) demonstrated that WWTPs are a direct source of microplastics to the surface waters of the Great Lakes. By collecting samples downstream of a WWTP in Lake Erie and the Detroit River (a tributary of the Great Lakes), the authors demonstrated high contamination (a mean of nearly ~ 500,000 particles/ km^2) across all WWTP sites (Cable et al., 2017). The maximum particle densities of ~ 900,000 particles/ km^2 in Lake Erie downstream of a WWTP and ~ 2 million particles/ km^2 in the Detroit River downstream of a WWTP were some of the highest concentrations found by the researchers (Cable et al., 2017).

Finally, three papers we reviewed suggested that the surface waters of tributaries can transport plastic directly into the Great Lakes (Baldwin et al., 2016; Cable et al., 2017; Corcoran et al., 2015). Plastic pellets were observed floating down the tributaries towards Lake Ontario, and the pellets in the river were similar in colour to those collected on the shorelines of Lake Ontario. This suggests that Humber River and its smaller tributaries (e.g. Mimico Creek, Etobicoke Creek), which flow through highly industrialized areas with manufacturers of plastic items located in their watersheds, transport microplastics directly into Lake Ontario (Corcoran et al., 2015). Despite their negative buoyancy, microfibers were found to be the dominant plastic shape in samples from the 29 tributaries. Baldwin et al. (2016) suggest the particles are able to remain in the surface water of tributaries due to the rapid movement of the river, suggesting that tributaries act as an important means of transport for microfiber pollution into the Great Lakes (Baldwin et al., 2016). High abundances of plastics in the surface waters of the Niagara and Detroit Rivers and the river plumes inside Lake Erie and Lake St. Clair, suggests that these tributaries may also be sources of plastic pollution into the Great Lakes (Cable et al., 2017).

The fate of plastic pollution in the Great Lakes

Three papers from the literature discussed the fate of plastic pollution within the Great Lakes. In the Great Lakes, transport models and surface-water sampling have shown that the highest particle densities are found near the largest populations, and thus the fate of microplastics in the Great Lakes is different than in the marine environment (Cable et al., 2017; Hoffman and Hittinger, 2017). The highest abundances of plastic pollution are also found near river plumes and close to the shorelines. This finding was surprising to many scientists who believed that high abundances of plastic would concentrate in the gyres of the large basins in the Great Lakes, much like in ocean gyres (Cable et al., 2017; Hoffman and Hittinger, 2017). In Lake Ontario, plastic particles were found in offshore sediment down to a depth of 8 cm, indicating that plastic has been accumulating in the benthic environment for almost 40 years (Corcoran, 2015). These small broken-up

particles contaminate resources, including drinking water, which has been demonstrated in all five of the Great Lakes (Kosuth et al., 2018).

Contamination in Great Lakes wildlife

We found six studies that reported the contamination of plastic pollution in wildlife from the Great Lakes region. Ten species of Great Lakes fishes have been reported to be contaminated with plastic debris. The most contaminated of these was the invasive bottom-feeder, the round goby (*Neogobius melanostomus*), containing an average of 19 particles/individual (McNeish et al., 2018). From the 11 fish species analyzed, there was a range in the number of particles found in various fish stomachs, from 0 particles found in gizzard shad (*Dorosoma cepedianum*) to ~23 particles found in the most contaminated round goby (*Neogobius melanostomus*) (McNeish et al., 2018). On average, the researchers found a mean of ~12 particles/individual and a median of ~11 particles/individual across the 11 fish species (McNeish et al., 2018). Multiple species of native birds have been found to ingest plastic, such as the mallard duck (*Anas platyrhynchos*) and the yellow-billed loons (*Gavia adamsii*) (Holland et al., 2016). The authors report a range of 0 to 8 microplastics/individual across these freshwater bird species (Holland et al., 2016). Double crested cormorant (*Phalacrocorax auratus*) chicks from Lake Ontario were found to have an average of ~6 plastic particles/individual, which is low considering cormorants in the Great Lakes region eat highly contaminated round goby (Brookson et al., 2019). Interestingly, microfibers are the type of microplastic most likely to be found in the stomachs of Great Lakes wildlife when compared to other particle shapes (McNeish et al., 2018; Brookson et al., 2019). This pattern was also noted by researchers who were unable to find contamination of microbeads within the *Dreissena* mussels of the St. Lawrence river; these authors hypothesized that the *Dreissena* mussels were unable to ingest particles >35 µm (Schessl et al., 2019).

In addition, two of the six studies found shifts in biofilms colonizing plastic substrates compared with other material substrates (Hoellein et al., 2014; McCormick et al., 2014). Hoellein et al. (2014) demonstrated a change in metabolism of biofilms on plastic litter compared to other anthropogenic litter in the Chicago River. The gross primary productivity of biofilms was significantly higher on the surfaces of plastic litter compared to the surfaces of aluminum and glass litter. The authors also found community respiration to be significantly lower for biofilms on plastic litter compared to tile substrate (Hoellein et al., 2014). McCormick et al. (2014) found distinct bacterial assemblages to form on microplastics in the Chicago River. The bacterial assemblages colonizing microplastics were found to be less diverse with significantly different taxonomic composition compared to bacterial assemblages from the water column and suspended organic matter. Several pathogens and 'plastic decomposing organisms' were more abundant on microplastic surfaces (McCormick et al., 2014).

Addressing plastic pollution in the Great Lakes

Nine papers from our literature search outlined issues and suggested strategies to address plastic pollution in the Great Lakes. Currently, there are more policy and management initiatives in marine waters compared to freshwater (Eerkes-Medrano et al., 2015). Nevertheless, the Great Lakes have been and continue to be important waterbodies for monitoring microplastics (Anderson et al., 2016). To properly evaluate the problem, we must be able to understand the trends, abundances, and sources of plastic across the lakes using standardized methods (Twiss, 2016). This information can then be used to inform policy changes towards mitigating the plastic pollution issue. In addition to more research,

we need strong directives from all levels of governance, including the federal level, to accomplish large-scale changes (Dauvergne, 2018). The Great Lakes Water Quality Agreement (GLWQA), prohibits the dumping of plastic waste from ships. However, we must address the input of plastic from land-based sources in order to stop plastic pollution from reaching the Great Lakes (Driedger et al., 2015). Designating microplastics as chemicals of mutual concern under Annex III of the GLWQA could ensure standardized quantification and mitigation of microplastics, as a suite of contaminants, from both sides of the Great Lakes international border (Great Lakes Water Quality Agreement, 2012). In 2019, the Canadian federal government announced they would "ban harmful single-use plastics and hold companies responsible for plastic waste" (Prime Minister Justin Trudeau, 2019). Public surveys in the Great Lakes region have shown support for these initiatives, suggesting that 75% of respondents are in favour of plastic bans and/or fees (Bartolotta and Hardy, 2018). Additionally, an expert focus-group concluded that "developing educational outreach on public signage, designating more designated smoking areas with proper disposal methods and reward programs such as tax increases or deposit programs" would help overcome normative behaviours of littering plastic cigar tips and thus reduce smoking-related plastic littering in the Great Lakes region (Hardy and Bartolotta, 2018). In the Great Lakes region, new technology to track waste through aquatic environments may help to determine the fate and pathway of plastic litter throughout the lakes (Sigler, 2014). It remains clear that interdisciplinary action will be required to solve the complex issue of plastic pollution in the Great Lakes (Belontz et al., 2018).

Effects of plastic pollution on freshwater biota

We found 55 papers investigating the effects of plastic pollution in freshwater biota published between November 26th, 2017 and June 7th, 2019, adding to the 20 papers found by Bucci et al. (2020), creating a total of 75 papers for data extraction (Fig. 2). From these studies, we extracted 390 instances where an effect was tested. Each instance included each plastic type, organism and/or effect tested, meaning multiple instances come from each manuscript. Still, testing for an effect using different concentrations of the same size/shape/polymer and/or organism was counted as a single instance. The vast majority of these tested effects used microplastics (98.9%) while only four tested with macroplastics (1.1%). Of the 390 tested effects, 234 (60%) were detected and 156 (40%) were not. Of the 234 detected effects, 79 (32%) were at suborganismal levels and 165 (68%) were at ecologically-relevant levels (organism, population, assemblage, ecosystem). Of the 156 non-detected effects, 34 (16%) were at suborganismal levels and 182 (84%) were at ecologically-relevant levels; see Fig. 6 for a visual representation of these trends, organized by biological level of organization and size of debris.

Of the 75 studies investigating the effects of plastic pollution in freshwater biota, 23 reported doses in particles per unit volume, and thus were used to explore underlying patterns in whether or not an effect was detected (Fig. 7). From these studies, we extracted 388 datapoints. Here, extracted data includes all combinations of endpoints and doses used in an experiment (i.e. if one study investigated effects for 2 endpoints and exposed organisms with 4 doses, that study would have 8 datapoints). Of the 388 datapoints extracted, 170 (44%) were detected effects and 218 (56%) were non-detected effects (Fig. 7a). An effect was detected in 58% of cases testing with fibers (14 of 24 total effects tested with fibers), 24% of cases using fragments (18 of 75), 45% of cases using spheres (110 of 246), and 65% of cases in the 'other' category (28 of 43), which includes microplastics described as 'disks' (Hossain et al., 2019) and 'sheets' (Eckert, 2018) (Fig. 7b). For polymer type,

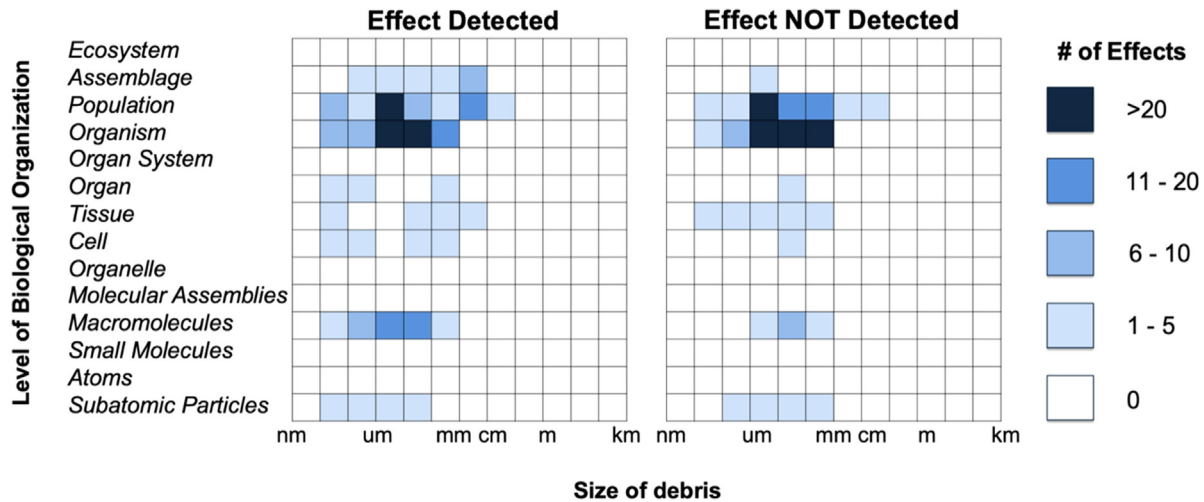


Fig. 6. Effects of plastic detected (left) and not detected (right) in freshwater biota. Rows represent different levels of biological organization and columns represent sizes of debris from smallest (left) to largest (right). Shading in the individual cells of the matrix represent the number of effects studied in peer-reviewed literature identified during our literature search. All effects described at multiple size ranges and levels of biological organization are represented such that there are more effects than there are papers.

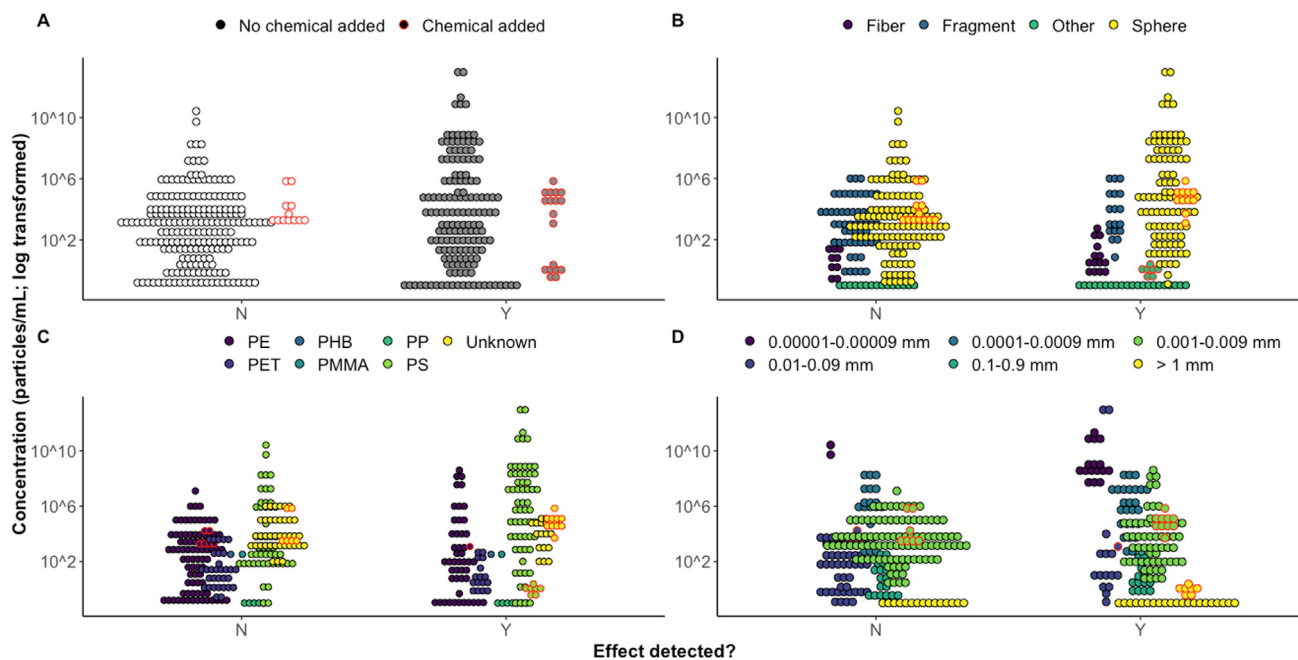


Fig. 7. Effects detected and not detected (Y = yes, N = no) from 20 studies that investigated the effects of microplastics on freshwater biota. Underlying patterns in whether or not an effect was detected were analyzed based on the concentration of plastics used in particles/mL (on the x-axis) and by plastic shape (B), polymer type (C), and particle size (D). Polymer types include polyethylene (PE), polyhydroxybutyrate (PHB), polypropylene (PP), polyethylene terephthalate (PET), Polymethyl methacrylate (PMMA), and polystyrene (PS). Effects tested using microplastics with added chemicals are outlined in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

an effect was detected in 36% of cases testing with PE (48 of 134), 34% of cases testing with PET (16 of 47), 50% of cases testing with PHB (1 of 2), 50% of cases testing with PMMA (1 of 2), 58% of cases testing with PP (7 of 12), and 58% of cases testing with PS (69 of 118) (Fig. 7c). Finally, for particle size, an effect was detected in 65% of cases testing with particles >1 mm (28 of 43), 42% of cases testing with particles between 0.1 and 0.9 mm (14 of 33), 22% of cases testing with particles between 0.01 and 0.09 mm (16 of 71), 39% of cases testing with particles between 0.001 and 0.009 mm (70 of 177), 56% of cases testing with particles between 0.0001 and 0.0009 mm (26 of 46), and 89% of cases testing with

0.00001 and 0.00009 mm (16 of 18) (Fig. 7d). Interestingly, when we isolate only the studies that tested with spheres, the percent of effects detected increases consistently from 0% detected in the largest size class to 88% detected in the smallest size class (Fig. 8). Finally, it is worth noting that of the 388 tested effects, 92% were conducted without additional chemicals (358 of 388), while 8% tested with microplastics and an added chemical (B[a]P, florfenicol, PCB, and WWTP effluent; 30 of 358). An effect was detected in 42% of cases that tested with 'virgin' microplastics (152 of 358), and 60% of cases that tested with an added chemical (18 of 30).

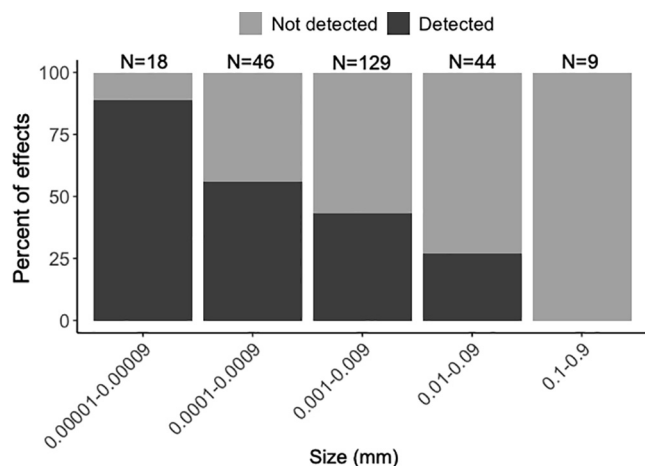


Fig. 8. Percent of effects detected (y-axis) in experiments dosing with different size classes of spheres (x-axis).

Discussion

The first review on plastic pollution in the Great Lakes was written in 2015 (Driedger et al., 2015). Since that time, there has been an increase in research published about plastic pollution in the Great Lakes (Fig. 2). Overall, the topic of plastic pollution is becoming increasingly acknowledged in interdisciplinary studies assessing the sources, contamination, fate, and effects of plastic debris in the Great Lakes. Still research gaps remain, and further research is necessary to better understand plastic pollution in the Great Lakes and to inform policy.

Surface water

The four published reports on plastics in the surface water of the Great Lakes showed large variation in counts across the different lakes and studies. These studies report surface water contamination in four out of five Great Lakes and Lake St. Clair. Since this review was completed, two studies reporting the concentration of microplastic pollution in surface waters of Lake Ontario have been published (Grbić et al., 2020; Mason et al., 2020).

To better understand the variability between studies, we assessed whether there were any major differences in sampling protocols and experimental design. All studies sampled surface water using manta trawls and used similar laboratory methods for sample processing. One difference among studies is that one did not include microfibers in its abundances (Eriksen et al., 2013). We now know that microfibers are the most abundant type of anthropogenic debris, making up >85% of microplastic counts in surface water samples around the globe (Carr, 2017; Baldwin et al., 2016; Hendrickson et al., 2018). However, the average diameter of a microfiber (28 μm) is much smaller than the mesh size of a typical manta net (333 μm), so manta trawls, such as those used in the Great Lakes studies, do not provide an accurate count of microfibers present in surface waters. This suggests that the concentration of microfibers (and therefore microplastics as a whole) is being seriously underestimated in the Great Lakes. Nevertheless, despite our initial hypothesis, removing the microfiber count from the total particle count in the Great Lakes surface water samples did not noticeably change the trend between studies (See ESM Fig. S1). The average microplastic concentrations, both with and without microfibers, are, from highest to lowest: Lake St. Clair, Lake Erie, Lake Huron, Lake Superior, and Lake Michigan. This may be because microfibers were already underestimated in these studies as a result of using manta trawls to collect the samples, or because of differences in counting and quality assurance

procedures employed by the different studies, among other potential reasons (Fig. 3B). Additionally, microfibers are negatively buoyant, meaning the microfiber particles sink once deposited into the lakes. Therefore, we expect to see a greater abundance of microfibers accumulating in the sediment of the Great Lakes compared to their surface waters. Our findings follow this trend; on average ~35% of sediment counts were made up of microfibers and only ~6% of surface water counts were made up of microfibers (Figs. S1 and S2). For further discussion of the contamination and fate of microfibers in the Great Lakes specifically, see the discussion on fibers in ESM Appendix S1.

In addition to microfibers, other factors that may help explain the discrepancies between studies within the same lake (Fig. 3B) include the number of samples taken, the sites they were taken from, the size of particles counted, and the timing of the study (e.g. season, time since rain event). For example, Eriksen et al. (2013) attributed the largest sample found in their study, ~466,000 particles/ km^2 , to the convergence of currents within the lake and the proximity of the sampling location to large coal burning plants which release coal and fly ash. Without proper chemical identification of microdebris (i.e. FTIR or Raman spectroscopy) these non-plastic particles could have been mistaken for plastic, inflating the reported concentrations. Nevertheless, while this high concentration seemed to be an outlier in the Eriksen et al. (2013) study, in our review as a whole, the outlier is dwarfed by concentrations found by Cable et al. (2017) and is now found in the middle range of abundances found in Lake Erie. Additionally, Cable et al. (2017) took triplicate samples of surface water in order to assess within-station variability. Their results demonstrate that there is low-accuracy in microplastic counts for single-trawl samples, as weather and wind can cause the precision to vary up to 3-fold amongst repeated trawls at the same location. Because of the variation in reported concentrations between studies, others have suggested that a standardized set of methods is needed to better quantify microplastic contamination across the Great Lakes (Twiss, 2016; Dris et al., 2015).

Standardized methods will enable better global comparisons of microplastic concentrations. Existing data indicate that the mean surface water concentration across all the Great Lakes (including Lake St. Clair) is approximately ~100,000 particles/ km^2 (Cable et al., 2017; Eriksen et al., 2013; Hendrickson et al., 2018; Mason et al., 2016). This average is five times greater than the mean microplastic abundance found in a remote mountain lake in Mongolia (~20,000 particles/ km^2 ; Free et al., 2014), and slightly lower than the mean particle density found in Lake Winnipeg (~120,000 particles/ km^2 ; Anderson et al., 2017). A better comparison can be made to a set of Swiss lakes (made up of more and less urbanized lakes) with an overall mean amongst lakes of ~90,000 particles/ km^2 ; (Faure et al., 2015). However, Mason et al. (2020) reports an average concentration of 230,000 particles/ km^2 in Lake Ontario suggesting that the addition of Lake Ontario data would increase the overall average.

The surface waters of the Great Lakes have much higher plastic abundances on average than areas of the marine environment including the North Atlantic (~7,758 particles/ km^2 ; Law et al., 2010) and the South Pacific (26,898 particles/ km^2 ; Eriksen et al., 2013) oceans; but have lower average plastic abundances than the North Pacific central gyre (334,271 particles/ km^2 ; Moore et al., 2001). However, because of the high variability in plastic counts from marine and freshwater environments, simply comparing average abundances can overlook important information about the actual concentrations being reported. For example, the maximum microplastic counts from the Great Lakes (at ~1.2 million particles/ km^2) surpass even the highest concentration of microplastics from the marine environment which are found in the North Pacific Gyre (969,777 particles/ km^2 ; Moore et al.,

2001). Overall, plastic is ubiquitous across the Great Lakes and comparable by count to both marine and other freshwater environments.

Shorelines

There was less variation in plastic counts across the shoreline environments of Lake Huron, Lake Erie, and Lake St. Clair. However, the maximum concentrations from Lake Huron (34 pieces/m²) and Lake St. Clair (8 pieces/m²) demonstrate the strong influence of industry on shoreline litter (Fig. 4A). For example, the plastic collected from Sarnia beach on Lake Huron was made up of >90% industry pellets (Zbyszewski et al., 2014), which can be released from industrial plants as waste or through accidental spills in transit. In fact, the samples from beaches on Lake Huron were all relatively high, surpassing average plastic counts on the shorelines of an Italian lake (Imhof et al., 2018) and rivaling industrial pellet counts found on marine beaches around the globe (Zbyszewski and Corcoran, 2011).

There is a lack of primary literature quantifying macroplastics across the Great Lakes. Three studies reported concentrations of macroplastics on the shorelines of Lake Huron, Lake Erie, Lake St. Clair and Lake Ontario (Corcoran et al., 2015; Zbyszewski et al., 2014; Zbyszewski and Corcoran, 2011). Corcoran et al. (2015) report overall contamination by weight. This was because expanded polystyrene littered their sampling sites at Humber Bay and were so fragile that they could only be included as mass. However, even when excluding the expanded polystyrene on the shoreline, they found the shorelines of Lake Ontario to have the second highest plastic abundance (by count) in the Great Lakes, rivaled only by Sarnia Beach (Corcoran et al., 2015). There are no studies that report macroplastic litter across Lake Superior or Lake Michigan. Nevertheless, by using data supplied by Ocean Conservancy, we were able to construct a map that helps us better understand the distribution of macroplastic on shorelines around the Great Lakes (Fig. 5). Trends in macroplastic abundance from citizen-science data show that there are higher concentrations of pollution found near city centers. This beach cleanup data, although valuable, must be interpreted with caution as it does not have the same quality control as data collected with more rigorous methods. This trend is likely also driven by larger populations leading to more cleanups (i.e. more plastic litter accounted for).

Sediment

Lake Ontario sediment samples had significantly higher microplastics on average than those of Lake Erie (Dean et al., 2018; Fig. 4B). The high concentrations found in Lake Ontario sediment is likely a result of high population density and industrial activity in the Greater Toronto Region (Ballent et al., 2016). The lower concentrations in Lake Erie may be a result of both samples being taken from the northern shoreline, which might have lower contamination due to wind and water patterns carrying pollutants to the southern shoreline, as well as lower population density on the Canadian side of the Lake (Dean et al., 2018). In order to better assess patterns of deposition and accumulation of plastic pollution in the Great Lakes, more studies are needed that quantify microplastics in the sediment of the southern basin of Lake Erie, as well as the other Great Lakes.

Sources and transport

Understanding the sources of plastic pollution to the Great Lakes can directly inform mitigation strategies. There are many different potential sources of plastics to the Great Lakes, some of which were discussed in the studies found during our literature

search. Still, many potential sources were not included. Sources of plastic pollution to the Great Lakes include tire- and road- wear particles, microfibers from textiles, fishing gear, microbeads from personal care products, littered single-use plastic items, plasticulture used in agriculture, and industrial pellets. These plastics can enter the lakes via several different pathways, including stormwater runoff, wastewater effluent, agricultural runoff, fishing practices, and industrial spillage. Papers found in our review provided evidence relevant to only some of these sources and pathways, others are discussed more thoroughly in Grbić et al. (2020).

Tributaries have been identified as a major pathway for microplastic particles into the Great Lakes (Cable et al., 2017; Baldwin et al., 2016). One study showed that the Humber River and its tributaries are a transportation route for microplastic pellets into Lake Ontario (Corcoran et al., 2015). Heavier, negatively buoyant particles, such as polyester microfibers, have been shown to be transported by the rapid motion of tributaries into the Great Lakes (Baldwin et al., 2016). Likewise, the Niagara River and the Detroit River have been identified as pathways for high concentrations of microplastics to travel directly into the Great Lakes (Cable et al., 2017). Tributaries are clearly an important source of microplastics into the Great Lakes. As the primary receivers of much of our urban and industrial plastic pollution, tributaries are an important source and pathway to understand how plastic ends up in our lakes and oceans (Alimi et al., 2018).

Several studies in our review showed that proximity to industry has an impact on the abundance of plastics in samples of surface water (Fig. 3), shorelines (Fig. 4A), and sediment (Fig. 4B). For example, Sarnia Beach (located near Chemical Valley, a large industrial area) on Lake Huron was one of the most contaminated sites in our review, and the sample collected there was composed of 94% industrial pellets (Zbyszewski et al., 2014). In addition, both Lake Erie and Lake Ontario have long-standing urbanized and industrial centers on their shorelines. Accordingly, high concentrations of microplastics are found in the sediment of both lakes (Fig. 4B). Following the trends predicted by the surface water and beach studies, both Lake Erie and Lake Ontario had the highest sediment abundances found close to their largest population centers, areas with heavy shipping traffic, and nearshore plastics manufacturing industries (Ballent et al., 2016; Dean et al., 2018).

Wastewater treatment plants (WWTPs) are another major route for microplastics entering freshwater environments (Alimi et al., 2018). Within the Great Lakes system, microfibers have been shown to pollute riverine environments downstream of WWTPs (Raju et al., 2018). One study showed a tenfold increase in the abundance of microfibers downstream from a WWTP in the Chicago River (McCormick et al., 2014). The same trend was demonstrated in the Ottawa River where almost three times as many microfibers were present downstream of a WWTP (Vermaire et al., 2017). In the study by Cable et al. (2017) the samples taken from WWTP effluent in the Detroit River and Lake Erie were some of the most contaminated samples across the Great Lakes, including the maximum of ~ 2 million particles/km² and an average of ~ 500,000 particles/km² (Cable et al., 2017). Research suggests that advanced, final-stage WWTP facilities, which have additional biological and chemical processing, are able to greatly reduce the output of microplastics (Ziajahromi et al., 2016). Unfortunately, even small emissions of microplastics from one WWTP could become a major source of pollution given the quantity of WWTP effluent released into the Great Lakes on an annual basis (Ziajahromi et al., 2016).

Effects of plastic pollution on freshwater biota

Plastics have been dispersing and accumulating in the Great Lakes for many decades and have been found to contaminate a

variety of organisms that live in the Great Lakes region. However, of the thousands of species that inhabit the Great Lakes, only 15 have been investigated for plastic contamination, and only two studies have tested for effects in Great Lakes wildlife. Due to the ubiquity of microplastics in the region, Great Lakes wildlife is likely just as contaminated as marine species. As such, more studies are required to better understand the patterns of wildlife contamination and potential effects in the Great Lakes ecosystem. Due to the lack of specific information regarding effects to Great Lakes species, in our systematic review, we assessed the weight of evidence regarding the effects of plastic pollution on freshwater biota in general to better understand effects in the Great Lakes.

Out of the 75 studies used in our systematic review, the majority were conducted in the laboratory (99%) versus in the field (1%), a trend that holds true when considering all freshwater, marine, and terrestrial effects studies (Bucci et al., 2020). Because ecological interactions are complex, field experiments will be necessary to gain a more realistic understanding of the ecological threats associated with plastic pollution. Moreover, laboratory experiments must also be conducted with environmentally relevant doses, types, shapes, and sizes of microplastics (Bucci et al., 2020; Rochman et al., 2019). Concentrations of microplastics used in laboratory studies are often many orders of magnitude higher than those observed in the environment (Bucci et al., 2020). Additionally, most studies found in our review (>98%) investigated the effects of microplastics rather than macroplastics. Based on our analysis of citizen science data, macroplastics are abundant on Great Lakes shorelines, indicating a need for more research on the effects of macroplastics on freshwater organisms.

Two thirds (60%) of the studies detected effects from plastics on freshwater biota. Effects of microplastics range from mechanical stress, to changes in reproduction, behaviour, growth, and development. Effects also span across nearly all levels of biological organization, including the ecologically relevant levels of organism, population, community, and ecosystem. For example, one study found microfibers can cause a population-level effect in one of the smaller organisms of freshwater food chains; the waterflea *C. Dubia*. *C. Dubia* suffered reduced reproductive output and a damaged carapace when exposed to microfibers (Ziajahromi et al., 2017). Another study, the only study that tested effects with macroplastics, exposed organisms to 28x48mm plastic sheets and observed changes in the community structure of biofilms that formed on certain types of plastic substrate (Vosshage et al., 2018). This study also demonstrated organismal effects on snails (*R. balthica*) which fed on biofilms that formed on plastic substrates; growth rates were reduced in snails feeding on all biofilms growing on plastic substrates compared to the control. Out of the 390 tested effects, many (40%) were not detected.

Based on our analysis of 20 studies, the likelihood of an effect being detected is affected by the shape, size, and type of microplastic used in the experiment. In general, an effect was more likely to be detected when using fibers (compared to fragments or spheres), either large or nano-sized particles (>1mm or < 0.0009 mm), and PP and PS (compared to PE and PET; not enough data on PHB and PMMA). Although fibers caused an effect in 58% of cases, it is important to note that all datapoints are from the same study. Spheres and fragments caused an effect in 45% and 24% of instances, respectively (data from 4 and 19 studies). Other studies have also shown that fibers and fragments tend to be more harmful than spheres (e.g. Ziajahromi et al., 2017). In our study, however, we found that spheres caused an effect in more than half of instances, and in fact were more likely to cause an effect than fragments.

While particle shape may contribute to the harmfulness of the plastic particle, the size of the particle is likely to be even more important. Here, we found that the smaller the particle is, the more

likely it is that an effect will be detected. This trend was especially apparent for spheres, the particle shape for which we had the most data. The smallest particles (0.00001–0.00009 mm) caused an effect in 88% of instances, while larger spherical particles were much less likely to cause an effect (Fig. 8). In fact, in the most commonly tested size class (0.001–0.009 mm) only 43% of effects are detected, and in the next larger size class (0.01–0.09), only 27% of effects are detected. Size-dependent effects have also been shown empirically, with the number and severity of effects increasing for smaller particles (e.g. Lu et al., 2016, Jeong et al., 2016, Lee et al., 2013). This is likely driven by smaller micro- and nano-sized plastics translocating through the digestive lining (Messinetti et al., 2019).

For larger plastics, the uptick in number of effects detected in the largest size class, >1mm, is due to two studies that investigated community-level responses to irregularly shaped plastics. Dosing with PS or PP microplastics was also more likely to cause an effect. It is likely that PS is more harmful because of the monomers that make up its chemical structure, which are currently considered carcinogenic and mutagenic and are suspected endocrine disruptors (Lithner et al., 2011). Because PP is not considered an inherently hazardous polymer type (Lithner et al., 2011), it is not clear why the likelihood of detecting an effect with PP is as high as it is. These datapoints originate from the same study, which investigated effects to a bacterial community. Thus, it is possible that the high likelihood of detecting an effect with PP is actually an effect of experimental design and the endpoints tested, rather than the type of plastic used. Finally, exposure to microplastics with sorbed environmental contaminants was more likely to cause an effect. Sorbed chemicals have been shown to enhance the detection of effects in empirical studies (e.g. Rainieri et al., 2018, Gandara e Silva et al., 2016, Rochman et al., 2013), suggesting that exposure to the chemical cocktail associated with the plastic is also important.

Directly testing the effects of plastic pollution in freshwater ecosystems is necessary because researchers have suggested that micro- and macro- plastic pollution may alter the abiotic characteristics of the environment differently relative to marine environments, due to the difference in size. For example, plastic can accumulate in benthic habitats, block light penetration in the water column, or change sediment characteristics (Eerkes-Medrano et al., 2015). These issues may be exaggerated in the Great Lakes where surface water samples can surpass the contamination found in oceanic gyres. Furthermore, the fate of plastic pollution in the Great Lakes differs from marine environments, due to differences in scale, water circulation, less dilution, differences in salinity, and the ratio of surface water to shorelines. Instead of accumulating in far-away oceanic gyres, plastic in the Great Lakes is expected to accumulate in sediment and shorelines, where it is more accessible to the human population and terrestrial wildlife (Hoffman and Hittinger, 2017). As such, more research is needed that addresses the effects of plastic pollution in freshwater environments, including in the Great Lakes.

Research gaps and needs

Since the first review on plastic pollution in the Great Lakes (Driedger et al., 2015), almost a threefold increase in published research has ensued (Fig. 2). The 2015 review highlighted the urgent need for further research, given the enormous gaps in knowledge that existed in this emerging field. In these last four years, many of the authors' questions regarding plastic pollution in the Great Lakes have been answered. However, there are still gaps in the knowledge about contamination, sources, transport and effects. In this section, we have outlined the most urgent research needs based on the current state of knowledge, informed by our systematic review.

Table 1

Summary of potential policy strategies to mitigate plastic pollution in the Great Lakes region.

Waste reduction	<ul style="list-style-type: none"> • Reduce production of single-use plastics (e.g. cigarette butts, food wrappers, bottle caps, plastic bottles, plastic bags, straws, stirrers, drink lids). • Provide incentives to recycle (e.g., an extended producer responsibility scheme).
Waste management	<ul style="list-style-type: none"> • Harmonize waste management systems across municipalities. • Adopt initiatives that improve recycling rates, (e.g. Gold box program). • Provide incentives to increase collection and recycling, (e.g., container deposit scheme). • Create standards for using more post-consumer recycled materials. • Require filters on washing machines. • Build rain gardens on storm drains or other storm drain technologies. • Set limits for the amounts of plastic pollution in sewers.
Clean-up	<ul style="list-style-type: none"> • Employ innovative trash capture technologies in harbors or at river mouths (e.g. 'Seabins' and 'Trash Wheel') • Support community clean-ups led by local leaders. • Fund government clean-ups using existing programs (e.g. Superfund in the USA).
Education & outreach	<ul style="list-style-type: none"> • Educate to increase waste literacy and behaviours that produce less waste. • Develop a Formal Education Curriculum that focuses on reduction and mitigation.

To accurately quantify contamination of microplastics in the Great Lakes, we need to standardize, or at least harmonize, methods of sampling, counting, and processing micro- and macro- plastic samples. Once methods are agreed upon, we need to systematically sample the surface waters, sediment, and shorelines of all five Great Lakes. The harmonized methods should include microplastic particles of smaller size ranges to include all shapes and types of microplastic debris, including fibers and tiny fragments and spheres that are likely more harmful to wildlife than microplastics >100 µm. These methods should also include defined strategies for the minimum number of particles to chemically identify, to assure that the particles being counted are actually plastic.

In addition to standardizing the methods used to sample for plastic pollution, extensive sampling of the Great Lakes region is needed to better understand the sources and fate of macro- and micro- plastic pollution. As of this review, studies have identified large population centers (Cable et al., 2017; Hoffman and Hittinger, 2017), industrial areas (Zbyszewski and Corcoran, 2011), and wastewater treatment plants (Cable et al., 2017; McCormick et al., 2014) as sources of plastic pollution to the Great Lakes. Additionally, two studies have suggested that tributaries flowing through urban areas may be a pathway for microplastics into the Great Lakes (especially for heavier particles such as fibers (Baldwin et al., 2016; Cable et al., 2017)). Further work is needed to assess stormwater and agricultural runoff as pathways. With regards to fate, more work is needed to quantify contamination of the Great Lakes food webs, which will help with future risk assessments. In addition, further research on the contamination of extracted drinking water is warranted to help us begin to understand exposure to humans.

More research into the effects of plastic pollution on Great Lakes biota is essential to understanding the ecological consequences of plastic pollution in the lakes. At present, there are 75 studies that investigate effects of plastic pollution on freshwater biota, and only two on Great Lakes wildlife specifically. More research into the effects of both micro- and macro- plastics on freshwater biota across all levels of biological organization is needed. More strategic experiments are required to understand how plastic shape, type, and size affect organisms in freshwater ecosystems. Furthermore, it is crucial that future experiments take into consideration the environmental relevancy and context of the contaminant; because plastics are diverse contaminants, with many sources, fates, and effects, scientists should adopt testing procedures that investigate the most common plastics and how they naturally behave in the environment. Future experiments should be conducted with types, shapes, sizes, and concentrations of microplastics that are actually found in nature. By building on the methods developed in the marine literature, we must build a

larger effects literature for freshwater biota, and more specifically biota from the Great Lakes, to understand the distinct impacts of plastic pollution on freshwater biodiversity (Rochman, 2018).

Science to inform solutions

Our current understanding of the sources, contamination, and impacts of plastic pollution in the Great Lakes can begin to inform policy. Using adaptive management strategies, we can begin to develop and implement solutions informed by the current state of knowledge while further research is being carried out to increase our understanding. Plastic pollution is complex and there is no silver bullet solution. Instead, implementation of many solutions along the supply chain from production to consumption are needed. Solutions should include waste reduction, improved waste management strategies, clean-up and education/outreach to inform behavioural change. Examples of potential policy strategies that fall under each of these four categories are summarized in Table 1.

In 1972 the federal governments of Canada and the United States signed the Great Lakes Water Quality Agreement to save a system of lakes that were deemed invaluable. The bilateral agreement was supposed to protect these bodies of water from pollution and keep them healthy for future generations. The Parties should consider designating the emerging contaminant suite of microplastics as a chemical suite of mutual concern under Annex III of the Agreement to ensure proper regulation, quantification, and understanding of this persistent pollutant in the Great Lakes. Today, we understand that the Great Lakes are once again threatened, and we must act now to combat the ubiquitous problem of plastic pollution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by Environment and Climate Change Canada. A. Earn was supported by a Center for Global Change Science fellowship and a Natural Sciences and Engineering Council Undergraduate Student Research Award. The authors wish to thank Ocean Conservancy for providing citizen-science data about the Great Lakes Region from the International Coastal Cleanup database.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jglr.2020.11.001>.

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