Canadian Science Publishing

REVIEW

Microplastics in lakes and rivers: an issue of emerging significance to limnology

Genevieve D'Avignon, Irene Gregory-Eaves, and Anthony Ricciardi

Abstract: Microplastics, i.e., plastic particles in the size range of planktonic organisms, have been found in the water columns and sediments of lakes and rivers globally. The number and mass of plastic particles drifting through a river can exceed those of living organisms such as zooplankton and fish larvae. In freshwater sediments, concentrations of microplastics reach the same magnitude as in the world's most contaminated marine sediments. Such particles are derived from a unique biogeochemical cycle that ultimately influences productivity, biodiversity, and ecosystem functioning. Furthermore, microplastics act as vectors of toxic substances to invertebrates, fishes, herpetofauna, and waterfowl. We contend that the concentration of this distinct particle component is an ecologically significant parameter of inland waterbodies because of its ubiquity, environmental persistence, and interactions with key ecological processes. No environmental field survey that has searched for microplastics has yet failed to detect their presence. Standardized limnological protocols are needed to compare spatio-temporal variation in the concentration of microplastics within and across watersheds. Data obtained from such protocols would facilitate environmental monitoring and inform policy for managing plastic waste; furthermore, they would enable more accurate modeling of contaminant cycling and the development of a global plastic budget that identifies sources, distribution and circulation pathways, reservoir size, and retention times.

Key words: microplastics, freshwater ecosystems, food webs, limnology, contaminants, monitoring, plastic budget, biogeochemical cycles.

Résumé : Des microplastiques - des particules de plastique de la taille d'organismes planctoniques - ont été trouvés dans les colonnes d'eau et les sédiments des lacs et des rivières dans le monde entier. Le nombre et la masse des particules plastiques dérivant dans une rivière peuvent dépasser ceux des organismes vivants tels que le zooplancton et les larves de poisson. Dans les sédiments d'eau douce, les concentrations de microplastiques atteignent la même ampleur que dans les sédiments marins les plus contaminés au monde. Ces particules proviennent d'un cycle biogéochimique unique qui, ultimement, influence la productivité, la biodiversité et le fonctionnement des écosystèmes. En outre, les microplastiques agissent comme des vecteurs de substances toxiques pour les invertébrés, les poissons, l'herpétofaune et les oiseaux aquatiques. Les auteurs soutiennent que la concentration de ce composant particulaire distinct constitue un paramètre écologiquement significatif des masses d'eau intérieures en raison de son ubiquité, de sa persistance dans l'environnement et de ses interactions avec des processus écologiques clés. Aucune étude environnementale de terrain qui a recherché des microplastiques n'a encore manqué de détecter leur présence. Des protocoles limnologiques normalisés sont nécessaires pour comparer les variations spatio-temporelles de la concentration de microplastiques dans et entre les bassins versants. Les données obtenues grâce à de tels protocoles faciliteraient la surveillance environnementale et éclaireraient les politiques de gestion des déchets plastiques ; par ailleurs, elles permettraient une modélisation plus précise du cycle des contaminants et l'élaboration d'un bilan plastique mondial qui identifie les sources, les voies de distribution et de circulation, la taille des réservoirs et les temps de rétention. [Traduit par la Rédaction]

Mots-clés : microplastiques, écosystèmes d'eau douce, réseaux alimentaires, limnologie, contaminants, surveillance, bilan plastique, cycles biogéochimiques.

Introduction

Plastics are engineered from long repeating chains of carbon molecules derived from oil and natural gas to produce a final product with desirable properties such as strength, rigidity or elasticity, and resistance to temperature and acidity (Crawford and Quinn 2016). Technological advancements have reduced the cost of plastic production, facilitating their increased use in manufacturing, packaging, and single-use containers. The mass of plastics in solid waste has been increasing steadily since the 1960s, generating escalating costs of waste management and environmental pollution, because most plastics do not decompose and their chemical components and additives pose barriers to recycling (Hahladakis et al. 2018). In the 1970s, attention began to focus on the drawbacks of these innovative materials when researchers reported alarming densities of floating plastics accumulating within oceanic gyres (Ryan 2015) and, later, in freshwater systems (Anderson et al. 2016). Nearly 80% of all plastics ever created has been accumulating in the environment (Geyer et al. 2017), underscoring a need to improve plastic waste

---

Received 27 May 2021. Accepted 27 September 2021.

G. D'Avignon and I. Gregory-Eaves. Department of Biology, 1205 Docteur Penfield Avenue, McGill University, Montreal, QC H3A 1B1, Canada; Groupe de Recherche Interuniversitaire en Limnologie (GRIL), Quebec, Canada.
A. Ricciardi. Redpath Museum, 859 Sherbrooke Street West, McGill University, Montreal, QC H3A 0C4, Canada; Bieler School of Environment, 3534 University, McGill University, Montreal, QC H3A 2A7, Canada; Groupe de Recherche Interuniversitaire en Limnologie (GRIL), Quebec, Canada.

Corresponding author: Anthony Ricciardi (email: Tony.Ricciardi@McGill.ca).

Environ. Rev. **30:** 228–244 (2022) dx.doi.org/10.1139/er-2021-0048

management and maintain efforts to reuse, recycle, incinerate, or increase their biodegradability.

Initial consensus defined microplastic as synthetic polymers $\leq$5 mm (Andrady 2015; Crawford and Quinn 2016; GESAMP 2016). Emerging classifications differentiate plastic particles into macro- (>1 cm), meso- (1 to <10 mm), micro- (1 to <1000 μm), nano- (1 to <100 nm), and submicrosizes (100 to <1000 nm), as well as characterizing particle shape, structure, and composition (Hartmann et al. 2019), as these factors affect their distribution, circulation, ingestion by biota, and impacts on environments. In this paper, microplastics refer to synthetic particles $\leq$5 mm in size.

Primary microplastics are manufactured as specific materials, of a specific shape and size for commercial or industrial use. These include polyethylene microbeads manufactured as small (5 μm to 2 mm) spherical particles for use as mild abrasives in cosmetic products (Fendall and Sewell 2009). A 150 mL container of a facial scrub can contain up to 2.8 million microbeads (Napper et al. 2015), and such products are the source of trillions of particles released with effluents daily (Rochman et al. 2015). Over a dozen countries have banned the use of microbeads in cosmetics; however, other types of microplastics are still produced and continue to be released to the environment (e.g., spillage of industrial pellets) (Zbyszewski et al. 2014). All large plastic debris can ultimately degrade into micro- or nanosized particles during their use (e.g., fibres released from garments or textiles, rubber fragments released by abrasion from car tires, plastic mulching, paint flakes, etc.; Horton et al. 2017) or through mechanical stress, photodegradation, and oxidation (Eerkes-Medrano and Thompson 2018). Synthetic fibres from nets, clothing, or textiles are typically predominant in microplastics found in waterbodies and aquatic biota (Lim 2021; Rebelein et al. 2021; Yang et al. 2021). A portion of these originate from the laundering of clothing, as a single synthetic garment can produce thousands of microfibres per wash (Browne et al. 2011; Napper and Thompson 2016; McIlwraith et al. 2019).

All land-based plastic waste (e.g., littering, landfills, plastic mulching, dredge piles, sewage sludge, organic fertilizers from biowaste fermentation and composting), can be released and transported into aquatic systems carried by winds, erosion and surface runoff. Wastewater treatment plants (WWTP) process domestic, industrial, and commercial effluent, and sometimes surface water runoff. Primary treatment removes 41%–93% of microplastic particles, whereas secondary and tertiary treatments remove 54%–99.9% and 82%–99.9%, respectively (Iyare et al. 2020). Despite their efficacy, owing to the sheer volume of water treated, a single WWTP can release 10^4 to 10^8 particles daily (Mason et al. 2016; Kalcikova et al. 2017; Edo et al. 2020). Considering ~80% of wastewater worldwide is estimated to be released directly into the environment without treatment (UNWWAP 2017), grey waters (from domestic sinks, showers, baths, washing machines) are a major source of microplastic to aquatic systems. The retained particles accumulate in WWTP sludge, which are often applied as fertilizer to agricultural fields (Zubris and Richards 2005; Edo et al. 2020); therefore, these microplastics may eventually enter inland waters via agricultural runoff (Fig. 1).

Furthermore, when microplastics become airborne and transported long distances by winds (Enyoh et al. 2019), they can eventually be deposited in areas ranging from a large metropolis (Dris et al. 2016) to a remote mountain catchment (Allen et al. 2019; Fig. 1). The presence of plastics is therefore not limited to the location at which they enter the environment; they can easily be redistributed by surface runoff and by atmospheric and ocean circulation, such that microplastics have been found to accumulate even in polar regions (Bergmann et al. 2019) and deep ocean trenches (Courtene-Jones et al. 2019).

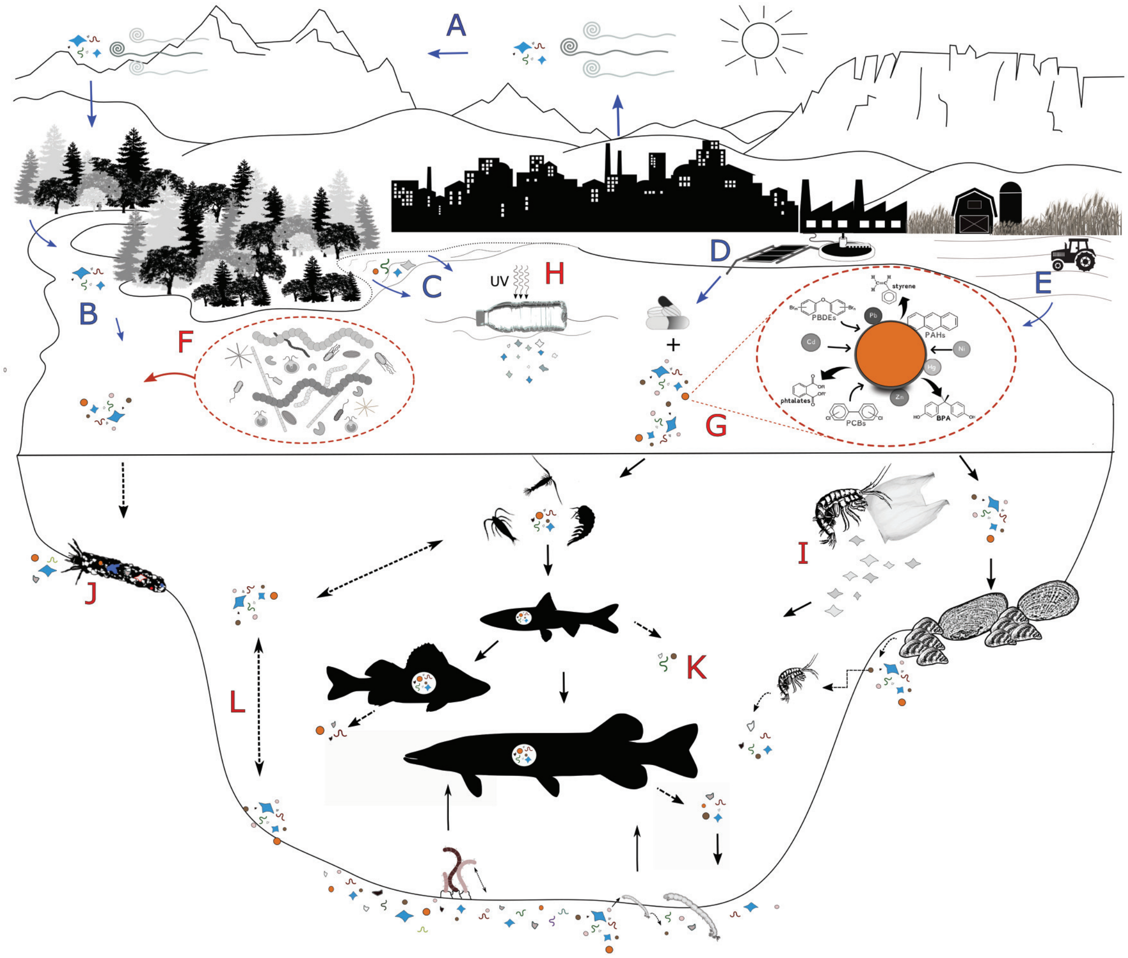
In aquatic systems, biota play active roles in the transport, temporary storage, and transformation of plastics. Given the general definition of microplastics, these particles overlap in size with coarse particulate organic matter (>1 mm; Cummins 1974), fine particulate organic matter (>0.45 to <1000 μm, including seston; Wallace et al. 2007), and dissolved organic matter (<0.45 μm; Lamberti and Gregory 2007). Many freshwater invertebrates (e.g., "shredders" such as gammarid amphipods, limnephilid caddisfly larvae, and pteronarcyid stonefly nymphs) play vital roles in the breakdown of particulate organic matter and could similarly interact with microplastics. A broad variety of aquatic organisms ingest microplastics including birds (Holland et al. 2016), fish (Jabeen et al. 2017; Azevedo-Santos et al. 2019), bivalves (Su et al. 2018; Baldwin et al. 2020; Wardlaw and Prosser 2020), crustaceans (Iannilli et al. 2020; Simmerman and Wasik 2020), other invertebrates (Nel et al. 2018; Ehlers et al. 2019; Windsor et al. 2019), and can transfer them through aquatic and terrestrial food webs. Plastic debris are also fragmented and transformed as a result of being chewed, shred, grazed upon, or partly digested by various organisms (Hodgson et al. 2018; Jang et al. 2018; McGivney et al. 2020; Po et al. 2020); some of which can metabolize carbon stored in the synthetic polymers (Taipale et al. 2019).

Each polymer has unique affinities to sorb and release heavy metals, persistent organic pollutants, pharmaceuticals products, and antibiotics (Menéndez-Pedriza and Jaumot 2020). The routes taken by these particles to reach aquatic realms (Fig. 1) dictate their associations with environmental contaminants. Particles circulating via sewers are temporarily retained along with chemicals, pharmaceuticals, bacteria, and viruses common in waste waters, thereby acquiring an assortment of hazardous chemicals and colonizing biota different from those of microparticles cycling via atmospheric circulation or runoffs. Weathering or microbial action on the surface of microplastics enhances the leaching of both additives (e.g., colorants, fillers, plasticizers, stabilisers, flame retardants, bisphenol-A; Hahladakis et al. 2018) and associated contaminants, which could become bioavailable (Avio et al. 2015; Boyle et al. 2020). Thus, a unique and complex mixture of associated chemicals and biofilms, distinct from surrounding water and sediments (McCormick et al. 2016), can evolve through time as the particle travels through an aquatic system. Owing to progressive fragmentation, weathering, and biotic interactions with larger size fractions of plastic, microplastic loads will continue to increase, perhaps for decades, even if a sharp decline in plastic production were to occur.

Limnology is concerned with the biological, chemical, physical, and geological characteristics of inland waters and their interactions with surrounding ecosystems. Given the pervasiveness of microplastics, their emerging impacts on aquatic biota, and their unique role in biogeochemical and contaminant cycling in aquatic environments, we suggest that limnologists should recognize them as a distinct particle component that is not derived from the same geological or physico-chemical processes as other inorganic seston, though subjected to similar forces of erosion (i.e., mechanical disintegration, chemical weathering driven by ultraviolet light and high temperatures) and sedimentation.

Here, we present evidence that microplastic concentration is an ecologically relevant parameter and thus should be integrated within standard limnological surveys and water quality assessments. By incorporating microplastics within standard sampling protocols in limnology, we can address a research priority within the field of plastic pollution and provide policy relevant information on the source, circulation, and distribution of plastics within aquatic realm (Provencher et al. 2020). Floating microplastics can outnumber plankton and larval fish in various rivers and marine systems, at ratios up to ~30:1 (Lechner et al. 2014; Steer et al. 2017; see Table 1); therefore, their presence cannot be ignored when assessing the health of inland waters. We have reviewed the ecological impacts of these particles in inland waters and identified key research gaps concerning their significance in animal physiology, trophic ecology, and aquatic ecosystem function based on current microplastic pollution research. Finally, we have made

Fig. 1. The biogeochemical cycle of plastics in inland waters. Blue letters represent microplastic transport pathways to aquatic systems. Microplastics are transported (A) via aerial transport and deposition (winds) or (B) by tributaries throughout the watershed. Terrestrial plastic waste and debris are carried by water via (C) flooding, (D) wastewater and stormwater effluents, or (E) runoff (e.g., urban, agricultural applications of contaminated sludge or biowaste, dredge piles). Red letters illustrate processes within aquatic environments: (F) biofilm formation via colonization by microbial organisms; (G) the sorption of associated contaminants (heavy metals, organic pollutants, pharmaceuticals) onto the surface of plastic particles (orange sphere represents a microbead); the fragmentation of plastics by (H) physical processes (exposure to UV light, mechanical or chemical erosion) or by (I) their interaction with organisms; (J) incorporation of microplastics in larval cases or shelters of aquatic insects; (K) introduction and circulation of microplastics in aquatic food webs; and (L) vertical movement of microplastics (e.g., changes in buoyancy, deposition, re-suspension, burial). Drawn using license-free clipart images and the Inkscape vector graphics editor.



recommendations for future directions that can be adopted to integrate microplastic monitoring in limnological research and demonstrated how these particles could serve as a marker of anthropogenic activities within a catchment area.

In this work, we compiled evidence from articles retrieved through Web of Science using the following search string for years 2010 to 2020, inclusive: *((TS=(microplastic* AND (aquatic OR river* OR lake* OR marine* OR sea OR ocean* OR estuary OR brack* OR *water* OR sediment* OR beach* OR shoreline*)))) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)*. Relevant papers among the 3731 articles retrieved were used to summarize some key aspects of our current understanding of microplastic pollution in aquatic environments. Although our focus is on inland waters, data from marine environments were considered for comparison and to gain further insight into ecological impacts likely to occur in freshwater ecosystems. We selected studies with comparable units of microplastic abundance and summarized only those that reported concentrations of plastic particles in the $\leq$5000 μm size range. Finally, we selected the 25 journals that accounted for >70% of the publications on microplastics (according to the Web of Science) and used them to calculate research effort on this topic, i.e., the percentage of publications that comprised microplastics studies (Fig. 2).

The pervasiveness of microplastics in inland waters

Increasing attention on microplastics in fresh waters

Within the last dozen years, microplastic pollution has become a growing subject of limnological research, beginning with lakes and subsequently expanding to rivers and reservoirs. However, it is clear that marine studies still dominate the microplastic literature, with over 60% of papers published in 2020 focusing on marine systems (Fig. 2). Likewise, as most published studies have emanated from Asia and Europe, the geographic cover is not homogeneous. To summarize the state of evidence and illustrate knowledge gaps, we have compiled information acquired since 2010 on reported microplastic densities across matrix types (i.e., on beaches, at the water surface, in the water column, in sediments, and within aquatic organisms; Table 1). Our summary shows that the Yangtze River catchment (including Lake Taihu, Lake Poyang, and the Xiangi River) in China is the most

Table 1. Microplastic (MP) contamination (particles ≤5 mm) of watersheds and their biota.

	MP concentration in water (MP·L^{-1})		MP concentration in sediments [MP·(kg dry mass)$^{-1}$]		MP concentration in biota[c]					
Watershed[a]	Surface	Column	Beach[b]	Benthic	Benthos	Fish	Birds	Frogs	Bioseston[d] ind.·L^{-1}	MP: Bioseston[e]%
Laurentian Great Lakes, USA and Canada										
Lake Erie and tributaries[2,10,40]	<0.001–0.032		50–391	117–5985		70%	1.8–9.8			
Lake Ontario and tributaries[2,4,7,8,15,37]	0.002–1.5		20–4270	40–27830		50%	1.8–9.8			
Lake Michigan and tributaries[2,20,28]	<0.001–0.007	<0.001–0.003		39–6229		0–19.1				
Kinnickinnic River[20,31]	0.003–0.006	0–0.001		32.9	4–20·g^{-1}	0–1242				
Milwaukee River[2,20,28]	0.002–0.017	0.002		1410–2110		4.5–6.5				
Yangtze River Basin, China										
Three Gorges Reservoir[11,45]	4.7–12.6			25–300					1–105000	<0.01–470
Lake Taihu[17,23,32,33,42]	0.53–25.8			11–320	0.2–10.4	0.2–17.2				
Lake Gaoyouhu[33,39]	0.7–3.1			17.6–208.9	1.6–5.0				2.0–13	0.54–155
Lake Poyang[5,23,32,33,44]	0.24–34		11–3153	7.1–506	0.4–1.6	0–18			137.6–219.2	0.11–24.7
Lake Dianshan[23,33]	0.5–1.8			14.8–140						
Lake Chao[23,33]	0.2–1.9			0.6–225	0.4–0.9					
Yangtze River Delta inland waters[16,39]	0.5–21.5			35.9–3185	0.4–1.4			0.17–3.51	2.4–117.3	0.43–896
Other										
Colorado River – Lake Mead area, USA[3,36]	0–1.99			88–2040	2–105	2.0–12.0				
Pearl River and tributaries, China[14,22,24,38,41,43,46]	0.015–53			20–9597	1.4–7.0	0.2–27.4				
Rhine River, Europe[1,19,21,26,27,30]	0.005–0.022		228–3763	250–11670	0–30·g^{-1}	0.2–1.0				
Rize inland waters, Turkey[18]	1.0–13.0		64.2–472					124–489·g^{-1}		
Lake Vicotria, Tanzania and Uganda[6,12,13]	0.02–2.19		50–1102	6.5–108		20%				
Braamfontein Spruit, South Africa[9]	0.16–2.08			4–1348	20–97·g^{-1}					
Melbourne inland waters, Australia[29,34,35]	0.03–1.7			4.5–172.7	0.07–1.4	0.7				

Note: Original data and references are listed in the Supplementary data, Table S1[1].

[a] Numerical superscripts indicate the references used to compile microplastic contamination values.

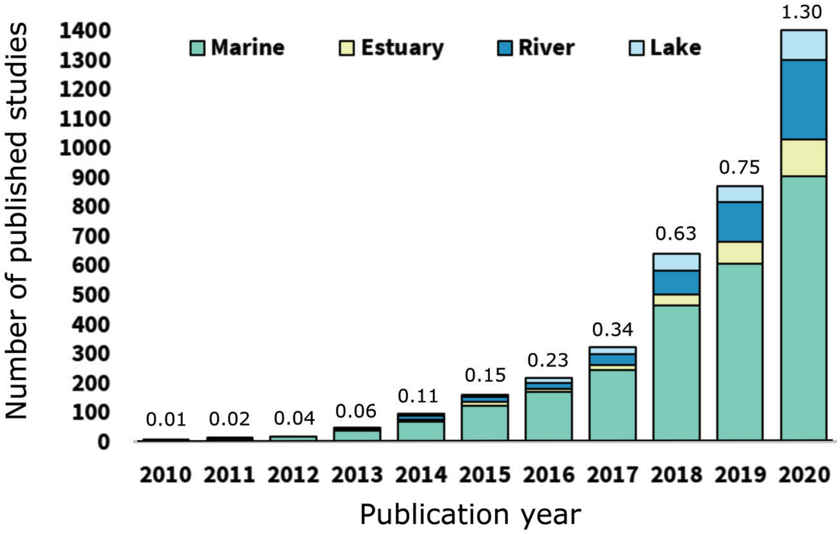
[b] Beach concentrations include samples taken in areas that are never, or only temporarily, submerged (e.g., shoreline, intertidal areas).

[c] The concentration of microplastics is reported as numbers of particles per individual (MP ind.$^{-1}$); where data are not available, the presence of microplastics is reported as either the proportion of animals contaminated (%) or as the number of particles per gram of tissue (g).

[d] Number of zooplankton per litre.

[e] Ratio of microplastic to zooplankton concentrations × 100.

Fig. 2. Number of studies on microplastic pollution (particles ≤ 5 mm) for various waterbody types, published between 2010 and 2020, inclusive, yielding a total of 3731 studies. Values above the bars are the percentages (%) of studies on microplastic pollution based on research effort in the 25 journals having the most publications on microplastic pollution (71% of all reviewed studies).



extensively studied water body in the world, yet information is still lacking on the spatiotemporal variation in microplastic concentrations throughout the catchment. Many European countries have reported on microplastic pollution, but less than a quarter of these studies focused on freshwater systems (with the Rhine River receiving the most attention). In North America, most studies have been conducted in the Great Lakes – St. Lawrence River system. Researchers have begun examining Lake Victoria on the African continent, but many other large inland waters are poorly represented (Table 1; Supplementary data, Tables S1 and S2[1]). As the sources and transport routes of microplastic are more fully described, we can begin to depict the complexity of their biogeochemical cycles in aquatic systems (Fig. 1). Much work is needed to identify missing or understudied links, including aerial deposits and the role of biota as temporary reservoirs of microplastics, as well as the many possible chemical interactions.

Different components of water bodies contain varying levels of contamination. Microplastic concentration at the water surface is highly dynamic and altered by flow regimes, precipitation, seasonality, and proximity to points of entry (e.g., sewage or storm water effluent, sludge discharge, road or agricultural runoff, litter) (Browne 2015; Horton et al. 2017). Recent environmental analyses show that concentrations in surface inland waters (mean value ~1.9 particles·L^{-1}) are lower than estuarine (3.1 particles·L^{-1}) or marine environments (16 particles·L^{-1}) (Fig. 3). However, when comparing median concentrations of these same compartments, results ranged from 0.007 particles·L^{-1} detected in lotic systems to ~1 particle·L^{-1} in lentic systems (Fig. 3). There is substantial heterogeneity in the abundance of surface-water microplastics in highly modified waterways or areas with high population densities. For example, in the Pearl River (China), concentrations of 8–53 particles·L^{-1} have been recorded in urban sections, compared with much smaller concentrations (<1 particle·L^{-1}) elsewhere along the river (Table 1; Supplementary data, Table S2[1]; Yan et al. 2019; Fan et al. 2019). Stations along the Gallatin River (USA) recorded 1–68 particles·L^{-1} (Barrows et al. 2018), and in Patagonian lakes (Argentina), concentrations were <0.001 particle·L^{-1}, with some individual samples reaching 44 particles·L^{-1} (Alfonso et al. 2020). Values for water samples from the canals of Amsterdam were recorded as 48–187 particles·L^{-1} (Leslie et al. 2017), whereas median microplastic concentrations in all lotic environments were below 0.01 particle·L^{-1} (Fig. 3).

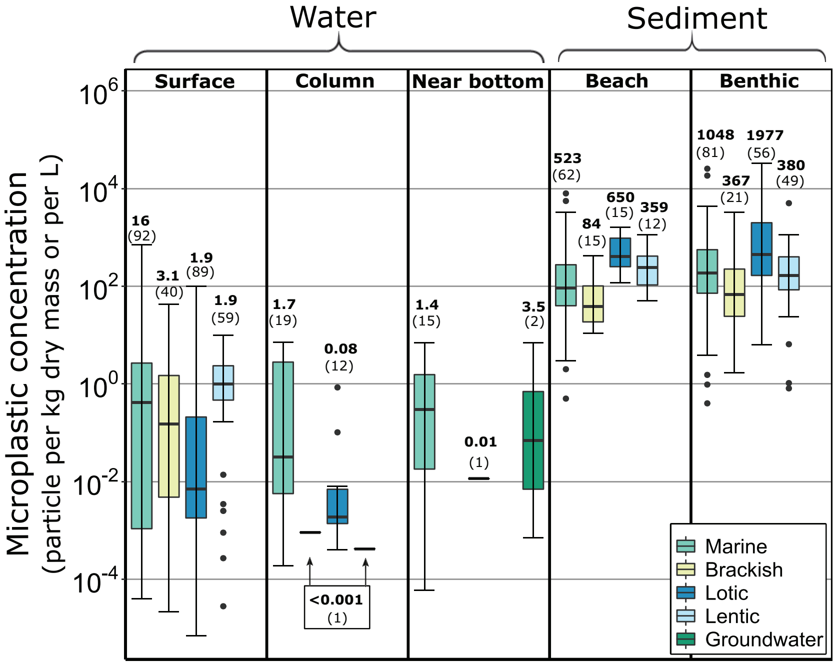
Specific hydrological conditions and sampling season can also play an important role in the abundances reported. Higher flow regimes in streams carry more particles per unit of time, but on average yield lower concentrations than areas with lower flows (Watkins et al. 2019). Seasonal changes in flow regimes (e.g., snow melt, flooding, drought), extreme rainstorms, or anthropogenic control of waterways (e.g., via dams, spillway gates) can alter the transport and concentration of microplastics. Spatial and temporal variations in particle abundance in surface waters and the water column highlight the need for repeated and broader sampling to establish more representative baseline concentrations. Such intensive sampling has rarely been conducted, owing in part to both the time-intensive effort required and the use of incomparable sampling methods. Investments in effort and harmonization of methods is encouraged so that a comprehensive understanding of microplastic pollution can be achieved. Limnologists would do well to coordinate with marine science colleagues to render data more easily comparable across realms.

An important insight is that the abundance of microplastics floating at the surface is not a reliable indicator of concentrations throughout the water column. For example, microplastic concentrations in six South Korean bays were four times higher at the surface than in the rest of the water column (Song et al. 2018). Over 85% of microplastic studies sample surface waters, and comparisons of abundance along depth profiles are not common (Fig. 3). In a study that quantified the vertical and longitudinal distribution of microplastics along the Lake Michigan watershed, concentrations of particles in surface waters were found to be generally higher than those measured deeper in the water column, but lower than those in the sediments (Lenaker et al. 2019). The pool of literature we reviewed (Fig. 3) indicates that lentic systems have higher densities of floating plastics than lotic systems, while the highest concentrations of microplastics are found along the shorelines and in the benthic sediments. Furthermore, the timing and geographic location of sampling programs also affect surface

---

[1] Supplementary data are available with the article at https://doi.org/10.1139/er-2021-0048.

Fig. 3. Microplastic concentrations (particles ≤ 5 mm) in various aquatic environmental matrices from 642 records (*n* = 220 articles). Box-and-whisker plots were constructed from a compilation of mean concentrations provided in the articles; when only a range of values was provided instead of a mean, the lowest values (if above zero) were included. Concentrations are reported as the number of particles per kilogram dry mass of sediments for beaches and benthic samples, whereas in water samples concentrations are reported as the number of microplastics per litre of water at the surface, within the water column, or near the bottom of the water column. Median lines are shown within the boxplot. Means are indicated as bold values above the boxplot, and values in parentheses indicate sample sizes. Original data and references are available in the Supplementary data, Table S2[1].



measurements: the salinity and temperature of water will influence biofilm colonization (Kaiser et al. 2017), causing microplastics to remain afloat longer during colder seasons or at higher latitudes (Chen et al. 2019*b*). Naturally occurring spring and fall mixing of lakes can also cause shifts in the vertical distribution of particles, suggesting the importance of implementing seasonal sampling protocols. We recommend that different ecosystem compartments be sampled repeatedly along the river continuum from freshwater to marine systems, to produce reliable baseline pollution data in inland waters.

Inland waters as sources and sinks of microplastics

The evidence suggests that rivers contribute substantively to ocean inputs (Schmidt et al. 2017; Meijer et al. 2021), and it has been estimated that rivers shuttle between 6000 and 1.5 million metric tonnes of microplastics to the ocean annually (Boucher and Friot 2017; Weiss et al. 2021). Most plastic transport models assume that no significant retention of plastics occurs along the river network from inland waters to the ocean (Jambeck et al. 2015; Weiss et al. 2021), despite ubiquitous river impoundment and myriad other anthropogenic and natural hydrological conditions that can cause the deposition of large numbers of plastic particles within the watershed. Buoyant particles can become trapped on the shorelines of lakes and rivers (Zbyszewski et al. 2014); median concentrations (per kilogram dry mass) along river shorelines are 4–10 times higher than along marine/estuarine coastal beaches (Fig. 3). Furthermore, microplastics can accumulate on the riverbed, where their concentrations are as much as four to five orders of magnitude higher than in the overlying water column (Fig. 3; Castañeda et al. 2014; Crew et al. 2020; Scherer et al. 2020). Although a portion of microplastics stored in riverbeds and on shorelines can be resuspended after dredging activities, storm disturbance, or seasonal flooding events, and be transported downstream (Ji et al. 2021), current mass transport models likely greatly overestimate the flux of plastic to the oceans.

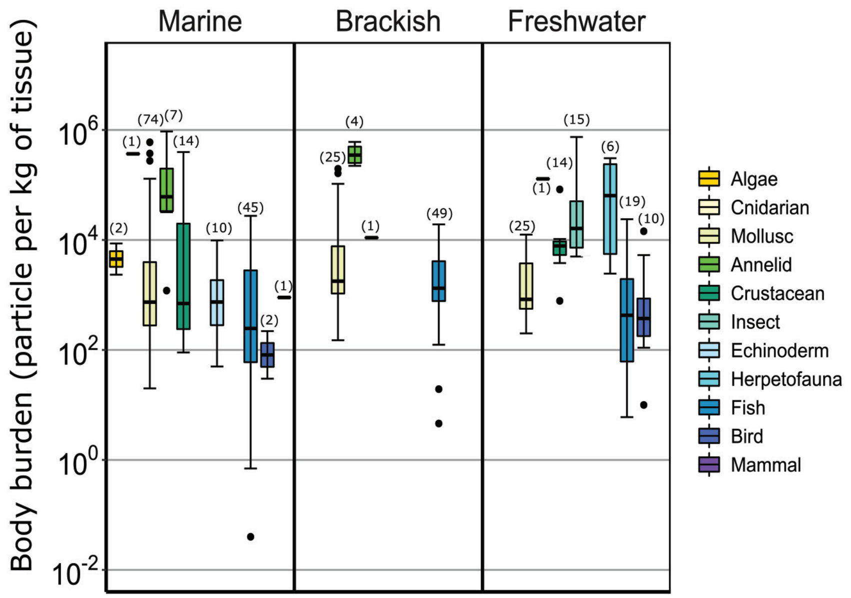
Benthic microplastics as an anthropogenic marker

The quantification and characterization of microplastics within sediments could serve as an indicator of anthropogenic pressure on inland waters. Areas where burial rates allow the preservation of plastics within the sediment layer without mineralization or fragmentation (Hoellein and Rochman 2021), such as the depositional zones of river beds and lakes, can function as a long-term or permanent storage for such particles. Analyses of lake sediment cores have been used to track temporal dynamics in microplastics, which date back to the early 1970s in Lake Ontario sediments (Corcoran et al. 2015) and to the 1950s in a lake in north London, UK (Turner et al. 2019). The presence of plastics in sediment layers are sufficiently pervasive and globally distributed that they can be used as an anthropogenic marker horizon in geological and paleolimnological records (Barnosky 2014; Bancone et al. 2020). Plastic debris is already used as a stratigraphic marker in archaeological studies (Zalasiewicz et al. 2016).

Aquatic biota are transient reservoirs for microplastics

From inland waters to marine systems, a growing diversity of aquatic organisms (algae, macrophytes, zooplankton, insects, crustaceans, molluscs, fish, amphibians, birds, and mammals; Fig. 4) have been reported to take up microplastics via feeding, drinking, respiration, swimming, and random adherence, among other processes. Contamination levels (number of particles per kilogram of tissue) of freshwaters and estuarine taxa are within of the same order of magnitude as their marine counterpart (Fig. 4). According to Covernton et al. (2021), freshwater fish are more frequently found with plastics in their gut and with a higher microplastic load per individual than marine fish. Recently, fish

Fig. 4. The abundance of microplastic particles (≤5 mm) per kilogram of tissue recorded for aquatic organisms of different waterbody types. Box-and-whisker plots were constructed from a compilation of mean concentrations provided in the articles; when only a range of values was provided instead of a mean, the lowest values and the highest values were included. Reports of body burden below 0.01 particle·kg^{-1} were excluded. Numbers in parentheses indicate sample size per group. Original data and references are available in the Supplementary data, Table S3[1].



from the Great Lakes recorded the highest load ever reported (Munno et al. 2021), illustrating the need for freshwater biologists to explore the impacts of this emerging stressor.

Although the mechanisms by which aquatic organisms acquire and retain plastics from their environment are still poorly documented, a comparison of body burdens within a taxonomic group suggest feeding mechanisms and the habitat preference along the watershed continuum could influence the contamination risk for aquatic organisms (Figs. 5). Benthic invertebrates, especially those associated with depositional areas of rivers, may be more vulnerable to microplastic pollution, being restricted to environments that accumulate and store microplastics (Fig. 5). Midge larvae (*Chironomus* sp.) and oligochaete worms (*Tubifex tubifex*) were found with the highest burdens, with 370–1200 particles·g^{-1} and 129 ± 65.4 particles·g^{-1}, respectively (Hurley et al. 2017; Nel et al. 2018). Nearly 60% of larval caddisflies (*Lepidostoma basale*) use plastic materials to construct their cases, incorporating an average of 0.36 ± 0.09 particles·(mg case)$^{-1}$ (Ehlers et al. 2019) — an addition that negatively affects case-integrity in ways that could potentially reduce larval survival (Ehlers et al. 2020).

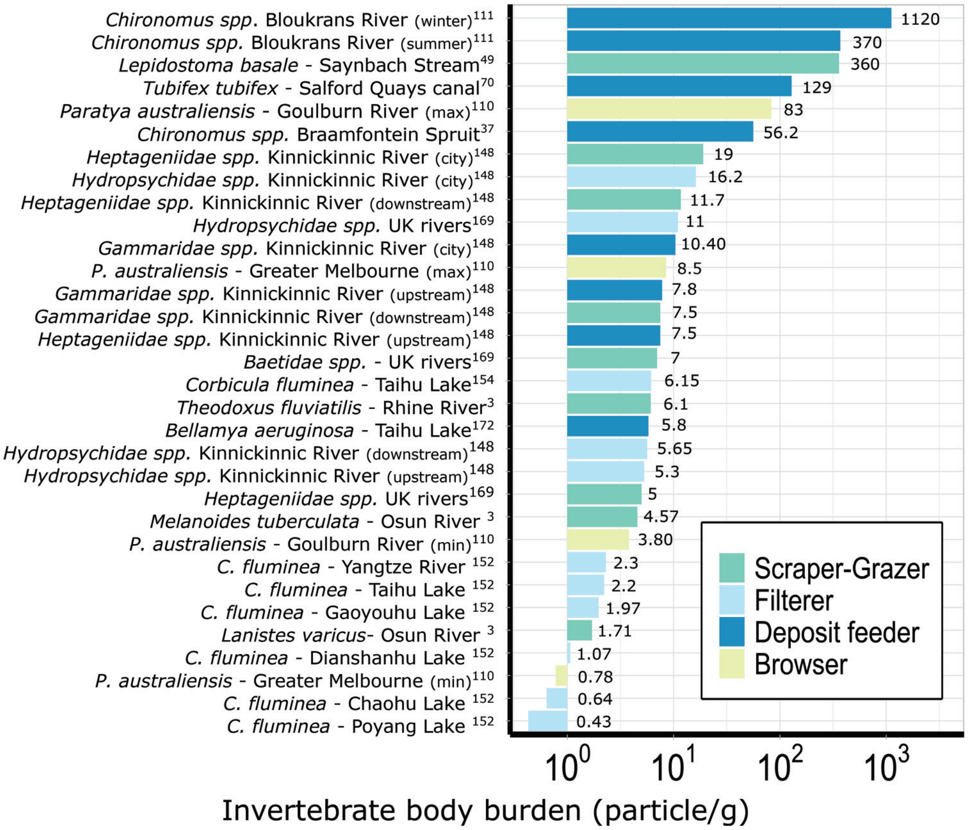
Biota act as transient reservoirs for these particles that, after entering an organism, can continue cycling within the animal, be egested, or be transferred through a food web. Retention time within the body depends on particle size and shape, metabolic activity, and the complexity of the animal's digestive tract or gill structure. Particles ≤500 μm in maximum dimension were found in the liver and filets of freshwater fish, suggesting that they were translocated from the gut to other organs (Collard et al. 2018; McIlwraith et al. 2021); whereas, by comparison, clay sized particles (<5 μm) can cross cell membranes and enter the bloodstream, where they can remain for 20–48 days (Browne et al. 2008; Farrell and Nelson 2013). Animals with high metabolic rates, like daphniid or gammarid crustaceans, can take up high concentrations of microplastics but usually expel them in their faeces quite rapidly (Mateos-Cárdenas et al. 2019; Elizalde-Velazquez et al. 2020). However, particles tend to be retained for longer periods of time in fish with irregular body shapes (Hoang and Felix-Kim 2020) or organisms with complex digestive tracts (Welden and Cowie 2016). When no translocation occurs, plastic particles are egested within 24–72 h (Scherer et al. 2017; Redondo-Hasselerharm et al. 2018), which is sufficient time for a contaminated animal to be eaten by a predator and thus transfer their plastic load to the next trophic level (Chae et al. 2018). Cedervall et al. (2012) demonstrated the trophic transfer of 25 nm polystyrene particles that were taken up by green algae (*Scenedesmus* sp.) and passed on to herbivorous water fleas (*Daphnia magna*), which were subsequently consumed by fish. Regardless of the mechanism, once microplastics are egested, the cycle can begin anew and the same particle can be re-ingested (Hoang and Felix-Kim 2020) or passed from one individual to another for an indeterminant period of time. Therefore, even without evidence of biomagnification (Covernton et al. 2021), a single plastic particle could cycle multiple times in and out of food webs with unknown consequences to its hosts.

Ecological impacts on freshwater ecosystems

Microplastics affect many biological and physico-chemical processes of significance for organisms, communities, and ecosystems. Dose-dependent biotic responses to plastic pollution have been shown for diverse groups including algae (Gambardella et al. 2018), suspension feeders (Pedersen et al. 2020), deposit feeders (Fueser et al. 2019), detritivores (Au et al. 2015), and predators (Kim et al. 2019). Yet, meta-analyses of the ecotoxicological effects of virgin plastics on organisms find that acute endpoints generally occur at doses higher than those typically observed in natural habitats (Foley et al. 2018; Cunningham and Sigwart 2019; Bucci et al. 2020) and biotic responses are modulated by the duration, particle size, types of exposure conditions, and associated contaminants.

We provide a non-exhaustive summary of the physical, physiological, and ecotoxicological effects reported for freshwater taxa in Table 2. Not all organisms tested displayed negative effects, but even small effects at the cellular or molecular levels can have repercussions at the community or ecosystem levels. For example, increased oxidative stress in plastic-exposed cyanobacteria promotes microcystin synthesis and release, thereby inducing toxic

Fig. 5. Comparison of the body burden (microplastic particle per gram of tissue) of freshwater invertebrates found along rivers. Only organisms that incorporated microplastics (particles ≤ 5 mm) into their body via ingestion or essential structures (e.g., the larval case of *Lepidostoma basale*) were used for this figure. Colours represent different functional groups. Species are listed individually with the locations sampled and the reference number. Original data and complete references are available in the Supplementary data, Table S3[1].



algal blooms (Feng et al. 2020). Other small changes, such as delays in aquatic insect emergence and reduced numbers of adults following exposure to environmentally relevant microplastic concentrations (Ziajahromi et al. 2018), or the ontogenic transfer of plastics from mosquito larvae to terrestrial adults (Al-Jaibachi et al. 2019), further highlight potential repercussions of this form of pollution across the aquatic–terrestrial ecotone. A full accounting of the presence of microplastics and their associated chemicals is crucial to understand the impacts of these stressors on freshwater systems.

Biodiversity

The surfaces of plastic particles host communities of microorganisms whose composition is sensitive to polymer type, size, and environmental conditions. Among these aggregates, bacterial communities on plastics have lower species abundance and diversity (richness, evenness) than those from surrounding natural substrates (McCormick et al. 2016; Miao et al. 2019) — except for microplastic-biofilms in oligo–mesotrophic lakes, whose functional richness was found to be higher than biofilms on natural substrates (Arias-Andres et al. 2018). Plastic biofilms tend to be dominated by particular taxa, including polymer-degrading bacteria (e.g., *Pseudomonas*), bacterial pathogens (e.g., *Arcobacteria*, *Vibrio*), and antibiotic-resistant bacteria, as well as parasitic and saprophytic fungi (Kettner et al. 2017; Sun et al. 2020). Plastic waste offers novel media on which some microorganisms thrive and could thus signal an attractive food source for higher-level consumers (Battin et al. 2003). However, plastic-bound biofilms may not offer the same food quality as biofilms on natural materials (Vosshage et al. 2018).

Considering that their plastic substrate is durable by design, colonizers have a stable surface on which to develop, rendering buoyant plastic debris of all sizes as potential transport vectors for non-native species, pathogens, and drug-resistant bacteria (Wang et al. 2021). Freshwater environments subjected to effluent from WWTP receive regular inputs of microplastics, with estimated daily discharges ranging from 50 000 to nearly 15 million particles in the USA (Mason et al. 2016). The plastic-associated bacterial communities from these WWTP exhibit higher gene exchanges, making microplastic a suitable environment for the development of antibiotic- and metal-resistant genes, as well as vectors to disperse these bacteria downstream (Eckert et al. 2018); in fact, multidrug-resistant *Escherichia coli* strains (Song et al. 2020) were found to be carried by microplastics across different environments.

Additionally, evidence from both marine and freshwater habitats suggests that continuous exposure to high microplastic concentrations near effluents can reduce community diversity. Repeated exposure to 80 $\mu g \cdot L^{-1}$ of microplastics had minimal impacts on oyster health and biological functioning, but the benthic community within the oyster beds experienced a 1.5-fold decline in numerical abundance (Green 2016). Similarly, benthic communities exposed to microsynthetic polymers for 15 months had altered community composition, whereby some species' abundances were affected positively and the more sensitive taxa were affected negatively (Redondo-Hasselerharm et al. 2020). Benthic communities are expected to be disproportionately affected, as their habitats typically contain the most contaminated aquatic matrix.

Table 2. The ecotoxicological effects of microplastic exposure on inland water organisms, compiled per taxonomic group.

	Physical and physiological effects										Toxicity						Ecological effects					
	Movement	Feeding	Digestion	Predatory performance	Respiration	Growth	Development	Protection/defence	Cell/organ damage	Reproduction	Mortality	Oxidative stress	Inflammation	Metabolic activities	Gene damage	Neurotoxicity	Productivity	Nutrient cycling	Toxic blooms	Trophic transfer	Ontogenic transfer	Bioaccumulation
Primary producers																						
Duckweed (*Lemna, Spirodela* spp.)[1–3]						●↑											●↑					
Submerged plants (*Elodea, Myriophyllum, Utricularia* spp.)[4,5]						↓											●↓					
Cyanobacteria (*Microcystis, Synechoccus* spp.)[6–9]						↓			↑			↑					↓	↑	↑			
Green algae (*Chlamydomonas, Chlorella, Pseudokirchneriella, Scenedesmus* spp.)[9–21]						●↓↑					●						↓↑	↑		*		
Invertebrates																						
Daphnids (*Ceriodaphnia, Daphnia* spp.)[10,12–14,22–40]	↓	↓				↓↑	Δ			↓↑	↓↑	↑					↓↑			*		
Hydrozoans (*Hydra* sp.)[40]		↓	↓														Δ	Δ				
Dipterans (*Culex, Chaoborus* spp.)[41–43]		●		●			●			↓	●									*	*	↓
Chironomids (*Chironomus* spp.)[44–45]						↓				↓	↑					↓						
Caddisflies (*Sericostoma, Lepidostoma* spp.)[46–47]		↓			↓	●		↓			↑						↓	↓				
Coleoptera (*Cybister* sp.)[48]	↑	↓		↓																		
Isopods (*Asellus* sp.)[49]						●					●											
Amphipods (*Gammarus, Hyalella* spp.)[2,49–52]	↓	●	↓↑		↓	●↓	●	↓↑		↓	●↑			●↓↑								
Snails (*Potamopyrgus* sp.)[53]							●			●												
Bivalves (*Corbicula, Dreissena, Sphaerium* spp.)[49,54–58]		↓			●	●			●	●↓	●	●↑			●	●↑		↓		*		●
Annelids (*Lumbriculus, Tubifex* spp.)[49,59]			↓↑			●	●			●	●	●										
Fish																						
Sturgeon (*Acipenser transmontanus*)[58]		Δ																				●
Carp (*Barbodes, Carassius* spp.)[13,60]		↓	↓						↑													
Zebra fish (*Danio rerio*)[18,61–66]			↓			●	●		●↑			↑	↑	●↓								●
Other cyprinids (*Pimephales, Zacco* sp.)[14,25]	Δ								↑											*		●
Ricefish (*Oryzias* spp.)[56,250]	↑Δ					↓														*	*	
Perciformes (*Dicentrarchus, Oreochromis, Pomatoschistus, Symphysodon* sp.)[68–71]			↓								↓	↑		Δ		↑						↓

Note: Superscript numbers indicate the reference reporting these outcomes. Complete references are provided in the Supplementary data, Table S4[1]. Symbols indicate the direction of the effects observed, where an upward arrow (↑) indicates an increase in the effect, and a downward arrow (↓) indicates a reduction in the effect; a bullet (•) indicates no effect was detected; a triangle (Δ) indicates a significant change in the parameter (other than an increase or decrease); and an asterisk (*) indicates an effect was observed. The presence of multiple symbols indicate multiple conditions were observed across trials or experiments.

Published by Canadian Science Publishing

Ecosystem productivity and functioning

The mineralization of plastics can alter the concentrations of key nutrients and affect the growth and composition of primary producers of aquatic systems. Bacterial strains, fungi, microbial assemblages, and biofilm communities can mineralize microplastics and reduce their mass by up to 20% (Yuan et al. 2020). In the photic zone, DOC compounds are released from plastics into the water as a by-product of photodegradation, which in turn can stimulate the activity of heterotrophic bacteria that degrade natural and anthropogenic polymers (Romera-Castillo et al. 2018; Zhu et al. 2020). Heterotrophic bacterial communities originating from boreal humic lakes containing recalcitrant sources of carbon are effective at mineralizing and using plastic-derived carbon for cell growth. Once released, plastic-derived carbon has been found in the cell membrane fatty acids of mixotrophic algae and herbivorous cladocerans, demonstrating that the microbial community can transform polyethylene molecules into nutritional biomolecules and pass them onto higher trophic levels (Taipale et al. 2019). Under specific conditions and microbial assemblage, a small fraction of the microplastic load accumulating in aquatic systems can become a new source of carbon to their food webs.

The type and density of polymers found in freshwater systems can further influence nutrient availability. For example, some polymers (e.g., polyurethane foams and polyactic acid) promote nitrification and denitrification processes in sediments, whereas others (e.g., polyvinyl chloride) inhibit both processes (Seeley et al. 2020). Changes in denitrification activity depends on whether the plastic surface and anaerobic conditions combine to promote the growth of denitrifying bacteria (Li et al. 2020*a*), which can accelerate the conversion of nitrate to nitrite and subsequently to N_2O, NO, or ultimately N_2. As the biofilm disintegrates, it releases P and N from its plastic substrate (Chen et al. 2020). The presence of specific plastic polymers in the riverbed sediment along Brisbane River negatively correlated with total N and P levels, while higher abundances of microplastics positively influenced the total carbon concentration levels measured (He et al. 2020). Overall, the presence of some microplastic polymers will induce the formation of specific biofilms, which can alter nutrient ratios in freshwater systems.

The presence of plastics also affects the performance of aquatic primary producers and herbivores (Table 2). Increasing exposure to microplastics is linked to lower rates of leaf litter decomposition by caddisflies as well as by microbial and fungal detritivores (Seena et al. 2019; Lopez-Rojo et al. 2020). In the laboratory, exposure of freshwater algae to high doses of nanoplastics (<1 μm) reduced population growth, chlorophyll content, and photosynthetic activity (Besseling et al. 2014; Li et al. 2020*b*). Plastic-induced reductions in the growth, development, and reproduction of zooplankton and small invertebrates can limit the abundance of secondary producers (Besseling et al. 2014; Ziajahromi et al. 2018). Conversely, plastic leachates induced increased photosynthetic activity in some microalgal species (Chae et al. 2018), emphasizing the complexity of potential responses to these pollutants. Although this has not been studied directly, plastic-induced changes in the feeding behaviour and habitat use by consumers (Cedervall et al. 2012; Chae et al. 2020), changes in shoaling behaviour (Mattsson et al. 2017), and the performance of top predators (de Sa et al. 2015), could conceivably alter trophic interactions sufficiently to affect ecosystem productivity in areas of high microplastic concentrations.

Nutrient cycling

Small plastic particles (300–4400 μm) tend to aggregate with biogenic materials or suspended sediments (Mohlenkamp et al. 2018); thus, they are often colonized by microorganisms and accumulate metals or minerals. The microbiome biomass alters the density of the microplastics and can accelerate the sinking of nutrients and other chemicals bound to these particles (Long et al. 2015). Nevertheless, the formation of biofilms can be insufficient to sink particles. For example, in a stratified reservoir, particles remained buoyant until a seasonal mixing event resuspended enough organic materials, cyanobacteria, and iron particles from deeper waters to allow colonization and aggregation of these particles, thereby inducing the sinking of floating plastic debris (Leiser et al. 2020).

Impacts related to the buoyancy of microplastics are also being revealed in freshwater invertebrates. The ingestion of microplastics by the sessile cnidarian *Hydra attenuata* can reduce the animal's specific gravity to the point where it loses its ability to remain attached to substrate (Murphy and Quinn 2018). Similarly, in marine systems, faecal pellets from zooplankton were observed to sink more slowly when ingested plastics were released with their waste material (Cole et al. 2016). Changes in the buoyancy of particulate matter imply potentially broader impacts on sedimentation rates and nutrient cycling for profundal communities, which depend on nutrient inputs from the pelagic zone.

The highest concentrations of microplastics have been found in benthic sediments, where maximum values can exceed 10 000 particles·(kg dry mass)$^{-1}$ in rivers and 5000 particles·(kg dry mass)$^{-1}$ in lake sediments (Fig. 3; Supplementary data, Table S2[1]). Such concentrations can negatively affect the growth of chironomid larvae, reducing their body length and head capsule size (Ziajahromi et al. 2018), which could impact their bioturbation activities in areas of lakes that tend to be oxygen limited. When offered a choice, ephemerid mayfly larvae preferred to burrow amongst microplastic substrates instead of natural sediments (Gallitelli et al. 2021), and tubificid worms retained ingested microplastics for longer periods than other particulate materials within sediments (Hurley et al. 2017). These results further demonstrate that key bioturbating species interact distinctly with plastic contaminated sediments. Among these species, tubificid worms could prove to be important biomonitors of plastic pollution in benthic habitats; they can accumulate higher loads while suffering negligible effects from polyethylene particle exposure (Redondo-Hasselerharm et al. 2018; Scopetani et al. 2020).

Bivalves are key players in the shuttling of suspended plastics and associated contaminants to benthic habitats. Through filtration and biodeposition, they transfer micro- and nanoplastics from the water column to the sediments (Vaughan et al. 2017), thus acting as a biological pump (Carl et al. 2021). Their normal activities — which contribute significantly to nutrient dynamics in lakes and rivers (Vaughn and Hakenkamp 2001) — could be altered through exposure to plastics (Table 2). For example, bivalves have lower recruitment success (Sussarellu et al. 2016) and reduced filtration rates (Pedersen et al. 2020) in the presence of microplastics. Therefore, changes in bivalve biomass and functioning in response to plastic pollution could affect water column turbidity and alter the amount of organic and inorganic material deposited to benthic habitats. Because bivalves are among the organisms reported to have the longest internal retention of microplastic particles (Supplementary data, Table S3[1]) and are rather tolerant to plastic contamination (Magni et al. 2018), their bodies could also serve as incubation chambers for the desorption of toxic substances associated with plastic particles, but this hypothesis needs to be examined further (Hoellein et al. 2021).

Contaminant cycling

Smaller, weathered polymer particles have a greater surface area-to-volume ratio than larger, unweathered plastics, thereby offering proportionally more substrate for microbial colonization and the sorption of pollutants (Menéndez-Pedriza and Jaumot 2020). The ecotoxicity of microplastic particles varies depending on their characteristics (e.g., shape, size, crystallinity, chemical composition) and adsorbed substances (Lambert et al. 2017). Toxicological risks stem from the particles themselves, their biofilm (Rummel et al. 2017), the release of contaminants (persistent organic pollutants, heavy metals, pharmaceuticals) adsorbed by the plastic, and the leaching of additives or chemicals associated with its polymer matrix (Rochman et al. 2013; Menéndez-Pedriza and Jaumot 2020).

An important research gap is the influence of micro- and nano-sized plastics on contaminant transfer to animals. Under laboratory conditions, microplastics loaded with benzo[a]pyrene, a polycyclic aromatic hydrocarbon (PAH), were transferred trophically from contaminated *Artemia* nauplii to zebrafish, and showed evidence of desorption within the predator's intestine (Batel et al. 2016). This example demonstrates the possibility of plastic-mediated contaminant transfer within freshwater food webs. In some cases, co-exposure of plastics and pollutants increased contaminant transfer to experimental fish by as much as 2.6-times the concentration found in the head and viscera when exposed to bisphenol A alone (Chen et al. 2017). The co-exposure of microplastics with antidepressants also amplified the drug's bioaccumulation factor by 10-fold in freshwater fish (Qu et al. 2019). With over 200 organic chemicals being reported to associate with marine plastics in the field (Hong et al. 2017), it seems likely freshwater plastics would also sorb an array of chemicals, though few studies have thus far demonstrated it. Given that the majority of the contaminants able to sorb to plastics are mutagenic, carcinogenic, teratogenic, or endocrine disruptors (Alimi et al. 2018; Fred-Ahmadu et al. 2020), the ecotoxicological potential of small plastic particles ($<$5000 μm) merits increased attention.

Context dependencies challenge risk evaluation of the role of microplastics in contaminant cycling. The sorption–desorption response is governed by ambient conductivity, pH, salinity (Holmes et al. 2014; Llorca et al. 2018), and dissolved organic matter content in water (Chen et al. 2019*a*). For example, Ziajahromi et al. (2019) observed that polyethylene particles reduced the availability of a chemical insecticide (bifenthrin) to chironomid larvae, because most of the chemical compound was sorbed to the plastic. However, when the microplastics were present with organic carbon, the toxicity of the pesticide was no longer reduced, suggesting water chemistry and DOC concentrations can mediate the role of microplastics as chemical vectors.

In comparison with sediments, the sorption of trace metals (e.g., Cd, Cs, Zn) is lower (Holmes et al. 2014; Johansen et al. 2018; Besson et al. 2020), PAHs are equal or higher (Teuten et al. 2007; Bartonitz et al. 2020), and mercury concentrations are at least one order of magnitude higher on plastics (Graca et al. 2014). However, the sorption of several elements (Holmes et al. 2014) and antibiotics (Li et al. 2018; Guo and Wang 2019) varies with salinity, suggesting that microplastics in freshwater environments may be more effective vehicles for some metals and for the spread antibiotic resistance. Likewise, the microplastic-associated biofilm community can induce higher dissipation rates of contaminants (e.g., DDTs, PAHs) and enhance their biotransformation (Wu et al. 2017).

Integrating microplastics into limnology

Given the ubiquity, pervasiveness, and emerging impacts of microplastics in lakes and rivers, we contend that they should be recognized by limnologists as a distinct particle component whose concentration is an ecologically relevant parameter. A lexicon for plastics is slowly being developed (Haram et al. 2020), but standard definitions remain to be developed and consistently applied. To promote strong policies applied beyond the boundaries of a single nation or discipline, the adoption of an international framework for plastic debris is justified (Hartmann et al. 2019). One way to encourage limnologists to incorporate microplastics in their standardized sampling protocol is to integrate the topic into their lexicon (perhaps using a distinct term, e.g., "plaston", to distinguish this particle type from seston, plankton, or neuston).

Mitigating the environmental impacts of plastic pollution will require a multidisciplinary limnology that integrates, inter alia, socioeconomics (sources of microplastics), hydrology (physical dynamics of nonbiodegradable particles), environmental chemistry, and ecotoxicology. Proposed guidelines are emerging to direct microplastic research with the aim of increasing reproducibility and comparability between studies (Cowger et al. 2020). We recommend these as starting points for integrating microplastics research into limnology.

To develop accurate risk assessments that describe the impacts of microplastics independent of interactions with other aquatic stressors, we must have sufficient data to establish reliable exposure scenarios that can be repeated and examined under controlled conditions. Currently, there is a large discrepancy between the doses of microplastics used in laboratory assays and the levels recorded in the field (Cunningham and Sigwart 2019; Bucci et al. 2020; O'Connor et al. 2020).

Another issue with choosing environmentally relevant concentrations for experimental studies is that field concentrations are typically based on samples from a single matrix (e.g., water surface, benthic sediments), and therefore do not account for organisms interacting with more than one matrix. Exposures to 100 particles·L^{-1} or per kilogram of sediment are implicitly considered to be realistic scenarios (Cunningham and Sigwart 2019), but the highest concentrations recorded in a single compartment of the environment can be a misleading representation of the bioavailability of microplastics. For example, a fish with an ontogenetic diet shift (e.g., yellow perch, *Perca flavescens*) may feed on zooplankton in the water column during its larval stage; on benthic invertebrates on the sediments during its juvenile stage; and on small pelagic fish when it reaches sufficient adult size. Thus, throughout its life it interacts with multiple potential sources of plastic contamination in the water, sediments, and in contaminated prey, sometimes simultaneously. A useful goal would be the compilation of realistic natural exposures within a plastic budget, by isolating sources, pathways, and recipient organisms (Horton and Dixon 2018; Bank and Hansson 2019; Waldschlager et al. 2020; Hoellein and Rochman 2021).

To date, few water bodies have been monitored with sufficient resolution to encompass the various matrices in which organisms and microplastics interact (see Table 1), especially for those animals using multiple habitats during their life cycle. Despite increasing numbers of studies published on microplastic pollution in marine and inland waters (Fig. 2), there are repeated studies for only a few model organisms — mainly daphniid waterfleas, bivalves, and zebrafish (Table 2). Experimental studies have generally been conducted on individual organisms using smaller particles sizes and greater concentrations than what is recorded in the field, and these are presented as pristine particles or associated with a single sorbed contaminant. Studies incorporating multiple foodweb links as well as realistic concentrations and contaminant exposure are needed to understand how biota retain, bioaccumulate, biomagnify, and transfer plastics and their contaminants in aquatic food webs (Schiavo et al. 2018; Provencher et al. 2019; Wang et al. 2019). Only under these circumstances will it be possible to bridge the gap between laboratory and field studies. However, some conditions, such as controlling the colonization of plastics by microorganisms, may be more difficult to apply. We must explicitly account for the scope and limitations of conditions in each experiment to assess the risk posed by microplastics as an individual stressor.

Toward standard practices and biomonitoring

Limnologists routinely collect water, plankton, and sediment samples, along with a plethora of environmental parameters; the incorporation of microplastic sampling would reveal baseline levels of contamination as well as temporal and spatial differences in the risk of exposure to organisms. However, determination of the abundance and distribution of microplastics is constrained by our ability to capture and detect the particles in various environmental matrices. Consequently (owing to the limitations of standard plankton meshes, sediment sieves, or other equipment selected by researchers), 30% of samples collected in the water column to date have been limited to particles >300 μm, whereas 40% of sediment samples use sieves of ~60 μm (Supplementary data, Table S2[1]). Given that a filtration mesh pore size of 300 μm is typically used for processing water samples, this can lead to an underestimate of smaller microplastic concentrations by up to four orders of magnitude (Covernton et al. 2019). The fraction comprising nanoplastics (particles <1 μm) has certainly been underestimated for many reported samples.

The continuous disintegration of plastics into progressively smaller particles in the aquatic environment suggests that the abundance of microplastics would be several-fold more numerous as particle sizes decrease; a phenomenon demonstrated in samples from surface water (Kooi and Koelmans 2019), sediments (Yang et al. 2021), and biota (Roch et al. 2019). New analytical techniques allow more effective characterization of micropolymers under 20 μm (e.g., μ-Raman, RT-Raman) but they have been rarely used in the past because of time requirements, costs, and cross-laboratory reliability (Cabernard et al. 2018; Muller et al. 2020). Considering that aquatic invertebrates are reported to retain higher numbers of particles that can be translocated within their bodies, and suffered stronger negative effects when ingesting smaller particles <63 μm (Jeong et al. 2016; Ziajahromi et al. 2018; Franzellitti et al. 2019), researchers must strive to harmonize sampling techniques and quantify smaller fractions of plastics in natural environments.

There is a need to harmonize practices and enforce strong quality assurance and control measures to allow data to be reproducible and comparable across aquatic systems. Many authors have recommended guidelines and best practices to improve initial study design and ensure a minimum standard quality for microplastic data (Twiss 2016; Connors et al. 2017; Hung et al. 2021; Miller et al. 2021). Cowger et al. (2020) compiled a checklist of elements for researchers to provide comparable information. We summarized the main recommendations under nine steps.

(1) Provide basic information on the subject or environmental matrix of interest (e.g., watershed characteristics, limnological parameters, full taxonomic name), the timing and location (coordinates) of sampling.
   a. Collect duplicate or triplicate environmental samples.
   b. For sediment samples, basic characterization should be performed (% organic content, granulometry of riverbed) (Enders et al. 2019).
   c. Pilot studies should be performed to develop estimates of measurement precision (e.g., ensure sample sizes are adequate to address the research question).
(2) Describe sampling techniques and equipment used (e.g., mesh size, volume, surface area, flow rate, mass, duration of collection, depth) to allow conversions across samples measured.
(3) Report sufficiently detailed methodological steps of the extraction procedure to allow replication.
(4) Clarify the quality assurance and control procedures followed (e.g., cotton lab coats, washing/decontamination procedures, use of air filtration unit, application of blanks, use of positive/negative controls) and report contamination levels.
(5) Classify plastic particles based on their morphological features: colour, shape, and size, and provide definitions or reference for the classification criteria.
(6) Verify polymer composition (e.g., polystyrene, polyethylene, polyester, nylon) and provide details on the analytical technique, analysis employed, and data transformation (Andrade et al. 2020).
(7) Measure the efficacy of the lab methodology used by reporting retention rates after spiking subsamples with known polymers of relevant size and shape.
(8) Specify whether the results presented (tables, figures, text) were corrected for contamination or adjusted based on method efficacy retention rates of the methods, and account for the size range of the particles defined by each size classes.
(9) Declare main findings within the limits of the experiment and account for limitations of the study.

To account for potential spatiotemporal changes to plastic concentrations in the environment, biomonitoring should employ appropriate sentinel organisms. Potential taxa that have been identified to monitor the presence of particles of <300 μm sizes include mosses (Capozzi et al. 2018), bivalves (Su et al. 2018; Merzel et al. 2020), chironomids (Nel et al. 2018), tubificid worms (Redondo-Hasselerharm et al. 2018; Scopetani et al. 2020), and fishes (Su et al. 2019). Appropriate sentinels should be selected based on their relative abundance in different sectors (lakes, rivers, estuaries) and ecosystem compartments (benthos, plankton), their site fidelity, lifespan, and ability to tolerate contamination a few orders of magnitude higher than currently found in nature. It is also essential to know the organism's dose–response to microplastic pollution and whether its natural history characteristics influences uptake, retention, and egestion of these particles. Further studies are needed to establish how well the organism indicates ambient pollution conditions and thus whether they could truly serve as sentinels (Doucet et al. 2021; Hoellein et al. 2021).

Interactions between microplastics and multiple stressors: a major research gap

Given the burgeoning influence of anthropogenic stressors (e.g., climate change, urbanization, river impoundment, nutrient pollution, invasive species) on aquatic environments, synergy between stressors and the fate of plastics should be explored. Under climate change, for example, increased frequency of extreme weather events (e.g., strong winds or heavy precipitation) can exacerbate the propagation of microplastics globally via wind dispersion (Fig. 1A), increased surface runoff (Figs. 1B, 1C, and 1E), increased release of untreated waste water (Fig. 1D), or by increased flooding events and erosion, which can re-suspend some of the microplastics stored on shorelines or in riverbeds, and transport them downstream (McCormick and Hoellein 2016; Tibbetts et al. 2018; Hitchcock 2020; Ockelford et al. 2020). Bacteria, viruses, and invasive microorganisms colonizing plastic, could be distributed faster and farther downstream as a result of increased flow, thereby altering the distribution of potential pathogens (Hoellein et al. 2017) and invaders.

Researchers have begun to test the ecological impacts of microplastics under elevated temperatures, as expected under climate warming. As temperature increases beyond the optimal thermal regimes, key functional groups could become more sensitive to microplastic pollution. Under elevated temperatures, the tolerance of daphnids to microplastic exposure decreased by three to five orders of magnitude (Jaikumar et al. 2018), while short-term exposure to environmentally relevant concentrations altered the metabolism of the freshwater detritivore *Gammarus pulex* (Kratina et al. 2019).

Elevated water temperatures also amplify the colonization of suspended particles by microorganisms (Villanueva et al. 2011). Higher colonization rates by assemblages capable of mineralizing microplastics would enhance their role in degrading plastics (Fig. 1G). This fragmentation can be further exacerbated by stronger currents, more intense sunlight, thus more physical weathering of particles. Moreover, elevated water temperatures could conceivably select for stress-resistant communities and accentuate microplastic–biofilm interactions that influence nutrient and contaminant cycling. Finally, the relationships between climate change, sediment re-suspension, and microplastic pollution could conceivably lead to mutual reinforcement and magnified eutrophication in shallow lakes (Zhang et al. 2020). Clearly, the interactions between microplastics and other stressors in inland waters is a potentially fertile area of research highly relevant to limnologists.

Conclusions and recommendations

Microplastics are increasingly prevalent in the waters and sediments of the world's lakes and rivers. Given their ubiquity and environmental persistence, microplastics in the water and sediments of aquatic environments can be recognized as a distinct particle component whose concentration is an ecologically significant parameter that should be monitored routinely by limnologists. Standardized limnological protocols are needed to measure the concentrations of micro- and nanosized plastic particles. Such data are crucial for (*i*) environmental assessments; (*ii*) informing policy for managing plastic pollution; and (*iii*) building accurate models of habitat quality, the fate and transport of plastic pollution, and contaminant transfer to freshwater biota. To facilitate the integration of microplastics into limnological research, we propose the following objectives:

- Develop harmonized sampling and extraction protocols that account for the diverse forms of plastics, and that are applicable across environmental matrices, to generate comprehensible and reproducible data.
- Encourage multidisciplinary approaches to studying microplastic pollution (e.g., socioeconomics, landscape ecology, environmental chemistry, ecotoxicology), thereby fostering collaborations toward understanding the sources, transport, fluxes, and fate of plastic in inland waters. These efforts should include adopting standard definitions internationally and a universal lexicon for plastic debris.
- Identify appropriate model sentinel species to monitor the spread, distribution, and accumulation of plastics, and to assess risks on different components of aquatic ecosystems.
- Create budget models for plastics to estimate the true bioavailability of plastics to organisms, and include associated pollutants and organisms in ecotoxicological studies to bridge the gap between field and laboratory exposure conditions.
- Investigate synergistic interactions between aquatic biota, microplastic pollution and other anthropogenic stressors (e.g., climate change, physical habitat/landscape/hydrological alterations, nutrient pollution, chemical pollution).

Microplastics in aquatic systems should not be the exclusive domain of ecotoxicologists, but should be recognized by aquatic scientists in general — and thus be included in the fundamental training of students in the field. Limnology courses and workshops are the most obvious starting points for encouraging best practices in monitoring and reporting microplastic concentrations and for promoting an understanding of their significance. However, interdisciplinary communication and analyses are needed to set the issue of microplastics in inland waters into a more global context.

Acknowledgements

McGill University is located on land which has long served as a site of meeting and exchange amongst Indigenous peoples, including the Haudenosaunee and Anishinabeg nations. We honour, recognize, and respect these nations as the traditional stewards of the lands and waters where our work has been conducted. We would like to thank the following students for their assistance in compiling literature data: Duncan Wang, Wendy Huang, Alex Crew, Michelle Cheng, and Helen Yu. We also extend a special thanks to Hélène Pfister and Jessie Ye for their help in drafting tables and figures for the manuscript. G.D. received financial support from the Natural Sciences and Engineering Research Council of Canada CREATE Ecolac Program, as well as the Arthur Willey Memorial Fellowship, Trottier Graduate Fellowship, and the Lawrence Light Fellowship; A.R. acknowledges support from the McGill Trottier Institute for Science and Public Policy; I.G.E. acknowledges support from the Canada Research Chairs program.

References

Alfonso, M.B., Scordo, F., Seitz, C., Manstretta, G.M.M., Ronda, A.C., Arias, A.H., et al. 2020. First evidence of microplastics in nine lakes across Patagonia (South America). Sci. Total Environ. **733**: 139385. doi:10.1016/j.scitotenv.2020.139385. PMID:32446091.

Alimi, O.S., Budarz, J.F., Hernandez, L.M., and Tufenkji, N. 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. **52**(4): 1704–1724. doi:10.1021/acs.est.7b05559. PMID:29265806.

Al-Jaibachi, R., Cuthbert, R.N., and Callaghan, A. 2019. Examining effects of ontogenic microplastic transference on *Culex* mosquito mortality and adult weight. Sci. Total Environ. **651**: 871–876. doi:10.1016/j.scitotenv.2018.09.236. PMID:30253369.

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Jimenez, P.D., Simonneau, A., et al. 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. **12**(5): 339–344. doi:10.1038/s41561-019-0335-5.

Anderson, J.C., Park, B.J., and Palace, V.P. 2016. Microplastics in aquatic environments: Implications for Canadian ecosystems. Environ. Pollut. **218**: 269–280. doi:10.1016/j.envpol.2016.06.074. PMID:27431693.

Andrade, J.M., Ferreiro, B., López-Mahía, P., and Muniategui-Lorenzo, S. 2020. Standardization of the minimum information for publication of infrared-related data when microplastics are characterized. Mar. Pollut. Bull. **154**: 111035. doi:10.1016/j.marpolbul.2020.111035. PMID:32174488.

Andrady, A.L. 2015. Persistence of plastic litter in the oceans. *In* Marine anthropogenic litter. *Edited by* M. Bergmann, L. Gutow, and M. Klages. Springer. pp. 57–72.

Arias-Andres, M., Kettner, M.T., Miki, T., and Grossart, H.P. 2018. Microplastics: New substrates for heterotrophic activity contribute to altering organic matter cycles in aquatic ecosystems. Sci. Total Environ. **635**: 1152–1159. doi:10.1016/j.scitotenv.2018.04.199. PMID:29710570.

Au, S.Y., Bruce, T.F., Bridges, W.C., and Klaine, S.J. 2015. Responses of *Hyalella azteca* to acute and chronic microplastic exposures. Environ. Toxicol. Chem. **34**(11): 2564–2572. doi:10.1002/etc.3093. PMID:26042578.

Avio, C.G., Gorbi, S., Milan, M., Benedetti, M., Fattorini, D., d'Errico, G., et al. 2015. Pollutants bioavailability and toxicological risk from microplastics to marine mussels. Environ. Pollut. **198**: 211–222. doi:10.1016/j.envpol.2014.12.021. PMID:25637744.

Azevedo-Santos, V.M., Goncalves, G.R.L., Manoel, P.S., Andrade, M.C., Lima, F.P., and Pelicice, F.M. 2019. Plastic ingestion by fish: A global assessment. Environ. Pollut. **255**: 112994. doi:10.1016/j.envpol.2019.112994. PMID:31541837.

Baldwin, A.K., Spanjer, A.R., Rosen, M.R., and Thom, T. 2020. Microplastics in Lake Mead National Recreation Area, USA: Occurrence and biological uptake. PLoS ONE, **15**(5): e0228896. doi:10.1371/journal.pone.0228896. PMID:32365121.

Bancone, C.E.P., Turner, S.D., Ivar do Sul, J.A., and Rose, N.L. 2020. The paleoecology of microplastic contamination. Front. Environ. Sci. **8**: 574008. doi:10.3389/fenvs.2020.574008.

Bank, M.S., and Hansson, S.V. 2019. The Plastic Cycle: A novel and holistic paradigm for the Anthropocene. Environ. Sci. Technol. **53**(13): 7177–7179. doi:10.1021/acs.est.9b02942. PMID:31198029.

Barnosky, A.D. 2014. Palaeontological evidence for defining the Anthropocene. *In* Stratigraphical Basis for the Anthropocene. *Edited by* C.N. Waters, J.A. Zalasiewicz, M. Williams, M. Ellis, and A.M. Snelling. Geological Society of London. pp. 149–165.

Barrows, A.P.W., Christiansen, K.S., Bode, E.T., and Hoellein, T.J. 2018. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. Water Res. **147**: 382–392. doi:10.1016/j.watres.2018.10.013. PMID:30336341.

Bartonitz, A., Anyanwu, I.N., Geist, J., Imhof, H.K., Reichel, J., Graßmann, J., et al. 2020. Modulation of PAH toxicity on the freshwater organism *G. roeseli* by microparticles. Environ. Pollut. **260**: 113999. doi:10.1016/j.envpol.2020.113999. PMID:32018198.

Batel, A., Linti, F., Scherer, M., Erdinger, L., and Braunbeck, T. 2016. Transfer of benzo a pyrene from microplastics to *Artemia nauplii* and further to zebrafish via a trophic food web experiment: CYP1A induction and visual tracking of persistent organic pollutants. Environ. Toxicol. Chem. **35**(7): 1656–1666. doi:10.1002/etc.3361. PMID:26752309.

Battin, T.J., Kaplan, L.A., Denis Newbold, J., and Hansen, C.M.E. 2003. Contributions of microbial biofilms to ecosystem processes in stream mesocosms. Nature, **426**: 439–442. doi:10.1038/nature02152. PMID:14647381.

Bergmann, M., Mutzel, S., Primpke, S., Tekman, M.B., Trachsel, J., and Gerdts, G. 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. **5**(8): eaax1157. doi:10.1126/sciadv.aax1157. PMID:31453336.

Besseling, E., Wang, B., Lurling, M., and Koelmans, A.A. 2014. Nanoplastic affects growth of *S. obliquus* and reproduction of *D. magna*. Environ. Sci. Technol. **48**(20): 12336–12343. doi:10.1021/es503001d. PMID:25268330.

Besson, M., Jacob, H., Oberhaensli, F., Taylor, A., Swarzenski, P.W., and Metian, M. 2020. Preferential adsorption of Cd, Cs and Zn onto virgin polyethylene microplastic versus sediment particles. Mar. Pollut. Bull. **156**: 111223. doi:10.1016/j.marpolbul.2020.111223. PMID:32510371.

Boucher, J., and Friot, D. 2017. Primary microplastics in the oceans: a global evaluation of sources. IUCN Gland, Switzerland.

Boyle, D., Catarino, A.I., Clark, N.J., and Henry, T.B. 2020. Polyvinyl chloride (PVC) plastic fragments release Pb additives that are bioavailable in zebrafish. Environ. Pollut. **263**: 114422. doi:10.1016/j.envpol.2020.114422. PMID:32244159.

Browne, M.A. 2015. Sources and pathways of microplastics to habitats. *In* Marine anthropogenic litter. *Edited by* M. Bergmann, L. Gutow, and M. Klages. Springer. pp. 229–244.

Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M., and Thompson, R.C. 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L). Environ. Sci. Technol. **42**(1 3): 5026–5031. doi:10.1021/es800249a. PMID:18678044.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., and Thompson, R. 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. **45**(21): 9175–9179. doi:10.1021/es201811s. PMID:21894925.

Bucci, K., Tulio, M., and Rochman, C.M. 2020. What is known and unknown about the effects of plastic pollution: a meta-analysis and systematic review. Ecol. Appl. **30**(2): e02044. doi:10.1002/eap.2044. PMID:31758826.

Cabernard, L., Roscher, L., Lorenz, C., Gerdts, G., and Primpke, S. 2018. Comparison of Raman and Fourier transform infrared spectroscopy for the quantification of microplastics in the aquatic environment. Environ. Sci. Technol. **52**(22): 13279–13288. doi:10.1021/acs.est.8b03438. PMID:30350953.

Capozzi, F., Carotenuto, R., Giordano, S., and Spagnuolo, V. 2018. Evidence on the effectiveness of mosses for biomonitoring of microplastics in fresh water environment. Chemosphere, **205**: 1–7. doi:10.1016/j.chemosphere.2018.04.074. PMID:29677573.

Carl, V.C., Lieke, M., Brecht, V., Henk, V., and Tom, M. 2021. The biological plastic pump: evidence from a local case study using blue mussel and infaunal benthic communities. Environ. Pollut. **274**: 115825. doi:10.1016/j.envpol.2020.115825.

Castañeda, R.A., Avlijas, S., Simard, M.A., and Ricciardi, A. 2014. Microplastic pollution in St. Lawrence River sediments. Can. J. Fish. Aquat. Sci. **71**(12): 1767–1771. doi:10.1139/cjfas-2014-0281.

Cedervall, T., Hansson, L.-A., Lard, M., Frohm, B., and Linse, S. 2012. Food chain transport of nanoparticles affects behaviour and fat metabolism in fish. PLoS ONE, **7**: e32254. doi:10.1371/journal.pone.0032254. PMID:22384193.

Chae, Y., Kim, D., Kim, S.W., and An, Y.J. 2018. Trophic transfer and individual impact of nano-sized polystyrene in a four-species freshwater food chain. Sci. Rep. **8**: 284. doi:10.1038/s41598-017-18849-y. PMID:29321604.

Chae, Y., Hong, S.H., and An, Y.J. 2020. Photosynthesis enhancement in four marine microalgal species exposed to expanded polystyrene leachate. Ecotoxicol. Environ. Saf. **189**: 109936. doi:10.1016/j.ecoenv.2019.109936.

Chen, C.Z., Chen, L., Yao, Y., Artigas, F., Huang, Q.H., and Zhang, W. 2019*a*. Organotin release from polyvinyl chloride microplastics and concurrent photodegradation in water: impacts from salinity, dissolved organic matter, and light exposure. Environ. Sci. Technol. **53**(18): 10741–10752. doi:10.1021/acs.est.9b03428. PMID:31403792.

Chen, Q.Q., Yin, D.Q., Jia, Y.L., Schiwy, S., Legradi, J., Yang, S.Y., and Hollert, H. 2017. Enhanced uptake of BPA in the presence of nanoplastics can lead to neurotoxic effects in adult zebrafish. Sci. Total Environ. **609**: 1312–1321. doi:10.1016/j.scitotenv.2017.07.144. PMID:28793400.

Chen, X.C., Xiong, X., Jiang, X.M., Shi, H.H., and Wu, C.X. 2019*b*. Sinking of floating plastic debris caused by biofilm development in a freshwater lake. Chemosphere, **222**: 856–864. doi:10.1016/j.chemosphere.2019.02.015. PMID:30743237.

Chen, X.C., Chen, X.F., Zhao, Y.H., Zhou, H., Xiong, X., and Wu, C.X. 2020. Effects of microplastic biofilms on nutrient cycling in simulated freshwater systems. Sci. Total Environ. **719**: 137276. doi:10.1016/j.scitotenv.2020.137276. PMID:32114222.

Cole, M., Lindeque, P.K., Fileman, E., Clark, J., Lewis, C., Halsband, C., and Galloway, T.S. 2016. Microplastics alter the properties and sinking rates of zooplankton faecal pellets. Environ. Sci. Technol. **50**(6): 3239–3246. doi:10.1021/acs.est.5b05905. PMID:26905979.

Collard, F., Gasperi, J., Gilbert, B., Eppe, G., Azimi, S., Rocher, V., and Tassin, B. 2018. Anthropogenic particles in the stomach contents and liver of the freshwater fish *Squalius cephalus*. Sci. Total Environ. **643**: 1257–1264. doi:10.1016/j.scitotenv.2018.06.313. PMID:30189542.

Connors, K.A., Dyer, S.D., and Belanger, S.E. 2017. Advancing the quality of environmental microplastic research. Environ. Toxicol. Chem. **36**(7): 1697–1703. doi:10.1002/etc.3829. PMID:28543985.

Corcoran, P.L., Norris, T., Ceccanese, T., Walzak, M.J., Helm, P.A., and Marvin, C.H. 2015. Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment record. Environ. Pollut. **204**: 17–25. doi:10.1016/j.envpol.2015.04.009. PMID:25898233.

Courtene-Jones, W., Quinn, B., Ewins, C., Gary, S.F., and Narayanaswamy, B.E. 2019. Consistent microplastic ingestion by deep-sea invertebrates over the last four decades (1976–2015), a study from the North East Atlantic. Environ. Pollut. **244**: 503–512. doi:10.1016/j.envpol.2018.10.090. PMID:30366298.

Covernton, G.A., Pearce, C.M., Gurney-Smith, H.J., Chastain, S.G., Ross, P.S., Dower, J.F., and Dudas, S.E. 2019. Size and shape matter: a preliminary analysis of microplastic sampling technique in seawater studies with implications for ecological risk assessment. Sci. Total Environ. **667**: 124–132. doi:10.1016/j.scitotenv.2019.02.346. PMID:30826673.

Covernton, G.A., Davies, H.L., Cox, K.D., El-Sabaawi, R., Juanes, F., Dudas, S.E., and Dower, J.F. 2021. A Bayesian analysis of the factors determining microplastics ingestion in fishes. J. Hazard. Mater. **4 13**: 125405. doi:10.1016/j.jhazmat.2021.125405. PMID:33930957.

Cowger, W., Booth, A., Hamilton, B., Thaysen, C., Primpke, S., Munno, K., et al. 2020. Reporting guidelines to increase the reproducibility and comparability of research on microplastics. Appl. Spectrosc. **74**(9): 1066–1077. doi:10.1177/0003702820930292. PMID:32394727.

Crawford, C.B., and Quinn, B. 2016. Microplastic pollutants. Elsevier.

Crew, A., Gregory-Eaves, I., and Ricciardi, A. 2020. Distribution, abundance, and diversity of microplastics in the upper St. Lawrence River. Environ. Pollut. **260**: 113994. doi:10.1016/j.envpol.2020.113994. PMID:31991358.

Cummins, K.W. 1974. Structure and function of stream ecosystems. BioScience, **24**(11): 631–641. doi:10.2307/1296676.

Cunningham, E.M., and Sigwart, J.D. 2019. Environmentally accurate microplastic levels and their absence from exposure studies. Integr. Comp. Biol. **59**(6): 1485–1496. doi:10.1093/icb/icz068. PMID:31127301.

de Sa, L.C., Luis, L.G., and Guilhermino, L. 2015. Effects of microplastics on juveniles of the common goby (*Pomatoschistus microps*): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. Environ. Pollut. **196**: 359–362. doi:10.1016/j.envpol.2014.10.026. PMID:25463733.

Doucet, C.V., Labaj, A.L., and Kurek, J. 2021. Microfiber content in freshwater mussels from rural tributaries of the Saint John River, Canada. Water Air Soil Pollut. **232**(1): 32. doi:10.1007/s11270-020-04958-4.

Dris, R., Gasperi, J., Saad, M., Mirande, C., and Tassin, B. 2016. Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? Mar. Pollut. Bull. **104**(1–2): 290–293. doi:10.1016/j.marpolbul.2016.01.006. PMID:26787549.

Eckert, E.M., Di Cesare, A., Kettner, M.T., Arias-Andres, M., Fontaneto, D., Grossart, H.P., and Corno, G. 2018. Microplastics increase impact of treated wastewater on freshwater microbial community. Environ. Pollut. **234**: 495–502. doi:10.1016/j.envpol.2017.11.070. PMID:29216487.

Edo, C., Gonzalez-Pleiter, M., Leganes, F., Fernandez-Pinas, F., and Rosal, R. 2020. Fate of microplastics in wastewater treatment plants and their environmental dispersion with effluent and sludge. Environ. Pollut. **259**: 113837. doi:10.1016/j.envpol.2019.113837. PMID:31884217.

Eerkes-Medrano, D., and Thompson, R. 2018. Occurrence, fate, and effect of microplastics in freshwater systems. *In* Microplastic contamination in aquatic environments: an emerging matter of environmental urgency. *Edited by* E.Y. Zhang. Elsevier. pp. 95–132.

Ehlers, S.M., Manz, W., and Koop, J.H.E. 2019. Microplastics of different characteristics are incorporated into the larval cases of the freshwater caddisfly *Lepidostoma basale*. Aquat. Biol. **28**: 67–77. doi:10.3354/ab00711.

Ehlers, S.M., Al Najjar, T., Taupp, T., and Koop, J.H.E. 2020. PVC and PET microplastics in caddisfly (*Lepidostoma basale*) cases reduce case stability. Environ. Sci. Pollut. Res. Int. **27**(18): 22380–22389. doi:10.1007/s11356-020-08790-5. PMID:32314284.

Elizalde-Velazquez, A., Carcano, A.M., Crago, J., Green, M.J., Shah, S.A., and Canas-Carrell, J.E. 2020. Translocation, trophic transfer, accumulation and depuration of polystyrene microplastics in *Daphnia magna* and *Pimephales promelas*. Environ. Pollut. **259**: 113937. doi:10.1016/j.envpol.2020.113937. PMID:31952101.

Enders, K., KäPpler, A., Biniasch, O., Feldens, P., Stollberg, N., Lange, X., et al. 2019. Tracing microplastics in aquatic environments based on sediment analogies. Sci. Rep. **9**((1): 1–15. doi:10.1038/s41598-019-50508-2. PMID:30626917.

Enyoh, C.E., Verla, A.W., Verla, E.N., Ibe, F.C., and Amaobi, C.E. 2019. Airborne microplastics: a review study on method for analysis, occurrence, movement and risks. Environ. Monit. Assess. **191**(11): 668. doi:10.1007/s10661-019-7842-0. PMID:31650348.

Fan, Y.J., Zheng, K., Zhu, Z.W., Chen, G.S., and Peng, X.Z. 2019. Distribution, sedimentary record, and persistence of microplastics in the Pearl River catchment, China. Environ. Pollut. **251**: 862–870. doi:10.1016/j.envpol.2019.05.056. PMID:31234251.

Farrell, P., and Nelson, K. 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ. Pollut. **177**: 1–3. doi:10.1016/j.envpol.2013.01.046. PMID:23434827.

Fendall, L.S., and Sewell, M.A. 2009. Contributing to marine pollution by washing your face: Microplastics in facial cleansers. Mar. Pollut. Bull. **58**(8): 1225–1228. doi:10.1016/j.marpolbul.2009.04.025. PMID:19481226.

Feng, L.J., Sun, X.D., Zhu, F.P., Feng, Y., Duan, J.L., Xiao, F., et al. 2020. Nanoplastics promote microcys tin synthesis and release from cyanobacterial *Microcystis aeruginosa*. Environ. Sci. Technol. **54**(6): 3386–3394. doi:10.1021/acs.est.9b06085. PMID:31961660.

Foley, C.J., Feiner, Z.S., Malinich, T.D., and Hook, T.O. 2018. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Sci. Total Environ. **631–632**: 550–559. doi:10.1016/j.scitotenv.2018.03.046. PMID:29529442.

Franzellitti, S., Canesi, L., Auguste, M., Wathsala, R., and Fabbri, E. 2019. Microplastic exposure and effects in aquatic organisms: A physiological perspective. Environ. Toxicol. Pharmacol. **68**: 37–51. doi:10.1016/j.etap.2019.03.009. PMID:30870694.

Fred-Ahmadu, O.H., Bhagwat, G., Oluyoye, I., Benson, N.U., Ayejuyo, O.O., and Palanisami, T. 2020. Interaction of chemical contaminants with microplastics: Principles and perspectives. Sci. Total Environ. **706**: 135978. doi:10.1016/j.scitotenv.2019.135978. PMID:31864138.

Fueser, H., Mueller, M.T., Weiss, L., Hoss, S., and Traunspurger, W. 2019. Ingestion of microplastics by nematodes depends on feeding strategy and buccal cavity size. Environ. Pollut. **255**: 113227. doi:10.1016/j.envpol.2019.113227. PMID:31574393.

Gallitelli, L., Cera, A., Cesarini, G., Pietrelli, L., and Scalici, M. 2021. Preliminary indoor evidences of microplastic effects on freshwater benthic macroinvertebrates. Sci. Rep. **11**(1): 720. doi:10.1038/s41598-020-80606-5. PMID:33436879.

Gambardella, C., Morgana, S., Bramini, M., Rotini, A., Manfra, L., Migliore, L., et al. 2018. Ecotoxicological effects of polystyrene microbeads in a battery of marine organisms belonging to different trophic levels. Mar. Environ. Res. **141**: 313–321. doi:10.1016/j.marenvres.2018.09.023. PMID:30274720.

GESAMP. 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. IMO, London.

Geyer, R., Jambeck, J.R., and Law, K.L. 2017. Production, use, and fate of all plastics ever made. Sci. Adv. **3**(7): e1700782. doi:10.1126/sciadv.1700782. PMID:28776036.

Graca, B., Bełdowska, M., Wrzesień, P., and Zgrundo, A. 2014. Styrofoam debris as a potential carrier of mercury within ecosystems. Environ. Sci. Pollut. Res. Int. **21**(3): 2263–2271. doi:10.1007/s11356-013-2153-4. PMID:24057963.

Green, D.S. 2016. Effects of microplastics on European flat oysters, *Ostrea edulis* and their associated benthic communities. Environ. Pollut. **216**: 95–103. doi:10.1016/j.envpol.2016.05.043. PMID:27239693.

Guo, X., and Wang, J.L. 2019. Sorption of antibiotics onto aged microplastics in freshwater and seawater. Mar. Pollut. Bull. **149**: 110511. doi:10.1016/j.marpolbul.2019.110511. PMID:31425847.

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., and Purnell, P. 2018. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. **344**: 179–199. doi:10.1016/j.jhazmat.2017.10.014. PMID:29035713.

Haram, L.E., Carlton, J.T., Ruiz, G.M., and Maximenko, N.A. 2020. A plasticene lexicon. Mar. Pollut. Bull. **150**: 110714. doi:10.1016/j.marpolbul.2019.110714. PMID:31753559.

Hartmann, N.B., Huffer, T., Thompson, R.C., Hassellov, M., Verschoor, A., Daugaard, A.E., et al. 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. **53**(3): 1039–1047. doi:10.1021/acs.est.8b05297. PMID:30608663.

He, B.B., Goonetilleke, A., Ayoko, G.A., and Rintoul, L. 2020. Abundance, distribution patterns, and identification of microplastics in Brisbane River sediments, Australia. Sci. Total Environ. **700**: 134467. doi:10.1016/j.scitotenv.2019.134467. PMID:31629260.

Hitchcock, J.N. 2020. Storm events as key moments of microplastic contamination in aquatic ecosystems. Sci. Total Environ. **734**: 139436. doi:10.1016/j.scitotenv.2020.139436. PMID:32470660.

Hoang, T.C., and Felix-Kim, M. 2020. Microplastic consumption and excretion by fathead minnows (*Pimephales promelas*): Influence of particles size and body shape of fish. Sci. Total Environ. **704**: 135433. doi:10.1016/j.scitotenv.2019.135433. PMID:31896224.

Hodgson, D.J., Brechon, A.L., and Thompson, R.C. 2018. Ingestion and fragmentation of plastic. carrier bags by the amphipod *Orchestia gammarellus*: Effects of plastic type and fouling load. Mar. Pollut. Bull. **127**: 154–159. doi:10.1016/j.marpolbul.2017.11.057. PMID:29475648.

Hoellein, T.J., and Rochman, C.M. 2021. The "plastic cycle": a watershed-scale model of plastic pools and fluxes. Front. Ecol. Environ. **19**(3): 176–183. doi:10.1002/fee.2294.

Hoellein, T.J., McCormick, A.R., Hittie, J., London, M.G., Scott, J.W., and Kelly, J.J. 2017. Longitudinal patterns of microplastic concentration and bacterial assemblages in surface and benthic habitats of an urban river. Freshw. Sci. **36**(3): 491–507. doi:10.1086/693012.

Hoellein, T., Rovegno, C., Uhrin, A.V., Johnson, E., and Herring, C. 2021. Microplastics in invasive freshwater mussels (*Dreissena* sp.): Spatiotemporal variation and occurrence with chemical contaminants. Front. Mar. Sci. **8**: 821. doi:10.3389/fmars.2021.690401.

Holland, E.R., Mallory, M.L., and Shutler, D. 2016. Plastics and other anthropogenic debris in freshwater birds from Canada. Sci. Total Environ. **571**: 251–258. doi:10.1016/j.scitotenv.2016.07.158. PMID:27476006.

Holmes, L.A., Turner, A., and Thompson, R.C. 2014. Interactions between trace metals and plastic production pellets under estuarine conditions. Mar. Chem. **167**: 25–32. doi:10.1016/j.marchem.2014.06.001.

Hong, S.H., Shim, W.J., and Hong, L. 2017. Methods of analysing chemicals associated with microplastics: a review. Anal. Methods, **9**(9): 1361–1368. doi:10.1039/C6AY02971J.

Horton, A.A., and Dixon, S.J. 2018. Microplastics: An introduction to environmental transport processes. Wiley Interdiscipl. Rev. Water, **5**(2): e1268. doi:10.1002/wat2.1268.

Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., and Svendsen, C. 2017. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. **586**: 127–141. doi:10.1016/j.scitotenv.2017.01.190. PMID:28169032.

Hung, C., Klasios, N., Zhu, X., Sedlak, M., Sutton, R., and Rochman, C.M. 2021. Methods matter: methods for sampling microplastic and other anthropogenic particles and their implications for monitoring and ecological risk assessment. Integr. Environ. Assess. Manage. **17**(1): 282–291. doi:10.1002/ieam.4325. PMID:32770796.

Hurley, R.R., Woodward, J.C., and Rothwell, J.J. 2017. Ingestion of microplastics by freshwater tubifex worms. Environ. Sci. Technol. **51**(21): 12844–12851. doi:10.1021/acs.est.7b03567. PMID:29019399.

Iannilli, V., Corami, F., Grasso, P., Lecce, F., Buttinelli, M., and Setini, A. 2020. Plastic abundance and seasonal variation on the shorelines of three volcanic lakes in Central Italy: can amphipods help detect contamination? Environ. Sci. Pollut. Res. Int. **27**(13): 14711–14722. doi:10.1007/s11356-020-07954-7. PMID:32052329.

Iyare, P.U., Ouki, S.K., and Bond, T. 2020. Microplastics removal in wastewater treatment plants: a critical review. Environ. Sci. Water Res. Technol. **6**(10): 2664–2675. doi:10.1039/D0EW00397B.

Jabeen, K., Su, L., Li, J.N., Yang, D.Q., Tong, C.F., Mu, J.L., and Shi, H.H. 2017. Microplastics and mesoplastics in fish from coastal and fresh waters of China. Environ. Pollut. **221**: 141–149. doi:10.1016/j.envpol.2016.11.055. PMID:27939629.

Jaikumar, G., Baas, J., Brun, N.R., Vijver, M.G., and Bosker, T. 2018. Acute sensitivity of three Cladoceran species to different types of microplastics in combination with thermal stress. Environ. Pollut. **239**: 733–740. doi:10.1016/j.envpol.2018.04.069. PMID:29723823.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al. 2015. Marine pollution. Plastic waste inputs from land into the ocean. Science, **347**(6223): 768–771. doi:10.1126/science.1260352. PMID:25678662.

Jang, M., Shim, W.J., Han, G.M., Song, Y.K., and Hong, S.H. 2018. Formation of microplastics by polychaetes (*Marphysa sanguinea*) inhabiting expanded polystyrene marine debris. Mar. Pollut. Bull. **131**: 365–369. doi:10.1016/j.marpolbul.2018.04.017. PMID:29886959.

Jeong, C.B., Won, E.J., Kang, H.M., Lee, M.C., Hwang, D.S., Hwang, U.K., et al. 2016. Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38 activation in the monogonont rotifer (*Brachionus koreanus*). Environ. Sci. Technol. **50**(16): 8849–8857. doi:10.1021/acs.est.6b01441. PMID:27438693.

Ji, X., Ma, Y., Zeng, G., Xu, X., Mei, K., Wang, Z., et al. 2021. Transport and fate of microplastics from riverine sediment dredge piles: Implications for disposal. J. Hazard. Mater. **404**: 124132. doi:10.1016/j.jhazmat.2020.124132. PMID:33022529.

Johansen, M.P., Prentice, E., Cresswell, T., and Howell, N. 2018. Initial data on adsorption of Cs and Sr to the surfaces of microplastics with biofilm. J. Environ. Radioact. **190–191**: 130–133. doi:10.1016/j.jenvrad.2018.05.001. PMID:29787932.

Kaiser, D., Kowalski, N., and Waniek, J.J. 2017. Effects of biofouling on the sinking behavior of microplastics. Environ. Res. Lett. **12**(12): 124003. doi:10.1088/1748-9326/aa8e8b.

Kalcikova, G., Alic, B., Skalar, T., Bundschuh, M., and Gotvajn, A.Z. 2017. Wastewater treatment plant effluents as source of cosmetic polyethylene microbeads to freshwater. Chemosphere **188**: 25–31. doi:10.1016/j.chemosphere.2017.08.131.

Kettner, M.T., Rojas-Jimenez, K., Oberbeckmann, S., Labrenz, M., and Grossart, H.P. 2017. Microplastics alter composition of fungal communities in aquatic ecosystems. Environ. Microbiol. **19**(11): 4447–4459. doi:10.1111/1462-2920.13891. PMID:28805294.

Kim, S.W., Chae, Y., Kim, D., and An, Y.J. 2019. Zebrafish can recognize microplastics as inedible materials: Quantitative evidence of ingestion behavior. Sci. Total Environ. **649**: 156–162. doi:10.1016/j.scitotenv.2018.08.310. PMID:30173025.

Kooi, M., and Koelmans, A.A. 2019. Simplifying microplastic via continuous probability distributions for size, shape and density. Environ. Sci. Technol. Lett. **6**(9): 551–557. doi:10.1021/acs.estlett.9b00379.

Kratina, P., Watts, T.J., Green, D.S., Kordas, R.L., and O'Gorman, E.J. 2019. Interactive effects of warming and microplastics on metabolism but not feeding rates of a key freshwater detritivore. Environ. Pollut. **255**: 113259. doi:10.1016/j.envpol.2019.113259. PMID:31563782.

Lambert, S., Scherer, C., and Wagner, M. 2017. Ecotoxicity testing of microplastics: Considering the heterogeneity of physicochemical properties. Integr. Environ. Assess. Manage. **13**(3): 470–475. doi:10.1002/ieam.1901. PMID:28440923.

Lamberti, G.A., and Gregory, S.V. 2007. CPOM Transport, Retention, and Measurement. *In* Methods in stream ecology. 2nd ed. *Edited by* F.R. Hauer and G.A. Lamberti. Academic Press, San Diego, Calif. pp. 273–289.

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., et al. 2014. The Danube so colourful: A potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environ. Pollut. **188**: 177–181. doi:10.1016/j.envpol.2014.02.006. PMID:24602762.

Leiser, R., Wu, G.M., Neu, T.R., and Wendt-Potthoff, K. 2020. Biofouling, metal sorption and aggregation are related to sinking of microplastics in a stratified reservoir. Water Res. **176**: 115748. doi:10.1016/j.watres.2020.115748. PMID:32247995.

Lenaker, P.L., Baldwin, A.K., Corsi, S.R., Mason, S.A., Reneau, P.C., and Scott, J.W. 2019. Vertical distribution of microplastics in the water column and surficial sediment from the Milwaukee River Basin to Lake

Michigan. Environ. Sci. Technol. **53**(21): 12227–12237. doi:10.1021/acs.est.9b03850. PMID:31618011.

Leslie, H.A., Brandsma, S.H., van Velzen, M.J.M., and Vethaak, A.D. 2017. Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. Environ. Int. **101**: 133–142. doi:10.1016/j.envint.2017.01.018. PMID:28143645.

Li, J., Zhang, K.N., and Zhang, H. 2018. Adsorption of antibiotics on microplastics. Environ. Pollut. **237**: 460–467. doi:10.1016/j.envpol.2018.02.050. PMID:29510365.

Li, L., Geng, S.X., Li, Z.Y., and Song, K. 2020*a*. Effect of microplastic on anaerobic digestion of wasted activated sludge. Chemosphere, **247**: 125874. doi:10.1016/j.chemosphere.2020.125874. PMID:31945722.

Li, S.X., Wang, P.P., Zhang, C., Zhou, X.J., Yin, Z.H., Hu, T.Y., et al. 2020*b*. Influence of polystyrene microplastics on the growth, photosynthetic efficiency and aggregation of freshwater microalgae *Chlamydomonas reinhardtii*. Sci. Total Environ. **714**: 136767. doi:10.1016/j.scitotenv.2020.136767. PMID:31981864.

Lim, X. 2021. Microplastics are everywhere – but are they harmful? Nature, **593**(7857): 22–25. doi:10.1038/d41586-021-01143-3. PMID:33947993.

Llorca, M., Schirinzi, G., Martinez, M., Barcelo, D., and Farre, M. 2018. Adsorption of perfluoroalkyl substances on microplastics under environmental conditions. Environ. Pollut. **235**: 680–691. doi:10.1016/j.envpol.2017.12.075. PMID:29339337.

Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., and Soudant, P. 2015. Interactions between microplastics and phytoplankton aggregates: impact on their respective fates. Mar. Chem. **175**: 39–46. doi:10.1016/j.marchem.2015.04.003.

Lopez-Rojo, N., Perez, J., Alonso, A., Correa-Araneda, F., and Boyero, L. 2020. Microplastics have lethal and sublethal effects on stream invertebrates and affect stream ecosystem functioning. Environ. Pollut. **259**: 113898. doi:10.1016/j.envpol.2019.113898. PMID:31927275.

Magni, S., Gagne, F., Andre, C., Della Torre, C., Auclair, J., Hanana, H., et al. 2018. Evaluation of uptake and chronic toxicity of virgin polystyrene microbeads in freshwater zebra mussel *Dreissena polymorpha* (Mollusca: Bivalvia). Sci. Total Environ. **631–632**: 778–788. doi:10.1016/j.scitotenv.2018.03.075. PMID:29544181.

Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., et al. 2016. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environ. Pollut. **218**: 1045–1054. doi:10.1016/j.envpol.2016.08.056. PMID:27574803.

Mateos-Cárdenas, A., Scott, D.T., Seitmaganbetova, G., van Pelt, F.N.A.M., O'Halloran, J., and Jansen, M.A.K. 2019. Polyethylene microplastics adhere to *Lemna minor* (L.), yet have no effects on plant growth or feeding by *Gammarus duebeni* (Lillj.). Sci. Total Environ. **689**: 413–421. doi:10.1016/j.scitotenv.2019.06.359. PMID:31279188.

Mattsson, K., Johnson, E.V., Malmendal, A., Linse, S., Hansson, L.A., and Cedervall, T. 2017. Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. Sci. Rep. **7**: 11452. doi:10.1038/s41598-017-10813-0. PMID:28904346.

McCormick, A.R., and Hoellein, T.J. 2016. Anthropogenic litter is abundant, diverse, and mobile in urban rivers: Insights from cross-ecosystem analyses using ecosystem and community ecology tools. Limnol. Oceanogr. **61**(5): 1718–1734. doi:10.1002/lno.10328.

McCormick, A.R., Hoellein, T.J., London, M.G., Hittie, J., Scott, J.W., and Kelly, J.J. 2016. Microplastic in surface waters of urban rivers: concentration, sources, and associated bacterial assemblages. Ecosphere, **7**(11): e01556. doi:10.1002/ecs2.1556.

McGivney, E., Cederholm, L., Barth, A., Hakkarainen, M., Hamacher-Barth, E., Ogonowski, M., and Gorokhova, E. 2020. Rapid physicochemical changes in microplastic induced by biofilm formation. Front. Bioeng. Biotechnol. **8**: 205. doi:10.3389/fbioe.2020.00205. PMID:32266235.

McIlwraith, H.K., Lin, J., Erdle, L.M., Mallos, N., Diamond, M.L., and Rochman, C.M. 2019. Capturing microfibers - marketed technologies reduce microfiber emissions from washing machines. Mar. Pollut. Bull. **139**: 40–45. doi:10.1016/j.marpolbul.2018.12.012. PMID:30686443.

McIlwraith, H.K., Kim, J., Helm, P., Bhavsar, S.P., Metzger, J.S., and Rochman, C.M. 2021. Evidence of microplastic translocation in wild-caught fish and implications for microplastic accumulation dynamics in food webs. Environ. Sci. Technol. **55**: 12372–12382. doi:10.1021/acs.est.1c02922. PMID:34499472.

Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., and Lebreton, L. 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. **7**: eaaz5803. doi:10.1126/sciadv.aaz5803.

Menéndez-Pedriza, A., and Jaumot, J. 2020. Interaction of environmental pollutants with microplastics: a critical review of sorption factors, bioaccumulation and ecotoxicological effects. Toxics, **8**(2): 40. doi:10.3390/toxics8020040. PMID:32498316.

Merzel, R.L., Purser, L., Soucy, T.L., Olszewski, M., Colon-Berna, I., Duhaime, M., et al. 2020. Uptake and retention of nanoplastics in quagga mussels. Glob. Challenges, **4**(6): 1800104. doi:10.1002/gch2.201800104. PMID:32685193.

Miao, L.Z., Wang, P.F., Hou, J., Yao, Y., Liu, Z.L., Liu, S.Q., and Li, T.F. 2019. Distinct community structure and microbial functions of biofilms colonizing microplastics. Sci. Total Environ. **650**: 2395–2402. doi:10.1016/j.scitotenv.2018.09.378. PMID:30292995.

Miller, E., Sedlak, M., Lin, D., Box, C., Holleman, C., Rochman, C.M., and Sutton, R. 2021. Recommended best practices for collecting, analyzing, and reporting microplastics in environmental media: Lessons learned from comprehensive monitoring of San Francisco Bay. J. Hazard. Mater. **409**: 124770. doi:10.1016/j.jhazmat.2020.124770. PMID:33450512.

Mohlenkamp, P., Purser, A., and Thomsen, L. 2018. Plastic microbeads from cosmetic products: an experimental study of their hydrodynamic behaviour, vertical transport and resuspension in phytoplankton and sediment aggregates. Elem. Sci. Anthropocene, **6**: 61. doi:10.1525/elementa.317.

Muller, Y.K., Wernicke, T., Pittroff, M., Witzig, C.S., Storck, F.R., Klinger, J., and Zumbülte, N. 2020. Microplastic analysis-are we measuring the same? Results on the first global comparative study for microplastic analysis in a water sample. Anal. Bioanal. Chem. **412**(3): 555–560. doi:10.1007/s00216-019-02311-1. PMID:31848670.

Munno, K., Helm, P.A., Rochman, C., George, T., and Jackson, D.A. 2021. Microplastic contamination in Great Lakes fish. Conserv. Biol. [In press.] doi:10.1111/cobi.13794. PMID:34219282.

Murphy, F., and Quinn, B. 2018. The effects of microplastic on freshwater *Hydra attenuata* feeding, morphology & reproduction. Environ. Pollut. **234**: 487–494. doi:10.1016/j.envpol.2017.11.029. PMID:29216486.

Napper, I.E., and Thompson, R.C. 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. Mar. Pollut. Bull. **112**(1-2): 39–45. doi:10.1016/j.marpolbul.2016.09.025. PMID:27686821.

Napper, I.E., Bakir, A., Rowland, S.J., and Thompson, R.C. 2015. Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. Mar. Pollut. Bull. **99**(1–2): 178–185. doi:10.1016/j.marpolbul.2015.07.029. PMID:26234612.

Nel, H.A., Dalu, T., and Wasserman, R.J. 2018. Sinks and sources: Assessing microplastic abundance in river sediment and deposit feeders in an Austral temperate urban river system. Sci. Total Environ. **612**: 950–956. doi:10.1016/j.scitotenv.2017.08.298. PMID:28886547.

Ockelford, A., Cundy, A., and Ebdon, J.E. 2020. Storm response of fluvial sedimentary microplastics. Sci. Rep. **10**(1): 1865. doi:10.1038/s41598-020-58765-2. PMID:32024953.

O'Connor, J.D., Mahon, A.M., Ramsperger, A., Trotter, B., Redondo-Hasselerharm, P.E., Koelmans, A.A., et al. 2020. Microplastics in freshwater biota: a critical review of isolation, characterization, and assessment methods. Glob. Challenges, **4**(6): 1800118. doi:10.1002/gch2.201800118.

Pedersen, A.F., Gopalakrishnan, K., Boegehold, A.G., Peraino, N.J., Westrick, J.A., and Kashian, D.R. 2020. Microplastic ingestion by quagga mussels, *Dreissena bugensis*, and its effects on physiological processes. Environ. Pollut. **260**: 113964. doi:10.1016/j.envpol.2020.113964. PMID:31991349.

Po, B.H.K., Lo, H.S., Cheung, S.G., and Lai, K.P. 2020. Characterisation of an unexplored group of microplastics from the South China Sea: Can they be caused by macrofaunal fragmentation? Mar. Pollut. Bull. **155**: 111151. doi:10.1016/j.marpolbul.2020.111151. PMID:32469771.

Provencher, J.F., Ammendolia, J., Rochman, C.M., and Mallory, M.L. 2019. Assessing plastic debris in aquatic food webs: what we know and don't know about uptake and trophic transfer. Environ. Rev. **27**(3): 304–317. doi:10.1139/er-2018-0079.

Provencher, J.F., Liboiron, M., Borrelle, S., Bond, A., Rochman, C., Lavers, J., et al. 2020. A Horizon Scan of research priorities to inform policies aimed at reducing the harm of plastic pollution to biota. Sci. Total Environ. **733**: 139381. doi:10.1016/j.scitotenv.2020.139381. PMID:32446089.

Qu, H., Ma, R.X., Wang, B., Yang, J., Duan, L., and Yu, G. 2019. Enantiospecific toxicity, distribution and bioaccumulation of chiral antidepressant venlafaxine and its metabolite in loach (*Misgurnus anguillicaudatus*) co-exposed to microplastic and the drugs. J. Hazard. Mater. **370**: 203–211. doi:10.1016/j.jhazmat.2018.04.041. PMID:29706475.

Rebelein, A., Int-Veen, I., Kammann, U., and Scharsack, J.P. 2021. Microplastic fibers — Underestimated threat to aquatic organisms? Sci. Total Environ. **777**: 146045. doi:10.1016/j.scitotenv.2021.146045. PMID:33684771.

Redondo-Hasselerharm, P.E., Falahudin, D., Peeters, E., and Koelmans, A.A. 2018. Microplastic effect thresholds for freshwater benthic macroinvertebrates. Environ. Sci. Technol. **52**(4): 2278–2286. doi:10.1021/acs.est.7b05367. PMID:29337537.

Redondo-Hasselerharm, P.E., Gort, G., Peeters, E., and Koelmans, A.A. 2020. Nano- and microplastics affect the composition of freshwater benthic communities in the long term. Sci. Adv. **6**(5): eaay4054. doi:10.1126/sciadv.aay4054. PMID:32064347.

Roch, S., Walter, T., Ittner, L.D., Friedrich, C., and Brinker, A. 2019. A systematic study of the microplastic burden in freshwater fishes of south-western Germany: Are we searching at the right scale? Sci. Total Environ. **689**: 1001–1011. doi:10.1016/j.scitotenv.2019.06.404. PMID:31280146.

Rochman, C.M., Hoh, E., Kurobe, T., and Teh, S.J. 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep. **3**: 3263. doi:10.1038/srep03263. PMID:24263561.

Rochman, C.M., Kross, S.M., Armstrong, J.B., Bogan, M.T., Darling, E.S., Green, S.J., et al. 2015. Scientific evidence supports a ban on microbeads. Environ. Sci. Technol. **49**(18): 10759–10761. doi:10.1021/acs.est.5b03909. PMID:26334581.

Romera-Castillo, C., Pinto, M., Langer, T.M., Alvarez-Salgado, X.A., and Herndl, G.J. 2018. Dissolved organic carbon leaching from plastics stimulates microbial activity in the ocean. Nat. Commun. **9**: 1430. doi:10.1038/s41467-018-03798-5. PMID:29651045.

Rummel, C.D., Jahnke, A., Gorokhova, E., Kuhnel, D., and Schmitt-Jansen, M. 2017. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environ. Sci. Technol. Lett. **4**(7): 258–267. doi:10.1021/acs.estlett.7b00164.

Ryan, P.G. 2015. A brief history of marine litter research. *In* Marine anthropogenic litter. *Edited by* M. Bergmann, L. Gutow, and M. Klages. Springer. pp. 1–25.

Scherer, C., Brennholt, N., Reifferscheid, G., and Wagner, M. 2017. Feeding type and development drive the ingestion of microplastics by freshwater invertebrates. Sci. Rep. **7**: 17006. doi:10.1038/s41598-017-17191-7. PMID:29208925.

Scherer, C., Weber, A., Stock, F., Vurusic, S., Egerci, H., Kochleus, C., et al. 2020. Comparative assessment of microplastics in water and sediment of a large European river. Sci. Total Environ. **738**: 139866. doi:10.1016/j.scitotenv.2020.139866. PMID:32806375.

Schiavo, S., Oliviero, M., Romano, V., Dumontet, S., and Manzo, S. 2018. Ecotoxicological assessment of virgin plastic pellet leachates in freshwater matrices. J. Environ. Accounting Manage. **6**(4): 345–353. doi:10.5890/JEAM.2018.12.007.

Schmidt, C., Krauth, T., and Wagner, S. 2017. Export of plastic debris by rivers into the sea. Environ. Sci. Technol. **51**(21): 12246–12253. doi:10.1021/acs.est.7b02368.

Scopetani, C., Esterhuizen, M., Cincinelli, A., and Pflugmacher, S. 2020. Microplastics exposure causes negligible effects on the oxidative response enzymes glutathione reductase and peroxidase in the oligochaete *Tubifex tubifex*. Toxics, **8**(1): 14. doi:10.3390/toxics8010014.

Seeley, M.E., Song, B., Passie, R., and Hale, R.C. 2020. Microplastics affect sedimentary microbial communities and nitrogen cycling. Nat. Commun. **11**(1): 2372. doi:10.1038/s41467-020-16235-3. PMID:32398678.

Seena, S., Graca, D., Bartels, A., and Cornut, J. 2019. Does nanosized plastic affect aquatic fungal litter decomposition? Fungal Ecol. **39**: 388–392. doi:10.1016/j.funeco.2019.02.011.

Simmerman, C.B., and Wasik, J.K.C. 2020. The effect of urban point source contamination on microplastic levels in water and organisms in a cold-water stream. Limnol. Oceanogr. **5**(1): 137–146. doi:10.1002/lol2.10138.

Song, J., Jongmans-Hochschulz, E., Mauder, N., Imirzalioglu, C., Wichels, A., and Gerdts, G. 2020. The Travelling Particles: Investigating microplastics as possible transport vectors for multidrug resistant *E. coli* in the Weser estuary (Germany). Sci. Total Environ. **720**: 137603. doi:10.1016/j.scitotenv.2020.137603. PMID:32143053.

Song, Y.K., Hong, S.H., Eo, S., Jang, M., Han, G.M., Isobe, A., and Shim, W.J. 2018. Horizontal and vertical distribution of microplastics in Korean coastal waters. Environ. Sci. Technol. **52**(21): 12188–12197. doi:10.1021/acs.est.8b04032. PMID:30295469.

Steer, M., Cole, M., Thompson, R.C., and Lindeque, P.K. 2017. Microplastic ingestion in fish larvae in the western English Channel. Environ. Pollut. **226**: 250–259. doi:10.1016/j.envpol.2017.03.062. PMID:28408185.

Su, L., Cai, H.W., Kolandhasamy, P., Wu, C.X., Rochman, C.M., and Shi, H.H. 2018. Using the Asian clam as an indicator of microplastic pollution in freshwater ecosystems. Environ. Pollut. **234**: 347–355. doi:10.1016/j.envpol.2017.11.075. PMID:29195176.

Su, L., Nan, B.X., Hassell, K.L., Craig, N.J., and Pettigrove, V. 2019. Microplastics biomonitoring in Australian urban wetlands using a common noxious fish (*Gambusia holbrooki*). Chemosphere, **228**: 65–74. doi:10.1016/j.chemosphere.2019.04.114. PMID:31022621.

Sun, X.M., Chen, B.J., Xia, B., Li, Q.F., Zhu, L., Zhao, X.G., et al. 2020. Impact of mariculture-derived microplastics on bacterial biofilm formation and their potential threat to mariculture: A case in situ study on the Sungo Bay, China. Environ. Pollut. **262**: 114336. doi:10.1016/j.envpol.2020.114336. PMID:32443196.

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E.J., et al. 2016. Oyster reproduction is affected by exposure to polystyrene microplastics. Proc. Natl. Acad. Sci. U.S.A. **113**(9): 2430–2435. doi:10.1073/pnas.1519019113. PMID:26831072.

Taipale, S.J., Peltomaa, E., Kukkonen, J.V.K., Kainz, M.J., Kautonen, P., and Tiirola, M. 2019. Tracing the fate of microplastic carbon in the aquatic food web by compound-specific isotope analysis. Sci. Rep. **9**: 19894. doi:10.1038/s41598-019-55990-2. PMID:31882692.

Teuten, E.L., Rowland, S.J., Galloway, T.S., and Thompson, R.C. 2007. Potential for plastics to transport hydrophobic contaminants. Environ. Sci. Technol. **41**(22): 7759–7764. doi:10.1021/es071737s. PMID:18075085.

Tibbetts, J., Krause, S., Lynch, I., and Sambrook Smith, G. 2018. Abundance, distribution, and drivers of microplastic contamination in urban river environments. Water, **10**: 1597. doi:10.3390/w10111597.

Turner, S., Horton, A.A., Rose, N.L., and Hall, C. 2019. A temporal sediment record of microplastics in an urban lake, London, UK. J. Paleolimnol. **61**(4): 449–462. doi:10.1007/s10933-019-00071-7.

Twiss, M.R. 2016. Standardized methods are required to assess and manage microplastic contamination of the Great Lakes system. J. Gt. Lakes Res. **42**(5): 921–925. doi:10.1016/j.jglr.2016.07.032.

United Nations World Water Assessment Programme (UNWWAP). 2017. The United Nations World Water Development Report 2017. Wastewater: the untapped resource. UNESCO, Paris.

Vaughn, C.C., and Hakenkamp, C.C. 2001. The functional role of burrowing bivalves in freshwater ecosystems. Freshw. Biol. **46**(11): 1431–1446. doi:10.1046/j.1365-2427.2001.00771.x.

Vaughan, R., Turner, S.D., and Rose, N.L. 2017. Microplastics in the sediments of a UK urban lake. Environ. Pollut. **229**: 10–18. doi:10.1016/j.envpol.2017.05.057. PMID:28575711.

Villanueva, V.D., Font, J., Schwartz, T., and Romaní, A.M. 2011. Biofilm formation at warming temperature: acceleration of microbial colonization and microbial interactive effects. Biofouling, **27**(1): 59–71. doi:10.1080/08927014.2010.538841. PMID:21113861.

Vosshage, A.T.L., Neu, T.R., and Gabel, F. 2018. Plastic alters biofilm quality as food resource of the freshwater gastropod *Radix balthica*. Environ. Sci. Technol. **52**(19): 11387–11393. doi:10.1021/acs.est.8b02470. PMID:30160948.

Waldschlager, K., Lechthaler, S., Stauch, G., and Schuttrumpf, H. 2020. The way of microplastic through the environment – Application of the source-pathway-receptor model (review). Sci. Total Environ. **713**: 136584. doi:10.1016/j.scitotenv.2020.136584. PMID:32019016.

Wallace, J.B., Hutchens, J.J., and Grubaugh, J.W. 2007. Transport and storage of FPOM. *In* Methods in stream ecology. 2nd ed. *Edited by* F.R. Hauer and G.A. Lamberti. Academic Press, San Diego, Calif. pp. 249–271.

Wang, J., Peng, C., Li, H., Zhang, P., and Liu, X. 2021. The impact of microplastic-microbe interactions on animal health and biogeochemical cycles: A mini-review. Sci. Total Environ. **773**: 145697. doi:10.1016/j.scitotenv.2021.145697. PMID:33940764.

Wang, W.F., Gao, H., Jin, S.C., Li, R.J., and Na, G.S. 2019. The ecotoxicological effects of microplastics on aquatic food web, from primary producer to human: a review. Ecotoxicol. Environ. Saf. **173**: 110–117. doi:10.1016/j.ecoenv.2019.01.113. PMID:30771654.

Wardlaw, C., and Prosser, R.S. 2020. Investigation of microplastics in freshwater mussels (*Lasmigona costata*) from the Grand River watershed in Ontario, Canada. Water Air Soil Pollut. **231**(8): 405. doi:10.1007/s11270-020-04741-5.

Watkins, L., Sullivan, P.J., and Walter, M.T. 2019. A case study investigating temporal factors that influence microplastic concentration in streams under different treatment regimes. Environ. Sci. Pollut. Res. Int. **26**(21): 21797–21807. doi:10.1007/s11356-019-04663-8. PMID:31134548.

Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.-F., Estournel, C., et al. 2021. The missing ocean plastic sink: Gone with the rivers. Science, **373**(6550): 107–111. doi:10.1126/science.abe0290. PMID:34210886.

Welden, N.A.C., and Cowie, P.R. 2016. Environment and gut morphology influence microplastic retention in langoustine, *Nephrops norvegicus*. Environ. Pollut. **214**: 859–865. doi:10.1016/j.envpol.2016.03.067. PMID:27161832.

Windsor, F.M., Tilley, R.M., Tyler, C.R., and Ormerod, S.J. 2019. Microplastic ingestion by riverine macroinvertebrates. Sci. Total Environ. **646**: 68–74. doi:10.1016/j.scitotenv.2018.07.271. PMID:30048870.

Wu, C.C., Bao, L.J., Liu, L.Y., Shi, L., Tao, S., and Zeng, E.Y. 2017. Impact of polymer colonization on the fate of organic contaminants in sediment. Environ. Sci. Technol. **51**(18): 10555–10561. doi:10.1021/acs.est.7b03310. PMID:28825800.

Yan, M.T., Nie, H.Y., Xu, K.H., He, Y.H., Hu, Y.T., Huang, Y.M., and Wang, J. 2019. Microplastic abundance, distribution and composition in the Pearl River along Guangzhou city and Pearl River estuary, China. Chemosphere, **217**: 879–886. doi:10.1016/j.chemosphere.2018.11.093. PMID:30458423.

Yang, L., Zhang, Y., Kang, S., Wang, Z., and Wu, C. 2021. Microplastics in freshwater sediment: A review on methods, occurrence, and sources. Sci. Total Environ. **754**: 141948. doi:10.1016/j.scitotenv.2020.141948. PMID:32916488.

Yuan, J.H., Ma, J., Sun, Y.R., Zhou, T., Zhao, Y.C., and Yu, F. 2020. Microbial degradation and other environmental aspects of microplastics/plastics. Sci. Total Environ. **715**: 136968. doi:10.1016/j.scitotenv.2020.136968. PMID:32014782.

Zalasiewicz, J., Waters, C.N., do Sul, J.A.I., Corcoran, P.L., Barnosky, A.D., Cearreta, A., et al. 2016. The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. Anthropocene, **13**: 4–17. doi:10.1016/j.ancene.2016.01.002.

Zbyszewski, M., Corcoran, P.L., and Hockin, A. 2014. Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. J. Gt. Lakes Res. **40**(2): 288–299. doi:10.1016/j.jglr.2014.02.012.

Zhang, Y., Liang, J., Zeng, G., Tang, W., Lu, Y., Luo, Y., et al. 2020. How climate change and eutrophication interact with microplastic pollution and sediment resuspension in shallow lakes: A review. Sci. Total Environ. **705**: 135979. doi:10.1016/j.scitotenv.2019.135979. PMID:31841912.

Zhu, K.C., Jia, H.Z., Sun, Y.J., Dai, Y.C., Zhang, C., Guo, X.T., et al. 2020. Long-term phototransformation of microplastics under simulated sunlight irradiation in aquatic environments: Roles of reactive oxygen species. Water Res. **173**: 115564. doi:10.1016/j.watres.2020.115564. PMID:32028245.

Ziajahromi, S., Kumar, A., Neale, P.A., and Leusch, F.D.L. 2018. Environmentally relevant concentrations of polyethylene microplastics negatively impact the survival, growth and emergence of sediment-dwelling invertebrates. Environ. Pollut. **236**: 425–431. doi:10.1016/j.envpol.2018.01.094. PMID:29414367.

Ziajahromi, S., Kumar, A., Neale, P.A., and Leusch, F.D.L. 2019. Effects of polyethylene microplastics on the acute toxicity of a synthetic pyrethroid to midge larvae (*Chironomus tepperi*) in synthetic and river water. Sci. Total Environ. **671**: 971–975. doi:10.1016/j.scitotenv.2019.03.425.

Zubris, K.A.V., and Richards, B.K. 2005. Synthetic fibers as an indicator of land application of sludge. Environ. Pollut. **138**(2): 201–211. doi:10.1016/j.envpol.2005.04.013. PMID:15967553.