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Gathering at the top? Environmental controls of microplastic uptake and biomagnification in freshwater food webs

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Abstract

Microplastics are ubiquitous in the environment, with high concentrations being detected now also in river corridors and sediments globally. Whilst there has been increasing field evidence of microplastics accumulation in the guts and tissues of freshwater and marine aquatic species, the uptake mechanisms of microplastics into freshwater food webs, and the physical and geological controls on pathway-specific exposures to microplastics, are not well understood. This knowledge gap is hampering the assessment of exposure risks, and potential ecotoxicological and public health impacts from microplastics.

This review provides a comprehensive synthesis of key research challenges in analysing the environmental fate and transport of microplastics in freshwater ecosystems, including the identification of hydrological, sedimentological and particle property controls on microplastic accumulation in aquatic ecosystems. This mechanistic analysis outlines the dominant pathways for exposure to microplastics in freshwater ecosystems and identifies potentially critical uptake mechanisms and entry pathways for microplastics and associated contaminants into aquatic food webs as well as their risk to accumulate and biomagnify.

We identify seven key research challenges that, if overcome, will permit the advancement beyond current conceptual limitations and provide the mechanistic process understanding required to assess microplastic exposure, uptake, hazard, and overall risk to aquatic systems and humans, and provide key insights into the priority impact pathways in freshwater ecosystems to support environmental management decision making.

1. Introduction

Besides the many technological benefits of living in the “plastic age” (Thompson, 2009), the sheer plethora of plastic products, their unsustainable use and disposal combined with their high durability in the environment cause pollution risks with widespread environmental and public health concerns (Andrady, 2009; Koelmans, 2015). A substantial increase in the worldwide production of plastics, from 2 million tons per year in 1950 to more than 335 million tons in 2016 have led to high global levels of plastic pollution (Bergmann, 2015; Dris, 2015; Eriksen, 2014). There is growing concern that waste management is largely incapable of handling the volumes of plastics being produced among the myriad disposal pathways (Koelmans, 2015), resulting in the release of large amounts of plastic waste into the environment. Up to 12.7 million tons of mismanaged plastic entered the world’s oceans in 2010

alone, and is predicted to increase by an order of magnitude by 2025 if no action is taken (Jambeck, 2015). Given that these estimates have arisen from consideration of a 50 km coastal margin only and thus, excluded riverine plastic contributions from the wider river basins, the real numbers of plastic inputs into the oceans are likely to be even higher.

While larger plastic items present a visible environmental risk, and a concern following ingestion by aquatic animals and birds (Besseling, 2015; Foekema, 2013), there is an increasing awareness and concern about the environmental and public health impacts of smaller microplastic (MP) particles of less than 5 mm size, originating from a variety of sources with different chemical properties (Avio, 2015; Koelmans, 2015). MPs, and their even smaller counterparts nanoplastics (i.e. particles < 100 nm) (Mattsson, 2015), are composed of a wide variety of polymer types resulting in distinct physical properties (i.e., in their shape, size, buoyancy). The variations in their physical properties ultimately influence particle transport and retention dynamics, their deposition, and bioavailability in the environment (Dris, 2015). The chemical and physical properties of MPs found in the environment are, in the first instance, controlled by their source. These can be classified as primary (manufactured) particles such as microbeads used in cosmetics and human care products, or secondary MPs, which result from the breakdown of larger plastic items (Figure 1). Fragmentation commonly results from industrial abrasive processes (GESAMP, 2016), or degradation via micro-cracking and embrittlement as a result of exposure to salt, wave action (Zbyszewski, 2014) and/or UV light and freezing and thawing cycles (Da Costa, 2018).

MP pollution is recognised as a global environmental threat with MPs being widely abundant in marine ecosystems, e.g. in the 5 ocean gyres, and stretching to the deep sea and remote arctic areas (Foley, 2018). While the transport, fate and behaviour of MPs have been studied predominantly in marine ecosystems, significant knowledge gaps remain in freshwater and terrestrial ecosystems (Hurley, 2018; Klein, 2015; Wagner, 2014; Windsor, 2019). MPs have been detected at alarming concentrations in river corridors and sediments (Horton, 2017; Rochman, 2018; Tibbetts, 2018). There is growing consensus that rivers are retention sites for MPs and serve as conduits for their downstream transport to the oceans (Fig. 1) (Ballent, 2016; Brennecke, 2016; Duis, 2016; Hoellein, 2019; Hurley, 2018; Klein, 2015; Lebreton, 2017; Thompson, 2004; Wolff, 2019).

Due to their unavoidable interactions with food webs they have been found in a wide range of marine organisms from phytoplankton to fishes, sea birds and even filtering cetaceans (Fossi, 2016; Setälä, 2014). Recent meta-analyses point towards highly heterogeneous responses to

MP ingestion in different groups of aquatic organisms. For some taxa negative effects were found in terms of impacts on consumption (and feeding), growth, reproduction, and survival of fish and aquatic invertebrates (Foley, 2018; Wright, 2013). Besides the physical impacts on animals (e.g. blocking of digestive pathways, choking), MPs may be potentially toxic to animals, either through the leaching of additives (Dris, 2015; Eerkes-Medrano, 2015; Wagner, 2014), or by acting as vectors for pathogens, bacteria, viruses (Lamb, 2018) and contaminants that adsorb to their surface (Hartmann, 2017; Lamb, 2018). Ingested MPs may cause numerous adverse impacts on aquatic organisms. Even pristine plastics can cause acute immobilization, depletion of energy reserves (Wright, 2013), a decrease in predatory performance or hepatic inflammation, while MPs associated with persistent organic pollutants have been shown to cause acute or chronic toxic effects (Rehse, 2016; Rochman, 2013; Van Cauwenberghe, 2014). Critically, additives (e.g. Bisphenol A – BPA, an endocrine disrupting substance) or flame retardants such as Poly-brominated Diphenyl Ethers (PBDEs) have been shown to have increased toxicity effects on organisms when associated with MPs than when exposed in solution (Planelló, 2008; Wardrop, 2016). The reason for this is ‘Trojan horse vector-effects’ whereby MPs carry toxic additives directly into the animal’s bodies after their ingestion (de Sá, 2018; Luís, 2015; Oliveira, 2013). With recent evidence of MPs entering the human food chain (Deng, 2017; Li, 2018; Wright, 2017), and nanoplastics having the potential to penetrate cell walls of organisms (Kashiwada, 2006; Rosenkranz, 2009), regulators, water and chemical industries globally are concerned about the environmental and public health impacts of additives such as BPA and other endocrine disrupting substances such as Nonylphenol (NP) leaching from MPs (Dris, 2015; Eerkes-Medrano, 2015; Wagner, 2014). However, some studies have found that MP presence reduced the short-term effects of BPA on freshwater zooplankton (Rehse, 2018), with long-term effects still being unknown.

Despite some recent studies of MP occurrence in rivers and lakes (Ballent, 2016; Besseling, 2015; Estahbanati, 2016; Foley, 2018; Klein, 2015), and their potential effects on a wide variety of organisms (Rehse, 2016; Rochman, 2013; Van Cauwenberghe, 2015), there remains a critical lack of understanding regarding the fate and transport mechanisms of MPs and how these affect their uptake and propagation in freshwater food webs (Eerkes-Medrano, 2015; Foley, 2018). While there is initial evidence of trophic transfer in simple food chains (Chae, 2018), major knowledge gaps remain on the direct and indirect uptake and transfer of MPs in the environment, including their capacity for biomagnification while moving through complex freshwater food webs.

Assessing the risk of MP uptake and propagation in aquatic food webs requires the development of detailed understanding of potential direct and indirect MP entry points and mechanistic pathways in food webs. In addition, understanding of how MP fate and transport processes control their accumulation in freshwater habitats, and of the magnitude of site-specific exposures, is needed to enable prediction of MP bioaccumulation and biomagnification and develop appropriate mitigation measures. Here, we present here a comprehensive review and synthesis of key research challenges in:

- (i) Characterising particle properties and their ageing, along with freshwater properties such as hydrodynamic and sediment conditions that control the environmental fate, transport and development of accumulation hotspots of MPs in freshwater ecosystems;
- (ii) Analysing how physical controls on MP presence in freshwater environments determine the environmental exposures and accessibility of MPs in freshwater ecosystems
- (iii) Identifying potential uptake mechanisms and entry pathways of MPs and associated contaminants into aquatic food webs, and their capacity to accumulate and biomagnify following initial entry.

We identify 7 key research challenges (Table 1) that represent milestones in understanding the controls of exposure, uptake and propagation of MPs in aquatic food webs, and discuss these in further detail below.

2. Fate and transport mechanisms control microplastic exposure

The exposure and potential entry points of MPs into aquatic food webs are determined by the spatial distributions and time scales of mechanisms that control the input, transport and transformation as well as the potential accumulation of different types of MPs in the environment. An assessment of MP uptake and potential propagation through aquatic food webs therefore requires detailed understanding of MP sources and their activation, as well as of the environmental fate and transport mechanisms of MPs (Fig 1).

MPs enter aquatic environments through a wide range of pathways, including runoff from land surfaces and roads, river bank waste disposal, atmospheric deposition and outfall of wastewater treatment plants (Fig 1) (Dris, 2016; GESAMP, 2016; Horton, 2017; Horton, 2018b; Wagner, 2014). While it has been shown that wastewater treatment plants can retain significant amounts

of MPs and are efficient to filter out some types of primary MP particles (Murphy, 2016; Prata, 2018; Ziajahromi, 2016), there is evidence that they are less effective in the retention of synthetic microfibers and nanoplastics (Rochman, 2015). Other MP entry pathways into terrestrial and aquatic ecosystems include agricultural sources including organic fertilizer products (Weithmann, 2018), plastic in potting soil, such as tree ties in forestry and plastic tarps on agricultural fields (Fig 1). Recognition of the specific entry pathways and related differences in transport mechanisms is crucial since the environmental fate of highly concentrated point source inputs (e.g. from wastewater treatment plants) is likely to differ significantly from lower concentration diffuse inputs (e.g. atmospheric fallout, road runoff or agriculture) (Fig 1).

Understanding of the chemical and physical properties of MPs, as well as how the hydrodynamic and substrate conditions at the sediment-water interface control MP transport in lakes and rivers is still very limited. Recent studies have hinted that MPs are omnipresent in freshwater ecosystems, and in particular at sediment-water interfaces (Besseling, 2015, 2018; Foley, 2018; Hurley, 2018), indicating that benthic and hyporheic zones of rivers may represent MP accumulation hotspots (Drummond et al., 2020; Frei et al., 2019) (Fig 1). Depending on their density and buoyancy, MPs of different origin are likely to differ in their transport properties, their probability of burial in riverbed sediments and thus, the types of interactions with different trophic levels of aquatic organisms. For instance, in contrast to the high-density polymers found in benthic and hyporheic accumulation zones in many rivers (Besseling, 2018; Foley, 2018; Hurley, 2018), most of the MPs polluting the water column of the Canadian Great Lakes were found to be low density synthetic polymers (polyethylene, polyester) (Ballent, 2016). Similar results were found within large river systems such as the Danube and Rhine rivers (Lechner, 2014; Mani, 2015). Yet, the fact that low density MPs have also been found in streambed sediments highlights the fact that the mechanisms which control deposition and entrapment (Hoellein, 2019), including potential interactions of the bed substrate and its associated benthic flora, remain to be quantified. While there is increasing understanding and insight into the relevance of the specific mechanisms controlling MP transport in freshwater ecosystems such as hyporheic exchanges (Drummond et al., 2020; Frei et al., 2019) or gravitational settling, including governing equations and quantitative models (Box 1), identifying the required parameters across the relevant spatial and temporal scales remains challenging.

Furthermore, the spatial patterns and temporal dynamics of proportional contributions of different types and sources of MPs still need to be determined, in order to parameterise transport and exposure models. The vast majority of freshwater MP studies to date have been conducted under steady flow conditions, and little attention has been paid to analysing the impact of hydrodynamic conditions at sampling sites (Fig 2). We have only just started to explore how the temporal dynamics of MP fragmentation, deposition, degradation and eventually removal are controlled by hydrodynamic variability (Drummond et al., 2020; Hurley, 2018), with the balance between these processes being defined by the local exposure time. It will be critical to identify how the hydrodynamic forcing and the variability in physical and chemical properties which affect MPs (Box 1) may change with dynamic flow conditions (e.g. temperature, nutrient content, UV exposure). It has yet to be established how this variation in flow may affect the deposition (Tibbetts, 2018) and transformation of MPs, such as their breakdown and decomposition or release of additives such as BPA and NP (Fig 2). This includes the distribution of MPs within the floodplains of rivers during high flow events as well as their behaviour under drastically different environmental conditions (i.e., when exposed to air during dry conditions in ephemeral streams or on elevated river banks (Fig 2)). Indeed, with globally increasing frequency and severity of droughts (Hoellein, 2019; Naumann, 2018), intermittency and flashiness of streams, understanding of the impact of stream drying and increased UV exposure on MP degradation will become increasingly important, as will understanding the disturbances to sediment-entrained MPs due to turbulent mixing as streams re-wet.

The transport mechanisms and accumulation of MPs (Box 1) are furthermore affected by biological processes, including MP particle ageing and decay as well as biomolecule adsorption and biofilm colonization (i.e. accumulation of micro-organisms on wetted MP surfaces) (Harrison, 2018; Nasser, 2016), and entrapment in biofilms at aquatic-terrestrial interfaces (Fig 2) (de Sá, 2015; Duis, 2016; Rummel, 2017). Biofilms growing on the surfaces of ageing MPs can change their hydrodynamic and buoyancy properties, potentially affecting their transport, fate, accumulation and uptake by organisms (Corcoran, 2015). The magnitude of such biological interactions and their dependency on environmental conditions such as temperature, light exposure and nutrient concentrations have yet to be established. Additionally, the formation of homo-aggregations (microfiber clumps) and hetero-aggregations (similar to marine snow) may also have an effect on the fate and transport of MPs (Alimi, 2018). Important lessons can be learned here for instance from recent advances in understanding MP settling

velocity in marine environments (Khatmullina, 2017), or using mechanistic behaviour of naturally occurring allochthonous particles as analogues (Hoellein, 2019). However, the stability of MPs and their likelihood to form aggregates may be different in freshwater versus saline sea water and will depend on the polymer type (Lagarde, 2016; Michels, 2018).

Addressing the interdisciplinary challenges of establishing how the fate and transport of MPs control their entry into freshwater food webs will require:

- The characterisation of spatially heterogeneous MP sources of different plastic types and how dynamic source activation controls the way MPs are released into the environment [*Challenge 1*] as well as,
- The identification of how MP properties, and freshwater hydrodynamic and biological processes interact in affecting MP fate and transport, including their degradation, ageing, break down and the release of toxins [*Challenge 2*] (Table 1).

For these challenges to be addressed successfully, scientific advances across traditional disciplinary boundaries are necessary that require to leave our current disciplinary ‘comfort zones’ in the material sciences and analytical chemistry, ecohydrology, environmental chemistry and biology (Table 1).

3. Microplastics entry points into freshwater food webs

Once they have entered freshwater environments, there is a risk that MPs may be taken up into freshwater food webs. The location and mechanism for MP entry into freshwater food webs is determined by site- and material-specific conditions. Recent investigations have focussed on the discrimination between various routes of entry according to whether the MP particles were primary or secondary MPs (Ballent, 2016; Dris, 2015; Duis, 2016; Weithmann, 2018).

Potential MP entry points through direct uptake into aquatic food webs exist at almost every trophic level and may involve suspended MPs that are filtered from the open water column or MPs accumulated in the benthos at the sediment-water interface (Fig 3). Phytoplankton can directly adsorb nanoplastics through cell-walls and zooplankton such as daphnia and fish can ingest nanoplastics and MPs directly from the water column (Costa, 2016). Lacustrine invertebrates such as oligochaete worms, amphipods, and freshwater snails can ingest artificially manufactured plastic microspheres under laboratory conditions (Imhof, 2013). However, so far only limited empirical evidence of MP uptake mechanisms and trophic transfer by freshwater fauna exists, as only isolated cases of direct ingestion under laboratory

conditions, or detection in the wild (without knowledge of the specific plastic sources) have been reported (Imhof, 2013; Pazos, 2017).

It is plausible that benthic fauna, especially filter feeders, like zebra and quagga mussels (*Dreissena sp.*) will ingest MPs suspended in the water column, with the risk of transferring them to the benthic food chain via coating in faeces or pseudofaeces (Lederer, 2006) (Fig 3). Pseudofaeces of *Dreissena* and other common freshwater bivalves (*Corbicula sp.* and Unionidae mussels) are rejected organic and inorganic particles covered by mucus in the mantle cavity of the mussel, and expelled outside (Dermott, 2005). It is well established that many benthic animals prefer to feed on *Dreissena* pseudofaeces because of their high nutritional values (Stewart, 1998). Due to their high biomass, filter feeding benthic macroinvertebrates such as bivalves may therefore be responsible for significant transfer of MP from the water column to benthic food webs.

A further preferential pathway of MPs to enter freshwater food webs is through their entrapment in benthic or hyporheic biofilms (Sgier, 2016), where they accumulate and are potentially made more readily available to other organisms. Here they can pose a critical risk for preferential direct MP uptake and subsequent ingestion by biofilm grazers (Fig 3) (McCormick, 2016). In marine environments, organic aggregates (so called marine snow) can trap MPs and transport the normally buoyant plastics to the deep ocean, ultimately increasing their bioavailability to deep-sea fauna (Porter, 2018).

So-called Trojan horse vector-effects may potentially increase the indirect uptake of xenobiotics from MPs, for instance when additives such as Bisphenol-A (BPA) leach from the biofilm after ingestion by biofilm grazers (Fig 3). Furthermore, biofilms on MP surfaces may create shortcuts for MPs to enter food webs at several trophic levels (Rummel, 2017). In addition to Trojan horse effects, MPs may affect the structure and metabolic functionality of biofilms (Harrison, 2018; Rummel, 2017). Since biofilms carry out a number of crucial ecosystem services in rivers, such as respiration, nutrient uptake and attenuation of pollutants, any MP induced damage to biofilms bears the risk of impacting ecosystem functioning at the river scale (Besseling, 2018; Harrison, 2018).

Beyond physical controls on MP fate and transport, it is important to advance the understanding of how animal behaviour and feeding types affect MP uptake and ingestion, which may vary by development stage and morphological characteristics (Scherer, 2017). For example, De Sá (2015), showed that the common goby (*Pomatoschistus microps*) ingests MP particles (420–

500 µm) of different colours together with natural prey (*Artemia salina*) (de Sá, 2015). Here, the selectivity of MP uptake was dependent on the particle colour, with similar behaviour found for sunfish (Peters, 2016). Similarly, benthic sea turtles showed strong selectivity for soft, clear plastic, suggesting that sea turtles ingested plastic because it resembled natural prey such as jellyfish (Schuyler, 2012). In contrast, pelagic turtles were found to be less selective in their feeding, though they showed a trend towards selectivity for rubber items such as balloons (Schuyler, 2012).

In order to assess the entry point of specific risks of MP uptake and their dependence on environmental exposure conditions, MP exposure hotspots (e.g. through filter feeding or biofilm entrapment) need to be identified and mechanisms of potential uptake pathways characterised and their relative contributions to total organism body-burdens quantified [*Challenge 3*] (Table 1). This includes uptake by phytoplankton as well as MP entrapment in aquatic biofilms, presenting a potential pathway for increased MP uptake by biofilm grazers and entry into freshwater food webs. The quantification of potential environmental and health consequences will require:

- Determination of the potential for Trojan Horse effects or shortcuts for xenobiotics into aquatic food webs [*Challenge 4*] and
- Quantification of the importance of ecological behavioural aspects (from colour preferences to bioturbation) that affect MP abundance, distribution and uptake [*Challenge 5*] (Table 1).

4. Migration and potential biomagnification of microplastics in freshwater food webs

Once MPs and nanoplastics enter freshwater food webs, there is a risk of biomagnification into higher trophic levels (Sanchez, 2014). The potential for biomagnification is generally not yet well established. Previous studies on MPs in freshwater food webs have been either limited to a single species (Rehse, 2016; Van Cauwenberghe, 2015), or trophic transfer in simple food chains (Chae, 2018; Rochman, 2017). Possible transfers across more complex aquatic food webs have not yet been assessed.

Direct ingestion and trophic transfer of MPs have been confirmed in several field and laboratory experiments (Kim, 2018; Ziccardi, 2016) and repeated occurrence of MP particles in fish have been explained by both direct ingestion and trophic transfer (Phillips, 2015). Indeed, fish have been most widely studied to date, with findings ranging from an absence of

MPs (Lake Geneva) (Faure, 2012), to 8% of the freshwater fish and 10% of marine fish in the Gulf of Mexico (Phillips, 2015), 12% of adult gudgeons (*Gobio gobio*) in 11 French streams (Sanchez, 2014), 45% of all sunfish (*Lepomis gibbosus*) specimens in the Brazos river (Texas, USA) (Peters, 2016) and 55% of Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*) from Lake Victoria (Biginagwa, 2016). Despite the growing number of case studies evidencing MP presence in fish (Collard, 2018; Horton, 2018a), there is little understanding of the mechanisms and drivers of their uptake and propagation in aquatic food webs. It has been suggested that the feeding behaviour of different species appears to significantly affect their risk of MPs ingestion. Given high benthic concentrations of MPs relative to water column concentrations, benthivore fish may have a greater MP exposure than planktivorous fish (Fig 3) (McNeish, 2018). The absence of MPs in the fish studied in Lake Geneva as compared to gudgeons in French streams may be explained by a difference in the feeding preferences of the different species. Gudgeons are primarily benthivores, thus might be exposed to a higher risk of MP ingestion than carnivorous, planktivorous or herbivorous fish (Sanchez, 2014).

Simplified food chain studies have demonstrated that when MPs are abundant, they can be readily transferred along trophic levels (Ivar do Sul, 2014). Trophic transfer of fluorescent plastic microspheres from *Artemia nauplii* to zebrafish (*Danio rerio*) (Batel, 2016) and Spined Stickleback (*Gasterosteus aculeatus*) was shown in laboratory studies (Katzenberger, 2015) where fish were fed with MP-exposed Nauplius (crustaceous larvae). Both, MPs and persistent organic pollutants associated with MPs such as BPA, have been shown to migrate to fish tissue (Batel, 2016), highlighting the risks of Trojan Horse effects. Furthermore, direct trophic transfer from mussels (*Mytilus edulis*) to crabs (*Carcinus maenus*) has been observed under laboratory conditions, with plastic microspheres being transferred into the crab's haemolymph, stomach, hepatopancreas, ovary and gills (Farrell, 2013).

Despite the mounting evidence of MPs within all levels of freshwater food webs described above, evidence for the transfer among different components of food webs is limited. It will be crucial to identify and understand the mechanisms of MP uptake and pathways in more complex food webs than previously studied in order to understand what risk potential biomagnification presents for human consumption [**Challenge 6**] (Table 1). In this respect it will be essential to understand how MPs are retained in tissues over long time scales, or if they are largely expelled during egestion, growth, or metamorphosis. For example, Al-Jaibachi et al. (2018) showed that fluorescently stained MP beads taken up by mosquito larvae remained after metamorphosis in the winged adults. This suggests that long term retention of MPs in

tissues is possible, and that insects with aquatic larval stages and terrestrial adult stages may represent an underappreciated flux of MPs among aquatic and terrestrial ecosystems (Al-Jaibachi, 2018).

5. The ecological and public health impacts - Microplastic effects on aquatic ecosystem functioning

The effects of MPs on freshwater ecosystem functioning remains largely unknown (Eerkes-Medrano, 2015; Lambert, 2016). Laboratory studies confirmed that water fleas (*Daphnia magna*), freshwater invertebrates and several fish species actively feed on MP particles (1-100 µm), and that uptake of MP particles caused acute immobilisation of these animals (Besseling, 2018; Oliveira, 2013; Rehse, 2016), and affected predator-prey relationships (Rochman, 2017). However, some studies also found MP impacts on ecosystem processes to be negligible (Canniff, 2018; Malinich, 2018; Redondo-Hasselerharm, 2018; Weber, 2018), complicating predictions of ecosystem level implications. Furthermore, transgenerational effects on *Daphnia magna* indicated only negligible effects on the first generation but when neonates were exposed to same concentration of MPs they went extinct after 2 generations (Martins, 2018). This highlights the need to expand testing further than the first generation. While it is reasonable to expect that some ecosystem effects occur at longer time scales or larger spatial scales, their specific relevance has yet to be established.

Many benthic consumers in freshwaters (e.g., Chironomidae larvae, Oligochaeta worms, gammaridae, amphipods) act as ecosystem engineers in sediments and are highly exposed to MPs, their chemical additives, sorbed contaminants, and potential microbial pathogens (Frère, 2018; McCormick, 2014), resulting in a critical risk of wide ranging impacts in particular on benthic ecosystem functioning (Izvekova, 1972; Ward, 2007). For example, lugworms (*Arenicola marina*) that ingested MPs showed decreased bioturbation (Wright, 2013), which lowered the primary productivity of bioturbated sediment and altered lugworm respiration (Green, 2016). Similar impacts on key bioturbators of freshwater ecosystems could have significant consequences at the ecosystem level. In shallow lakes, filter-feeding benthic species such as *Chironomus plumosus* larvae filter large volumes of water, importing oxygen and particulate matter down to 20 cm into the sediment and regulate lake's phosphorus concentrations and trophic status (Hölker, 2015; Lewandowski, 2007; Roskosch, 2011). Thus,

any reduction of the activity of *C. plumosus* larvae due to MPs might severely impact on the entire lake ecosystem.

In addition to identifying pathways and mechanisms of how MPs enter and propagate within aquatic food webs, future research should establish how freshwater MPs impact the behaviour and performance of organisms and key ecosystem processes. We suggest new research to move beyond the assessment of individual species interactions with MPs. The next frontier in this research will measure MP effects on food webs and ecosystem functioning, as well as quantifying the potential combined impacts of MPs and their associated additives, sorbed contaminants and pathogens [*Challenge 7*] (Table 1).

6. Concluding remarks and a look forward

Increasing evidence and rising public awareness of the omnipresence of MPs in understudied freshwater ecosystems and within humans at the end of the food chain (e.g. identification of MPs in human stool samples (Parker, 2018)), highlight that scientific interactions and knowledge exchange across disciplinary boundaries are critical for evaluating the environmental and public health risks of MPs. There are increasing concerns of MP uptake through food and bottled drinking water or by inhalation of microfibers from clothing or soft furnishings (Catarino, 2018), in particular with the proven transport of microplastics in the atmosphere along large distances (Allen, 2019). The challenges we present are interlinked and require interdisciplinary collaboration among aquatic ecologists, (eco)hydrologists, fluvial geomorphologists, biogeochemists, analytical chemists and microbiologists, cell biologists and physicians. The seven major challenges outlined here will help interdisciplinary researchers to facilitate collective goals and direct future systematic analyses of MP fate and transport controls on potential entry points and uptake mechanisms into aquatic food webs. The resulting knowledge will enable confirmation of the major propagation and biomagnification routes and subsequent organismal and ecosystem impacts of MPs in freshwater ecosystems and determination of the relative risks to human health, allowing targeted mitigation strategies with maximum impact to be developed.

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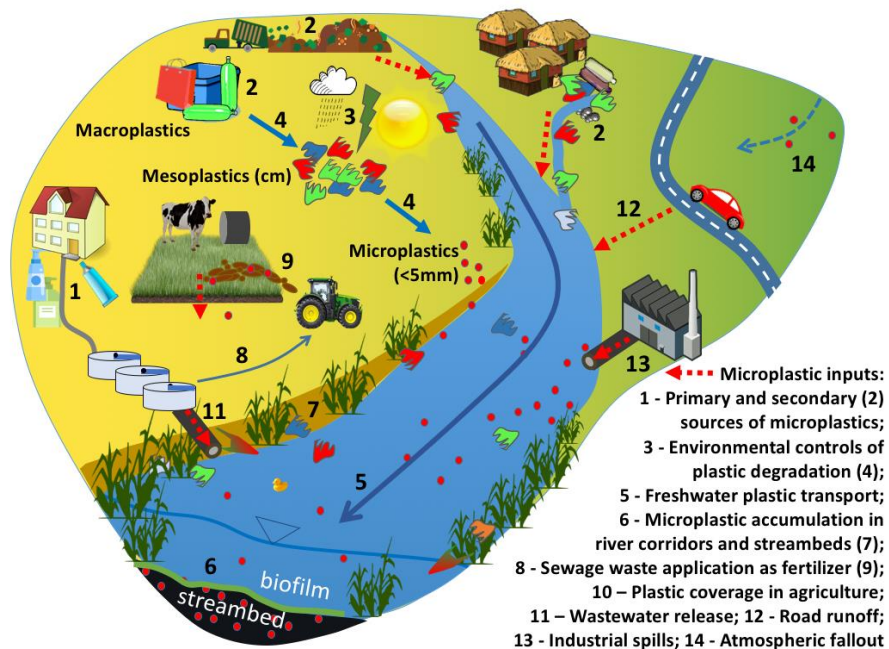
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Author contributions

All co-authors contributed to the drafting of the manuscript, and all have approved the final version.

Figures:

Figure 1 Mechanisms of plastic fate and transport processes across the river basin continuum, highlighting sources, input pathways and accumulation and breakdown mechanisms.



Box 1 Quantification of key microplastic transport processes in freshwater systems: While many of the processes that control the dynamics of small, light, organic particles in freshwater systems are reasonably well understood, understanding of which specific processes and system conditions dominate the fate of different types of microplastics is still lacking. Consequently, microplastic transport and ecological uptake can only be partially quantified at the present time. The current approaches used in modeling microplastic transport processes are illustrated in Figure 2. Models for *microplastic transport and retention in streams* currently assume that Stokes' settling velocity describes the transport of microplastics to the sediment bed. Stokes' settling velocity depends on particle density, size, and shape (Chubarenko et al., 2016; Dietrich, 1982; Kooi et al., 2017). Hydrodynamic transport – specifically *hyporheic exchange* – also delivers microplastic to the streambed, and this process is generally more important than settling of microplastic, especially for smaller particles (Drummond et al., 2020). Hyporheic exchange is caused by flow interactions with sediment beds and benthic algal mats, and is generally proportional to the square of in-stream velocity (Arnon et al., 2010; Boano et al., 2014; Packman et al., 2000). *Remobilization* of microplastics occurs during both baseflow and stormflow (Drummond et al., 2014; Drummond et al., 2017; Phillips et al., 2019), and remobilization has been modeled as a function of stream power, bed friction factor and particle size (Nizzetto et al., 2016). *Filtration, aggregation and other immobilization processes* within the sediments have been observed in laboratory columns and the processes parameterized in ways that can be incorporated into larger-scale models (Alimi, 2018). *Bioturbation* mixes particles in sediment beds, and models are available to describe both the burial of microplastic and their remobilization to the sediment-water interface (Roche et al., 2016). *Photodegradation* of microplastic has been measured in laboratory experiments and been shown to be both polymer-specific and flow-dependent (Hebner and Maurer-Jones, 2020). Note that episodic burial/remobilization will definitely influence the amount of time microplastics are exposed to light vs. benthic/hyporheic biodegradation; while this is unlikely to have been observed directly *in situ*, the significance of this process is known (Ward et al., 2015). Biochemical pathways of polymer biodegradation by bacteria and fungi are highly complex, and include polymer hydrolysis and oxidative degradation, which can transform both hydrolyzable and nonhydrolyzable polymers (Yuan et al., 2020). *Uptake and bioaccumulation* of microplastics and nanomaterials in organisms is dependent on particle size and species-specific uptake rates that vary based on their developmental stage (Fueser et al., 2019; McNeish et al., 2018; Scherer, 2017; van den Brink et al., 2019). The role of atmospheric transport and disposition as routes of environmental exposure and transport are just beginning to be explored (Lim et al., 2020). The parameterization of the governing equations in aforementioned models for quantifying MP fate, transport, degradation and uptake processes remains a challenge, with further experimental evidence needed to evaluate the range in polymer types and environmental conditions which alter each of the rates quantified for each process.

Figure 2 Physical (A), and biological (B) controls of microplastic fate and transport in freshwater ecosystems, including (C) impacts of flow variability and increased temperature during low-flow conditions and flow intermittence on microplastic accumulation and breakdown

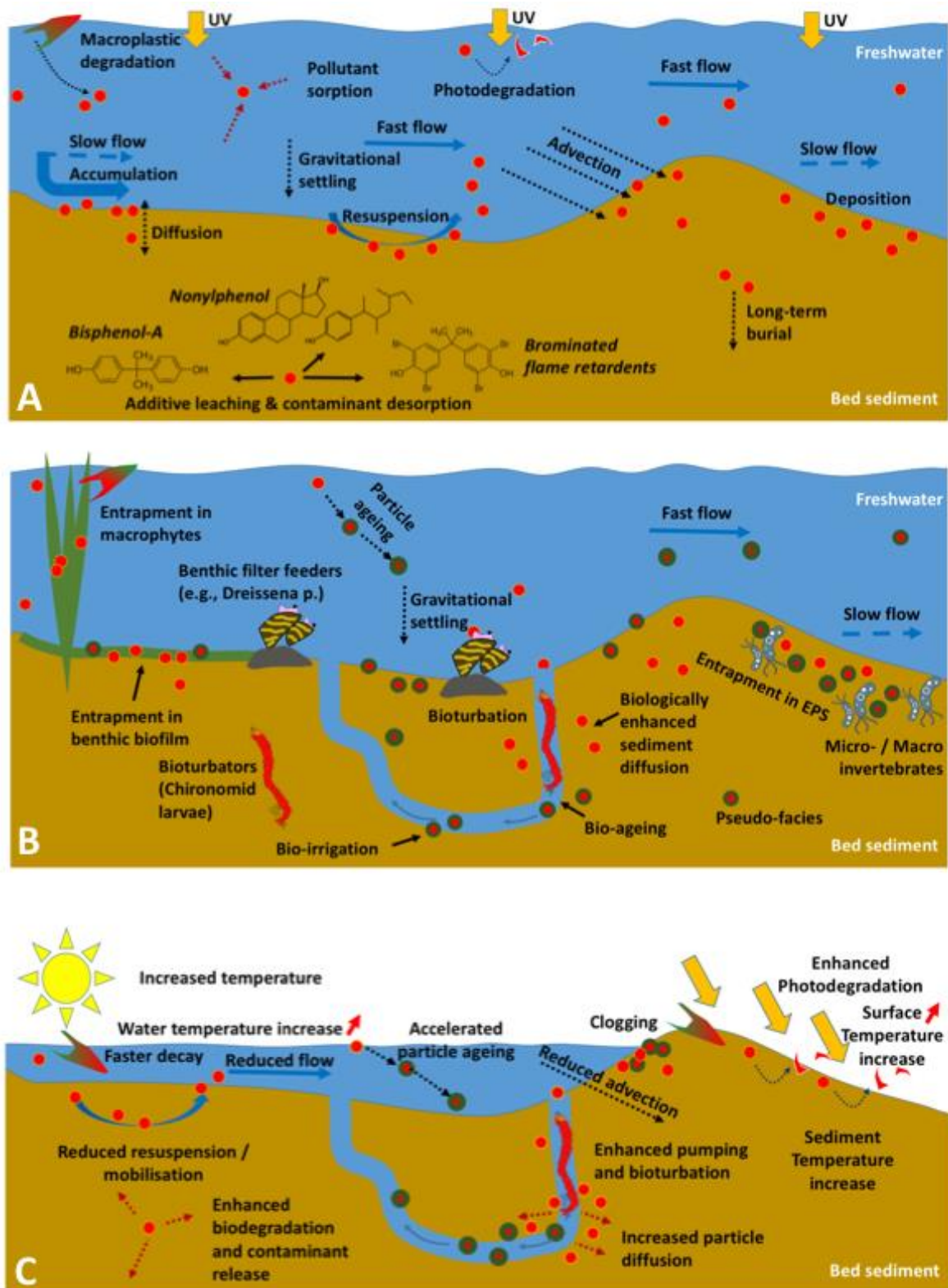
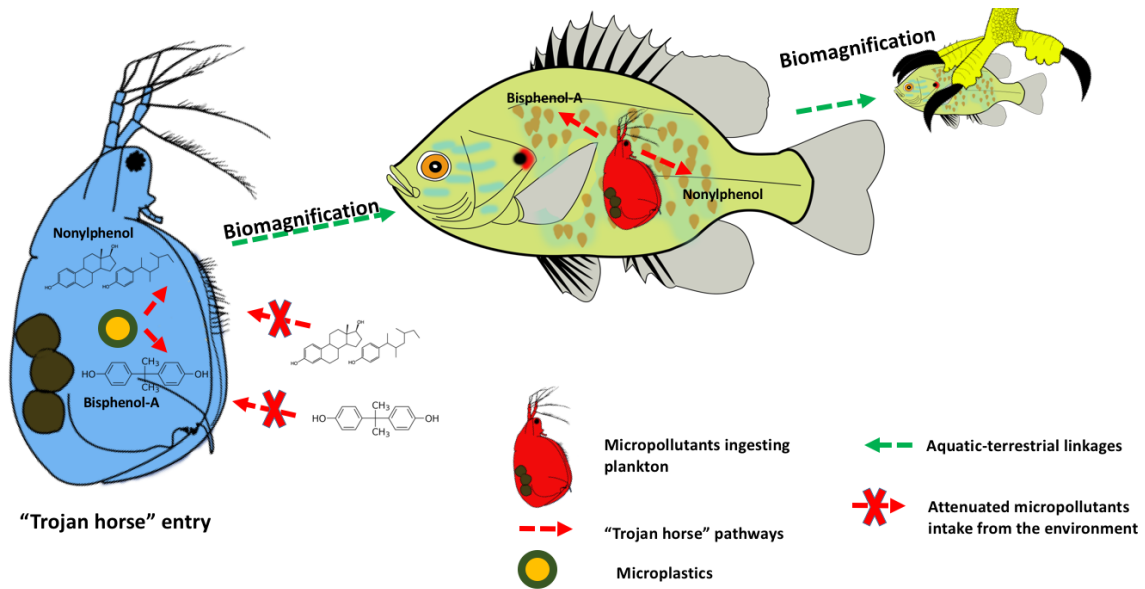


Figure 3 Microplastic uptake and propagation in an example aquatic food web, including leaching of additives and sorbed contaminants as part of Trojan horse effects, and potential biomagnification pathways



| | Research need | Scientific advances needed to achieve this |
|---------------------|--|--|
| Challenge 1: | Characterize the spatially heterogeneous sources of different plastic types and how their activation and contribution to river corridor plastic pollution vary over time. | <p>Agreed and validated methods and protocols for sampling, identification and quantification of MPs of different compositions and shapes</p> <p>Global baseline of MP abundance in freshwater ecosystems and characterisation of MP properties.</p> <p>Temporally and spatially dynamic sampling strategies that support identification of event-based (drought, flooding and re-wetting) inputs of MPs from point versus diffuse sources</p> |
| Challenge 2: | Establish how microplastic properties, hydrodynamics, and biological processes affect the fate and transport of microplastics, their degradation, ageing, breakdown, and the release of toxins | <p>Analytical tools for assessment of MP ageing, degradation, and determination of the relative contribution of different processes (e.g. abrasion, UV-irradiation) on degradation as a function of MP composition (e.g. shape, density)</p> <p>Lab-assays for assessment of release of additives from MPs under ecologically and biologically relevant conditions (ionic strengths, pH, natural organic matter and abundance of other biomolecules)</p> <p>Flume and field-scale approaches for assessing the impacts of hydrodynamics, geological setting on accumulation of MPs in sediment; agreed sampling methods will be needed here also to allow comparisons of different hydrological conditions</p> <p>Full characterisation of MP ageing of different polymer products under the influence of variable environmental conditions, and re-evaluation using aged MPs where relevant</p> |
| Challenge 3: | Quantify microplastic exposure hotspots and mechanisms of uptake pathways into food webs | <p>Based on knowledge from Challenges 1 and 2 confirm hotspots of MP accumulation, and characterise conditions for deposition and accumulation; and for MP degradation</p> <p>From these determine organisms at specific risk, and undertake targeted lab and mesocosm studies to determine if these organisms do preferentially accumulate MPs (pristine versus variously aged and bio-fouled)</p> <p>Laboratory experiments of food webs of increasing realism to assess role of amongst others, food, water, natural organic</p> |

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| | | matter, pseudofaeces on MP uptake and accumulation in target organisms. Again, comparison of pristine and variously aged and bio-fouled MPs is needed. |
| Challenge 4: | Identify potential Trojan Horse effects and other shortcuts for xenobiotics into aquatic food webs | <p>Lab-based experiments under realistic exposure conditions (e.g. presence of natural organic matter and other competitive binders) to assess affinity of pollutants for MP surfaces and residence times – comparison of pristine and variously aged and bio-fouled MPs binding affinities, loading capacities and retention times</p> <p>Studies mimicking gut pH of target organisms to assess release of additives from the MPs before / during / following uptake into target organisms, including biofilms again considering pristine and aged/bio-fouled variants</p> <p>Investigation of the role of natural organic matter as a sink / source for additives / xenobiotics and how this influences MP Trojan Horse effects</p> |
| Challenge 5: | Determine the importance of ecological behavioural aspects (from colour preferences to bioturbation) that affects microplastic abundance and uptake. | <p>Grouping of recognition mechanisms and food preferences of different organisms and determination of correlations with different types / sources of plastics and their resulting MP degradation products</p> <p>Targeted lab-based experiments to confirm if preferential uptake occurs under realistic exposure conditions, i.e. in the presence of equal or larger quantities of test organisms preferred food sources and whether aged or bio-fouled MPs are taken up preferentially</p> <p>Analysis of MP abundance effects and thresholds relative to natural food sources to determine if tipping point effects are likely</p> |
| Challenge 6: | Identify microplastic propagation pathways in | Mesocosm experiments with complex food-webs and realistic environmental and ecological conditions, including also realistic |

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| | complex food webs and assess risks of potential biomagnification for human health | hydrological conditions (e.g. using recirculating streams) and aged / bio-fouled MPs Comparison / quantification of various uptake routes – direct exposure, indirect exposure via food / pseudofaeces – and their relative contributions to total uptake under food abundant and food scarcity scenarios |
| Challenge 7: | Assess the impacts of freshwater microplastic accumulation and associated additives, sorbed contaminants, and pathogens on the behaviour and performance of host organisms and key ecosystem functioning | Ecotoxicity tests related to target organisms and under the realistic and competitive exposure conditions outlined above with appropriate controls for the various additives that can potentially be released Spiking experiments for additives to assess co-exposure effects, again under realistic / competitive conditions since the target xenobiotic will not be the only species that binds to the MP surface under environmental conditions Co-investigation of MPs and flow conditions (flooding/drought / riffles for deposition etc.) on bioavailability, uptake and retention of MPs. Assessment of wider ecosystems services, such as water purification by biofilms, bioturbation by benthic species etc. |

Table 1 The key research challenges whose resolution will represent milestones in understanding the controls of exposure, uptake and propagation of microplastics in aquatic food webs and selection of scientific advances required to address those key challenges.

References

- Al-Jaibachi, R., Cuthbert, R.N., Callaghan, A., 2018. Up and away: ontogenic transference as a pathway for aerial dispersal of microplastics. *Biol. Lett.* 14.
- Alimi, O.S., Farner Budarz, J., Hernandez, L. M., Tufenkji, N., 2018. Microplastics and Nanoplastics in Aquatic Environments: Aggregation, Deposition, and Enhanced Contaminant Transport. *Environmental Science & Technology* 52, 1704-1724.
- Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., Galop, D., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience* 12, 339-344.
- Andrady, A.I., Neal, M. A., 2009. Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1977-1984.
- Arnon, S., Marx, L.P., Searcy, K.E., Packman, A.I., 2010. Effects of overlying velocity, particle size, and biofilm growth on stream–subsurface exchange of particles. 24, 108-114.
- Avio, C.G., Gorbi, S., Regoli, F., 2015. Experimental development of a new protocol for extraction and characterization of microplastics in fish tissues: First observations in commercial species from Adriatic Sea. *Marine Environmental Research* 111, 18-26.
- Ballent, A., Corcoran, P. L., Madden, O., Helm, P. A., Longstaffe, F. J., 2016. Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. *Marine Pollution Bulletin* 110, 383-395.
- Batel, A., Linti, F., Scherer, M., Erdinger, L., 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. *Environmental Toxicology and Chemistry* 35, 1656-1666.
- Bergmann, M., Gutow, L., Klages, M., 2015. *Marine Anthropogenic Litter*. Springer.
- Besseling, E., Foekema, E. M., Van Franeker, J. A., Leopold, M. F., Kühn, S., Bravo Rebolledo, E. L., Heße, E., Mielke, L., Ijzer, J., Kamminga, P., Koelmans, A. A., 2015. Microplastic in a macro filter feeder: Humpback whale *Megaptera novaeangliae*. *Marine Pollution Bulletin* 95, 248-252.
- Besseling, E., Redondo-Hasselerharm, P., Foekema, E. M., Koelmans, A. A., 2018. Quantifying ecological risks of aquatic micro- and nanoplastic. *Critical Reviews in Environmental Science and Technology*, 1-49.
- Biginagwa, F.J., Mayoma, B. S., Shashoua, Y., Syberg, K., Khan, F. R., 2016. First evidence of microplastics in the African Great Lakes: Recovery from Lake Victoria Nile perch and Nile tilapia. *Journal of Great Lakes Research* 42, 146-149.
- Boano, F., Harvey, J.W., Marion, A., Packman, A.I., Revelli, R., Ridolfi, L., Wörman, A., 2014. Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications. 52, 603-679.
- Brennecke, D., Duarte, B., Paiva, F., Caçador, I., Canning-Clode, J., 2016. Microplastics as vector for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science* 178, 189-195.
- Canniff, P.M., Hoang, T. C., 2018. Microplastic ingestion by *Daphnia magna* and its enhancement on algal growth. *Science of The Total Environment* 633, 500-507.
- Catarino, A.I., Macchia, V., Sanderson, W. G., Thompson, R. C., Henry, T. B., 2018. Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environmental Pollution* 237, 675-684.

- Chae, Y., Kim, D., Kim, S. W., An, Y.-J., 2018. Trophic transfer and individual impact of nano-sized polystyrene in a four-species freshwater food chain. *Scientific Reports* 8, 284.
- Chubarenko, I., Bagaev, A., Zobkov, M., Esiukova, E., 2016. On some physical and dynamical properties of microplastic particles in marine environment. *Marine Pollution Bulletin* 108, 105-112.
- Collard, F., Gasperi, J., Gilbert, B., Eppe, G., Azimi, S., Rocher, V., Tassin, B., 2018. Anthropogenic particles in the stomach contents and liver of the freshwater fish *Squalius cephalus*. *Science of The Total Environment* 643, 1257-1264.
- Corcoran, P.L., Norris, T., Ceccanese, T., Walzak, M. J., Helm, P. A., Marvin, C. H., 2015. Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment record. *Environmental Pollution* 204, 17-25.
- Costa, M.F., Barletta, M., 2016. Special challenges in the conservation of fishes and aquatic environments of South America. *Journal of Fish Biology* 89, 4-11.
- Da Costa, J.P., Nunes, A. R., Santos, P. S. M., Girão, A. V., Duarte, A. C., Rocha-Santos, T., 2018. Degradation of polyethylene microplastics in seawater: Insights into the environmental degradation of polymers. *Journal of Environmental Science and Health, Part A* 53, 866-875.
- de Sá, L.C., Luís, L. G., 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. *Environmental Pollution* 196, 359-362.
- de Sá, L.C., Oliveira, M., Ribeiro, F., Rocha, T. L., Futter, M. N., 2018. Studies of the effects of microplastics on aquatic organisms: What do we know and where should we focus our efforts in the future? *Science of The Total Environment* 645, 1029-1039.
- Deng, Y., Zhang, Y., Lemos, B., Ren, H., 2017. Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. *Scientific Reports* 7, 46687.
- Dermott, R., Munawar, M., Carou, S., Bonnell, R., Niblock, H., 2005. Is sediment or pseudofaeces toxicity responsible for the decline of the amphipod *Diporeia hoyi* in Lakes Erie and Ontario? *Aquatic Ecosystem Health & Management* 8, 11-20.
- Dietrich, W.E., 1982. Settling velocity of natural particles. 18, 1615-1626.
- Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin* 104, 290-293.
- Dris, R., Imhof, H., Sanchez, W., Gasperi, J., Galgani, F., Tassin, B., Laforsch, C., 2015. Beyond the ocean: contamination of freshwater ecosystems with (micro-)plastic particles. *Environmental Chemistry* 12, 539-550.
- Drummond, J.D., Aubeneau, A.F., Packman, A.I., 2014. Stochastic modeling of fine particulate organic carbon dynamics in rivers. 50, 4341-4356.
- Drummond, J.D., Larsen, L.G., González-Pinzón, R., Packman, A.I., Harvey, J.W., 2017. Fine particle retention within stream storage areas at base flow and in response to a storm event. 53, 5690-5705.
- Drummond, J.D., Nel, H.A., Packman, A.I., Krause, S., 2020. Significance of Hyporheic Exchange for Predicting Microplastic Fate in Rivers. *Environmental Science & Technology Letters*.
- Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. *Environmental Sciences Europe* 28, 2.
- Eerkes-Medrano, D., Thompson, R. C., Aldridge, D. C., 2015. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research* 75, 63-82.

- Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLoS ONE* 9, e111913.
- Estahbanati, S., Fahrenfeld, N. L., 2016. Influence of wastewater treatment plant discharges on microplastic concentrations in surface water. *Chemosphere* 162, 277-284.
- Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). *Environmental Pollution* 177, 1-3.
- Faure, F., Corbaz, M., Baecher, H., de Alencastro, L., 2012. Pollution due to plastics and microplastics in Lake Geneva and in the Mediterranean Sea. *Arch. Sci.* 65, 157-164.
- Foekema, E.M., De Gruijter, C., Mergia, M. T., van Franeker, J. A., Murk, A. J., Koelmans, A. A., 2013. Plastic in North Sea Fish. *Environmental Science & Technology* 47, 8818-8824.
- Foley, C.J., Feiner, Z. S., Malinich, T. D., Höök, T. O., 2018. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. *Science of The Total Environment* 631-632, 550-559.
- Fossi, M.C., Marsili, L., Baini, M., Giannetti, M., Coppola, D., Guerranti, C., Caliani, I., Minutoli, R., Lauriano, G., Finioia, M. G., Rubegni, F., Panigada, S., Bérubé, M., Urbán Ramírez, J., Panti, C., 2016. Fin whales and microplastics: The Mediterranean Sea and the Sea of Cortez scenarios. *Environmental Pollution* 209, 68-78.
- Frei, S., Piehl, S., Gilfedder, B.S., Löder, M.G.J., Krutzke, J., Wilhelm, L., Laforsch, C., 2019. Occurrence of microplastics in the hyporheic zone of rivers. *Scientific Reports* 9, 15256.
- Frère, L., Maignien, L., Chalopin, M., Huvet, A., Rinnert, E., Morrison, H., Kerninon, S., Cassone, A.-L., Lambert, C., Reveillaud, J., Paul-Pont, I., 2018. Microplastic bacterial communities in the Bay of Brest: Influence of polymer type and size. *Environmental Pollution* 242, 614-625.
- Fueser, H., Mueller, M.-T., Weiss, L., Höss, S., Traunspurger, W., 2019. Ingestion of microplastics by nematodes depends on feeding strategy and buccal cavity size. *Environmental Pollution* 255, 113227.
- GESAMP, 2016. Sources, Fate and Effects of Microplastics in the Marine Environment (Part 2).
- Green, D.S., Boots, B., Sigwart, J., Jiang, S., Rocha, C., 2016. Effects of conventional and biodegradable microplastics on a marine ecosystem engineer (*Arenicola marina*) and sediment nutrient cycling. *Environmental Pollution* 208, 426-434.
- Harrison, J.P.H., T.J.; Sapp, M.; Tagg, A.S.; Ju-Nam, Y.; Ojeda, J.J., 2018. Microplastic-Associated Biofilms: A Comparison of Freshwater and Marine Environments, in: Wagner, M.L., S. (Ed.), *Freshwater Microplastics : Emerging Environmental Contaminants?* Springer International Publishing, Cham, pp. 181-201.
- Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H.S., Schmidt, S.N., Mayer, P., Meibom, A., Baun, A., 2017. Microplastics as vectors for environmental contaminants: Exploring sorption, desorption, and transfer to biota. *Integrated Environmental Assessment and Management* 13, 488-493.
- Hebner, T.S., Maurer-Jones, M.A., 2020. Characterizing microplastic size and morphology of photodegraded polymers placed in simulated moving water conditions. *Environmental Science: Processes & Impacts* 22, 398-407.
- Hoellein, T.J., Shogren, A. J., Tank, J. L., Risteca, P., Kelly, J. J., 2019. Microplastic deposition velocity in streams follows patterns for naturally occurring allochthonous particles. *Scientific Reports* 9, 3740.
- Hölker, F., Vanni, M. J., Kuiper, J. J., Meile, C., Grossart, H.-P., Stief, P., Adrian, R., Lorke, A., Dellwig, O., Brand, A., Hupfer, M., Mooij, W., Nützmann, G., Lewandowski, J., 2015. Tube-dwelling

invertebrates: tiny ecosystem engineers have large effects in lake ecosystems. *Ecological Monographs* 85, 333-351.

Horton, A.A., Jürgens, M.D., Lahive, E., van Bodegom, P.M., Vijver, M.G., 2018a. The influence of exposure and physiology on microplastic ingestion by the freshwater fish *Rutilus rutilus* (roach) in the River Thames, UK. *Environmental Pollution* 236, 188-194.

Horton, A.A., Walton, A., Spurgeon, D. J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of The Total Environment* 586, 127-141.

Horton, A.A.D., S. J., 2018b. Microplastics: An introduction to environmental transport processes. *WIREs Water* 5.

Hurley, R., Woodward, J., Rothwell, J.J., 2018. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. *Nature Geoscience* 11, 251-257.

Imhof, H.K., Ivleva, N.P., Schmid, J., Niessner, R., Laforsch, C., 2013. Contamination of beach sediments of a subalpine lake with microplastic particles. *Current Biology* 23, PR867-R886.

Ivar do Sul, J.A., Costa, M. F., 2014. The present and future of microplastic pollution in the marine environment. *Environmental Pollution* 185, 352-364.

Izvekova, E., Ivova-Katchanova, A., 1972. Sedimentation of suspended matter by *Dreissena polymorpha* Pallas and its subsequent utilization by Chironomidae larvae. *Pol. Arch. Hydrobiol. Arch. Hydrobiol.* 19 203–210.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., Law, K. L., 2015. Plastic waste inputs from land into the ocean. *Science* 347, 768-771.

Kashiwada, S., 2006. Distribution of nanoparticles in the see-through medaka (*Oryzias latipes*). *Environmental health perspectives* 114, 1697-1702.

Katzenberger, T.D., 2015. Assessing the Biological Effects of Exposure to Microplastics in the Three-Spined Stickleback (*Gasterosteus aculeatus*) (Linnaeus 1758). University of York. .

Khatmullina, L., Isachenko, I., 2017. Settling velocity of microplastic particles of regular shapes. *Marine Pollution Bulletin* 114, 871-880.

Kim, S.W., Kim, D., Chae, Y., An, Y.-J., 2018. Dietary uptake, biodistribution, and depuration of microplastics in the freshwater diving beetle *Cybister japonicus*: Effects on predacious behavior. *Environmental Pollution* 242, 839-844.

Klein, S., Worch, E., Knepper, T. P., 2015. Occurrence and Spatial Distribution of Microplastics in River Shore Sediments of the Rhine-Main Area in Germany. *Environmental Science & Technology* 49, 6070-6076.

Koelmans, A.A., Besseling, E., Shim, W. J., 2015. Nanoplastics in the Aquatic Environment. *Critical Review.*, in: M., B.M.G.L.K. (Ed.), *Marine Anthropogenic Litter*. Springer, Cham.

Kooi, M., Nes, E.H.v., Scheffer, M., Koelmans, A.A., 2017. Ups and Downs in the Ocean: Effects of Biofouling on Vertical Transport of Microplastics. *Environmental Science & Technology* 51, 7963-7971.

Lagarde, F., Olivier, O., Zanella, M., Daniel, P., Hiard, S., Caruso, A., 2016. Microplastic interactions with freshwater microalgae: Hetero-aggregation and changes in plastic density appear strongly dependent on polymer type. *Environmental Pollution* 215, 331-339.

Lamb, J.B., Willis, B. L., Fiorenza, E. A., Couch, C. S., Howard, R., Rader, D. N., True, J. D., Kelly, L. A., Ahmad, A., Jompa, J., Harvell, C. D., 2018. Plastic waste associated with disease on coral reefs. *Science* 359, 460-462.

- Lambert, S., Wagner, M., 2016. Exploring the effects of microplastics in freshwater environments. *Integrated Environmental Assessment and Management* 12, 404-405.
- Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. *Nature Communications* 8, 15611.
- Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., Glas, M., Schludermann, E., 2014. The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. *Environmental pollution (Barking, Essex : 1987)* 188, 177-181.
- Lederer, A., Massart, J., Janssen, J., 2006. Impact of Round Gobies (*Neogobius melanostomus*) on Dreissenids (*Dreissena polymorpha* and *Dreissena bugensis*) and the Associated Macroinvertebrate Community Across an Invasion Front. *Journal of Great Lakes Research* 32, 1-10.
- Lewandowski, J., Laskov, C., Hupfer, M., 2007. The relationship between *Chironomus plumosus* burrows and the spatial distribution of pore-water phosphate, iron and ammonium in lake sediments. *Freshwater Biology* 52, 331-343.
- Li, J., Green, C., Reynolds, A., Shi, H., Rotchell, J. M., 2018. Microplastics in mussels sampled from coastal waters and supermarkets in the United Kingdom. *Environmental Pollution* 241, 35-44.
- Lim, D., Jeong, J., Song, K.S., Sung, J.H., Oh, S.M., Choi, J., 2020. Inhalation toxicity of polystyrene micro(nano)plastics using modified OECD TG 412. *Chemosphere*, 128330.
- Luís, L.G., Ferreira, P., Fonte, E., Oliveira, M., Guilhermino, L., 2015. Does the presence of microplastics influence the acute toxicity of chromium(VI) to early juveniles of the common goby (*Pomatoschistus microps*)? A study with juveniles from two wild estuarine populations. *Aquatic Toxicology* 164, 163-174.
- Malinich, T.D., Chou, N., Sepúlveda, M. S., Höök, T. O., 2018. No evidence of microplastic impacts on consumption or growth of larval Pimephales promelas. *Environ Toxicol Chem.* 37, 2912-2918.
- Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine River. *Scientific Reports* 5, 17988.
- Martins, A., Guilhermino, L., 2018. Transgenerational effects and recovery of microplastics exposure in model populations of the freshwater cladoceran *Daphnia magna* Straus. *Science of The Total Environment* 631-632, 421-428.
- Mattsson, K., Hansson, L. A., Cedervall, T., 2015. Nano-plastics in the aquatic environment. *Environmental Science: Processes & Impacts* 17, 1712-1721.
- McCormick, A., Hoellein, T. J., Mason, S. A., Schlupe, J., Kelly, J. J., 2014. Microplastic is an Abundant and Distinct Microbial Habitat in an Urban River. *Environmental Science & Technology* 48, 11863-11871.
- McCormick, A.R., Hoellein, T. J., London, M. G., Hittie, J., Scott, J. W., Kelly, J. J., 2016. Microplastic in surface waters of urban rivers: concentration, sources, and associated bacterial assemblages. *Ecosphere* 7, e01556.
- McNeish, R.E., Kim, L.H., Barrett, H.A., Mason, S.A., Kelly, J.J., Hoellein, T.J., 2018. Microplastic in riverine fish is connected to species traits. *Scientific Reports* 8, 11639.
- McNeish, R.E., Kim, L. H., Barrett, H. A., Mason, S. A., Kelly, J. J., Hoellein, T. J., 2018. Microplastic in riverine fish is connected to species traits. *Scientific Reports* 8, 11639-11639.
- Michels, J., Stippkugel, A., Lenz, M., Wirtz, K., Engel, A., 2018. Rapid aggregation of biofilm-covered microplastics with marine biogenic particles. *Proceedings of the Royal Society B: Biological Sciences* 285.

- Murphy, F., Ewins, C., Carbonnier, F., Quinn, B., 2016. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environmental Science & Technology* 50, 5800-5808.
- Nasser, F., Lynch, I., 2016. Secreted protein eco-corona mediates uptake and impacts of polystyrene nanoparticles on *Daphnia magna*. *Journal of Proteomics* 137, 45-51.
- Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R. A., Carrao, H., Spinoni, J., Vogt, J., Feyen, L., 2018. Global changes in drought conditions under different levels of warming. *Geophysical Research Letters* 45, 3285–3296.
- Nizzetto, L., Bussi, G., Futter, M.N., Butterfield, D., Whitehead, P.G., 2016. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. *Environmental Science: Processes & Impacts* 18, 1050-1059.
- Oliveira, M., Ribeiro, A., Hylland, K., Guilhermino, L., 2013. Single and combined effects of microplastics and pyrene on juveniles (0+ group) of the common goby *Pomatoschistus microps* (Teleostei, Gobiidae). *Ecological Indicators* 34, 641-647.
- Packman, A.I., Brooks, N.H., Morgan, J.J., 2000. Kaolinite exchange between a stream and streambed: Laboratory experiments and validation of a colloid transport model. 36, 2363-2372.
- Parker, L., 2018. In a first, microplastics found in human poop, *The National Geographic*.
- Pazos, R.S., Maiztegui, T., Colautti, D. C., Paracampo, A. H., Gómez, N., 2017. Microplastics in gut contents of coastal freshwater fish from Río de la Plata estuary. *Marine Pollution Bulletin* 122, 85-90.
- Peters, C.A., Bratton, S. P., 2016. Urbanization is a major influence on microplastic ingestion by sunfish in the Brazos River Basin, Central Texas, USA. *Environmental Pollution* 210, 380-387.
- Phillips, C.B., Dallmann, J.D., Jerolmack, D.J., Packman, A.I., 2019. Fine-Particle Deposition, Retention, and Resuspension Within a Sand-Bedded Stream Are Determined by Streambed Morphodynamics. 55, 10303-10318.
- Phillips, M.B., Bonner, T. H., 2015. Occurrence and amount of microplastic ingested by fishes in watersheds of the Gulf of Mexico. *Marine Pollution Bulletin* 100, 264-269.
- Planelló, R., Martínez-Guitarte, J. L., Morcillo, G., 2008. The endocrine disruptor bisphenol A increases the expression of HSP70 and ecdysone receptor genes in the aquatic larvae of *Chironomus riparius*. *Chemosphere* 71, 1870-1876.
- Porter, A., Lyons, B. P., Galloway, T. S., Lewis, C., 2018. Role of Marine Snows in Microplastic Fate and Bioavailability. *Environmental Science & Technology* 52, 7111-7119.
- Prata, J.C., 2018. Microplastics in wastewater: State of the knowledge on sources, fate and solutions. *Marine Pollution Bulletin* 129, 262-265.
- Redondo-Hasselerharm, P.E., de Ruijter, V. N., Mintenig, S. M., Verschoor, A., Koelmans, A. A., 2018. Ingestion and Chronic Effects of Car Tire Tread Particles on Freshwater Benthic Macroinvertebrates. *Environmental Science & Technology* 52, 13986-13994.
- Rehse, S., Kloas, W., Zarfl, C., 2016. Short-term exposure with high concentrations of pristine microplastic particles leads to immobilisation of *Daphnia magna*. *Chemosphere* 153, 91-99.
- Rehse, S., Kloas, W., Zarfl, C., 2018. Microplastics Reduce Short-Term Effects of Environmental Contaminants. Part I: Effects of Bisphenol A on Freshwater Zooplankton Are Lower in Presence of Polyamide Particles. *International Journal of Environmental Research and Public Health* 15, 280.
- Roche, K.R., Aubeneau, A.F., Xie, M., Aquino, T., Bolster, D., Packman, A.I., 2016. An Integrated Experimental and Modeling Approach to Predict Sediment Mixing from Benthic Burrowing Behavior. *Environmental Science & Technology* 50, 10047-10054.

- Rochman, C.M., 2018. Microplastics research—from sink to source. *Science* 360, 28-29.
- Rochman, C.M., Parnis, J.M., Browne, M.A., Serrato, S., Reiner, E.J., Robson, M. , 2017. Direct and indirect effects of different types of microplastics on freshwater prey (*Corbicula fluminea*) and their predator (*Acipenser transmontanus*). *PLoS ONE* 12, e0187664.
- Rochman, C.M.H., E.; Kurobe, T.; Teh, S. J., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports* 3, 3263.
- Rochman, C.M.T., A.; Williams, S. L.; Baxa, D. V.; Lam, R.; Miller, J. T.; Teh, F.-C.; Werorilangi, S.; Teh, S. J., 2015. Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Scientific Reports* 5, 14340.
- Rosenkranz, P., Chaudhry, Q., Stone, V., Fernandes, T. F., 2009. A comparison of nanoparticle and fine particle uptake by *Daphnia magna*. *Environmental Toxicology and Chemistry* 28, 2142-2149.
- Roskosch, A., Hupfer, M., Nützmann, G., Lewandowski, J., 2011. Measurement techniques for quantification of pumping activity of invertebrates in small burrows. *Fundamental and Applied Limnology* 178, 89 - 110.
- Rummel, C.D., Jahnke, A., Gorokhova, E., Kühnel, D., Schmitt-Jansen, M., 2017. Impacts of Biofilm Formation on the Fate and Potential Effects of Microplastic in the Aquatic Environment. *Environmental Science & Technology Letters* 4, 258-267.
- Sanchez, W., Bender, C., Porcher, J.-M., 2014. Wild gudgeons (*Gobio gobio*) from French rivers are contaminated by microplastics: Preliminary study and first evidence. *Environmental Research* 128, 98-100.
- Scherer, C., Brennholt, N., Reifferscheid, G., Wagner, M., 2017. Feeding type and development drive the ingestion of microplastics by freshwater invertebrates. *Scientific Reports* 7, 17006.
- Schuyler, Q., Hardesty, B. D., Wilcox, C., Townsend, K., 2012. To eat or not to eat? Debris selectivity by marine turtles. *PLoS ONE* 7, e40884-e40884.
- Setälä, O., Fleming-Lehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of microplastics in the planktonic food web. *Environmental Pollution* 185, 77-83.
- Sgier, L., Freimann, R., Zupanic, A., Kroll, A., 2016. Flow cytometry combined with viSNE for the analysis of microbial biofilms and detection of microplastics. *Nature Communications* 7, 11587.
- Stewart, T.W., Miner, J. G., Lowe, R. L., 1998. Macroinvertebrate Communities on Hard Substrates in Western Lake Erie: Structuring Effects of *Dreissena*. *Journal of Great Lakes Research* 24, 868-879.
- Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H. , 2009. Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of the Royal Society of London B: Biological Science* 364, 2153-2166.
- Thompson, R.C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., Russell, A. E., 2004. Lost at Sea: Where Is All the Plastic? *Science* 304, 838-838.
- Tibbetts, J., Krause, S., Lynch, I., Sambrook Smith, G.H., 2018. Abundance, Distribution, and Drivers of Microplastic Contamination in Urban River Environments. *Water* 10, 1597.
- Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M. B., Janssen, C. R., 2015. Microplastics are taken up by mussels (*Mytilus edulis*) and lugworms (*Arenicola marina*) living in natural habitats. *Environmental Pollution* 199, 10-17.
- Van Cauwenberghe, L., Janssen, C. R., 2014. Microplastics in bivalves cultured for human consumption. *Environmental Pollution* 193, 65-70.

- van den Brink, N.W., Jemec Kokalj, A., Silva, P.V., Lahive, E., Norrfors, K., Baccaro, M., Khodaparast, Z., Loureiro, S., Drobne, D., Cornelis, G., Lofts, S., Handy, R.D., Svendsen, C., Spurgeon, D., van Gestel, C.A.M., 2019. Tools and rules for modelling uptake and bioaccumulation of nanomaterials in invertebrate organisms. *Environmental Science: Nano* 6, 1985-2001.
- Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., Fries, E., Grosbois, C., Klasmeier, J., Marti, T., Rodriguez-Mozaz, S., Urbatzka, R., Vethaak, A. D., Winther-Nielsen, M., Reifferscheid, G., 2014. Microplastics in freshwater ecosystems: what we know and what we need to know. *Environmental Sciences Europe* 26, 12.
- Ward, A.S., Cwiertny, D.M., Kolodziej, E.P., Brehm, C.C., 2015. Coupled reversion and stream-hyporheic exchange processes increase environmental persistence of trenbolone metabolites. *Nature Communications* 6, 7067.
- Ward, J.M., Ricciardi, A., 2007. Impacts of *Dreissena* invasions on benthic macroinvertebrate communities: a meta-analysis. *Diversity and Distributions* 13, 155-165.
- Wardrop, P., Shimeta, J., Nugegoda, D., Morrison, P. D., Miranda, A., Tang, M., Clarke, B. O., 2016. Chemical Pollutants Sorbed to Ingested Microbeads from Personal Care Products Accumulate in Fish. *Environmental Science & Technology* 50, 4037-4044.
- Weber, A., Scherer, C., Brennholt, N., Reifferscheid, G., Wagner, M., 2018. PET microplastics do not negatively affect the survival, development, metabolism and feeding activity of the freshwater invertebrate *Gammarus pulex*. *Environmental Pollution* 234, 181-189.
- Weithmann, N., Möller, J. N., Löder, M. G. J., Piehl, S., Laforsch, C., Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Science Advances* 4, eaap8060.
- Windsor, F.M., Tilley, R. M., Tyler, C. R., Ormerod, S. J., 2019. Microplastic ingestion by riverine macroinvertebrates. *Science of The Total Environment* 646, 68-74.
- Wolff, S., Kerpen, J., Prediger, J., Barkmann, L., Müller, L., 2019. Determination of the microplastics emission in the effluent of a municipal waste water treatment plant using Raman microspectroscopy. *Water Research X* 2, 100014.
- Wright, S.L., Kelly, F. J., 2017. Plastic and Human Health: A Micro Issue? *Environmental Science & Technology* 51, 6634-6647.
- Wright, S.L., Rowe, D., Thompson, R. C., Galloway, T. S., 2013. Microplastic ingestion decreases energy reserves in marine worms. *Current Biology* 23, R1031-R1033.
- Yuan, J., Ma, J., Sun, Y., Zhou, T., Zhao, Y., Yu, F., 2020. Microbial degradation and other environmental aspects of microplastics/plastics. *Science of The Total Environment* 715, 136968.
- Zbyszewski, M., Corcoran, P. L., Hockin, A., 2014. Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. *Journal of Great Lakes Research* 40, 288-299.
- Ziajahromi, S., Neale, P. A., Leusch, F. D. L., 2016. Wastewater treatment plant effluent as a source of microplastics: review of the fate, chemical interactions and potential risks to aquatic organisms. *Water Science and Technology* 74, 2253-2269.
- Ziccardi, L.M., Edgington, A., Hentz, K., Kulacki, K. J., Kane Driscoll, S., 2016. Microplastics as vectors for bioaccumulation of hydrophobic organic chemicals in the marine environment: A state-of-the-science review. *Environmental Toxicology and Chemistry* 35, 1667-1676.