Microplastics: an introduction to environmental transport processes

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Abstract

Microplastic pollution is widespread across the globe, pervading land, water and air. These environments are commonly considered independently, however in reality these are closely linked. This review gives an overview of the background knowledge surrounding sources, fate and transport of microplastics within the environment. We introduce a new 'Plastic Cycle' concept in order to better understand the processes influencing flux and retention of microplastics between and across the wide range of environmental matrices. As microplastics are a pervasive, persistent and potentially harmful pollutant, an understanding of these processes will allow for assessment of exposure to better determine the likely long-term ecological and human health implications of microplastic pollution.

Keywords: plastic pollution, plastic cycle, sediment, soil, freshwater, fate

1. Introduction

Plastic has many appealing characteristics to manufacturers and consumers, including being versatile, lightweight, durable, cheap and watertight. As a result, production of plastic has increased enormously since the introduction of commercially available plastics. In 1950 an estimated 1.7 Mt were produced,[1] with production estimates for the year 2015 ranging between 322 Mt and 380 Mt.[2, 3] An estimated 8300 million metric tons (Mt) of virgin plastic has been manufactured to date.[3] Today, around 40% of plastic produced is for packaging, with these items generally designed for a single use before disposal.[2] Unfortunately, this surge in the use of plastic has led to a massive increase in plastic items being released to the environment, due to intentional or unintentional losses.[4] It is estimated that around 60% of all plastics ever made have accumulated in landfill or the natural environment.[3]

Plastic items are manufactured in all shapes and sizes, with the smallest sizes (< 5mm) considered to be ‘microplastics’. Those specifically manufactured to be of this small size are called ‘primary microplastics’ and are produced as ‘nurdles’ (small pellets used as a raw material to make plastic products, Fig. 1), glitter and microbeads, which are added to cosmetics and personal care products. Once in the environment, plastic items can break down and therefore even large items may eventually form hundreds if not thousands of ‘secondary microplastics’ in the form of fragments, fibres or films (Fig. 1). There are a number of mechanisms by which this breakdown can occur, including mechanical degradation such as road wear, tyre abrasion, physical weathering of large items and washing of synthetic textiles,[5-8] chemical degradation (e.g. exposure to acids or alkalis) and UV degradation (exposure to UV radiation). Biological degradation can also occur in the presence of organisms with the capacity to ingest and degrade plastics, for example waxworms,[9] mealworms,[10] and some microbes.[11] Additionally, over time the plasticisers added to plastics during manufacture to give them their flexible and durable properties leach out, rendering the plastic brittle and more susceptible to degradation.[12, 13]

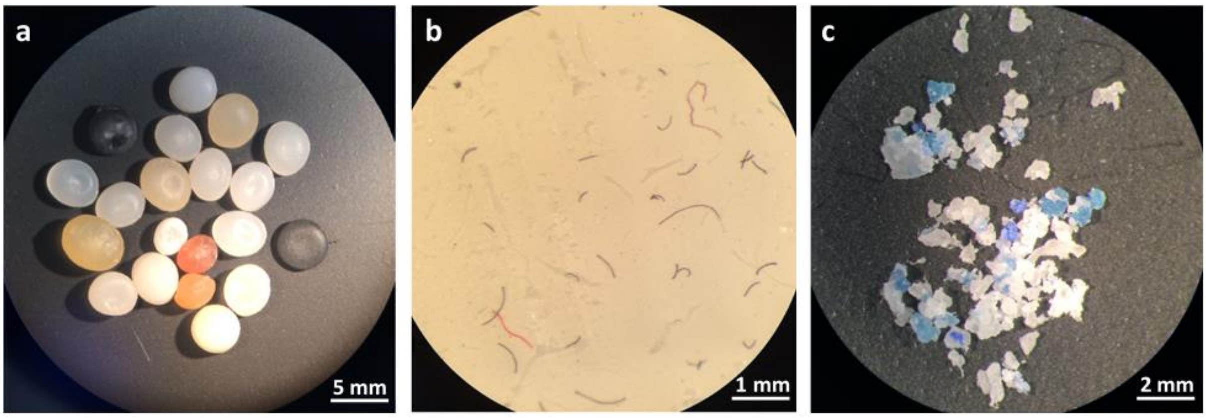

Fig 1. Images of different types of plastic particles a) pellets/nurdles, b) fibres and c) fragments. Scale bars are approximate.

2. Presence and sources of microplastics within the environment

There are many ways in which plastics can be released to the environment, either as primary microplastics or as larger plastic items (‘macroplastics’) which will break down to form secondary microplastics (Fig. 2). Primary microplastics from domestic products, such as microbeads, can be present in waste water and subsequently discharged to rivers, while nurdles can be lost to freshwaters during production processes. Examples of secondary microplastic sources include intentional release (illegal dumping), mismanaged waste (litter) or unintentional losses (e.g. fishing gear and loss of shipping cargo),[14] with the magnitude of different sources and pathways for microplastic release varying between the terrestrial, freshwater and marine environments.

2.1. Microplastics on land

All plastic is manufactured on land and, other than maritime or fishing uses, it is also where the majority of plastic is used in consumer products. The pathways for release of waste consumer products to land include direct littering and inefficient waste management e.g. loss during the waste disposal chain, industrial spillages, or release from landfill sites (Figure 2a).[15,

[16] Modern agricultural practises make use of plastic in a variety of ways including as mulches, which can degrade *in situ*, in addition to bale twine and wrapping which can be improperly disposed of.[17] These items can degrade to form secondary microplastics within the environment.

Microplastics may also be released directly to land along with sewage sludge applied to agricultural land as a fertiliser. Wastewater treatments plants are quite effective at removing microplastic particles from the wastewater stream, often with ~99% removal,[18-20] and many of these particles will settle to the sludge. It is estimated that throughout Europe, between 125-850 tons of microplastics per million inhabitants are added annually to agricultural soils as a result of sewage sludge application.[17] Horton et al.[21] calculated that 473,000-910,000 metric tonnes of plastic waste is retained within European continental environments (terrestrial and freshwater) annually, which includes microplastics derived from sewage sludge, in addition to predicted inputs of litter and inadequately managed waste. Where plastics are not transported from land to rivers or the sea, this could lead to massive accumulation. However, few studies have investigated abundance of microplastics within terrestrial environments, or linked abundance to input pathways, therefore it is not currently possible to directly link accumulation with specific environmental characteristics or anthropogenic activities.

2.2. Microplastics in freshwater environments

Freshwaters represent the most complex system regarding microplastic transport and retention, as they receive microplastics from the terrestrial environment, function as conduits for microplastics to the marine environment (Figure 2b), act as a means of microplastic production through breakup of larger items and act as sinks retaining microplastics in sediments. Additionally, ‘freshwater’ represents rivers, streams, ditches, lakes and ponds, all with very different characteristics.

Larger plastic items can enter the freshwater environment through inadequate waste disposal, either through littering or loss from landfill and transported from land via wind or surface runoff. In addition to macroplastics, there are significant direct inputs of microplastics to freshwater systems. Agricultural drainage and runoff from farmland can result in input of agricultural plastics or sewage-sludge derived fibres and microbeads. Storm drainage and urban runoff is often unfiltered and untreated, and can contain microplastics from degraded road paint and wear from vehicles.[5, 14] Despite the efficiency of wastewater treatment plants in removing microplastics, direct effluent input can also contain microplastics.[20] Additionally, during very high flow conditions, combined sewage overflows (CSOs) are designed to release untreated sewage into surrounding rivers to reduce the pressure on drainage systems, releasing both micro- and macroplastic waste. Studies suggest that although hotspots of microplastics may occur in close proximity to urban areas, the majority of microplastics are likely to enter waterbodies as a result of drainage systems and thus attention must also be paid to inputs including CSOs, storm drains and effluent outfalls, which may be set apart from the most densely populated areas.[5, 22]

Although the majority of freshwater microplastic studies tend to focus on rivers, it is understood that microplastics are also prevalent within ponds and lakes.[23-25] In the same way as rivers, these will receive inputs from land runoff and wind-blown debris, however due to the enclosed nature of lakes it is likely that inputs of microplastics to standing waterbodies will lead to accumulation over time.[23]

2.3. Microplastics in the marine environment

The presence and abundance of microplastics within the oceans have been widely studied. Sources of microplastics to marine environments are widespread, as oceans are generally considered to be the ultimate sink for all plastic within the environment.[22, 26] In addition to the inputs from rivers, plastics will also enter oceans directly via mismanaged maritime or fishing waste, including abandoned fishing gear, accidental cargo loss and illegal dumping. This will most likely be in the form of macroplastic waste that will degrade to form microplastics within the marine environment (Figure 2c). Microplastics have been found to be widespread throughout various locations and within marine organisms worldwide, with ocean currents leading to specific areas of accumulation such as the well-known 'Great Pacific Garbage Patch'.[27] Models have been developed to investigate transport processes and fate of microplastics within the oceans[28-30] which may also add to our understanding of the processes that influence microplastic transport within freshwater environments.

Fig. 2. Images of plastic pollution across a range of environments a) terrestrial, b) riverine, c) marine and d) coastal. Any large items can degrade to form secondary microplastics. *Image attributions a) PDPics on Pixabay CC-0, b) BiH via Wikimedia commons CC BY-SA 3.0, c) Ben Mierement, NOAA NOS CC-0, d)Michael Dorausch on Flickr CC BY-SA 2.0*

2.4. Microplastics in the atmosphere

It has recently been recognised that due to their lightweight nature, many microplastic particles will become suspended and transported within the air as 'urban dust'.[31, 32] These commonly originate from road dust (e.g. tyre and paint particles) and fibres from synthetic textiles, especially from soft furnishings[5, 33] and can lead to deposition of microplastics to land or aquatic environments. Although urban dust will originate especially in cities and highly populated areas, air currents and wind can lead particles to be transported far from the source.[34] Weather events such as heavy rainfall will facilitate the deposition of particles to land.[31] Given the diverse range of sources, the varying characteristics of particles affecting their behaviour and the range of environmental factors influencing particle transport, airborne microplastic contamination is extremely difficult to trace and predict. It is not currently known to what extent atmospheric fallout contributes to aquatic and terrestrial contamination, therefore more research is needed in this area.

3. Transport processes

It is widely considered that the ocean represents a sink for a large proportion of microplastics, with the terrestrial and freshwater environments acting as important sources and pathways for microplastics to the sea.[4, 35] Due to their lightweight nature and potential for widespread dispersal it is also likely that air currents act as a means of particulate transport, contributing to microplastic contamination on land and within aquatic systems.[31, 36] A number of studies have provided evidence for macro and microplastic litter reaching oceans from rivers[16, 37, 38] with particles often originating on land[5]. However, it is increasingly becoming recognised that far from being merely conveyor belts for waste plastic, freshwaters and soils can act as sinks themselves, retaining much of the microplastic pollution that they receive.[5, 39] In some cases, due to the proximity and scale of plastic inputs, certain terrestrial and freshwater areas could actually accumulate microplastics at higher concentrations than in the ocean.[17, 39] For future understanding of microplastic pollution within the environment it will therefore be important to link sources, particle behaviours and transport mechanisms, to understand how and where microplastics will accumulate.

Agricultural soils may be an important source for microplastics to rivers through the application of sewage sludge as fertiliser, although it is likely that a high proportion will also be retained. A study on microplastic retention within soils found synthetic fibres derived from sewage sludge retained within treated agricultural soil up to 15 years after the last sludge application.[40] This study also suggested that accumulation hotspots can occur even at depth, with fibres found at more than 25cm depth in areas where downward drainage flow through the soil was high.[40] Retention within soils will be further facilitated by processes such as bioturbation which will draw particles away from the surface and into the deeper layers of the soil.[41] Agricultural and forest soils are more likely to retain particles than urban land due to permeable soils and lower rates of overland flow.[42]

Where particles do enter rivers, they will be subject to the same transport processes which mobilise other sediments, such as sand and silt, in channels. In simple terms, the faster a river flows the more energy it has, and thus it can entrain and transport a greater volume of particles.[43] However, in the case of microplastics, most rivers are likely to be supply-limited with respect to transport, meaning rivers will be capable of transporting all plastics that are delivered to them. Despite the buoyancy of many plastics, where river energy drops, for example in slow-moving sections of water, it is likely that microplastics will settle out along with sinking sediment particles. Additionally, this sediment deposition may aid in the burial of microplastic particles, whether microplastics are simultaneously deposited or are already present within the sediment[44]. It is therefore likely that on their journey throughout the freshwater environment, many particles will also be retained within sediments.[17, 42] Within lakes where sediment accumulation rates are high, it has been suggested that retention and incorporation of microplastics into sediments could lead to burial and long-term preservation within the sediment.[44, 45]

The density and shape of microplastic particles will have important effects on their transport and retention in sediments. Although many polymer particles have low densities, so are buoyant and will float, there are also many types of polymer that are denser than water and so will naturally sink. Dense plastics include commonly used polymers such as polyvinyl chloride (PVC), polyethylene terephthalate (PET) and nylon (Table 1), in addition to polymer composites such as those found in paints.[5] The density of plastic polymers is also not constant, with the growth of microalgae on particles (biofouling) increasing their density, leading to them sinking and being deposited in sediments.[46] Additionally, size and shape play a role in retention of microplastics within sediments, with irregularly shaped particles having highly complex settling mechanics compared to spherical particles.[47] For buoyant particles, those which are irregularly-shaped are most likely to be drawn down from the surface of the water and be retained underwater, rather than return to the surface, compared to spherical particles.[29] In river bed sediments, larger microplastic particles have been found to be more likely to be retained.[42] However, previous work on comparable sediment particles has shown that shape may have a greater influence than size, with larger plate-like particles more likely to be mobilised in preference to finer, spherical particles.[48] This difference in particle behaviours dependent on size, shape and density illustrates the complexity in predicting and modelling microplastic fate and transport in river environments.

Polymer name	**Abbreviation**	**Density (g/cm^3)**
Polystyrene (non-expanded)	PS	1.04-1.08 [a]
Expanded polystyrene	EPS	0.015-0.03 [b]
Low-density polyethylene	LDPE	0.89-0.94 [a]
High-density polyethylene	HDPE	0.94-0.97 [a]
Polypropylene	PP	0.89-0.91 [a]
Polyvinyl chloride	PVC	1.3-1.58 [a]
Polyethylene terephthalate	PET	1.29-1.4 [a]
Polyester	-	1.01-1.46 [a]
Polyamide (nylon)	-	1.13-1.35 [c]

Table 1. Densities of commonly-used polymers. [a]US EPA (1992)[49], [b]Nuelle et al (2014)[50], [c]British Plastics Federation (2017)[51]

Sediment transport and deposition in rivers also has a great degree of temporal and spatial variability. At a local scale, instantaneous, small-scale changes in turbulence can apply energy to an area of river bed and act to entrain previously deposited particles.[52] At a wider scale, higher energy flows from floods are likely to lead to resuspension of dense microplastics along with other sediment particles.[43, 53] At longer timescales, progressive change in the morphology of river channels could lead to erosion of river bars or banks, remobilising previously deposited microplastics from floodplain sediment as has been shown for heavy metals.[54, 55]

Due to currents, winds and the large area covered, once they reach the oceans (micro)plastics can be rapidly and widely dispersed, travelling significant distances from the source.[56] Additionally, microplastics are subject to vertical transport within the oceans due to biofouling, egestion in faecal pellets and incorporation into marine snows (sinking detritus).[30, 57, 58] This wide-ranging vertical and horizontal transport is highlighted by the fact that microplastics have been discovered in all locations that have been investigated, including in the deep sea, Southern Ocean and Arctic ice cores.[59-61]

Little is known about the processes governing transport of microplastics within the air, although it is understood that this is likely to be a significant transport pathway of microplastics.[31, 33] Importantly, this mode of transport is likely to lead to the widest dispersal as it is the least limited by environmental boundaries, influenced mainly by the directions of air movement rather than the unidirectional flows that are generally the case on land and within waterbodies. Due to the limited data currently available, further research will be needed to better understand the processes involved in atmospheric microplastic transport and how this links with aquatic and terrestrial contamination.[31]

4. The Plastic Cycle

Currently, environmental microplastic research commonly focuses on independent environmental ‘compartments’, as highlighted above: terrestrial, freshwater and marine, and more recently, atmosphere.[31] However, with regard to movement, transport and fate of particulate (and chemical) matter, in reality these environmental compartments are very closely interlinked, with indistinct, permeable boundaries. Interactions between compartments can vary depending on weather and environmental conditions. This means the abundance and fate of microplastics in any given environment will be dependent on the degree of connectivity with adjacent environments, which can be highly variable in space and time. Further, processes that affect microplastics within one compartment can influence the way that a particle behaves within another. For example, degradation, association with chemicals or acquisition of an organic coating on particles derived from a terrestrial environment are factors that can have a significant bearing on particle behaviour and ecological interactions once within the freshwater environment. Therefore, it is not appropriate to consider these environments as separate, discrete regions governed by different processes.[21]

Microplastics are now so ubiquitous throughout the globe that a paradigm shift is needed, considering them as integrated into earth surface processes. A novel way of conceptualising microplastic pollution within the environment is through a ‘plastic cycle’ (Fig. 3). There are many pathways by which microplastics may travel between environmental compartments, from land via rivers to the sea. However, although the dominant transport direction will be from land to the marine environment, it is not necessarily the case that microplastics that reach the oceans will remain there, as they can return to land with high tides and storm events. This is highlighted not only in the abundance of plastic washed up on beaches following storm events (Figure 2d),[62] but also in the fact that microplastic particles can be found even on the shores of remote and uninhabited islands.[63, 64] Similarly, other transport pathways are not unidirectional, for example particles within rivers may return to land during flooding events.[21]

There are also regions where the compartmental boundaries blur, for example estuaries can contain predominantly fresh or marine water depending on the state of the tides, while ephemeral rivers only flow at specific times of year, for example drying out completely during the summer. In the case of dryland rivers, these may even cease to flow for multi-year periods.[65] During these dry periods terrestrial organisms may be exposed to riverine microplastic deposits in these environments. Furthermore, dryland rivers readily mobilise previously deposited sediments in flow events,[65, 66] meaning these environments could experience large scale pulses of microplastic transport. In fact, most rivers are characterised by seasonal flows, meaning the transfer of microplastics from land to rivers and the mobilisation of microplastics from river sediments will be highly variable throughout the year. Microplastic research should therefore seek to consider these environmental associations and interactions to enhance understanding of how marginal environments may inhibit, alter or facilitate the movement or sequestration of microplastics.

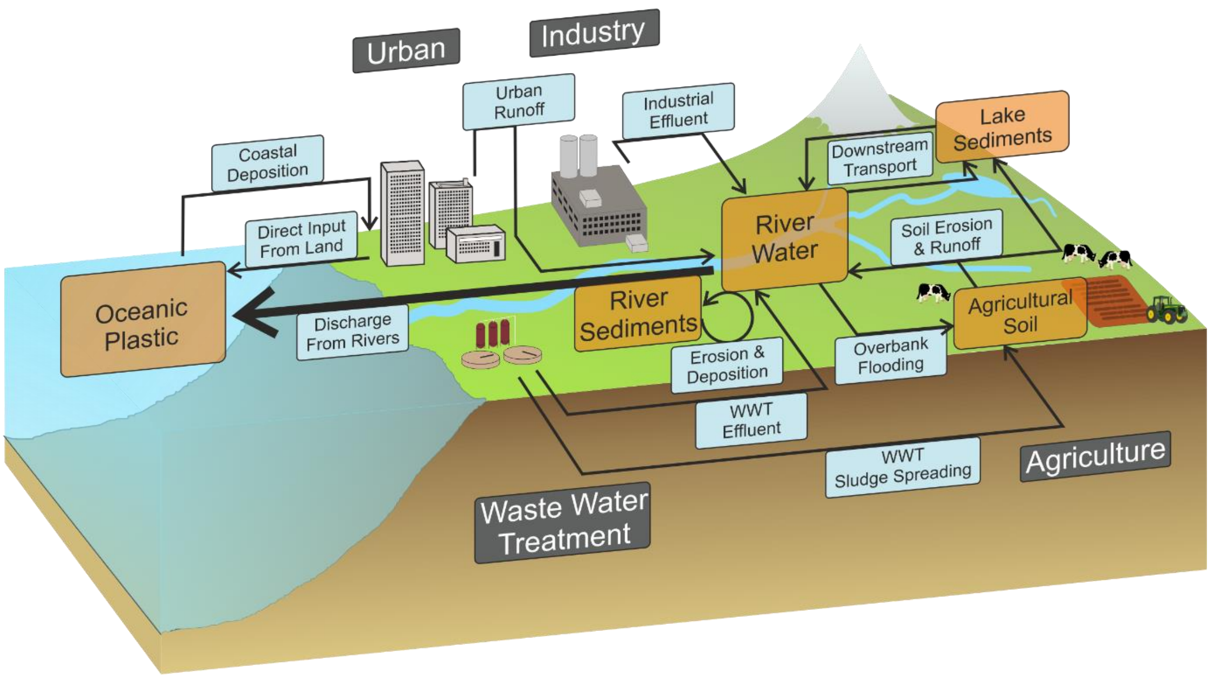

Fig. 3. Conceptual model representing the 'Plastic Cycle' concept (WWT refers to wastewater treatment). Orange boxes represent sinks, blue boxes represent transport mechanisms and arrows

represent transport pathways, Atmospheric microplastics are not included within the model as they cannot be attributed to a specific compartment or route of transport.

5. Implications

It is clear from the research published to date that microplastics are abundant and widespread across the globe, and that their rate of input is increasing. The main concern with this is the potential damage that microplastics may cause to ecosystems. Large-scale macroplastic waste has been prominent within the global media in contributing to the deaths of numerous marine animals including whales, turtles and seabirds.[67-69] A variety of studies have also shown harm by microplastics to a wide variety of smaller aquatic organisms including zooplankton and large invertebrates including mussels and crabs and fish larvae [70, 71].[72] Harm may occur as a result of physical damage due to clogging of the gut or gills, or internal lacerations following ingestion due to sharp edges.[73] Damage to organisms and populations at lower trophic levels has the potential for knock-on effects in food webs, either due to reduced populations of smaller organisms leading to a reduced food source, or due to predators ingesting large numbers of contaminated prey and concentrating microplastics in their own bodies.[74, 75] Additionally, toxicity or bioaccumulation of chemicals associated with the plastics may occur, for example organic pollutants sorbed to plastics may become available to organisms following ingestion, while plasticiser chemicals can leach out within the environment.[76, 77]

Microplastics may have implications for soil ecosystem function, for example experimental studies have shown effects of microplastics on reproduction of earthworms – a key organism for nutrient cycling and aeration within soils.[8, 78] This will be especially pertinent for agricultural areas given the likely prevalence of microplastics on agricultural land.[17] The resultant chemical or particulate toxic effects to organisms could have detrimental impacts on agricultural productivity.[79]

Recently, concerns have been raised about the possible consequences of widespread microplastic pollution on human health, with microplastics highly likely to be ingested or inhaled on a regular basis.[80, 81] The potential for health implications has been highlighted by workers in textile industries suffering respiratory disorders following inhalation of synthetic particulate matter,[80] although this has not yet been directly compared to the effects of non-polymeric dust such as cotton fibres, which may be similarly inhaled.[82] As little clinical data is available on short or long-term health effects of this microplastic exposure, this remains a priority research question to be addressed.

6. Conclusions

Microplastics are widespread throughout terrestrial, freshwater, marine and atmospheric systems. They are easily dispersed away from their sources, can be generated in the environment from larger plastic items, and may ultimately end up being retained within a specific location due to incorporation into soils and sediments. Alternatively, they may continuously cycle throughout different environments influenced by weather and currents. Although particle properties will influence behaviour and fate, this is not the only determining factor, as biological, chemical and physical interactions will also affect particle transport. In order to develop a holistic understanding of the drivers, magnitude and effects of microplastic pollution at a large system scale, it will be necessary for future research to consider interactions between microplastics and the environment across the range of environmental matrices, and how the fate of microplastics may affect their ecological impact.

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References

1. PlasticsEurope. Plastics - the Facts 2012. An analysis of European plastics production, demand and waste data for 2011. 2012.

2. PlasticsEurope. Plastics - the Facts 2016. An analysis of European plastics production, demand and waste data. 2016.

3. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv. 2017, 3(7).

4. Jambeck J, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady AL, Narayan R, Law KL. Plastic waste inputs from land into the ocean. Science. 2015, 347(6223):768-71.

5. Horton AA, Svendsen C, Williams RJ, Spurgeon DJ, Lahive E. Large microplastic particles in sediments of tributaries of the River Thames, UK - Abundance, sources and methods for effective quantification. Mar Pollut Bull. 2017, 114(1):218-26.

6. Hernandez E, Nowack B, Mitrano DM. Synthetic Textiles as a Source of Microplastics from Households: A Mechanistic Study to Understand Microfiber Release During Washing. Environ Sci Technol. 2017.

7. Napper IE, Thompson RC. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. Mar Pollut Bull. 2016, 112(1):39-45.

8. Rillig MC. Microplastic in terrestrial ecosystems and the soil? Environ Sci Technol. 2012, 46(12):6453-4.

9. Yang J, Yang Y, Wu WM, Zhao J, Jiang L. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environ Sci Technol. 2014, 48(23):13776-84.

10. Yang Y, Yang J, Wu WM, Zhao J, Song Y, Gao L, Yang R, Jiang L. Biodegradation and Mineralization of Polystyrene by Plastic-Eating Mealworms: Part 1. Chemical and Physical Characterization and Isotopic Tests. Environ Sci Technol. 2015, 49(20):12080-6.

11. Gu J-D. Microbiological deterioration and degradation of synthetic polymeric materials: recent research advances. Int Biodeterior Biodegrad. 2003, 52(2):69-91.

12. Cole M, Lindeque P, Halsband C, Galloway TS. Microplastics as contaminants in the marine environment: a review. Mar Pollut Bull. 2011, 62(12):2588-97.

13. Talsness CE, Andrade AJ, Kuriyama SN, Taylor JA, vom Saal FS. Components of plastic: experimental studies in animals and relevance for human health. Philos Trans R Soc Lond B Biol Sci. 2009, 364(1526):2079-96.

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

15. Lechner A, Ramler D. The discharge of certain amounts of industrial microplastic from a production plant into the River Danube is permitted by the Austrian legislation. Environ Pollut. 2015, 200:159-60.

16. Sadri SS, Thompson RC. On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. Mar Pollut Bull. 2014, 81(1):55-60.

17. Nizzetto L, Futter M, Langaas S. Are Agricultural Soils Dumps for Microplastics of Urban Origin? Environ Sci Technol. 2016, 50(20):10777-9.

18. Carr SA, Liu J, Tesoro AG. Transport and fate of microplastic particles in wastewater treatment plants. Water Res. 2016, 91:174-82.

19. Talvitie J, Mikola A, Setala O, Heinonen M, Koistinen A. How well is microlitter purified from wastewater? - A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. Water Res. 2017, 109:164-72.

20. Murphy F, Ewins C, Carbonnier F, Quinn B. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. Environ Sci Technol. 2016, 50(11):5800-8.

21. Horton AA, Walton A, Spurgeon DJ, Lahive E, Svendsen C. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci Total Environ. 2017, 586:127-41.

22. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ Sci Technol. 2011, 45(21):9175-9.

23. Vaughan R, Turner SD, Rose NL. Microplastics in the sediments of a UK urban lake. Environ Pollut. 2017, 229:10-8.

24. Imhof HK, Ivleva NP, Schmid J, Niessner R, Laforsch C. Contamination of beach sediments of a subalpine lake with microplastic particles. Curr Biol. 2013, 23(19):R867-8.

25. Free CM, Jensen OP, Mason SA, Eriksen M, Williamson NJ, Boldgiv B. High-levels of microplastic pollution in a large, remote, mountain lake. Mar Pollut Bull. 2014, 85(1):156-63.

26. Law KL, Thompson RC. Microplastics in the seas. Science. 2014, 345(6193):144-5.

27. Zhang Y, Zhang YB, Feng Y, Yang XJ. Reduce the plastic debris: a model research on the great Pacific ocean garbage patch. Adv Mat Res. 2010, 113: 59-63.

28. Sherman P, van Sebille E. Modeling marine surface microplastic transport to assess optimal removal locations. Environ Res Lett. 2016, 11(1):014006.

29. Ballent A, Purser A, de Jesus Mendes P, Pando S, Thomsen L. Physical transport properties of marine microplastic pollution. Biogeosci Disc. 2012, 9(12):18755-98.

30. Kowalski N, Reichardt AM, Waniek JJ. Sinking rates of microplastics and potential implications of their alteration by physical, biological, and chemical factors. Mar Pollut Bull. 2016, 109(1):310-9.

31. Dris R, Gasperi J, Saad M, Mirande C, Tassin B. Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? Mar Pollut Bull. 2016, 104(1-2):290-3.

32. Dehghani S, Moore F, Akhbarizadeh R. Microplastic pollution in deposited urban dust, Tehran metropolis, Iran. Environ Sci Pollut Res. 2017, 24(25):20360-20371.

33. Dris R, Gasperi J, Mirande C, Mandin C, Guerrouache M, Langlois V, Tassin B. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ Pollut. 2017, 221:453-8.

34. Zylstra ER. Accumulation of wind-dispersed trash in desert environments. J Arid Environ. 2013, 89:13-5.

35. Lechner A, Keckeis H, Lumesberger-Loisl F, Zens B, Krusch R, Tritthart M, Glas M, Schludermann E. The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environ Pollut. 2014, 188:177-81.

36. Cai L, Wang J, Peng J, Tan Z, Zhan Z, Tan X, Chen Q. Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environ Sci Pollut Res. 2017, 24(32):24928-24935.

37. Morritt D, Stefanoudis PV, Pearce D, Crimmen OA, Clark PF. Plastic in the Thames: a river runs through it. Mar Pollut Bull. 2014, 78(1-2):196-200.

38. Lebreton LC, Van der Zwet J, Damsteeg J-W, Slat B, Andrady A, Reisser J. River plastic emissions to the world's oceans. Nat Commun. 2017, 8.

39. Castañeda RA, Avlijas S, Simard MA, Ricciardi A, Smith R. Microplastic pollution in St. Lawrence River sediments. Can J Fish Aquat Sci. 2014, 71(12):1767-71.

40. Zubris KA, Richards BK. Synthetic fibers as an indicator of land application of sludge. Environ Pollut. 2005, 138(2):201-11.

41. Lwanga EH, Gertsen H, Gooren H, Peters P, Salánki T, van der Ploeg M, Besseling E, Koelmans AA, Geissen V. Incorporation of microplastics from litter into burrows of *Lumbricus terrestris*. Environ Pollut. 2017, 220:523-31.

42. Nizzetto L, Bussi G, Futter MN, Butterfield D, Whitehead PG. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environ Sci Process Impacts. 2016, 18(8):1050-9.

43. Knighton D. Fluvial forms and processes: a new perspective: Routledge; 2014, Abingdon, UK.

44. Corcoran PL, Moore CJ, Jazvac K. An anthropogenic marker horizon in the future rock record. GSA Today. 2014, 24(6):4-8.

45. Corcoran PL, Norris T, Ceccanese T, Walzak MJ, Helm PA, Marvin CH. Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment record. Environ Pollut. 2015, 204:17-25.

46. Lagarde F, Olivier O, Zanella M, Daniel P, Hiard S, Caruso A. Microplastic interactions with freshwater microalgae: Hetero-aggregation and changes in plastic density appear strongly dependent on polymer type. Environ Pollut. 2016, 215:331-9.

47. Bridge JS, Bennett SJ. A model for the entrainment and transport of sediment grains of mixed sizes, shapes, and densities. Water Resour Res. 1992, 28(2):337-63.

48. Prager EJ, Southard JB, Vivoni-Gallart ER. Experiments on the entrainment threshold of well-sorted and poorly sorted carbonate sands. Sedimentology. 1996, 43(1):33-40.

49. US EPA. Plastic Pellets in the Aquatic Environment: Sources and Recommendations. Final Report 842/B-92/010. Duxbury, Massachusetts; 1992.

50. Nuelle MT, Dekiff JH, Remy D, Fries E. A new analytical approach for monitoring microplastics in marine sediments. Environ Pollut. 2014, 184:161-9.

51. British Plastics Federation. Nylons (polyamide) 2017 http://www.bpf.co.uk//plastipedia/polymers/Polyamides.aspx

52. Nelson JM, Shreve RL, McLean SR, Drake TG. Role of near-bed turbulence structure in bed load transport and bed form mechanics. Water Resour Res. 1995, 31(8):2071-86.

53. Hoellein TJ, McCormick AR, Hittie J, London MG, Scott JW, Kelly JJ. Longitudinal patterns of microplastic concentration and bacterial assemblages in surface and benthic habitats of an urban river. Freshwater Science. 2017, 36(3):491-507.

54. Lecce SA, Pavlowsky RT. Storage of mining-related zinc in floodplain sediments, Blue River, Wisconsin. Physical Geography. 1997, 18(5):424-39.

55. Walling D, Owens P, Carter J, Leeks G, Lewis S, Meharg A, Wright J. Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems. Appl Geochem. 2003, 18(2):195-220.

56. Van Sebille E, England MH, Froyland G. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ Res Lett. 2012, 7(4):044040.

57. Rummel CD, Jahnke A, Gorokhova E, Kühnel D, Schmitt-Jansen M. Impacts of Biofilm Formation on the Fate and Potential Effects of Microplastic in the Aquatic Environment. Environ Sci Technol Lett. 2017, 4(7):258-67.

58. Cole M, Lindeque PK, Fileman E, Clark J, Lewis C, Halsband C, Galloway TS. Microplastics Alter the Properties and Sinking Rates of Zooplankton Faecal Pellets. Environ Sci Technol. 2016, 50(6):3239-46.

59. Obbard RW, Sadri S, Wong YQ, Khitun AA, Baker I, Thompson RC. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future. 2014, 2(6):315-20.

60. Woodall LC, Sanchez-Vidal A, Canals M, Paterson GL, Coppock R, Sleight V, Calafat A, Rogers AD, Narayanaswamy BE, Thompson RC. The deep sea is a major sink for microplastic debris. R Soc Open Sci. 2014, 1(4):140317.

61. Cincinelli A, Scopetani C, Chelazzi D, Lombardini E, Martellini T, Katsoyiannis A, Fossi MC, Corsolini S. Microplastic in the surface waters of the Ross Sea (Antarctica): Occurrence, distribution and characterization by FTIR. Chemosphere. 2017, 175:391-400.

62. Esiukova E. Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. Mar Pollut Bull. 2017, 114(2):1072-80.

63. Imhof HK, Sigl R, Brauer E, Feyl S, Giesemann P, Klink S, Leupolz K, Loder MG, Loschel LA, Missun J, et al. Spatial and temporal variation of macro-, meso- and microplastic abundance on a remote coral island of the Maldives, Indian Ocean. Mar Pollut Bull. 2017, 116(1-2):340-7.

64. Lavers JL, Bond AL. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. PNAS. 2017:201619818.

65. Tooth S. Process, form and change in dryland rivers: a review of recent research. Earth-Sci Rev. 2000, 51(1):67-107.

66. Reid I, Laronne JB. Bed load sediment transport in an ephemeral stream and a comparison with seasonal and perennial counterparts. Water Resour Res. 1995, 31(3):773-81.

67. Jacobsen JK, Massey L, Gulland F. Fatal ingestion of floating net debris by two sperm whales (*Physeter macrocephalus*). Mar Pollut Bull. 2010, 60(5):765-7.

68. Pierce KE, Harris RJ, Larned LS, Pokras MA. Obstruction and starvation associated with plastic ingestion in a Northern Gannet Morus bassanus and a Greater Shearwater Puffinus gravis. Mar Ornithol. 2004, 32(2):187-9.

69. Santos RG, Andrades R, Boldrini MA, Martins AS. Debris ingestion by juvenile marine turtles: an underestimated problem. Mar Pollut Bull. 2015, 93(1):37-43.

70. Browne MA, Dissanayake A, Galloway TS, Lowe DM, Thompson RC. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). Environ Sci Technol. 2008, 42(13):5026-31.

71. Lu Y, Zhang Y, Deng Y, Jiang W, Zhao Y, Geng J, Ding L, Ren H. Uptake and Accumulation of Polystyrene Microplastics in Zebrafish (Danio rerio) and Toxic Effects in Liver. Environ Sci Technol. 2016, 50(7):4054-60.

72. Rehse S, Kloas W, Zarfl C. Short-term exposure with high concentrations of pristine microplastic particles leads to immobilisation of *Daphnia magna*. Chemosphere. 2016, 153:91-9.

73. Wright SL, Thompson RC, Galloway TS. The physical impacts of microplastics on marine organisms: a review. Environ Pollut. 2013, 178:483-92.

74. Watts AJ, Lewis C, Goodhead RM, Beckett SJ, Moger J, Tyler CR, Galloway TS. Uptake and retention of microplastics by the shore crab *Carcinus maenas*. Environ Sci Technol. 2014, 48(15):8823-30.

75. Mattsson K, Johnson EV, Malmendal A, Linse S, Hansson L-A, Cedervall T. Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. Sci Rep. 2017, 7(1):11452.

76. Besseling E, Wegner A, Foekema EM, van den Heuvel-Greve MJ, Koelmans AA. Effects of microplastic on fitness and PCB bioaccumulation by the lugworm *Arenicola marina* (L.). Environ Sci Technol. 2013, 47(1):593-600.

77. Lithner D, Damberg J, Dave G, Larsson K. Leachates from plastic consumer products - screening for toxicity with *Daphnia magna*. Chemosphere. 2009, 74(9):1195-200.

78. Lwanga EH, Gertsen H, Gooren H, Peters P, Salanki T, van der Ploeg M, Besseling E, Koelmans AA, Geissen V. Microplastics in the Terrestrial Ecosystem: Implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae). Environ Sci Technol. 2016, 50(5):2685-91.

79. Steinmetz Z, Wollmann C, Schaefer M, Buchmann C, David J, Troger J, Munoz K, Fror O, Schaumann GE. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci Total Environ. 2016, 550:690-705.

80. Wright SL, Kelly FJ. Plastic and Human Health: A Micro Issue? Environ Sci Technol. 2017, 51(12):6634-47.

81. Van Cauwenberghe L, Janssen CR. Microplastics in bivalves cultured for human consumption. Environ Pollut. 2014, 193:65-70.

82. Pauly JL, Stegmeier SJ, Allaart HA, Cheney RT, Zhang PJ, Mayer AG, Streck RJ. Inhaled cellulosic and plastic fibers found in human lung tissue. Cancer Epidemiol Biomarkers Prev. 1998, 7(5):419-28.