

Article (refereed) - postprint

This is the peer reviewed version of the following article:

Horton, Alice A.; Dixon, Simon J. 2018. **Microplastics: an introduction to environmental transport processes**. *Wiley Interdisciplinary Reviews: Water*, 5 (2), e1268, which has been published in final form at <https://doi.org/10.1002/wat2.1268>

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1 **Microplastics: an introduction to environmental transport** 2 **processes**

3
4 **Article type: Primer**

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22 23 **Abstract**

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

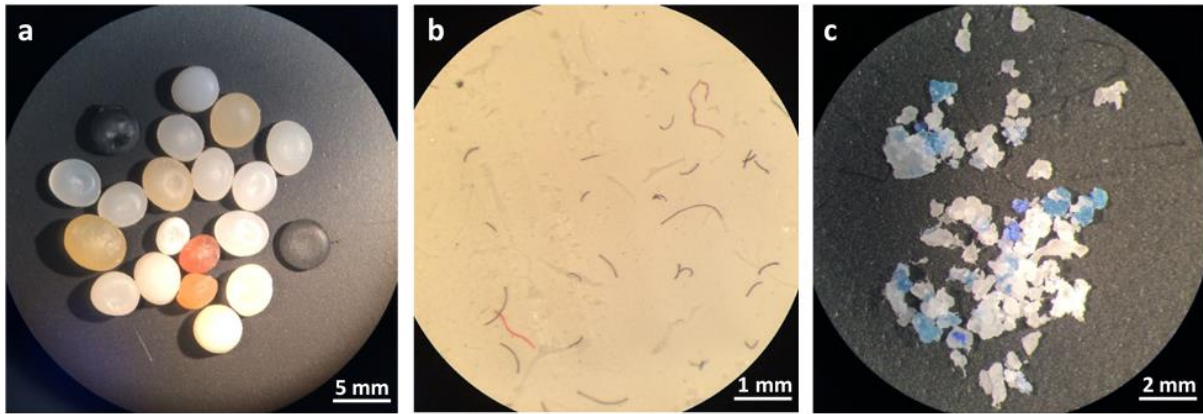
33
34
35 **Keywords:** plastic pollution, plastic cycle, sediment, soil, freshwater, fate

36 **1. Introduction**

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

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

62



63

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

66

67 **2. Presence and sources of microplastics within the environment**

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

77

78 **2.1. Microplastics on land**

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

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

87 Microplastics may also be released directly to land along with sewage sludge applied to
88 agricultural land as a fertiliser. Wastewater treatments plants are quite effective at removing
89 microplastic particles from the wastewater stream, often with ~99% removal,¹⁸⁻²⁰ and many of
90 these particles will settle to the sludge. It is estimated that throughout Europe, between 125-
91 850 tons of microplastics per million inhabitants are added annually to agricultural soils as a
92 result of sewage sludge application.¹⁷ Horton et al.²¹ calculated that 473,000-910,000 metric
93 tonnes of plastic waste is retained within European continental environments (terrestrial and
94 freshwater) annually, which includes microplastics derived from sewage sludge, in addition to
95 predicted inputs of litter and inadequately managed waste. Where plastics are not transported
96 from land to rivers or the sea, this could lead to massive accumulation. However, few studies
97 have investigated abundance of microplastics within terrestrial environments, or linked
98 abundance to input pathways, therefore it is not currently possible to directly link accumulation
99 with specific environmental characteristics or anthropogenic activities.

100

101 **2.2. Microplastics in freshwater environments**

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

108 Larger plastic items can enter the freshwater environment through inadequate waste
109 disposal, either through littering or loss from landfill and transported from land via wind or

110 surface runoff. In addition to macroplastics, there are significant direct inputs of microplastics
111 to freshwater systems. Agricultural drainage and runoff from farmland can result in input of
112 agricultural plastics or sewage-sludge derived fibres and microbeads. Storm drainage and
113 urban runoff is often unfiltered and untreated, and can contain microplastics from degraded
114 road paint and wear from vehicles.^{5, 14} Despite the efficiency of wastewater treatment plants
115 in removing microplastics, direct effluent input can also contain microplastics.²⁰ Additionally,
116 during very high flow conditions, combined sewage overflows (CSOs) are designed to release
117 untreated sewage into surrounding rivers to reduce the pressure on drainage systems,
118 releasing both micro- and macroplastic waste. Studies suggest that although hotspots of
119 microplastics may occur in close proximity to urban areas, the majority of microplastics are
120 likely to enter waterbodies as a result of drainage systems and thus attention must also be
121 paid to inputs including CSOs, storm drains and effluent outfalls, which may be set apart from
122 the most densely populated areas.^{5, 22}

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

128

129 **2.3. Microplastics in the marine environment**

130 The presence and abundance of microplastics within the oceans have been widely
131 studied. Sources of microplastics to marine environments are widespread, as oceans are
132 generally considered to be the ultimate sink for all plastic within the environment.^{22, 26} In
133 addition to the inputs from rivers, plastics will also enter oceans directly via mismanaged
134 maritime or fishing waste, including abandoned fishing gear, accidental cargo loss and illegal
135 dumping. This will most likely be in the form of macroplastic waste that will degrade to form
136 microplastics within the marine environment (Figure 2c). Microplastics have been found to be

137 widespread throughout various locations and within marine organisms worldwide, with ocean
138 currents leading to specific areas of accumulation such as the well-known 'Great Pacific
139 Garbage Patch'.²⁷ Models have been developed to investigate transport processes and fate
140 of microplastics within the oceans²⁸⁻³⁰ which may also add to our understanding of the
141 processes that influence microplastic transport within freshwater environments.



142
143 Fig. 2. Images of plastic pollution across a range of environments a) terrestrial, b) riverine, c) marine
144 and d) coastal. Any large items can degrade to form secondary microplastics. *Image attributions a) PDPics*
145 *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*
146 *Flickr CC BY-SA 2.0*

147

148 **2.4. Microplastics in the atmosphere**

149 It has recently been recognised that due to their lightweight nature, many microplastic
150 particles will become suspended and transported within the air as 'urban dust'.^{31, 32} These

151 commonly originate from road dust (e.g. tyre and paint particles) and fibres from synthetic
152 textiles, especially from soft furnishings^{5, 33} and can lead to deposition of microplastics to land
153 or aquatic environments. Although urban dust will originate especially in cities and highly
154 populated areas, air currents and wind can lead particles to be transported far from the
155 source.³⁴ Weather events such as heavy rainfall will facilitate the deposition of particles to
156 land.³¹ Given the diverse range of sources, the varying characteristics of particles affecting
157 their behaviour and the range of environmental factors influencing particle transport, airborne
158 microplastic contamination is extremely difficult to trace and predict. It is not currently known
159 to what extent atmospheric fallout contributes to aquatic and terrestrial contamination,
160 therefore more research is needed in this area.

161

162 **3. Transport processes**

163 It is widely considered that the ocean represents a sink for a large proportion of
164 microplastics, with the terrestrial and freshwater environments acting as important sources
165 and pathways for microplastics to the sea.^{4, 35} Due to their lightweight nature and potential for
166 widespread dispersal it is also likely that air currents act as a means of particulate transport,
167 contributing to microplastic contamination on land and within aquatic systems.^{31, 36} A number
168 of studies have provided evidence for macro and microplastic litter reaching oceans from
169 rivers^{16, 37, 38} with particles often originating on land⁵. However, it is increasingly becoming
170 recognised that far from being merely conveyor belts for waste plastic, freshwaters and soils
171 can act as sinks themselves, retaining much of the microplastic pollution that they receive.^{5, 39}
172 In some cases, due to the proximity and scale of plastic inputs, certain terrestrial and
173 freshwater areas could actually accumulate microplastics at higher concentrations than in the
174 ocean.^{17, 39} For future understanding of microplastic pollution within the environment it will
175 therefore be important to link sources, particle behaviours and transport mechanisms, to
176 understand how and where microplastics will accumulate.

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

187 Where particles do enter rivers, they will be subject to the same transport processes
188 which mobilise other sediments, such as sand and silt, in channels. In simple terms, the faster
189 a river flows the more energy it has, and thus it can entrain and transport a greater volume of
190 particles.⁴³ However, in the case of microplastics, most rivers are likely to be supply-limited
191 with respect to transport, meaning rivers will be capable of transporting all plastics that are
192 delivered to them. Despite the buoyancy of many plastics, where river energy drops, for
193 example in slow-moving sections of water, it is likely that microplastics will settle out along
194 with sinking sediment particles. Additionally, this sediment deposition may aid in the burial of
195 microplastic particles, whether microplastics are simultaneously deposited or are already
196 present within the sediment⁴⁴. It is therefore likely that on their journey throughout the
197 freshwater environment, many particles will also be retained within sediments.^{17, 42} Within
198 lakes where sediment accumulation rates are high, it has been suggested that retention and
199 incorporation of microplastics into sediments could lead to burial and long-term preservation
200 within the sediment.^{44, 45}

201 The density and shape of microplastic particles will have important effects on their
202 transport and retention in sediments. Although many polymer particles have low densities, so
203 are buoyant and will float, there are also many types of polymer that are denser than water

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

219

Polymer name	Abbreviation	Density (g/cm³)
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

220

221 Table 1. Densities of commonly-used polymers. ^aUS EPA (1992)⁴⁹, ^bNuelle et al (2014)⁵⁰, ^cBritish
222 Plastics Federation (2017)⁵¹

223

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

232 Due to currents, winds and the large area covered, once they reach the oceans
233 (micro)plastics can be rapidly and widely dispersed, travelling significant distances from the
234 source.⁵⁶ Additionally, microplastics are subject to vertical transport within the oceans due to
235 biofouling, egestion in faecal pellets and incorporation into marine snows (sinking detritus).^{30,}
236 ^{57, 58} This wide-ranging vertical and horizontal transport is highlighted by the fact that
237 microplastics have been discovered in all locations that have been investigated, including in
238 the deep sea, Southern Ocean and Arctic ice cores.⁵⁹⁻⁶¹

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

247

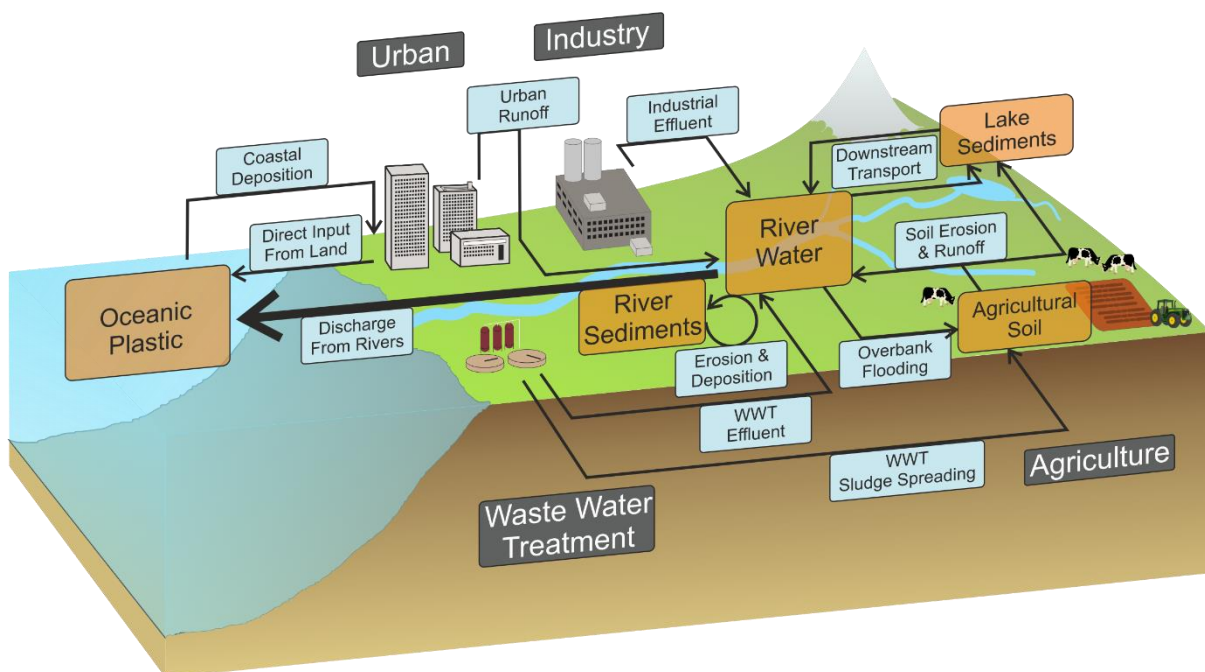
248 **4. The Plastic Cycle**

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

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

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

287



288

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

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

293

294 **5. Implications**

295 It is clear from the research published to date that microplastics are abundant and
296 widespread across the globe, and that their rate of input is increasing. The main concern with
297 this is the potential damage that microplastics may cause to ecosystems. Large-scale
298 macroplastic waste has been prominent within the global media in contributing to the deaths
299 of numerous marine animals including whales, turtles and seabirds.⁶⁷⁻⁶⁹ A variety of studies
300 have also shown harm by microplastics to a wide variety of smaller aquatic organisms
301 including zooplankton and large invertebrates including mussels and crabs and fish larvae⁷⁰,
302 ^{71,72} Harm may occur as a result of physical damage due to clogging of the gut or gills, or
303 internal lacerations following ingestion due to sharp edges.⁷³ Damage to organisms and
304 populations at lower trophic levels has the potential for knock-on effects in food webs, either
305 due to reduced populations of smaller organisms leading to a reduced food source, or due to
306 predators ingesting large numbers of contaminated prey and concentrating microplastics in
307 their own bodies.^{74, 75} Additionally, toxicity or bioaccumulation of chemicals associated with
308 the plastics may occur, for example organic pollutants sorbed to plastics may become
309 available to organisms following ingestion, while plasticiser chemicals can leach out within the
310 environment.^{76, 77}

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

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

325

326 **6. Conclusions**

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

338

339 **Acknowledgements**

340 AAH would like to thank Elma Lahive for her input during the preparation of this manuscript.
341 SJD would like to thank Iseult Lynch and John Lewin for their stimulating discussions which
342 helped form some of the ideas presented in this manuscript, and to Nick Kettridge for

343 supporting the writing process. This work was funded by the UK Natural Environment
344 Research Council through National Capability funding of the Centre for Ecology and Hydrology
345 Pollution and Environmental Risk Program.

346

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