Microplastics in freshwater and soil

An evidence synthesis

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Contents

List of acronyms

Organisations

BBC The British Broadcasting Corporation

CONTAM The Panel on Contaminants in the Food Chain of the European Food Safety Authority

Defra Department for Environment, Food & Rural Affairs

ECHA European Chemicals Agency

EFSA European Food Safety Authority

EU European Union

GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

IUCN International Union for Conservation of Nature

NIVA Norwegian Institute for Water Research

NOAA The National Oceanic and Atmospheric Administration of the United States Department of Commerce

REACH Registration, Evaluation, Authorisation & restriction of CHemicals

SAM The Scientific Advice Mechanism Unit of the European Commission

SAPEA Scientific Advice for Policy by European Academies

USEPA United States Environmental Protection Agency

Chemicals

BPA Bisphenol A

DDT Dichlorodiphenyltrichloroethane

POPs Persistant Organic Pollutants

PVC Polyvinyl Chloride

Misc.

NGO Non-governmental organisation

GDPR General Data Protection Regulation

Executive summary

Context

This synthesis presents the evidence of the impact of micoplastics on animals and humans, focusing on freshwater and soil environments, and identifies the most significant gaps in the evidence for future study.

Plastics have been gaining increased public attention due to a growing awareness of their impact on the natural environment. Political interest has mirrored public concern, with a number of policy measures introduced within the last few years to target plastic pollution in the UK, EU and internationally.

Despite this heightened profile, there is relatively little scientific evidence on the impacts of microplastics in the environment. Much of the research on plastics, including microplastics, has been in the marine environment and within the last few years. Therefore, while this topic is now seen as a priority and is increasingly being studied, research into the impacts of microplastics, especially in freshwater and soil, is still in its infancy. Major evidence gaps remain. This lack of knowledge is combined with the fact that plastics are persistent environmental pollutants and their use and subsequent presence in the environment is increasing.

This report considers three potential types of impact of microplastics on animals: direct physical harm caused by microplastics; harm caused by chemicals leaching from microplastics; and the potential for microplastics to act as a vector for other pollutants already in the environment and to transport these pollutants into animals. The report also considers potential impacts on human health.

Summary of findings

Our findings present a mixed picture due to the fact that significant evidence gaps exist in some areas. Moreover, where evidence does exist it is sometimes contradictory and/or based on results from laboratory studies using unrealistically high concentrations of microplastic and therefore difficult to translate to actual exposure in real-world environments[1]. This makes interpretation complicated and we have tried to caveat our findings as best as possible.

Despite these evidence gaps and the limitations with the published literature, the evidence does suggest that microplastics could cause harm at high concentrations and we do not yet know the implications of long-term exposure at low concentrations. Combined with the fact that once released into the environment microplastics are persistent, and given the high environmental concentrations expected in the future, the likelihood of negative consequences emerging is high. Without interventions to reduce plastic use and move towards a more circular economy, it is estimated that ecological risks from microplastics may be widespread within a century[2]. However, as with all diffuse pollutants, demonstrating significant effects in the environment will be difficult and even impossible in some cases.

Without interventions to reduce plastic use and move towards a more circular economy, it is estimated that ecological risks from microplastics may be widespread within a century.

There is evidence demonstrating the presence of microplastics in freshwater and soil environments and within the organisms that inhabit them as well as in humans and the human diet.

There is currently a very limited amount of research into nanoplastics (which are smaller than microplastics), but initial evidence suggests that nanoplastics may be a particular concern. Laboratory studies, have shown that they are capable of entering tissues and crossing the blood-brain barrier. However, measuring exposure to nanoplastics in natural environments is very challenging due to their size so we do not yet understand real-world concentrations and impacts. Given that almost all plastics will gradually degrade into smaller and smaller micro and then nano sized particles, there is a risk that these particular impacts could increase in the future.

Direct impacts of microplastics on animals

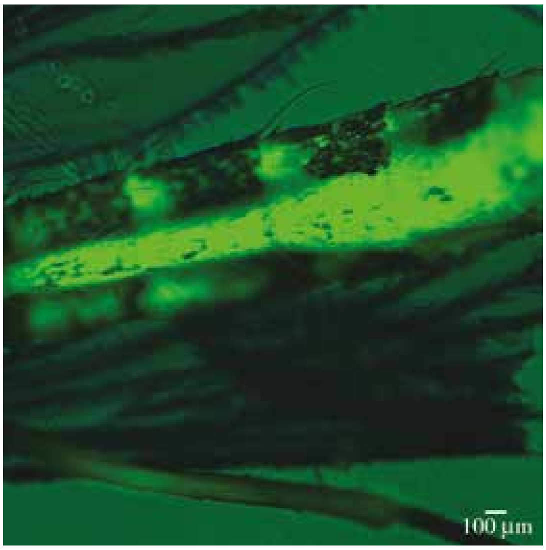
There is evidence demonstrating the presence of microplastics in freshwater and soil environments and within the organisms that inhabit them[3 – 6], as well as in humans and the human diet[7, 8].

For example, studies have demonstrated that 33% of roach sampled in the River Thames contain microplastics[9] and that animals such as earthworms[10 – 12], mice[13], and ducks[14] ingest microplastics. The likelihood that microplastics will be ingested by an organism seems to relate to its ability to distinguish between microplastics and actual food sources. Microplastics are found predominantly in the gut of animals, with a few examples of them passing into tissues or other organs at very high concentrations.

Laboratory studies have shown that the presence of microplastics in animals can affect their behaviour in a range of ways. Examples include decreased feeding (due to a false feeling of satiation), decreased movement, and increased buoyancy which affects feeding and swimming behaviour.

FIGURE 1

Fluorescent microplastic in the stomach of an adult mosquito glows green under a microscope. Researchers found an average of 40 microplastic particles in the stomach of each adult mosquito they studied[28].



A reduction in feeding success following exposure to microplastics has been observed in a number of species, including fish[15 – 17] and crustaceans[18, 19]. Microplastics can also cause physical damage to animals, for example to the mouth cavity[20] or internal organs such as the gut, liver[21 – 25] or stomach due to gut blockages[26, 27] (Figure 1). However, we do not know how much microplastics contribute to these negative effects relative to other non-digestible suspended organic matter and debris. Also, as we have noted, the applicability of these high-concentration laboratory studies to real-world environments is not straightforward.

There is a need to formulate viable and testable hypotheses to address current knowledge gaps. For example, whilst some have suggested that microplastics may have wider effects on whole populations or ecosystems – such as gut blockages in worms subsequently affecting soil structure and plant growth[29] – there are currently few studies that explore these systems-level effects in any detail.

Microplastics and chemicals

This synthesis examines both the impact of chemicals added to microplastics, and the impact of pollutants already in the environment that bind to microplastics.

Chemicals such as bisphenol A (BPA) and phthalates are routinely added to plastics during the manufacturing process to improve its strength and flexibility. It is widely known that these chemicals can be harmful to humans and animals at high concentrations. Effects of phthalates and BPA mostly relate to the functioning of hormones, leading to negative effects on reproduction and development[30, 31]. Both amphibians and crustaceans appear to be particularly sensitive to the presence of chemicals in freshwater. However, it is not yet clear how significant a role microplastics play in contributing to exposure to these chemicals in freshwater and soil.

Microplastics may also act as a vector for chemical pollutants and pathogens. Whilst we know that these pollutants do bind to microplastics, what is less clear is whether they have the potential to leave the microplastic once inside the animal or whether they just pass straight through[32 – 34].

Some research suggests that pollutants can be released from microplastics inside organisms, particularly in laboratory conditions where high concentrations are used[35 – 46]. Other research suggests that the microplastics themselves are such an attractive surface for hydrophobic pollutants that these pollutants are very unlikely to leave the plastics whilst inside an organism[47 – 59] and that microplastics may even have a detoxifying effect. Whether or not a chemical pollutant is released from the microplastics is likely to be very context dependent. It might depend the type of pollutant, the type and shape of the microplastic particle, the type of animal, and the experimental concentrations. It is not known how significant a vector for pollutants microplastics might be in freshwater and soil environments when compared to organic debris or normal food sources such as plankton or sediment[60], nor how this compares to the risk of direct exposure to pollutants. Further research is required and in an environmentally realistic context before any firm conclusions can be drawn.

Priorities for research and next steps

As well as synthesising the available evidence, we have also highlighted the evidence gaps. Most significant among these is the lack of research into the effects of long-term exposure to microplastics at environmentally realistic concentrations, and the lack of understanding of exposure rates in the natural environment. As with all diffuse pollutants, measuring exposure and demonstrating significant effects in the natural environment will be very challenging and we do not currently have the methods available to do this.

This synthesis does not look at potential solutions in detail. It is impossible to disentangle the control of microplastics from wider plastic debates. Moving towards a more circular economy is likely to be the single biggest influencer in terms of limiting the amount of plastics and therefore microplastics in freshwater and soil environments. It is likely that this will require a combination of regulation, incentives, penalties, voluntary agreements and new solutions, as well as collaborative and collective action by many different countries, industries, sectors and government departments.

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Introduction

The popularity of plastic is due to its many helpful properties. It is cheap to produce, adaptable, water-resistant, has a high strength-to-weight ratio, low thermal and electrical conductivity, is hardwearing and resistant to corrosion.

Microplastics, small fragments of plastic less than 5 mm in size, are an emerging environmental contaminant. This report gathers together evidence of their impact on animals and humans, focusing on freshwater and soil environments, and identifies the most significant gaps in the evidence for future study.

Concern about plastics

Plastics have been a common feature across most societies since the first synthetic plastic capable of being produced at scale was invented in 1907. The popularity of plastic is due to its many helpful properties. It is cheap to produce, adaptable, water-resistant, has a high strength-to-weight ratio, low thermal and electrical conductivity, is hardwearing and resistant to corrosion. This means plastic has a vast range of applications, from paper clips to spacecraft.

More recently, plastics have gained increasing public attention due to a growing awareness of their impact on the natural environment. The final episode of the BBC's *Blue Planet II* series focused on plastic pollution. This along with the photograph of a seahorse carrying a plastic cotton bud, from the Natural History Museum's 2017 'Wildlife Photographer of the Year' competition (Figure 2), focussed public attention on the stark reality of plastic pollution in the oceans.

Political interest in plastics has mirrored public concern. In the last few years, the UK government has banned the manufacture and sale of some cosmetic and personal care products containing microbeads[62] and made commitments to new marine protected areas[63]. It has also introduced the 5p plastic bag charge[64] and is currently consulting on a deposit return scheme for plastic bottles[65] and a tax scheme for plastic packaging[66].

A ban on the sale of plastic straws, stirrers and cotton buds will come into force in April 2020[67]. Internationally, a range of comparable policy interventions targeting single-use plastics or microplastics have been developed in the past few years.

FIGURE 2

Sewage Surfer by Justin Hofman, Finalist in the Natural History Museum's 2017 'Wildlife Photographer of the Year' competition[61].

Regulation of chemical pollutants, including the European Union's (EU's) Water Framework Directive and the Registration, Evaluation, Authorisation & restriction of CHemicals (REACH) regulations, have also sought to assess and control the chemicals used to treat plastics[68]. The EU is considering extending these REACH regulations to include biodegradable plastics and intentional microplastics from 2020[69]. The EU's Plastic Strategy[70] also aims to restrict the use of intentional microplastics.

Despite this public and political profile, there is a comparative lack of scientific evidence on the impacts of microplastics in the environment. Much of the research on plastics (including microplastics) has been in the marine environment and only within the last few years. Therefore, whilst this topic is now seen as a priority and increasingly being studied, research into the impacts of microplastics, especially in freshwater and soil, is still in its infancy and major evidence gaps remain.

Given recent publicity, it would be easy to assume that plastics are the biggest threat to the natural environment. However, in the context of other threats, such as climate change, ocean acidification, land use change, noise pollution, invasive species, nutrient and chemical pollution, plastic is a relatively new and emerging threat to ecosystems. In freshwater and oceans, common pollutants (alongside plastic) include fertilizers, sediment, toxic chemicals, oil, sewage and other litter. This synthesis will not consider the impact of these other threats or pollutants, but it is important to recognise that modern ecosystems often have to deal with multiple, cumulative stressors.

Distribution of plastics and microplastics

It is estimated that around 8 billion tonnes of plastics were manufactured from 1950 to 2015[72] (Figure 3). Of this, around 6 billion tonnes have become plastic waste and 79% of this still remains on the planet, either as landfill or in the terrestrial, freshwater or marine environment[73]. It is this persistence that makes plastic a particularly concerning environmental pollutant. The cumulative volume of plastic on the planet is still rapidly increasing and unless the world moves towards a more circular economy, more and more of this is likely to end up in the natural environment. Figure 4 demonstrates the tiny proportion of plastic produced that is currently recycled effectively. Of the plastic that remains in the environment, most will degrade over time and become microplastics and eventually nanoplastics.

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FIGURE 3

Cumulative global plastics production, 1950 – 2015[71].

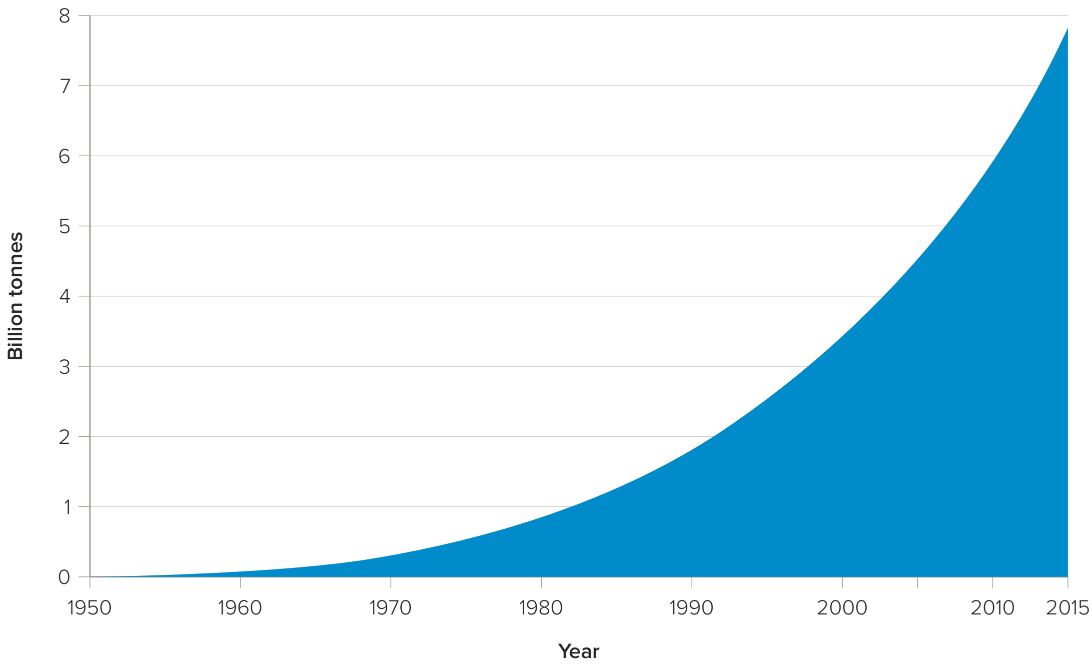
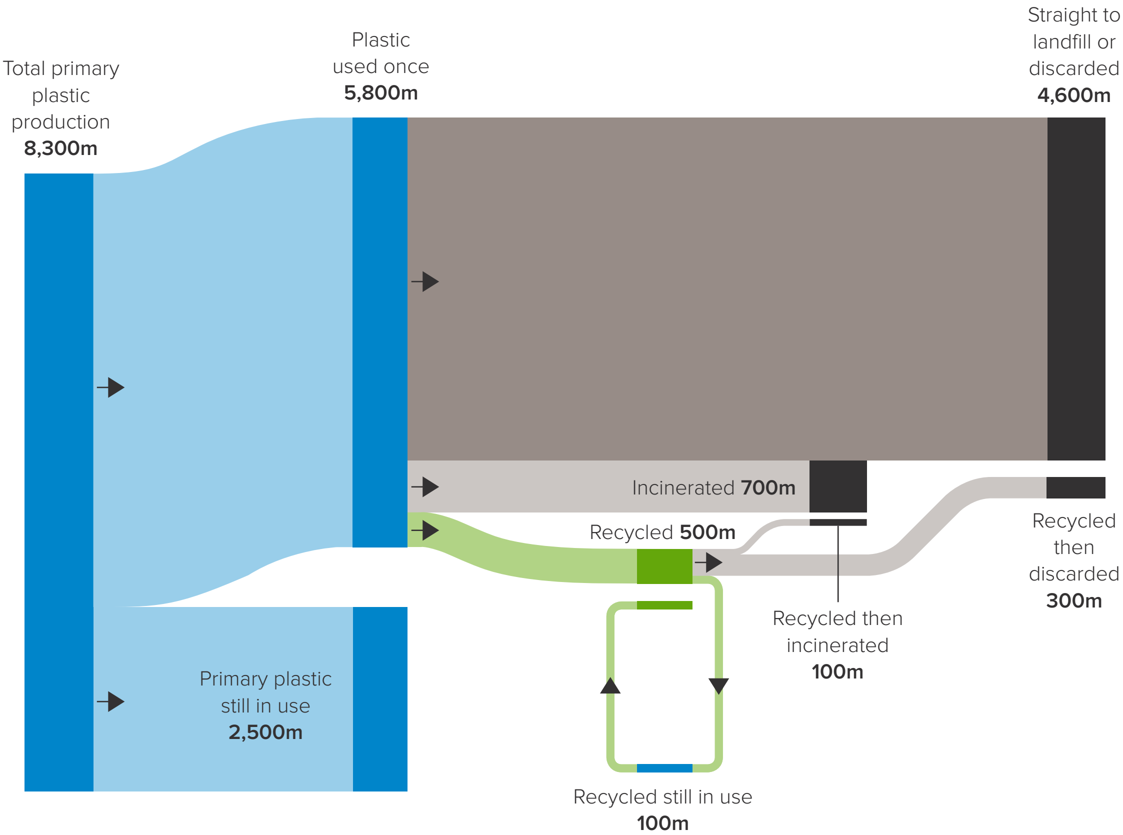


FIGURE 4

The fate of global plastic production 1950 – 2015[74].



Balance of plastic production and fate (m = million tonnes)
8,300 produced → 4,900m discarded + 800m incinerated + 2,600 still in use (100m recycled plastic)

Plastics are not evenly distributed in the environment. There are local as well as global hotspots. However, data relating to the quantity and distribution of plastic in the environment are lacking and so estimates are still highly speculative. For example, the current highest recorded concentrations of microplastics in freshwater were in river catchments in the north-west of England, measuring 517,000 particles per square metre (Figure 5)[75], but this reflects the current lack of globally validated and standardised methods for measuring microplastics in the environment. Rivers in other parts of the world are likely to have a far higher concentration of microplastics. Figure 6 shows the top 20 polluting rivers (based on the current sparse and speculative data), suggesting that rivers in Asia might be the most polluted in terms of plastic waste[76]. To produce repeatable and comparable monitoring results from sites across the globe, standardised sampling and measurement methodologies are required. Microplastics have now been observed in some of the most remote areas of the planet, including deep sea sediments[77, 78] and Arctic sea ice[79].

FIGURE 5

Global microplastic concentrations at different river sites around the world[80].

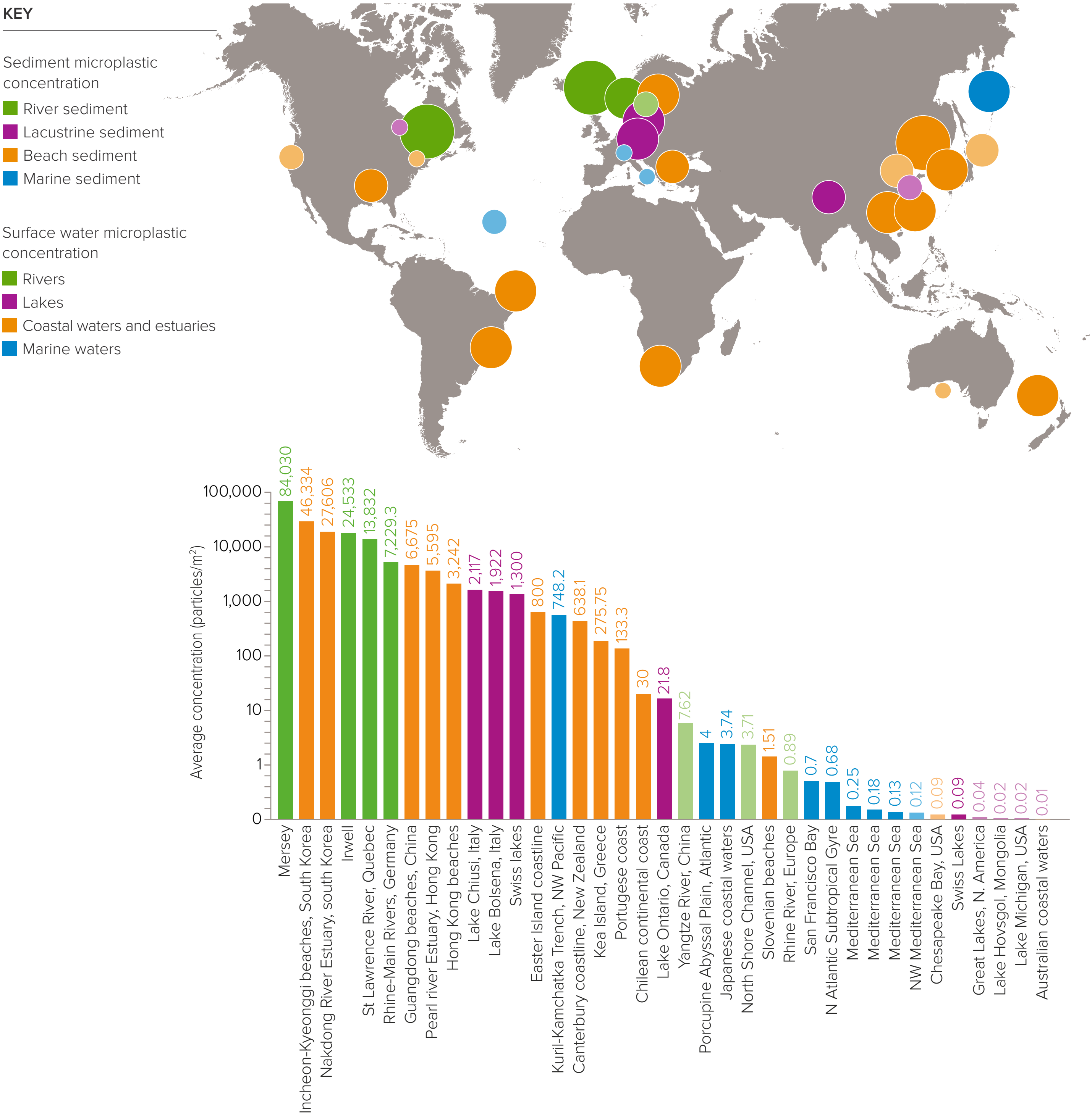
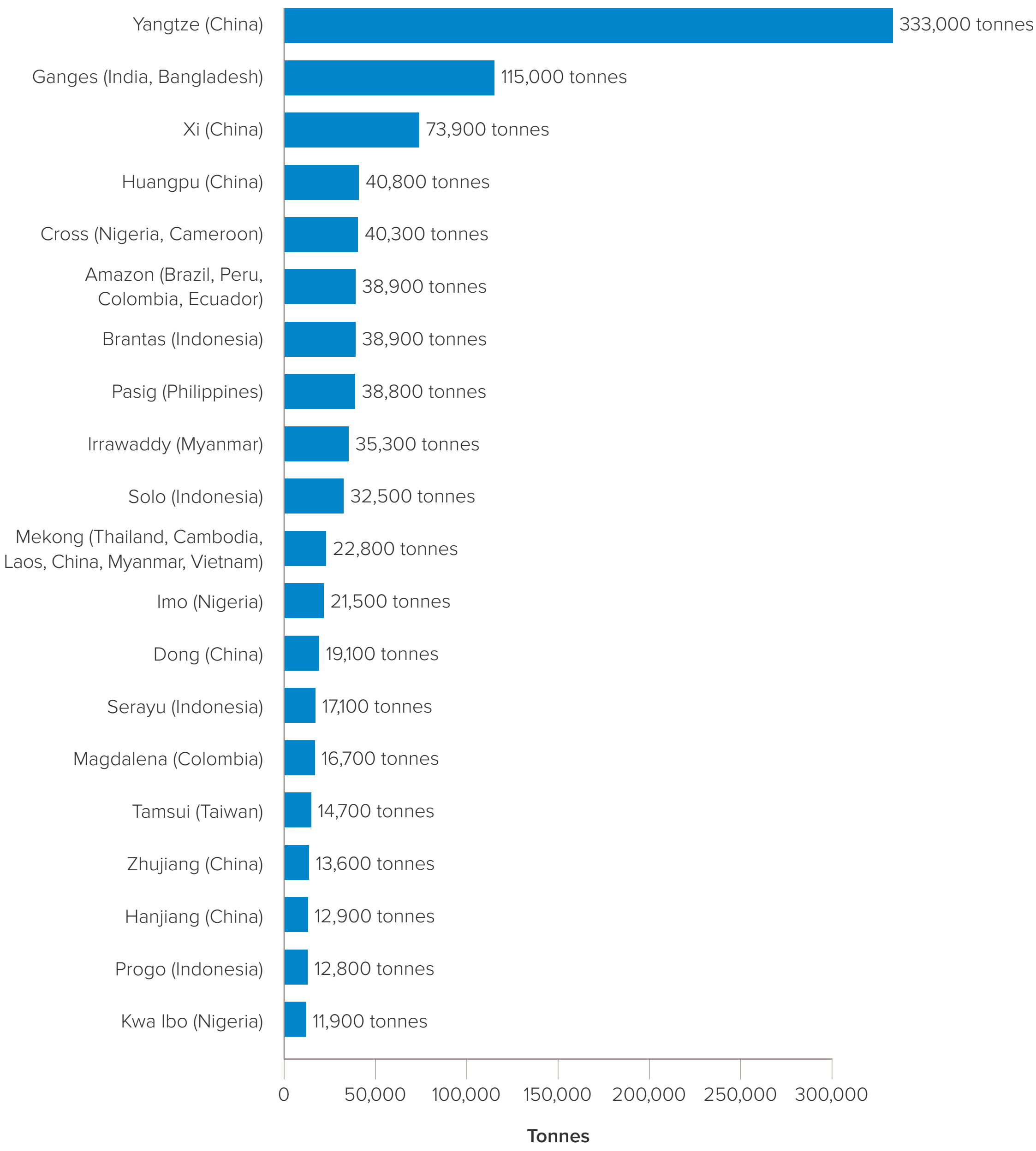


FIGURE 6

Plastic ocean input from rivers, 2015[81].



It is very difficult to accurately predict the exact amount of microplastics in the environment as sources, stores and movements are not well understood. For example, determining the amount of microplastics relies on an accurate estimate of 'mismanaged waste', which is differently reported for different countries. There are also a large number of different pathways through which plastic and microplastic can enter the environment (Figure 7) and it is very difficult to get an accurate measure of all of these. In addition, measuring and monitoring microplastics once they are in the environment is challenging, especially once they sink below the surface or become very small. The amount of microplastic in freshwater and soil also varies with patterns of rainfalls and stream flows, including flooding events[82].

Estimates of the quantity of microplastics in the ocean vary widely, from 93,000 to 236,000 tonness[83]. However these estimates are based on plastic visible on the surface of the ocean. Given recent local estimates in freshwater, sediments and soil, and the complexity and connectivity of these systems (Figure 7), this could be a substantial underestimate in terms of the total amount of plastic and microplastic in the environment[84].

Sources of microplastics

Microplastics come in a number of different forms (fibres, beads, pellets, fragments and film, Box 1 and Figure 8) and from a number of different sources. Some plastics are specifically manufactured as microplastics, for use as industrial abrasives, or in personal care products such as exfoliants. These are termed intentional or primary microplastics. Other microplastics come from the degradation of larger plastic items and also the wear and tear of items such as car tyres and synthetic fabrics. They also come in the form of 'city dust', a collective term for particles produced by other synthetic items associated with urban environments, such as shoe soles, artificial turf and building coatings. These sources are termed secondary microplastics. Figure 7 illustrates some of these sources.

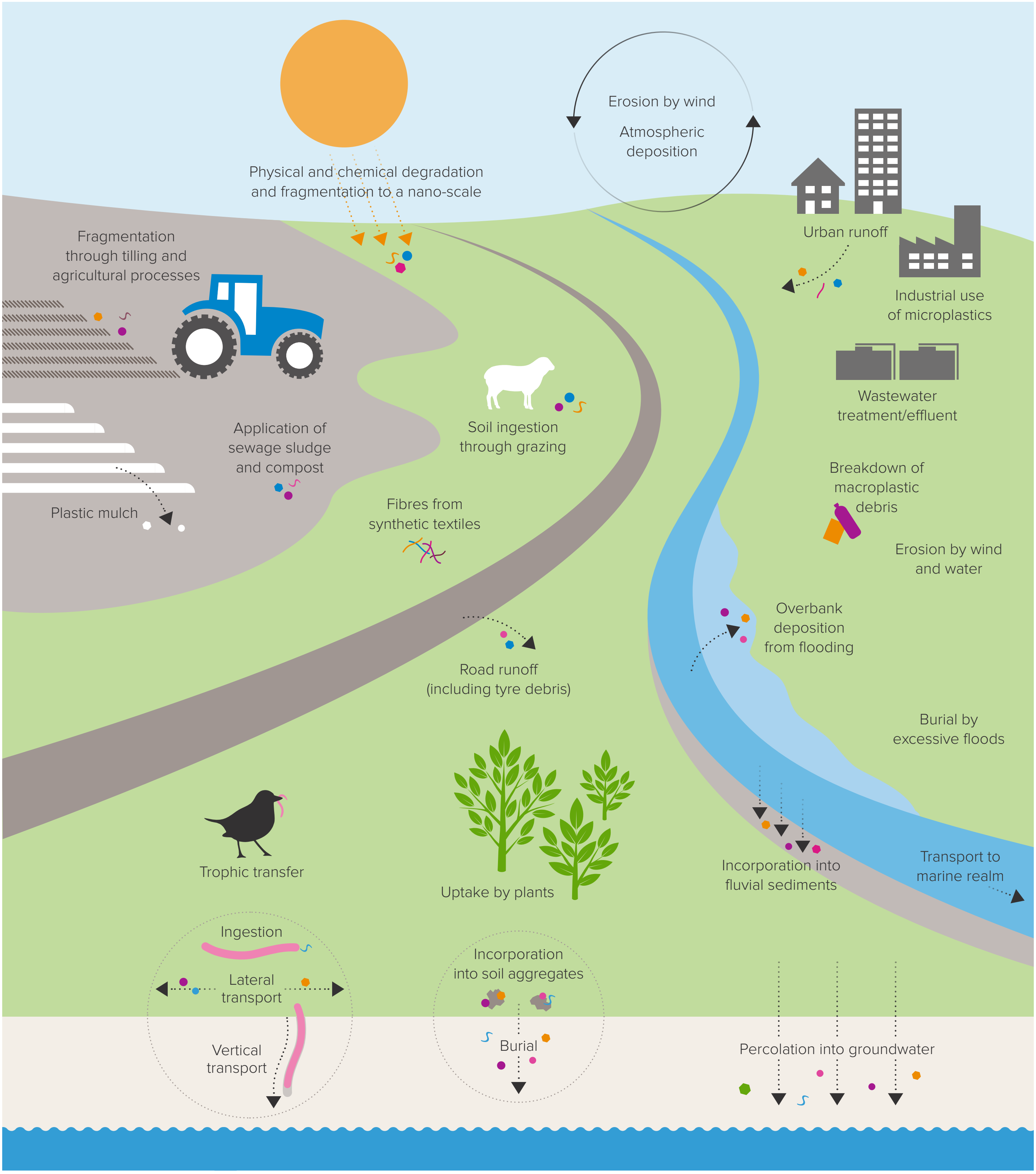
It is likely that the majority of microplastics come from the fragmentation of larger pieces of plastic litter in the environment. Larger plastic items fragment due to UV radiation, temperature change and physical erosion.

Microplastics make their way into the environment via a number of different routes. These include: industrial and sewage effluents, runoff from roads and urban environments, from sewage sludge applied to agricultural lands, and via airborne pollution. Once in the environment, plastics and microplastics may move in cycles between terrestrial, freshwater and marine environments, as shown in Figure 7[85].

It is likely that the majority of microplastics come from the fragmentation of larger pieces of plastic litter in the environment.

FIGURE 7

Microplastic sources and cycles of movement between freshwater and soil environments.



BOX 1

The shape of microplastic particles

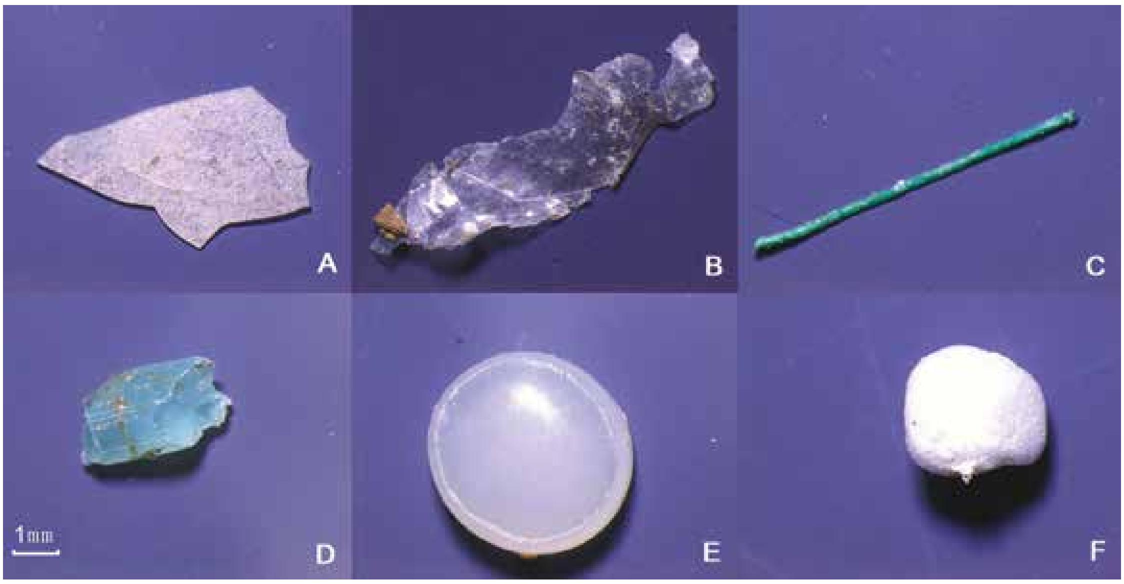
Fibres and fragments of irregularly shaped, weathered, non-pristine microplastics are most commonly found in the natural environment[86] (Figure 8, showing shapes of typical microplastics collected from inland waters in China), whereas lab studies often use pristine, spherical pellets[87]. Therefore the applicability of many of these studies to exposure in the natural environment is questionable. Irregularly shaped fragments have been shown to remain in the digestive system longer than spherical pellets[88] and may bind to more pollutants due to their larger surface area[89].

Fibres, mostly shed from synthetic textiles, have been identified as a particular source of concern given their abundance in both soil and water environments[90]. A laboratory study that investigated the physical damage caused to goldfish found that while pellets and irregularly shaped fragments damaged the jaw, fibres were more likely to be ingested and cause harm to the internal organs[91]. However, another study on fish concluded that while shape affects toxicity, there are no easily generalisable trends[92].

It is thought that previous sampling studies may have underestimated the number of microplastic fragments in the natural environment as they can be relatively easily mistaken for organic particles. New measurement techniques for microplastics are being developed that use fluorescence to better highlight the range of microplastic particles in collected samples. This makes the detection of irregularly shaped particles more straightforward.

FIGURE 8

Shapes of typical microplastics collected from inland waters (Qinghai Lake and Three Gorges Reservoir) in China (A, sheet; B, film; C, line/fiber; D, fragment; E, pellet/granule; F, foam)[93].



Most plastic in the oceans originates from the land and rivers, yet the presence and impacts of microplastics in these terrestrial and freshwater systems has been far less studied.

Focus of this synthesis

This synthesis focuses on microplastics in freshwater and soil, looking specifically at the impact of microplastics and the chemicals associated with them, on animals in freshwater and soil environments. The synthesis also considers the limited amount of published research on nanoplastics, as well as potential impacts on human health.

Most plastic in the oceans originates from the land and rivers, yet the presence and impacts of microplastics in these terrestrial and freshwater systems has been far less studied. Less than 4% of microplastic-related studies focus on freshwater[94] and there are even fewer published studies on microplastics in soil. Estuarine environments have been included as part of this remit.

The study of microplastics faces unique challenges compared to larger plastics. Microplastics can be difficult to detect or distinguish, and so are harder to identify, monitor and remove. There is also a higher chance that animals will ingest them and that they will move through food chains and affect a wider range of species, including humans[95]. However, as microplastics come predominantly from the breakdown of larger plastic items, the microplastics debate cannot be fully separated from the wider debate on plastic production, consumption and pollution.

BOX 2

Size definitions of microplastics and nanoplastics

Current consensus is to group plastic particles according to their diameter, with plastics described as macro, micro or nano depending on their size. However there is a lack of agreement on the precise upper and lower boundaries of particle diameter that defines each group. The majority of papers define microplastics as plastics where no diameter is larger than 5 mm[96]. However, the lower limit is less well defined[97 – 99]. Microplastics have often been detected by visually examining samples of particle matter using a microscope, and for practical reasons this means that papers usually define the lower limits as being around 0.1 – 0.3 mm in diameter, though some significantly diverge from this definition.

Nanoplastics also lack a standard definition. The most common definition used in published papers recognises nanoplastics as those particles where at least two dimensions are in the size range 1 – 100 nm[100 – 104]. Nanoplastics require advanced techniques to detect, and are therefore predominantly studied in a laboratory context. The lower size limit here is defined according to the smallest size commonly studied using current techniques.

There is a notable gap in published studies on particles smaller than 100 µm[105] and larger than 0.1 µm, ie between the common micro and nano particle ranges (Figure 9 demonstrates this challenge). This discrepancy is likely due to the difficulty of measuring particles that are smaller than can be seen with a microscope, yet larger than those commonly used in lab studies[106].

This synthesis focuses on plastic particles below 5 mm in size, reflecting the most widely accepted definition of microplastics. We also consider nanoplastics, but there is less agreement over the size range within the published papers and so we do not attempt to define them here. The challenges related to the size definitions of microplastics and nanoplastics are described in Box 2.

This synthesis is split into four key sections:

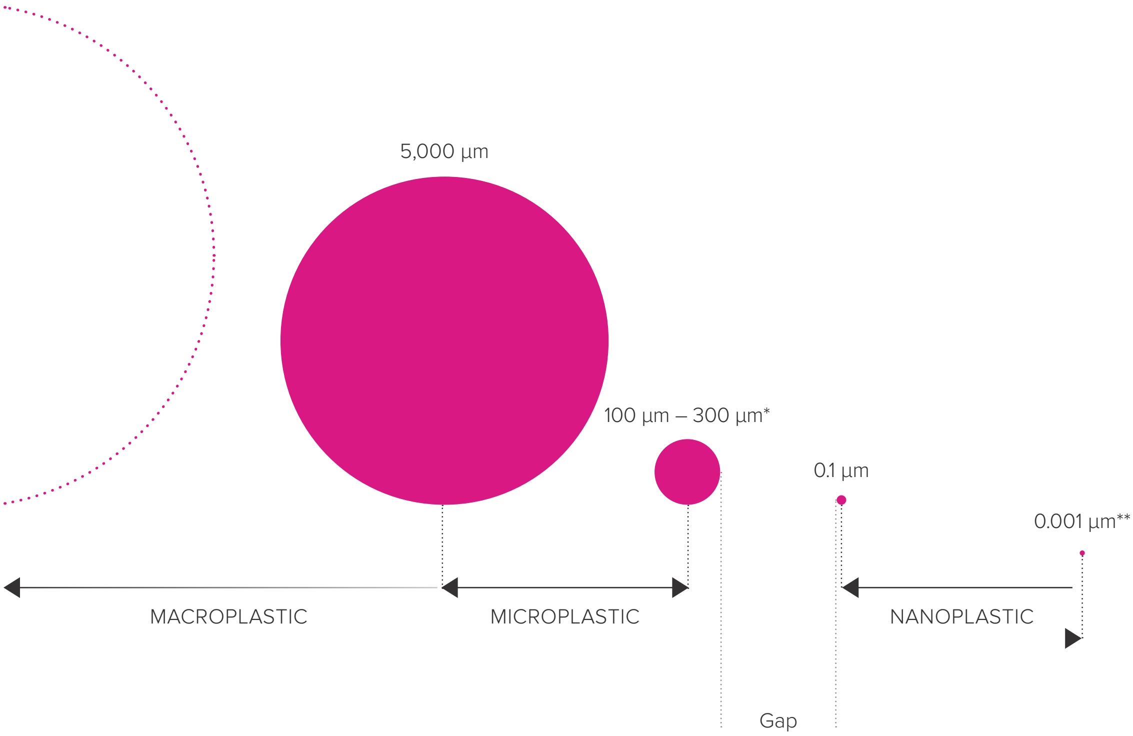
1. The direct behavioural and physical effects of microplastics on animals;
2. The chemical additives present in microplastics;
3. Microplastics as a vector for toxic chemicals; and
4. The impact of microplastics and associated chemicals on humans.

Evidence gaps are discussed throughout and also explicitly presented in Annex 1 and as part of the Discussion section.

This synthesis is intended predominantly for a policy audience and follows the Royal Society's 'principles for good evidence synthesis for policy'[107]. A full methodology, including search terms is presented in Annex 3.

FIGURE 9

The most commonly used definitions and relative sizes of microplastic and nanoplastic particles.



Not to scale.
*Not well defined or agreed.
**As determined by limit which is studied using current methods.

Direct effects of microplastics on animals

This section presents the research relating to the direct effects of microplastics on animals. Initially we consider the evidence demonstrating the presence of microplastics in animals living in freshwater and soil. We then move on to the more speculative evidence relating to the potential effects. These effects are considered in terms of: a) effects on behaviour and reproduction; b) evidence relating to physical damage and mortality and c) evidence related to trophic transfer and wider ecosystem effects.

Note that presence and impacts of microplastics in humans are considered in Chapter 4.

Much of the published evidence on the effects of microplastics and nanoplastics on animals is from laboratory studies that use very high concentrations of microplastics.

The applicability of these studies to the natural environment, where concentrations are much lower and exposure rates unknown, is not straightforward. The type of microplastics used in these studies also often involves plastic materials and sizes that are different to those found in natural systems. These caveats are considered in more detail in the discussion (Section 6) but must be kept in mind when interpreting these findings.

Presence of microplastics in animals

Microplastics have been found in a variety of freshwater animals including the water flea, *Daphnia magna*[108], a range of other invertebrates[109], tadpoles[110], bivalves such as the freshwater mussel[111], and numerous species of fish[112 – 118]. For example, studies have demonstrated that 33% of roach sampled in the river Thames contain microplastics[119] and 15% of chub sampled from rivers in Paris contain microplastic[120].

In addition, in laboratory experiments, microplastics have been shown to be ingested by clams[121 – 123], zebra mussels[124], crustaceans[125 – 127] and invertebrates such as the freshwater polyp[128].

Microplastics and nanoplastics have also been found in a range of terrestrial animals. Studies show that animals such as earthworms[129 – 132], mice[133], and ducks[134] have ingested microplastics, and that microplastics can be detected in the gut[135], liver[136] and faeces[137 – 140] of various animals. Contrastingly, other studies that have found no evidence of ingestion, such as in insect-like springtails[141, 142]. The likelihood that microplastics will be ingested by an animal seems to relate to its ability to distinguish between microplastics and actual food sources, with filter feeding animals likely to be particularly susceptible[143].

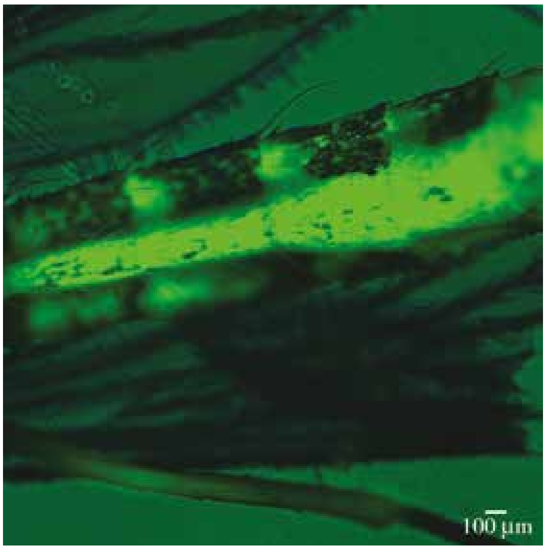
Microplastics are predominantly found within the digestive system of animals and will pass through the body in a number of hours or days, depending on the species.

Microplastics are predominantly found within the digestive system of animals and will pass through the body in a number of hours or days, depending on the species. However, there are a few examples of microplastics passing into tissues and other organs at very high concentrations. Microplastics have also been found to move through different parts of an animal's internal structure. For example, exposed to very high concentrations of microplastics, one study showed that in the freshwater zebra mussel, microplastics could pass through the gut wall and into the soft tissue of the body[144]. However, these results were observed under unnaturally high conditions of microplastic and should be received with some caution.

Observations have also shown that once ingested, microplastics might be retained in an animal's body through multiple stages of their development. For example, mosquitos, who spend their juvenile stages in water but adult stages on land, retain microplastics in their bodies over the course of their development[145] (Figure 10). This is most notable in those parts of their body that do not undergo extensive reorganisation during development, such as the renal system[146].

FIGURE 10

Fluorescent microplastic in the stomach of an adult mosquito glows green under a microscope. Researchers found an average of 40 microplastic particles in the stomach of each adult mosquito they studied[147].



Impact on behaviour

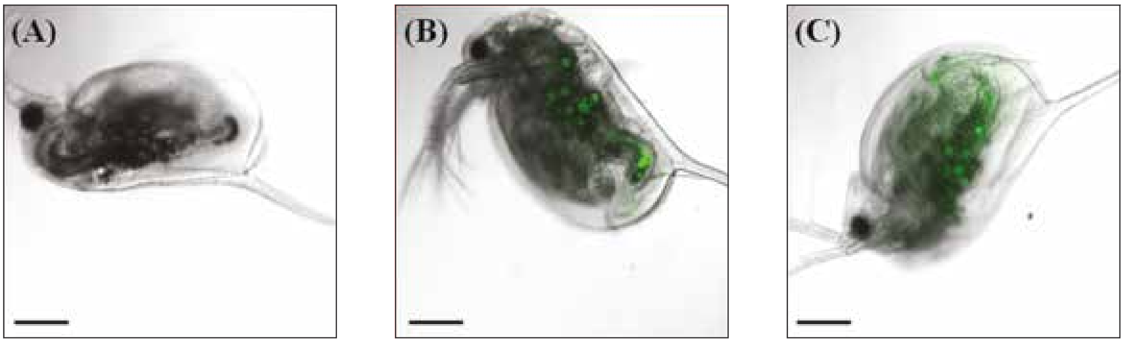
Freshwater

The presence of microplastics in animals can affect their behaviour in a range of ways, such as false satiation (feeling full when not), decreased movement, or increased buoyancy, (which affects swimming behaviour). Behaviour changes can also be caused by the chemicals present in microplastics. These are considered in Chapter 2.

For example, following exposure to microplastics, studies have observed a reduced dietary intake in fish[148 – 150], crustaceans[151, 152] and other freshwater animals such as freshwater polyps[153]. However, other studies have observed no changes, such as in freshwater amphipod crustaceans[154].

FIGURE 11

Image of *Daphnia magna* exposed through the diet to nano-sized polystyrene[158].



Following laboratory exposure to microplastic beads, a reduction in feeding behaviour was observed in freshwater polyps[155]. In some cases the polyps' digestive tracts were filled with microplastics, preventing the ingestion of their normal prey. This also led to increased buoyancy, potentially preventing the polyps from feeding in their preferred position in the water column. Increased buoyancy as a result of microplastic consumption has also been observed in *Daphnia magna* (Figure 11)[156].

It was also observed that freshwater polyps take 24 hours to expel microplastics from their bodies, as opposed to the usual eight for other debris, suggesting that microplastics might require more energy to process, possibly reducing the energy available for survival and reproduction[157].

Predators that rely on sight to detect their prey, such as the common goby, could be particularly vulnerable to mistaking microplastics for food sources[159]. However, there is evidence to suggest that these fish are able to distinguish between microplastics and prey in a laboratory setting[160]. This differentiation could be due to size, shape or lack of movement of microplastics compared to prey.

Paler microplastics appeared to be more likely to be ingested than coloured ones[161]. Similar results were observed in goldfish, where they too appear to be able to differentiate between microplastics and actual food items[162], though this may not translate to the weathered and fragmented microplastics present in the natural environment.

There is still limited evidence of the impact of nanoplastics on animals. One study found that *Daphnia magna* were five times more likely to ingest nanoplastic particles than microplastics, resulting in a reduction in feeding and excretion rate[163].

In another study, nanoplastics were observed to cross the blood-brain barrier in carp, resulting in noticeable behavioural changes, including a slower eating rate, longer hunting time and lower activity[164]. This suggests a mechanistic link between the observed behavioural changes and the presence of nanoplastics in the brain[165].

Despite observations showing the tadpoles' digestive tracts being full of microplastics, there were no observed effects on body growth or swimming activity.

Soil

Microplastic exposure may affect the feeding habits and body weight of soil animals, partly via changes to the gut microbiome. However, evidence is mixed. Some experiments have shown no effects of microplastics on ingestion rate or body mass in woodlice[166], whilst certain species of springtail and worms saw a significant reduction in gut microbiome diversity, which indicates less feeding or a more restricted diet[167].

Several studies on earthworms have shown a reduction in the size and weight of earthworms in microplastic polluted soil[168, 169]. This is thought to be due to microplastics causing obstruction and abrasion of the digestive tract, therefore limiting the uptake of nutrients. Reduced uptake and processing of soil by worms might also have wider implications for soil structure and plant growth[170], though there are currently few studies that explore these systems-level effects in any detail.

Impact on reproduction

There is mixed evidence concerning the impact of microplastics on reproductive rates in individual animal species. A decrease in reproductive rates were observed in freshwater amphipod crustaceans[171]. However, studies in earthworms[172, 173], *Daphnia magna*[174, 175] and the freshwater polyp[176], show no evidence of impact on reproductive rates.

In one study, a population of *Daphnia magna* were exposed to high concentrations of pristine microplastic beads in a laboratory environment[177]. This population experienced increased mortality rates and reduced growth and reproduction rates. Subsequent generations that were not further exposed to microplastics still displayed reduced growth and reproductive rates, up to the third generation. This indicates that recovery from exposure to microplastics could take several generations. It should be noted that there are few other studies investigating this and no examples showing inter-generational effects within the natural environment.

The chemicals associated with microplastics may also affect reproduction. Evidence relating to this is presented in Chapters 2 and 3.

Physical damage

Freshwater

Some studies have observed physical damage to freshwater animals following exposure to microplastics. In freshwater animals, nanoplastic and microplastic exposure has resulted in some non-lethal internal damage to the animal, typically in the gut, liver[178 – 181] and mouth cavity[182]. In one study, 80% of goldfish displayed physical damage to the mouth cavity following the chewing and expelling of microplastic fragments[183].

Microplastics have been observed in the digestive tract and gills of tadpoles exposed to microplastics during their development, showing that they can ingest microplastics at an early life stage. However, despite observations showing the tadpoles' digestive tracts being full of microplastics (Figure 12), there were no observed effects on body growth or swimming activity[184].

Nanoplastics have been shown to bind to proteins involved in metabolism in fish, suggesting that animals which ingest these nanoparticles could experience adverse metabolic effects[185], with longer exposures resulting in higher toxicity[186].

FIGURE 12

Microplastic beads in the digestive system of tadpoles at different microplastic concentrations[187].

In both freshwater and soil environments, there is an evidence gap in terms of understanding the effect of realistic concentrations of microplastics on animals' long-term health and survival.

Soil

Studies have suggested that microplastics can cause non-lethal damage to the organs of several terrestrial animals[188]. In addition, one study showed that earthworms and isopods such as the common rough woodlouse showed increased mortality when exposed to microplastics at high concentrations, whereas lower concentrations had no effect[189].

In both freshwater and soil environments, there is an evidence gap in terms of understanding the effect of realistic concentrations of microplastics on animals' long-term health and survival.

Transfer between animals

Recent evidence suggests that microplastics can pass up the food chain, leading them to accumulate in larger animals. This trophic transfer of microplastics has been demonstrated in the laboratory environment[190 – 192]. In one study, algae that were briefly exposed to nanoplastics led to the plastic being passed up two levels of the food chain, being ultimately detected within predator fish[193 – 195]. Another study showed that the effects of microplastics appear to become more severe as the trophic level increases. In this study, ingestion of nanoplastics by *Daphnia magna* appeared to have few negative effects, but changes in behaviour and brain structure were observed in secondary consumer fish[196].

Despite these results, microplastics do not routinely pass through biological membranes (there are just a few examples of this at unrealistically high concentrations).

A recent study found that the presence of microplastics in the soil led to fewer seeds germinating and reduced plant growth, perhaps due to negative impacts on earthworms.

The majority if not all microplastics will pass through the animal and be expelled via the faeces and will not be stored in internal organs or tissues. Therefore bioaccumulation is only likely to occur in the gut of the animal. Tropic transfer has not yet been demonstrated in the natural environment.

There is also some limited evidence that nanoplastics might be passed down through generations, with one study demonstrating that nanoplastics within adult freshwater fish were transferred to embryos during a 24 hour exposure period[197].

Wider ecosystem effects

Little evidence currently exists regarding the wider ecosystem effects of microplastics. It is possible that microplastics might have the potential to affect soil structure[198, 199], plant growth[200] and soil or freshwater ecosystem functioning[201]. Considerable further research would be required to validate these hypotheses.

Freshwater

There is currently little research on population level or wider ecosystem effects of microplastics in freshwater. It has been hypothesised that synthetic debris, including plastics and microplastics, may have an effect on wider ecosystem functioning[202]. A summary of how this could occur is presented in Figure 13. This refers to macroplastic debris in birds but the same system-wide effects could plausibly apply to a smaller organism ingesting microplastic. Microplastics have been shown to affect the ecological functioning of marine habitats through reducing the filtration rate of mussels and oysters[203] and reducing the abundance of invertebrates[204]. It is plausible that similar effects would be seen in freshwater environments.

Soil

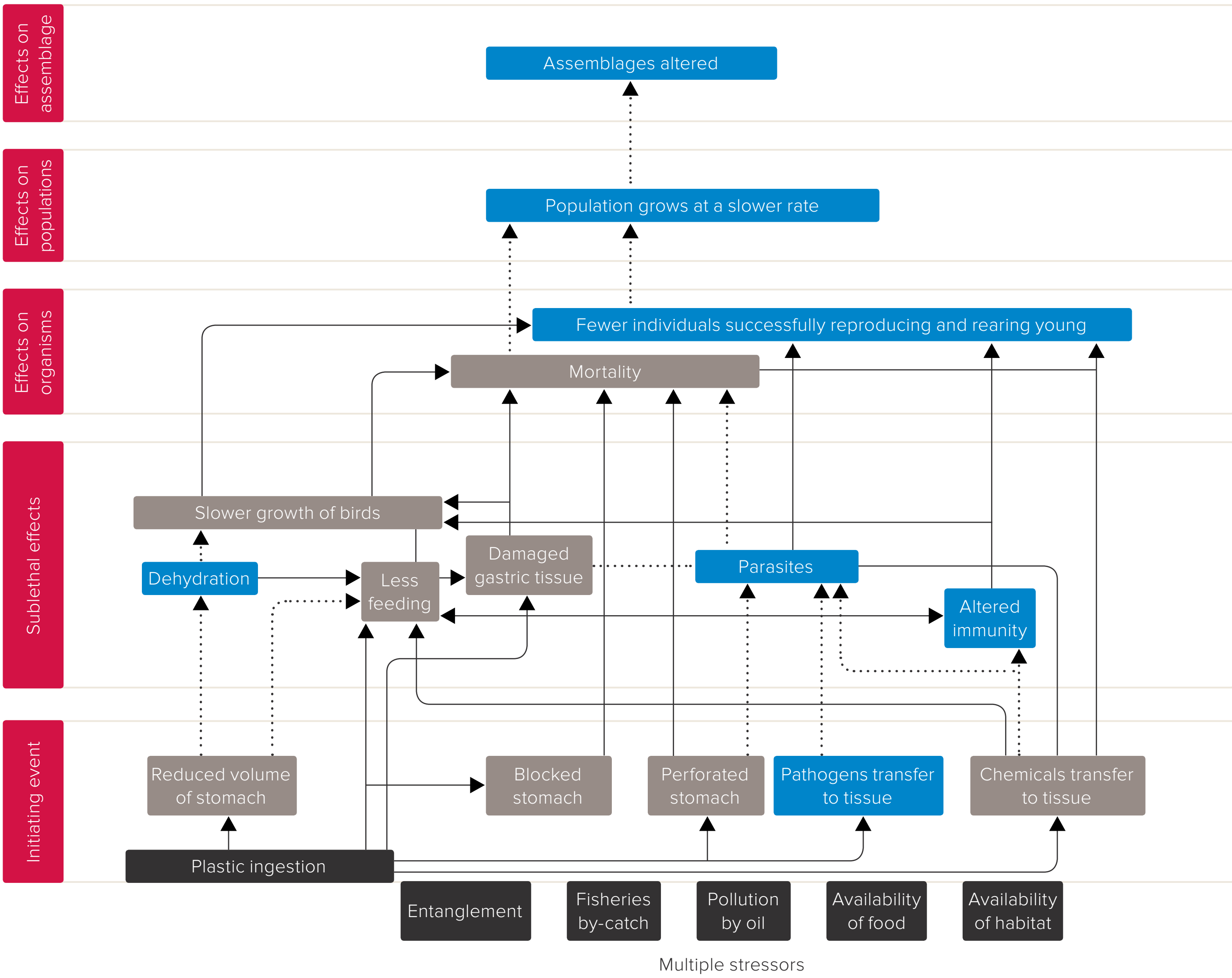
Within soil the presence of microplastics may make the soil structure more permeable, which could lead to better infiltration of rainwater, root penetration and enhanced root growth[206]. However this increased aeration could also lead to increased evaporation of water and consequently drier soils, which could have a negative impact on plant growth or nutrient cycling[207]. A recent study found that the presence of microplastics in the soil led to fewer seeds germinating and reduced plant growth, perhaps due to negative impacts on earthworms[208]. It is possible that changes in soil structure could change plant community diversity or composition, perhaps favouring more drought tolerant species[209]. Studies have also suggested that microplastics may increase the activity of soil microbial communities[210, 211] which could have effects on wider ecosystem function[212] though the mechanisms for this are not yet understood.

In terms of nanoplastics, it has been hypothesised that nanoplastics could be taken up by plant roots and potentially cause direct damage to the plants or enter the livestock and human food chain, but this has yet to be proven in field or laboratory studies[213].

FIGURE 13

Wider ecosystem effects of plastic debris ingestion by birds, highlighting the interconnectedness of natural systems. The same system-wide effects could plausibly apply to a smaller organism ingesting microplastic[205].

Hypothetical and observed impacts to birds ingesting debris. Grey-shaded boxes identify impacts caused by plastic debris at different levels of biological organization and solid lines indicate proven linkages between levels, whereas dotted lines indicate unproven but hypothesized links from published experiments. Based on existing hypotheses and evidence, we would expect birds with more plastic in their gut to hold less water and food, and contain more chemical pollutants. Dehydrated birds are known to feed and grow more slowly, and have damaged gastric tissue and immunocytes. Similarly, birds on diets with fewer lipids grow more slowly, forage less efficiently and have poorly functioning immune systems. The immune system may also be damaged from chemicals that transfer from ingested plastic. Birds with activated immune systems feed and grow at slower rates, and produce smaller and fewer offspring, whereas birds that accumulate pollutants frequently found on debris have more parasites, smaller reproductive outputs and suffer mortality.



Chemical additives in microplastics

Through chemical additives, manufacturers can choose to alter the properties of the plastics they are producing.

A number of chemicals are added to plastic products during their manufacture and use. Here we focus on bisphenol A (BPA) and phthalates, two of the most common plastic additives. This section outlines some of the impacts that these additives have on animals in freshwater and soil.

Through chemical additives, manufacturers can choose to alter the properties of the plastics they are producing. These chemical additives have been instrumental in making plastic the diverse and prevalent material it is today.

Plasticisers are additives used to alter the strength, durability and flexibility of plastic. In total there are around 50 plasticisers in commercial use. Phthalates (or phthalate esters) are by far the most common plasticiser, routinely added to plastics during production, including to PVC (Polyvinyl Chloride) which is widely used to make products such as pipes, cables and rubber ducks. Alongside plasticisers, other common additives are flame retardants, pigments and antifouling agents.

BPA is a chemical used in the production of plastic. Not all BPA is fully incorporated during the production process and can leach out in an unreacted form. BPA is found in many mass-produced plastic products including medical devices, food packaging and cosmetics[214].

As plastic disintegrates, these chemicals can leach into the environment. Plasticisers are not particularly stable molecules when combined into plastic materials and can leach out into the environment with relative ease[215]. The rate at which chemicals are released from the product is determined by many factors, including the size, concentration and volatility of the additive, the permeability of the plastic itself, and the temperature and pH of the surrounding medium (air, water, soil, body tissue)[216].

Microplastics leach more chemical additives than larger plastic items due to their larger surface area to volume ratio. Chemicals may also be leached as larger items of plastic degrade into microplastic form[217].

Almost all of the research relating to microplastics and chemical additives focuses on phthalates and BPA. The potentially harmful effects of these chemicals are already known and regulation already exists at the EU (summarised in Box 3).

Note that we have only reviewed papers that mention microplastics specifically, and there is a much larger body of literature relating to the direct effects of these chemicals on animals and on human health that our search will not have considered.

BOX 3

Current regulation of BPA and phthalates

BPA

There is strict regulation around the amount of BPA allowed in plastic that has contact with food[218]. In the UK, while still a member of the EU, phthalates and BPA are regulated by the European Food Safety Authority (EFSA) and the European Chemicals Agency (ECHA). In January 2017, the ECHA listed BPA in the Candidate List of substances of very high concern, following concerns about its effects on human health and the environment. BPA was banned from infant feeding bottles in 2011 and in January 2018 the European Commission adopted a proposal to strengthen the regulation on the use of BPA in food contact materials over an outright ban of the substance. The EU plans to ban its use in thermal paper (used for printing receipts) by 2020.

Phthalates

The EU has introduced legislative measures to restrict some phthalates, where evidence suggests that these could have adverse impacts on human health[219]. While phthalate plasticisers still dominate the market, low-molecular-weight phthalates are being gradually replaced by high-molecular-weight phthalates (those containing more than six carbon atoms) which have increased permanency and durability, and are theoretically less likely to leach into the environment. In addition, other newer non-phthalate plasticisers are becoming more common, though their environmental impacts are not well understood.

The evidence of harm is very mixed, with some studies indicating evidence of harm and others in the same species showing no evidence. This is likely due to differences in concentrations and experimental conditions.

Impacts of chemical additives on animals

There is clear evidence that chemicals used in the production of plastic accumulate in animals and are potentially harmful[220, 221]. However, the evidence of harm is very mixed, with some studies indicating evidence of harm and others in the same species showing no evidence. This is likely due to differences in concentrations and experimental conditions. It is also often not clear in the literature how much of this potential harm might be attributable to exposure via microplastics.

Much of the available data relates to exposure in a few well-studied species under laboratory conditions. As with studies on microplastics themselves, there is some argument as to how translatable these laboratory studies are to the natural environment and wider ecosystems. In the natural environment concentrations are likely to be lower and more variable, and exposure likely to be confounded by interactions with other pollutants.

Most chemicals appear to act by interfering with the functioning of hormones, but some have wider effects[222]. Generally, greater concentrations of chemicals are found in invertebrates compared to vertebrate species, especially in some mollusc and crustacean species[223].

Freshwater

Fish

Fish are likely to be exposed to microplastics and chemicals from the water itself, from the sediments they forage in and from their prey. In freshwater, some have suggested that concentrations of BPA in sediment are higher than within the water column itself[224]. Real world conditions are incredibly variable and there are hotspots of microplastic contamination such as areas near landfill sites and sewage treatment plants, where concentrations of both phthalates and BPA may be highest.

Despite the fact that phthalates can accumulate in fish[225], there is currently limited evidence of adverse health effects in wild populations and laboratory evidence is inconclusive. The effects of BPA and phthalates on fish appear to be mostly related to hormonal changes, reproduction and development[226, 227], the impacts of which vary depending on the species and exposure levels. The effects of phthalates and BPA on fish are summarised in Box 4.

BOX 4

Observed effects of BPA and phthalates in fish

Effects of BPA in fish

- Morphological deformities[228]
- Slow brain development[229]
- Impaired bone development[230]
- Altered sex cell ratios[231]
- Reduced number of mature sperm[232]
- Reduced sperm quality[233]
- Delayed or inhibited ovulation[234]
- Abnormal development of sexual organs[235]

Effects of phthalates in fish

- Increased metabolism[236]
- Decreased sperm mobility[237]
- Altered steroid hormones[238]
- Decreased reproduction rates[239]
- Increased feeding activity[240]

Crustaceans

The effect of phthalate exposure differs significantly for different species of crustacean, but overall crustaceans appear to be particularly sensitive. It has been suggested that *Hyalella azteca*, a small crustacean found in freshwaters in North America is 10 – 20 times more sensitive to phthalates than *Daphnia magna*[241], though toxicity varies depending on the type of phthalate. Evidence of harmful effects include reduced movement in the crustacean *Gammarus pulex*, and reduced movement[242] and immune responses in giant freshwater prawns[243] and green neon shrimp[244].

Effects of BPA on crustaceans mostly include developmental[245 – 248] and reproductive effects[249].

Amphibians

Amphibians are particularly susceptible to the presence of chemicals in the water[250]. This is because they have a highly permeable skin and remain in aquatic environments during crucial hormone-regulated development stages.

The presence of phthalates in sediment has been shown to negatively affect reproduction rates in the moor frog[251]. Phthalates also negatively affect the sexual development of the Japanese wrinkled frog[252] and African clawed frog[253, 254]. However, other studies in frogs have shown no obvious hormone or metabolic related changes[255 – 257].

BPA was found to inhibit tadpole metamorphosis in the western clawed frog[258]. However a contrasting study using higher concentrations on African clawed frog tadpoles showed no observable effects[259].

Amphibians are particularly susceptible to the presence of chemicals in the water. This is because they have a highly permeable skin and remain in aquatic environments during crucial hormone-regulated development stages.

The two studies that have examined the effects of BPA on wild mammals are on field voles and polecats. There were no obvious effects in polecats, but in field voles BPA exposure resulted in increased testosterone levels.

Other studies on the effect of BPA on African clawed frog embryos produced a range of effects including disfigurement of the head, spine and organs as well as fluid retention[260]. In the Japanese pond frog disfigurement of the tail has been observed[261]. Laboratory studies have also demonstrated that BPA influences the sexual development of frogs, leading to a significant female-biased sex ratio[262, 263].

Other freshwater animals

The impact of phthalates and BPA on *Daphnia magna* has been relatively well studied. Effects of phthalates include a reduction in body size, lifespan and reproductive rates[264]. Effects of BPA include damage to genetic information[265], the triggering of metabolic stress responses[266] and decreased rates of reproduction[267].

It has been suggested that freshwater molluscs are also particularly sensitive to BPA[268]. In freshwater ramshorn snails, exposure to BPA resulted in abnormal sexual development and increased mortality[269].

In species with temperature-dependent sex determination such as the broad-snouted caiman, BPA seems to induce sex changes in embryos[270].

Terrestrial animals

Insects and worms

Phthalates appear to have a range of effects on insects, though these are not currently well understood. For example, there is some evidence that phthalates may alter hormonal activity in the common fruit fly, but only at very high concentrations[271]. Exposure in harlequin fly larvae resulted in an increase in female body volume and a toxic but non-lethal effect on adult flies[272], and exposure in the lake fly appears to increase susceptibility to heat shock[273].

Studies demonstrate that phthalates can enter terrestrial and freshwater worms but appear to have a low toxicity when duration of exposure is short[274, 275].

When it comes to BPA, research suggests insect larvae are particularly sensitive[276]. For example, BPA inhibits development at relatively low concentrations in the small copepod *Tigriopus japonicus*[277].

The common woodlouse is also affected by BPA, with high exposures resulting in a reduced time to moult, slower overall growth and female-biased sex ratios[278 – 280].

Birds and mammals

Our search returned no studies on the effects of phthalates on birds and mammals via microplastics and there have been very few studies on the effects of BPA on birds and mammals.

Research on BPA in birds focuses on chickens and quail. In male chickens, studies have observed feminisation of testes[281] and delayed growth of the comb, wattle and testes[282]. In the female Japanese quail, BPA has led to oviduct abnormalities[283].

Most studies in mammals are on laboratory rats and mice, using high concentrations of BPA. Observed effects include obesity[284], pregnancy complications[285], changes to male and female reproductive organs[286, 287] and cancerous growths[288].

Specific effects of BPA are difficult to determine in the natural environment as mammals are likely to be exposed to very low levels[289]. The two studies that have examined the effects of BPA on wild mammals are on field voles and polecats. There were no obvious effects in polecats[290], but in field voles BPA exposure resulted in increased testosterone levels[291].

Microplastics as a vector for environmental pollutants

This section presents the research relating to microplastics as a vector for environmental pollutants. Initially we describe the mechanisms by which microplastics may transport chemicals into animals. We then present the evidence relating to whether pollutants are released from the microplastics once inside the animal and therefore have the potential to cause harm.

Microplastics can absorb pollutants and also concentrate them on their surface. This means that microplastics could act as a vector, transporting chemicals and other pollutants around freshwater environments and from freshwater and soil into animals. This has been the subject of a number of reviews[292 – 295]. Microplastics could also extend the range of these pollutants by transporting them further downriver or deeper into the soil than they would normally travel[296 – 301]. We know that many of these pollutants can cause harm at high concentrations, but the role that microplastics play in concentrating these pollutants in animals and the risks posed at environmentally realistic concentrations are still not well known.

The large surface area to volume ratio of microplastics makes them an attractive surface for pollutants, therefore pollutants will preferentially bind to them as opposed to other debris[302]. In addition, both the plastics and some pollutants are hydrophobic (water hating) meaning they are attracted to one another instead of interacting with the surrounding water[303]. The binding capacity of hydrophobic organic pollutants and plastics is so good that it has led to the use of microplastics as devices to monitor the contamination of water and sediment[304].

Various types of pollutant have been shown to interact with microplastics, including hydrophobic organic chemicals and trace metals, such as mercury and zinc[305 – 307]. One of the most frequently examined groups of chemicals has been Persistent Organic Pollutants (POPs) – a group of long-lived contaminants that were formerly used in agricultural products (such as the insecticide DDT) or industrial processes[308, 309]. While less researched, some studies have clearly shown that pharmaceuticals, including a range of antibiotics, also bind to microplastics[310, 311].

A range of factors can affect how effectively pollutants bind to microplastics. The aging and weathering of microplastic particles leads to an increase in their surface area to volume ratio and porosity, and therefore increases the concentration of chemicals possible[312]. The type of plastic also has an effect, with polyethylene (the plastic used for shopping bags and shampoo bottles) having one of the greater capacities for binding with pollutants[313, 314].

There is clear evidence that a wide variety of animals in freshwater consume microplastics and associated chemicals in their natural habitat[315 – 319]. This has led a number of scientists to suggest that microplastics act as an important vector for transporting environmental pollutants into animals[320 – 323].

However, there is ongoing debate and conflicting evidence as to whether the chemicals associated with microplastics can leave the plastic and cause harm once consumed. We know that these chemicals can be harmful, but it is unclear whether their effects are worse or more concentrated when microplastics act as a vector. The key point of contention is whether the pollutant particles are so strongly associated with the microplastic particles that they do not leach into the gut, even when consumed.

Microplastics can absorb pollutants and also concentrate them on their surface. This means that microplastics could act as a vector, transporting chemicals and other pollutants around freshwater environments and from freshwater and soil into animals.

In studies looking at the exposure of animals to both microplastics and chemicals, many show that the presence of microplastics does not increase the toxicity of the chemicals.

Whether chemicals are released from the microplastics and into the animal depends on the difference between the attractiveness of the microplastic and the attractiveness of the animal's tissue usually comprised of lipids. If there is no difference then the microplastics and chemicals will pass through the animal with no transfer. However if the animal's tissue is more attractive, then the animal may be exposed to the chemicals[324].

That said, this leaching assumes that the chemicals are able to transfer during the relatively short gastrointestinal residence time of a few hours to a few days for most species[325, 326]. This leaching potential is affected by a variety of factors, including temperature, friction and acidity[327 – 329], as well as the type of plastic and chemical[330]. Microplastics are more likely to act as a vector where chemicals leach from them quickly or easily, as in the case of the contaminant pentachlorobenzene, which is used in fungicides and fire retardants[331].

A number of studies have suggested that the release or 'desorption' of pollutants from microplastics following ingestion does or could happen[332 – 343]. Pharmaceutical products have been shown to leach from microplastics following 48 hours in water[344]. One laboratory study using a solution that simulates the conditions inside a worm's gut showed that zinc was desorbed, suggesting that microplastics could act as a vector for metals in soil environments[345].

Other studies suggest that because the microplastics themselves are so attractive to pollutants, the pollutants may be unlikely to leave the microplastics inside the gastrointestinal tract[346 – 351]. In studies looking at the exposure of animals to both microplastics and chemicals, many show that the presence of microplastics does not increase the toxicity of the chemicals[352 – 354]. Furthermore, other authors have suggested that microplastics could draw pollutant chemicals from the animals they pass through, in effect 'cleaning' them or acting as a detoxifier[355]. A recent review found evidence of this in a number of species, including fish, worms and birds[356].

There are several complexities and caveats associated with investigating the relationship between pollutants, microplastics and animals. Due to the complex relationships between these, some studies have produced unexpected results.

In one study, mussels exposed to mercury and microplastics absorbed less mercury than those exposed to the metal alone[357]. However, the microplastics were observed to have physically damaged the mussels' gills, thereby reducing all filter feeding activity. Another study noted that the presence of nanoplastics reduced the inhibitory effect of a herbicide on the growth of blue-green algae. As the herbicide was attracted to the nanoplastic, its available concentration in the water was reduced. However, the polluted nanoplastics then stuck to the outside of the algae, potentially causing them to accumulate in predator species[358]. These results illustrate how the complexity of natural systems means that interactions between an ecosystem, microplastics and other pollutants are likely to be multifaceted and context-dependent.

A number of caveats need to be kept in mind when using laboratory studies to understand the role of microplastics as vectors for pollutants. One limitation of laboratory studies for demonstrating harm is that they use animal samples that are already 'clean', potentially increasing the amount of particles that they can absorb[359]. They also use 'pristine' or un-weathered microplastics and high or variable concentrations of both plastics and pollutants resulting in unrealistic test gradients. Combined, these features may contribute to the inconsistency in results within the published literature[360] and mean that many of these studies should be treated with caution.

Regarding exposure within the natural environment, it is important to consider microplastics in the context of other potential vectors and uptake routes for environmental pollutants. Microplastics as a vector may be an insignificant route for chemicals to enter animals compared to direct consumption or inhalation[361]. Microplastics are also far less common within the environment than other potential vectors such as biological materials or other types of debris. It has been suggested that sediment or normal food sources such as plankton may be more significant vectors for the uptake of pollutants than microplastics[362, 363].

Microplastics as a vector for bacteria or other pathogens

In addition to acting as a vector for chemical pollutants, there is also a risk that microplastics could act as a vector for biological agents, such as bacteria or other pathogens. While there is substantively less evidence in this area, there has been speculation that this could pose a threat to animal health, including human health. In one study, microplastics were found to be coated in a different bacterial community to those found in surrounding waters[364] or on other types of non-plastic debris[365]. In another study a type of bacteria harmful to fish (*Aeromonas salmonicida*) was identified on sampled microplastics, with the suggestion that microplastics may have been responsible for extending its range[366]. Microplastics also appear to concentrate common human intestinal pathogens on their surface, when sampled downstream of water treatment plants[367, 368]. However, there are still major gaps in terms of understanding the mechanisms linking pathogens, microplastics and harmful effects on animals.

For further detail see Annex 1: Evidence gaps.

It has been suggested that sediment or normal food sources such as plankton may be more significant vectors for the uptake of pollutants than microplastics.

Impacts of microplastics and associated chemicals on human health

Microplastics have been detected in humans yet there is very limited evidence regarding the health impacts of this.

Much of the research relating to the impact of microplastics on human health is highly speculative. Microplastics have been detected in humans yet there is very limited evidence regarding the health impacts of this. Human health risks from the chemicals associated with microplastics have been more widely studied, particularly phthalates and BPA. These chemicals are present in many plastics as described in Chapter 2.

It is extremely difficult to predict the risks associated with human exposure to plastics and their additives, given the vast complexity and variability of possible combinations, their varied uses in everyday life, and a lack of understanding regarding their environmental distribution once discarded[369]. Our current lack of knowledge is also compounded by ethical barriers to testing human exposure and the difficulty of identifying a non-contaminated control group[370].

Pathways for human exposure to microplastics

There are several potential pathways for human exposure to microplastics, however exposure via the diet is the most frequently cited. Microplastics have been detected in seafood[371 – 373], table salt[374, 375], sugar[376], beer[377], drinking water[378 – 380], canned fish[381], mussels[382], and chicken meat[383].

However due to gaps in microplastic research, there is insufficient information to assess the true amount of microplastics humans may be exposed to via food[384]. Total microplastic intake from salt in China has been estimated at 37 particles per individual annually[385]. It is also estimated that a European shellfish consumer eats approximately 11,000 plastic particles annually[386 – 388]. However, the human body's excretory system is effective at eliminating microplastics, likely disposing of more than 90% of ingested micro- and nanoplastics via faeces[389, 390].

The relative importance of microplastic exposure via the diet is questioned by some, with the inhalation of dust cited as a more significant pathway[391].

Impact of microplastics on humans

Laboratory studies have suggested a range of potential, but still speculative, impacts on human health, which tend to focus on the presence of microplastics in the gut. Researchers have suggested that the ingestion of microplastics could cause localised effects on the immune system, damage cells (possibly increasing the risk of cancer), increase gut inflammation and damage the gut microbiome[392 – 395].

By studying mammals such as mice, researchers have also suggested that microplastics can move between cells, accumulate in organs, and impact the immune system and cell health[396 – 399].

However, these effects are not yet demonstrated in humans.

The World Health Organisation (WHO) published a report on the potential human health risks of microplastics in drinking water and concluded that while it may be possible for microplastics to pass through the gut wall and enter tissues, this may not necessarily translate to health risk. More data is required under realistic exposure scenarios[400].

Impact of chemicals associated with microplastics on humans

The human health impacts of chemicals associated with plastics, such as BPA and phthalates, have received greater scientific attention and it is well known that these chemicals are present in humans[401]. Exposure of American adults to BPA is likely to occur from multiple sources and BPA was shown to remain in the body for an average of 43 hours, far longer than previously estimated[402]. There are likely to be detrimental effects of low doses of BPA over a prolonged period, but the full extent to which BPA is transported into the human population from microplastics is yet to be confirmed[403].

Suggested impacts of chemicals leaching from microplastics are numerous[404]. However data is often mixed or patchy, and claims sometimes over-exaggerated, making it difficult to determine the strength of this evidence.

Negative reproductive and developmental outcomes have been observed in the general population associated with BPA exposure[405]. There are also suggested links between BPA and cardiovascular disease[406], type 2 diabetes, and abnormalities in liver enzymes[407].

The effects of phthalates in humans mostly relate to effects on the endocrine system (responsible for the regulation of hormones)[408 – 415]. The most significant adverse effects are on foetal development, changes to the reproductive system[416, 417] and metabolic effects such as insulin resistance and obesity[418 – 423]. Other speculative effects include abnormal sexual development and birth defects[424].

The WHO concluded that at current levels of exposure, the risk to human health from these chemicals via microplastics is likely to be low, but that further evidence is required[425].

Nanoplastics and human health

Nanoplastics and human health is a new and emerging area of research. As such, the available evidence on the impact of nanoplastics on human health is limited. However, it has been suggested that nanoplastics, due to their very small size, may be capable of being transported from the gut into the blood and then through the blood-brain barrier and placenta[426]. They may also make their way into the lungs[427].

For example, one study has demonstrated that nanoplastics can be transferred across the gut wall and into other tissues in humans, dogs and rodents[428]. These plastics affected cell viability and gene expression and also had an inflammatory effect[429]. Smaller nanoplastics (44nm) produced a greater inflammatory effect than larger (100 nm) particles.

The small size of nanoplastics also makes them very chemically reactive and laboratory studies have shown that they are toxic to lung, liver and brain cells[430]. However, there remain major knowledge gaps relating to the impacts of humans ingesting and inhaling nanoplastics[431, 432].

Discussion

> Despite these evidence gaps and the limitations with the published literature, the evidence does suggest that microplastics could cause harm at high concentrations and we do not yet know the implications of long-term exposure at low concentrations.

In the main body of this synthesis, we have summarised the best available evidence relating to the impact of microplastics on animals, including humans. However, in doing so we recognise that the most significant challenge with this evidence base is that there are still numerous evidence gaps. These are summarised in Annex 1.

Should we be worried?

The results of our synthesis present a mixed picture due to the fact that significant evidence gaps remain in many areas, and that where evidence does exist it is sometimes conflicting or difficult to translate to real-world environments[433]. This is because much of the research comes from laboratory studies using unrealistically high microplastic concentrations.

Despite these evidence gaps and the limitations with the published literature, the evidence does suggest that microplastics could cause harm at high concentrations and we do not yet know the implications of long-term exposure at low concentrations. Combined with the fact that once released into the environment microplastics are persistent, and given the high environmental concentrations expected in the future, the likelihood of negative consequences emerging is high. However, as with all diffuse pollutants, demonstrating significant effects in the environment will be difficult and even impossible in some cases.

There is evidence demonstrating the presence of microplastics in freshwater and soil environments and within the animals that inhabit them, as well as in humans and the human diet. However, the evidence of harm is more mixed. Microplastics can cause both physical harm and have negative effects related to chemical toxicity. However, these effects vary within different animals, with different types of plastic and at different concentrations. We also do not know the extent to which microplastics contribute to these negative effects relative to other non-digestible suspended organic matter and debris.

There are examples of harm from across a range of species from high-concentration laboratory studies. These include: inflammation, stress, reduced growth, effects on reproduction, and blockages of the gastrointestinal tract. In terms of impacts on human health, the evidence is highly speculative. There seems to be little evidence as yet that microplastics themselves do harm to humans[434], but they are certainly present in the human food chain. We also considered chemicals associated with microplastics and their effect on human health. However, a deliberate limitation of this evidence synthesis was that it focused only on those papers where exposure to the chemicals was related to microplastics, and therefore did not consider the much larger literature on chemicals alone. Based on our findings it seems that whilst the harm that chemicals such as BPA and phthalates can do to humans is known, the evidence linking these effects to exposure via microplastics and in the natural environment is still lacking.

There is also an important time factor associated with plastics in the environment. Most microplastics come from the degradation of larger plastic items. Over time almost all plastic degrades into smaller and smaller fragments, eventually becoming nanoplastics. Nanoplastics are almost impossible to see, measure, remove from the environment and therefore control, and initial research into their potential impact suggests that they may pose a greater risk to animals than larger particles such as microplastics. For instance, it appears that they can enter cells at high concentrations, disrupting normal cell function, and can cross the blood-brain barrier[435, 436].

Complexities and challenges

Microplastics in freshwater and soil is a challenging topic for an evidence synthesis. This is mostly because it is such a new and emerging area of science. Here we describe briefly some of the particular complexities and challenges with this evidence base.

1. **Impact studies on microplastics are often conducted in the laboratory using high concentrations, and these findings are not easily translatable to real-world conditions.**

   The major challenge with this evidence base is that many studies look at rapid exposure at high concentrations, whereas real world exposure it likely to be to lower concentrations but over a longer timeframe. The type and shape of the microplastics used in laboratories is also not always similar to those that animals may encounter in the natural environment. The applicability of this research to the natural environment is therefore not straightforward[437].

   Species like *Daphnia magna*, zebrafish and certain species of frog are the most widely studied, mainly for the reason that these species are readily available in laboratory environments. Studies on a wider range of species in the natural environment are required, as well as studies into the effects of much more realistic exposures in terms of particle concentration, particle shape and condition, duration of exposure, plastic type and size distribution. This applies to both studies on the effects of microplastics themselves, and studies on the effects of microplastic-associated chemicals.

   However, it is worth noting that if current rates of microplastic production continue, and given the persistence and bio-accumulative nature of this material, future environmental concentrations are only likely to increase. Under this scenario, the ecological risks seen from high exposure experiments in the laboratory may become commonplace within a century[438].

2. **The exposure of humans and other species to microplastics in the real-world environment is currently not well known.**

   Accurate exposure assessment is required which involves first developing methods to monitor, detect and trace microplastics in the natural environment and within animals living in natural environments. Following this, new analytical risk assessment techniques and models can be developed to better characterise the risks of harm from microplastics to different species and ecosystems. Accurate exposure assessment is an important precursor to many of the other evidence gaps identified.

Studies on a wider range of species in the natural environment are required, as well as studies into the effects of much more realistic exposures in terms of particle concentration, particle shape and condition, duration of exposure, plastic type and size distribution.

Some more recent papers suggest that microplastics are such an attractive surface for chemicals and pathogens that they may even have a 'detoxifying' effect and may lower internal exposure to pollutants.

3. **There have been very few studies looking into the effects of microplastics on the wider ecosystem.**

   Given that there may be a wide range of observed effects of microplastics on animal species, such as changes to feeding behaviour, reduced reproductive success and transporting animals beyond their usual range (due to increased buoyancy), we can assume that there are likely to be wider effects at the ecosystem level, but these have not yet been investigated.

4. **Some of the evidence gaps relating to impacts in humans cannot be so easily addressed.**

   For ethical reasons, the relationship between microplastic exposure, ingestion and harm cannot be easily explored in humans. Therefore, much of the research relies on laboratory studies of human tissue or in animal models. Human exposure to microplastics in the real-world environment is not well known and there is the potential that microplastics may have effects in humans than are not currently understood.

5. **There is currently a polarised and contentious debate about the potential role of microplastics as a vector for transporting harmful chemicals and pathogens into humans and animals.**

   Microplastics do seem to concentrate toxic chemicals on their surface and within their structure, but the literature is split in terms of whether these chemicals can leave the microplastic once inside the animal. Some more recent papers suggest that microplastics are such an attractive surface for chemicals and pathogens that they may even have a 'detoxifying' effect and may lower internal exposure to pollutants. It is likely that this varies according to the type of chemical, concentration and species. Far more consensus is required within the literature before any firm conclusions can be drawn.

Application to policy and potential solutions

The following suggestions are based both on our literature review and discussions with experts. However, our synthesis did not look at regulation or potential solutions in any detail and therefore they are by no means exhaustive.

Legislation already exists in the UK and EU to limit the number of microplastics released into the environment from personal care products, such as microbeads from face scrubs. Plastic bags and bottles have also received recent attention (Section 1. Introduction). However, these represent a small proportion of environmental microplastics.

The majority of microplastics come from the degradation of larger macroplastic items and therefore it is impossible to disentangle the control of microplastics from wider plastic debates. Since macroplastics are known to cause harm to animals and ecosystems, a lack of evidence of harm from microplastics is not a reason for inaction on macroplastics. A reduction in consumption and moving towards a more circular economy is likely to be the single biggest influencer in terms of limiting the amount of all plastics, including microplastics, in freshwater and soil environments. There are a huge range of different sources of plastic pollution coming from many different industries and it is likely that a combination of regulation, incentives, penalties, voluntary agreements and new solutions will be required to address this challenge. Also required will be collaborative and collective action by many different countries, industries, sectors and government departments.

Other potentially important specific sources of microplastics include synthetic clothing and tyres. Further research into the relative contribution of different sources of microplastics is required. It may be that improvements in washing machine technology or incentivising the use of lower shedding fabrics may play a role. In terms of tyres and microplastics from other urban sources, there is technology that could capture runoff from roads and pavements and filter this before it enters the environment.

Wastewater treatment plant technology could also help to reduce microplastics in the environment. Depending on effectiveness 75 – 99%[439] of plastics are removed from effluent waters leaving treatment plants. However sewage sludge containing microplastics is commonly spread onto farmland, meaning that microplastics are applied in a concentrated form directly back into the natural environment[440].

One complex area is that which relates to biodegradable plastics. A range of materials are used to construct such plastics, and while these may help to alleviate some of the harm caused by macroplastics, it seems few of them are likely to fully degrade in natural habitats[441, 442]. If these materials simply disintegrate more quickly into small pieces then they present the same challenges as other microplastics: they may travel further, be harder to control, and be ingested more easily by a wider range of animals.

The development of new materials may provide important alternatives to plastic in the future. There is not likely to be one new material that replaces plastic entirely, but rather a range of different solutions, each suited to particular purposes. For example, new materials made from corn, seaweed or fungi, or repurposed waste products such as palm leaves and wood pulp.

Scientists are also experimenting with microbial enzymes or "plastic eating bacteria", which could be used to degrade certain types of plastic more quickly or fully. We have not looked at these in detail here, and research will be required into their impacts on the environment.

Another complex area concerns alternatives to potentially harmful plastic additives, such as BPA. There is a danger that as the regulation of BPA and other additives tightens, perverse incentives will lead to the increased use of other, perhaps equally damaging but less well known, additives. As with biodegradable plastic, further research is required into safer alternatives before these become commonplace.

The development of new materials may provide important alternatives to plastic in the future. There is not likely to be one new material that replaces plastic entirely, but rather a range of different solutions, each suited to particular purposes.

Waiting until we fully understand exposure rates and impacts may simply delay action unnecessarily, especially as removing plastics and microplastics once they are in the environment is likely to be far more challenging and, in most instances, nearly impossible.

In order to enable effective regulation, an internationally harmonised definition of microplastics would be helpful. The current challenges are summarised in Box 2. The British Standards Institution is developing a standardised definition and way of measuring microplastics. However, for research results to be fully comparable and regulatory approaches more consistently applied, collective agreement on measurement and sampling approaches would need to occur on a global scale[443].

Coming up with safe thresholds for microplastics in freshwater and soil is likely to be challenging and there may be no safe threshold. This is due to likely differences in impacts and exposure pathways between invertebrates, fish, mammals and humans. Waiting until we fully understand exposure rates and impacts may simply delay action unnecessarily, especially as removing plastics and microplastics once they are in the environment is likely to be far more challenging and, in most instances, nearly impossible.

Limitations and caveats

From a methodological perspective, this work represents a rapid evidence assessment rather than a full systematic review. The exact methodology and rationale for the papers considered and included are presented in Annex 2.

There are a few other points to note.

- As this is a relatively new and fast-moving field of research, it is likely that since this was written many new papers will have been published. Given the extent of current gaps in the literature on microplastics and the large number of unknowns, we are mindful that new research could significantly alter our understanding. It will be important to keep abreast of new findings on this topic as they emerge.
- Microplastics in the ocean have been more extensively studied than those in freshwater. It may well be that many of these findings could be extrapolated to freshwater environments[444]. This will require detailed testing of the limits of transferability of such knowledge. However, due to the specific focus of our synthesis on freshwater and soil, marine papers were not considered in detail.
- In terms of potential solutions, we did not look at these in detail and simply suggest a few potential actions based on our reading and interviews. These are by no means exhaustive.
- Finally, as we note in the introduction, microplastics are just one threat that animals living in freshwater and soil face. These results must be considered within the context that many of these animals (and the ecosystems in which they live) are subject to multiple, unconsidered stressors. For example, new threats such as pharmaceuticals and enduring threats such as nutrient pollution from agriculture are likely to be equally important pollutants to address in freshwater and soil systems, at least in the short term.

Concluding remarks and next steps

As this synthesis demonstrates, we do not yet have a comprehensive understanding of this complex and fast-moving area of research. We are currently missing a vast body of evidence on microplastics, and evidence gaps range from understanding the sources, fate and transport of microplastics in the environment, to rates of exposure and their impact on animal and human health and wider ecosystems under environmentally realistic conditions.

However, despite the evidence gaps, this synthesis has attempted to draw together the evidence that does exist on microplastics in freshwater and soil. It highlights the range of possible effects that microplastics and associated chemicals may have on animals at high concentrations. Laboratory studies have shown physical damage to small organisms as well as effects on behaviour and reproduction. We have also clearly articulated and presented the areas that require additional research so that funders, policymakers and scientists can pursue them.

Filling in the current evidence gaps, alongside a move towards a more circular economy and the development of new materials will be required if we are to avoid further polluting the environment with this pervasive, and potentially harmful substance.

Annex 1: Evidence gaps

As microplastics research is such a new and emerging field, many evidence gaps remain. Here we aim to highlight some of the most pressing.

Microplastics in soil

Whilst we included the existing evidence regarding the impact of microplastics on soil within this synthesis, this is a very new area and research in this space is limited.

Environmental monitoring of sources and fate

It is very difficult to find accurate estimates of the total amount of microplastics in the natural environment. There are two challenges. First, at a global scale, sources of microplastic are not well understood and there is very little monitoring on either the sources of microplastics or the pathways through which microplastics enter the environment. This is true both for intentional microplastics (such as industrial abrasives or microbeads) and for larger plastic items which then degrade into microplastics. Additionally, further understanding the mechanisms and kinetics of plastic degradation is important and little studied.

Secondly, the definition of plastic waste varies by country. Even when plastic is effectively 'disposed of' we do not know how much plastic waste from landfill eventually makes its way into the environment through erosion and runoff.

Once microplastics and larger plastics do enter the natural environment, it is very hard to monitor where they end up and their concentration, especially when these particles become too small to easily see with a microscope. It is likely that plastics move through the environment extensively, interacting with a range of different ecosystems and animals in the process, but these patterns are currently not well understood. The development of markers that trace plastics and microplastics through the environment, as well as identifying the source, would be extremely valuable.

Monitoring of exposure

Alongside sources and fate, there are also gaps in the monitoring of exposure. Many studies on the impact of microplastics are conducted in a laboratory environment, using acute short-term exposure at high concentrations. These studies are arguably not particularly environmentally realistic, as exposure to microplastics is more often likely to be chronic (longer term) and at low concentrations. Accurately understanding exposure is an important precursor to understanding the impacts of microplastics on animals. Longitudinal studies, which monitor species in their natural environment and record their exposure to and interactions with microplastics are required.

Further understanding the impact of the shape and texture of the microplastic

Microplastics become weathered in the natural environment, meaning that their surfaces are not uniformly smooth. However, many studies are based in the laboratory and use pristine microplastics or microbeads which have a smooth surface and often round shape. It is not known how surface texture affects (a) the release of chemicals, (b) the role of microplastics as a vector, (c) how likely they are to be ingested (ie different shapes may look more or less like food sources) and (d) their impact on an animal once ingested. From our synthesis, we saw evidence that microplastics of different shapes may have different effects (Box 1). For example, long and thin microplastics were ingested by goldfish whereas pellets and fragments were spat out[445]. Certain colours also seem to be more or less attractive to animals. Further consideration of the effects of texture, shape, size and colour is required in future research.

Population and ecosystem level effects

Despite a few examples[446], investigations on population level or wider ecosystem level effects of microplastics in freshwater and soils are almost entirely absent from the literature. The majority of research currently focuses on impacts on a single animal. However, if microplastics affect feeding and reproductive behaviour then it seems likely that they also have population level effects in terms of survival and fitness (Figure 13). If effects are seen at a population level for an entire species, it is also plausible that this may affect the functioning of the ecosystem more broadly. Identifying particularly vulnerable food-webs and then monitoring these in the natural environment should be a research priority, as well as further research into population level effects.

Effects of microplastic associated chemicals

There are a range of questions that would be worth exploring here. What additives (and in what concentrations) are present in different synthetic polymer products? How do additives behave (and leach) from plastics under different environmental conditions? What impacts can different additives cause to different receptor systems? How do individual toxicities interact? What are the critical exposures for each of these chemical additives?

Further to this, some have suggested that chemicals associated with microplastics may have a bigger effect on animals at critical stages of development due to their hormone related effects. Critical stages of development could include the embryonic phase or when changing form (such as from a tadpole to a frog). These types of effects have not been studied in detail and studies are required that look at the impact of these chemicals on the full life cycle of animals.

Microplastics as a vector for bacteria and pathogens

Chapter 3 of this synthesis looks at microplastics as a vector. Much of the research examines microplastics as a vector for chemicals, however microplastics can also act a vector for bacteria and pathogens – transporting these far beyond their usual range and potentially increasing the likelihood they are ingested. Little is known about these mechanisms including how easily bacteria and pathogens bind to microplastics and how far microplastics may transport bacteria and pathogens. We also lack understanding of the relative importance of microplastics compared to other vectors; both in promoting the ingestion of bacteria and pathogens, and transporting bacteria and pathogens through the environment.

Microplastics as part of contaminant mixtures

Much of the research that we have summarised either focuses on the impact of microplastics themselves or the impact of the chemicals associated with microplastics. An evidence gap exists relating to the role of microplastics as part of contaminant mixtures. Within an aquatic environment, an animal is rarely exposed to just one contaminant at a time. There is a mixture of different microplastics, chemicals, pathogens, metals and other pollutants and the animal has to respond effectively to a range of these. The elements within these complex mixtures may interact with one another and the effect of these mixtures on feeding behaviour, reproductive behaviour and physical health has not been investigated.

We also do not know how much microplastics contribute to the negative effects observed relative to other non-digestible suspended organic matter and debris. Understanding the relative risk that microplastics poses, is also a current evidence gap.

Nanoplastics

If research relating to microplastics is in its infancy, then nanoplastics research is embryonic. Here we have summarised the available literature, but there are still major challenges with understanding the impact of nanoplastics on animal health – including humans. In addition, hardly any information is available on measurement methods or sources.

Due to their small size, it is almost impossible to measure and record the sources, fate and impact of microplastics; both in the environment and once inside an animal[447] (especially one as comparatively large as a human). The development of new measurement methods and techniques is required. Many mechanistic questions remain: what shape and size do plastics have to be, in order to be mistaken for food by different animals? How small do microplastics have to be before they are transported inside animals, or cross the blood brain barrier? There is also a poor understanding of how microplastics break down into nanoplastics.

As we have described in Box 2, there also remains a major gap in studies looking at particles between the micro and nano size range criteria.

Annex 2: Acknowledgements

Lead Fellows	
Professor Keith Beven FRS	Professor, Emeritus, Lancaster University
Professor Charles Godfray FRS	Professor of Population Biology and Director, Oxford Martin School, University of Oxford.
Professor John Skehel FRS	Vice President and Biological Secretary, The Royal Society

Expert Review Group	
Professor Alistair Boxall	Professor of Environmental Science, University of York
Dr Rachel Hurley	Postdoctoral Researcher, Norwegian Institute for Water Research
Professor Stefan Krause	Professor of Ecohydrology and Biogeochemistry, University of Birmingham
Dr Luca Nizzetto	Senior Research Scientist, Norwegian Institute for Water Research
Professor Richard Thompson OBE	Professor of Biological and Marine Sciences, University of Plymouth

Royal Society Staff	
Edward Clarke	Project Coordinator
Anna Dickson	UKRI Intern (January – April 2019)
Dr Sarah Giles	Senior Policy Adviser
Timothy Rees Jones	Project Coordinator
Emma Woods	Head of Policy

Annex 3: Methodology

A1. Question setting

Initially, a wider topic of 'water quality' was identified following a mapping of priority policy areas in Summer 2018. We then conducted desk-based research and consulted with Royal Society Fellows, key policy stakeholders in the Department for Environment, Food & Rural Affairs (Defra) and other relevant groups including NGO's and industry. Microplastics in freshwater and soil emerged as a priority and the exact questions to be addressed in the synthesis were then further refined through additional conversations with key stakeholders.

A2. Literature review

To capture academic literature, the team commissioned an information specialist to perform searches of relevant databases using a search strategy devised in conjunction with the Royal Society team (see Section A7.).

Search terms were run on three different databases: Greenfile, CAB Abstracts, and Web of Science. The Greenfile search was run first to allow an assessment of the relevance of the results and minor tweaks to the search terms were made at this stage. Early returns were compared against the list of 64 papers derived from the key informant interviews to ensure the relevant literature was being captured. Once refined, the Greenfile search was then repeated and the same search conducted on the other databases. These searches were conducted in January 2019 (Greenfile 9 January, CAB Abstracts 27 January, Web of Science 29 January), incorporating papers published from 1990 until that time. The searches returned a total of 14,856 results, after removing duplicates.

Following the search, all articles were screened for inclusion based on reading their titles and abstracts. We decided to only include studies from 2009 to 2019, to reduce the volume to a manageable amount, and represent the most up to date work. The screening process was trialled on a small sample of articles by the whole team, and each study was then screened by only one member of the team. In cases where team members were uncertain on the inclusion of an article, these articles were highlighted for discussion and reviewed by 1 – 2 other team members. This screening process resulted in a shortlist of 172 studies. Where appropriate, further studies cited by the articles in this body of literature were then added to the shortlist and included.

The full text of all papers in this shortlist was reviewed and details entered into an extraction table capturing information on the following:

- Bibliographical information on the article
- Type of data used
- Habitat covered (freshwater, soil, marine, etc)
- Country or regional focus
- Definitions used of microplastics and nanoplastics
- Evidence of impacts on individual animals
- Evidence of interaction with chemicals
- Evidence of population level effects
- Evidence of impacts on humans
- Sources of micro and nanoplastics, and potential interventions
- Article quality

The extraction template was piloted for a subset of articles by the whole team, and extraction was then conducted in parallel, with each article reviewed in detail by one member of the team. Where appropriate, very relevant references from the articles reviewed in full-text form were added to the list of articles for review. Additional relevant literature was suggested during key informant interviews, focusing in particular on including grey literature and policy documents – these totalled 64 papers and were also reviewed.

A3. Key informant interviews

As part of the data collection we interviewed ten key experts in the field in a personal capacity (Table 1) to refine the exact focus of the evidence synthesis, and to develop a deeper understanding of the broader topic and understand the evidence for the impact of microplastics on animals. Interviews were conducted by telephone using a semi-structured approach. The protocol used is provided in Section A6. The interviews were conducted in parallel with the literature search. Interviewees were selected based on desk research and recommendations.

TABLE 1

Interviewee	Institution	Sector
Professor Alistair Boxall	University of York	Academia
Dr Matt Hill	Yorkshire Water	Industry
Professor Andrew Johnson	Centre for Ecology and Hydrology	Academia
Professor Lorraine Maltby	University of Sheffield	Academia
Dr Steven Morris	Defra water quality team	Government
Dr Luca Nizzetto	Norwegian Institute for Water Research	Academia
Dr Ninja Reineke	ChemTrust	NGO
Dr Julie Schneider	ChemTrust	NGO
Dr Roger Sweeting	South Cumbria Rivers Trust	NGO
Professor Richard Thompson	University of Plymouth	Academia

A4. Analysis

To analyse and combine the information, an internal staff workshop was held to review the preliminary findings and finalise a synthesis structure. Each section of the synthesis was assigned to a member of the team, who reviewed the extracted data from the studies and interviews related to that section and summarised key findings. These findings were then written up, with further reference back to the papers cited where necessary. The overall messages, focus and evidence gaps that constitute the discussion section were discussed with the team, and written up by a team member. Each section of the synthesis was reviewed by one or two other team members to ensure accuracy and completeness. The synthesis was subsequently sent out to expert reviewers:

- Professor Alistair Boxall, University of York
- Dr Rachel Hurley, Norwegian Institute for Water Research
- Professor Stefan Krause, University of Birmingham
- Dr Luca Nizzetto, Norwegian Institute for Water Research
- Professor Richard Thompson, University of Plymouth

A5. Limitations and caveats of the methodology

This study is subject to a number of important caveats and limitations, including the following:

1. The literature review was a rapid evidence assessment rather than a systematic review. This means we did not cover all possible literature. However, the review included a diverse set of carefully selected articles, informed by expert guidance, and therefore paints a wide-ranging picture of the state of play with respect to microplastics and nanoplastics in soil and freshwater and their impacts on animals and humans.
2. We have not been able to reflect the full complexity of the literature in this overview synthesis. The aim of this synthesis is to provide a concise, policy-relevant overview of the key issues and evidence. Inevitably, there are many details and nuances that could not be included given the scope and length of this study.
3. We conducted interviews with key experts in the field, from a range of academic, policy, industry and NGO perspectives. However, we only spoke to a sample of individuals working in the field; therefore, the information provided may not be representative of all researchers in the relevant fields, or the full range of work conducted (particularly in an international context).

4. The interviews were semi-structured, meaning that not all interviewees were asked identical questions. In addition, all the results from interviews are based on the knowledge and perceptions of the participants, and it is not possible to verify every piece of information provided. Additionally, the interviews were carried out by multiple interviewers; therefore, different styles and approaches will have been used. We tried to mitigate against this by developing standardised protocols for the interviews. All interviews were written up as comprehensive notes rather than a verbatim transcript, meaning that some information may have been lost. To minimise this risk, all interviews were conducted in pairs, with the notes verified by both interviewers once they had been written up.
5. Available evidence in some areas is thin, or subject to debate, which limits the extent of our analysis and the degree to which our findings can be concrete. We have attempted to reflect this uncertainty and the strength of the evidence. Evidence gaps are presented in Annex 1.
6. All papers within our review included the term microplastics or nanoplastics specifically. Therefore, papers relating to the impacts of microplastic related chemicals on humans or animals were not included unless microplastics were mentioned. The full search terms are presented in Section A7.

A6. Informant Interview protocol

The Royal Society is conducting an evidence synthesis on microplastics in freshwater and soil. The aim of the work is to collect evidence to support policymaking relating to water quality and land use.

The work will be conducted over a nine month period and the outcomes of the study will be made publicly available and disseminated among policymakers by the Royal Society.

As part of the project, we are conducting key informant interviews with experts on the topic to test our understanding, ensure we have identified key literature and also supplement our search with unpublished data or relevant sources beyond academic journal articles.

The project will be written up as an evidence synthesis which will be available on the Royal Society websites.

Do you have any questions about the project?

Any quotes included in the Royal Society's final synthesis will not be explicitly or directly attributed to you without your permission. Should we wish to use a quote which we believe that a reader would reasonably attribute to you or your organisation, a member of the Royal Society project team will contact you to inform you of the quote we wish to use and obtain your separate consent for doing so.

All records will be kept in line with the General Data Protection Regulation (GDPR) 2018. Further information about the Royal Society's data security practices can be provided upon request.

To keep all processes in line with the GDPR 2018, we would like to ask you to confirm a few data protection statements:

1. Do you agree that the interview can be transcribed by the Royal Society for the purpose of providing an accurate record of the interviews?
   Yes ☐ No ☐
2. Do you agree that the Royal Society can store this data securely on password-protected computers and its servers for the duration of the project?
   Yes ☐ No ☐
3. Do you agree to us recontacting you if we wish to use a quote which we believe that a reader would reasonably attribute to you or your organisation?
   Yes ☐ No ☐

Background

- Please could you briefly describe your main areas of focus and expertise.

Sources and risks

- To what extent are microplastics a cause for concern?
- Are you aware of any chemical-microplastic interactions that should be of concern to policy-makers?
  - Prompt: Are POPs a cause for concern
  - Prompt: Are Heavy Metals a cause for concen?
  - Prompt: Are Persistent, bioaccumulative and toxic substances (PBTs) a cause for concern?
  - Prompt: are there any further chemicals that should be a cause for concern?
- What are the key sources of these chemicals on rural land?
- What are the potential risks of microplastic-chemical interactions?
  - Prompt: what are the risks to ecosystems and biodiversity?
  - Prompt: what are the potential risks to soil health?
  - Prompt: what are the potential risks for polluted water?
  - Prompt: what are the risks to human health?
- Are there important sources or vectors of microplastics we are missing in the systems diagram provided?

Intervention

- What are the options for intervention to reduce the amount of microplastic in land management?
  - Might want to prompt: biosolid application
- What are the options for intervention to reduce the amount of chemicals that interact with microplastics in land management?

State of knowledge

- Do you know any key publications on this topic that we should definitely include?
  - Prompt: are there key publications within the grey literature eg from NGO's, policymakers or others that we should consider?
- What policy question do you believe is most pressing in this area?
- What are the main evidence gaps in this field?
- What are the areas of emerging knowledge in this field?
- Do you forsee any challenges or complexities with this topic that we should be aware of?

Any other comments

- Are there any key documents or reports that we should review?
  - Prompt: is there grey literature we should be aware of?
- Is there anybody you think would be particularly relevant for us to speak with?

A7. Search Terms

1. Greenfile (Ebsco) – Searched 9 January 2019

S15 S3 AND S7 AND S10 AND S14 1,526—Freshwater Results

S14 S11 OR S12 OR S13 111,591

S13 DE "WETLAND animals" OR DE "STREAM animals" OR DE "ESTUARINE animals" OR DE "EFFECT of pollution on animals" OR DE "ANIMAL populations" OR DE "RESERVOIR animals" OR DE "POND animals" OR DE "PASTURE animals" OR DE "GRASSLAND animals" OR DE "ANIMAL communities" OR DE "AQUATIC animals" OR DE "FRESHWATER organisms" OR DE "AQUATIC organisms" OR DE "FRESHWATER animals" OR DE "FRESHWATER bacteria" OR DE "MICROORGANISMS" OR DE "EFFECT of water pollution on aquatic organisms" OR DE "EFFECT of contaminated sediments on aquatic organisms" OR DE "AQUACULTURE industry" Limiters - Publication Date: 20080101-20191231

4,449

S12 TI(health or gastrointestinal or gastro-intestinal or intestin* or gut or absorb* or absorp* or adsorb* or adsorp* or sorption or desorb* or desorption or organism* or animal* or food*) or AB(health or gastrointestinal or gastro-intestinal or intestin* or gut or absorb* or absorp* or adsorb* or adsorp* or sorption or desorb* or desorption or organism* or animal* or food*) OR SU(health or gastrointestinal or gastro-intestinal or intestin* or gut or absorb* or absorp* or adsorb* or adsorp* or sorption or desorb* or desorption or organism* or animal* or food*) Limiters - Publication Date: 20080101-20191231 109,792

S11 DE "Health" OR DE "Environmental Health" OR DE "Health Risk Assessment" OR DE "Groundwater & Health" OR DE "Hazardous Substances & Health" OR DE "Hazardous Wastes" OR DE "Gastrointestinal system" OR DE "SHELLFISH contamination" OR DE "MEAT contamination" OR DE "FOOD contamination" OR DE "CONTAMINATION of drinking water" OR DE "OYSTER contamination" OR DE "DAIRY product contamination" OR DE "CONTAMINATION of edible fish" OR DE "FOOD of animal origin — Contamination" OR DE "MICROBIAL contamination" OR DE "SEAFOOD contamination" Limiters - Publication Date: 20080101-20191231

9,796

S10 S8 OR S9 355,757

S9 DE "POLLUTION measurement" OR DE "POLLUTION experiments" OR DE "TOXICOLOGY of water pollution" OR DE "SOIL pollution testing" OR DE "SOIL pollution prevention" OR DE "SOIL pollution monitoring" OR DE "SOIL pollution" OR DE "RISK assessment of water pollution" OR DE "POLLUTION risk assessment" OR DE "WATER pollution testing" OR DE "WATER pollution remote sensing" OR DE "WATER pollution remediation" OR DE "WATER pollution prevention" OR DE "WATER pollution potential" OR DE "WATER pollution point source identification" OR DE "WATER pollution monitoring" OR DE "WATER pollution measurement" OR DE "WATER

pollution experiments" OR DE "WATER pollution — Mathematical models" OR DE "POLLUTION" OR DE "WATER pollution" OR DE "EFFECT of water pollution on fishes" OR DE "AGRICULTURAL pollution" OR DE "GROUNDWATER pollution" OR DE "EFFECT of pollution on animals" OR DE "POLLUTION prevention"
42,560

S8 TI (pollut* or contaminat* or contaminant* or ecolog* or ecosystem* or habitat* or environment* or biodiversity or species or genus or genera or degrad* or leach* or toxic* or chemical* or chemistry or waste*) OR AB (pollut* or contaminat* or contaminant* or ecolog* or ecosystem* or habitat* or environment* or biodiversity or species or genus or genera or degrad* or leach* or toxic* or chemical* or chemistry or waste*) OR SU (pollut* or contaminat* or contaminant* or ecolog* or ecosystem* or habitat* or environment* or biodiversity or species or genus or genera or degrad* or leach* or toxic* or chemical* or chemistry or waste*) Limiters - Publication Date: 20080101-20191231
332,728

S7 S4 OR S5 OR S6 188,341

S6 (DE "SOIL absorption & adsorption" OR DE "SOIL biodiversity" OR DE "SOIL chemistry" OR DE "SOIL conservation" OR DE "AERIAL photography in soil conservation" OR DE "PLANTS for soil conservation" OR DE "SOIL conservation projects" OR DE "SOIL conservation research" OR DE "SOIL conservation services (Government)" OR DE "WATERSHED management" OR DE "SOIL conservation laws" OR DE "SOIL conservation projects" OR DE "SOIL conservation research" OR DE "SOIL degradation" OR DE "SOIL ecology" OR DE "SOIL management" OR DE "SOIL microbial ecology" OR DE "SOIL microbiology" OR DE "SOIL particles" OR DE "SOIL pollution" OR DE "SOIL pollution monitoring" OR DE "SOIL pollution prevention" OR DE "SOIL pollution testing" OR DE "SOIL protection" OR DE "SOIL quality" OR DE "SOIL remediation" OR DE "SOIL restoration" OR DE "SOIL-structure interaction" OR DE "SOILS" OR DE "AGRICULTURE & the environment" OR DE "AGRICULTURAL wastes & the environment" OR DE "AGRICULTURAL wastes" OR DE "AGRICULTURAL pollution" OR DE "WETLAND agriculture" OR DE "WATER in agriculture & the environment" OR DE "PLASTICS in agriculture" OR DE "IRRIGATION farming" OR DE "FLOODPLAIN agriculture" OR DE "AGRICULTURAL water-supply" OR DE "FARM management & the environment" OR DE "FARM ponds" OR DE "DOMESTIC animals" OR DE "PASTURE animals" OR DE "GRASSLAND animals" OR DE "FISH farming" DE "MARICULTURE" OR DE "AQUACULTURE industry") OR TI(soil OR earth OR terrestrial OR loam OR sod OR sediment OR sediments OR ground OR silt OR subsoil OR loam OR dirt OR clay OR turf OR topsoil* OR mould OR humus OR "organic matter" OR marl OR dust OR agricultur* OR farm*) OR AB(soil OR earth OR terrestrial OR loam OR sod OR sediment OR sediments OR ground OR silt OR subsoil OR loam OR dirt OR clay OR turf OR topsoil* OR mould OR humus OR "organic matter" OR marl OR dust OR agricultur* OR farm*) OR SU(soil OR earth OR terrestrial OR loam OR sod OR sediment OR sediments OR ground OR silt OR subsoil OR loam OR dirt OR clay OR turf OR topsoil* OR mould OR humus OR marl OR "organic matter" OR dust OR agricultur* OR farm*) Limiters - Publication Date: 20080101-20191231

113,365

S5 DE “FRESH water” OR DE “WATER pollution” OR DE “GROUNDWATER disposal in rivers, lakes, etc.” OR DE “RIVER pollution” OR DE “SEWAGE disposal in rivers, lakes, etc.” OR DE “WASTE disposal in rivers, lakes, etc.” OR DE “WATER pollution monitoring” OR DE “WATER pollution remediation” OR DE “WATER quality” OR DE “LAND-water ecotones” Limiters - Publication Date: 20080101-20191231 12,230

S4 TI(Freshwater* or “fresh water” or lake or lakes or river* or water* or groundwater or “ground water” or wastewater or “waste water” or bog or peatland* or heathland* or wetland* or tributar* OR estuar* or pond*) OR AB(Freshwater* or “fresh water” or lake or lakes or river* or water* or groundwater or “ground water” or wastewater or “waste water” or bog or peatland* or heathland* or wetland* or tributar* OR estuar* or pond*) or SU(Freshwater* or “fresh water” or lake or lakes or river* or water* or groundwater or “ground water” or wastewater or “waste water” or bog or peatland* or heathland* or wetland* or tributar* OR estuar* or pond*) Limiters - Publication Date: 20080101-20191231 119,331

S3 S1 OR S2 13,404

S2 (DE “PLASTICS” OR DE “BIODEGRADABLE plastics” OR DE “THERMOPLASTICS” OR DE “PLASTICS & the environment” OR DE “PLASTIC scrap & the environment”) Limiters - Publication Date: 20080101-20191231

1,290

S1 TI((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or “polyvinyl chloride” or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or “polylactic acid” or styrofoam or styrene or “acrylonitrile butadiene” or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or “plastic surgery” or “plastic scintillation” or “plastic scintillator” or “plastic scintillating” or metallurg* or “grain boundaries”)) OR AB(plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or “polyvinyl chloride” or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or “polylactic acid” or styrofoam or styrene or “acrylonitrile butadiene” or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or “plastic surgery” or “plastic scintillation” or “plastic scintillator” or “plastic scintillating” or metallurg* or “grain boundaries”)) OR SU((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or “polyvinyl chloride” or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or “polylactic acid” or styrofoam or styrene or “acrylonitrile butadiene” or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or “plastic surgery” or “plastic scintillation” or “plastic scintillator” or “plastic scintillating” or metallurg* or “grain boundaries”)) Limiters - Publication Date: 20080101-20191231
13,365

2. CAB Abstracts (Ovid) <1990 to 2019 Week 03> Searched 27th January 2019

1. ((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or "polyvinyl chloride" or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or "polylactic acid" or styrofoam or styrene or "acrylonitrile butadiene" or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or "plastic surgery" or "plastic scintillation" or "plastic scintillator" or "plastic scintillating" or metallurg* or "grain boundaries")).ti,ab. (84869)
2. plastics/ or biodegradable plastics/ or waste plastic/ or glassfibre reinforced plastics/ or laminated plastics/ or thermoplastics/ or vinyl plastics/ or plastic cladding/ or plastic film/ or plastic nets/ or plastic panels/ or "poly(vinyl acetate)"/ or "poly(vinyl chloride)"/ or polyesters/ or polyethylene/ or polymers/ or polypropylenes/ or polystyrenes/ or polyurethanes/ (30845)
3. or/1-2 (99226)
4. (freshwater* or "fresh water" or lake or lakes or river* or water* or groundwater or "ground water" or wastewater or "waste water" or bog or peatland* or heathland* or wetland* or tributar* or estuar* or pond*).ti,ab. (1079617)
5. water/ or drainage water/ or drinking water/ or fresh water/ or freshwater ecology/ or groundwater/ or ice/ or irrigation water/ or meltwater/ or river water/ or runoff water/ or soil water/ or surface water/ or tap water/ or thermal spring water/ or wastewater/ or wastewater aquaculture/ or wastewater treatment/ or open water/ or reservoirs/ or water content/ or water intake/ or water quality/ or water resources/ or water reuse/ or water supply/ or water systems/ or water table/ or water uptake/ or "water use"/ or water treatment/ or waste disposal/ or waste treatment/ or sewage/ or sewage effluent disposal/ or sewage treatment/ (486095)
6. or/4-5 (1156760)
7. (soil or earth or terrestrial or loam or sod or sediment or sediments or ground or silt or subsoil or loam or dirt or clay or turf or topsoil* or mould or humus or "organic matter" or marl or dust or agricultur* or farm*).ti,ab. (1426747)
8. soil/ or soil analysis/ or soil biology/ or soil chemistry/ or soil conservation/ or soil degradation/ or soil pollution/ or soil surveys/ or soil testing/ or soil toxicity/ or soil bacteria/ or agriculture/ or agricultural land/ or arable land/ or animal husbandry/ or crop production/ or farming/ or farming systems/ or farms/ or food production/ or pastures/ or plantations/ or agricultural wastes/ or dairy wastes/ or animal wastes/ or crop residues/ (425214)
9. or/7-8 (1515849)
10. 6 or 9 (2232183)
11. (pollut* or contaminat* or contaminant* or ecolog* or ecosystem* or habitat* or environment* or biodiversity or species or genus or genera or degrad* or leach* or toxic* or chemical* or chemistry or waste*).ti,ab. (2484197)
12. pollution/ or soil pollution/ or water pollution/ or polluted water/ or contamination/ or effluents/ or environmental impact/ or pollutants/ or polluted soils/ or toxic substances/ or ecological disturbance/ or biodiversity/ or biodegradation/ or biodeterioration/ or soil toxicity/ (432703)
13. or/11-12 (2541091)

14. (health or gastrointestinal or gastro-intestinal or intestin* or gut or absorb* or absorp* or adsorb* or adsorp* or sorption or desorb* or desorption or organism* or animal* or food*).ti,ab. (1571791)

15. health/ or animal health/ or environmental health/ or public health/ or reproductive health/ or health hazards/ or health impact assessment/ or digestive tract/ or digestive system/ or digestive absorption/ or intestinal absorption/ or aquatic organisms/ or aquatic invertebrates/ or food contamination/ or food chains/ or food/ (607091)

16. or/14-15 (1859059)

17. 3 and 10 and 13 and 16 (9103)

18. limit 17 to (english language and yr="2008 -Current") (6287)—Freshwater Results

3. Web of Science (Science Citation Index & Social Sciences Citation Index) – Searched 29 January 2019

11 6,193 - Freshwater

#10 AND #9 AND #8 AND #5
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

10 3,002,596
(TS=(health or gastrointestinal or gastro-intestinal or intestin* or gut or absorb* or absorp* or adsorb* or adsorp* or sorption or desorb* or desorption or organism* or animal* or food*)) AND LANGUAGE: (English)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

9 3,882,350
(TS=(pollut* or contaminat* or contaminant* or ecolog* or ecosystem* or habitat* or environment* or biodiversity or species or genus or genera or degrad* or leach* or toxic* or chemical* or chemistry or waste*)) AND LANGUAGE: (English)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

8 2,354,634

#7 OR #6
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

7 1,214,665
(TS=(soil or earth or terrestrial or loam or sod or sediment or sediments or ground or silt or subsoil or loam or dirt or clay or turf or topsoil* or mould or humus or "organic matter" or marl or dust or agricultur* or farm*)) AND LANGUAGE: (English)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

6 1,504,851
((TS=(freshwater* or "fresh water" or lake or lakes or river* or water* or groundwater or "ground water" or wastewater or "waste water" or bog or peatland* or heathland* or wetland* or tributar* or estuar* or pond*))) AND LANGUAGE: (English)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

55,310

#4 OR #2
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

4 39,172
(TS=((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or "polyvinyl chloride" or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or "polylactic acid" or styrofoam or styrene or "acrylonitrile butadiene" or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or "plastic surgery" or "plastic scintillation" or "plastic scintillator" or "plastic scintillating" or metallurg* or "grain boundaries"))) AND LANGUAGE: (English)

Refined by: WEB OF SCIENCE CATEGORIES: (MICROBIOLOGY OR AGRICULTURE DAIRY ANIMAL SCIENCE OR AGRICULTURE MULTIDISCIPLINARY OR MULTIDISCIPLINARY SCIENCES OR ENVIRONMENTAL SCIENCES OR BIOLOGY OR FISHERIES OR CELL BIOLOGY OR GASTROENTEROLOGY HEPATOLOGY OR GREEN SUSTAINABLE SCIENCE TECHNOLOGY OR HORTICULTURE OR MARINE FRESHWATER BIOLOGY OR ECOLOGY OR REPRODUCTIVE BIOLOGY OR TOXICOLOGY OR WATER RESOURCES OR ZOOLOGY)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

3 317,871
(TS=((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or “polyvinyl chloride” or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or “polylactic acid” or styrofoam or styrene or “acrylonitrile butadiene” or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or “plastic surgery” or “plastic scintillation” or “plastic scintillator” or “plastic scintillating” or metallurg* or “grain boundaries”))) AND LANGUAGE: (English)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

2 48,859
(TS=((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or “polyvinyl chloride” or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or “polylactic acid” or styrofoam or styrene or “acrylonitrile butadiene” or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or “plastic surgery” or “plastic scintillation” or “plastic scintillator” or “plastic scintillating” or metallurg* or “grain boundaries”))) AND LANGUAGE: (English)

Refined by: RESEARCH AREAS: (GASTROENTEROLOGY HEPATOLOGY OR NUTRITION DIETETICS OR MICROBIOLOGY OR ENVIRONMENTAL SCIENCES ECOLOGY OR BIOCHEMISTRY MOLECULAR BIOLOGY OR VETERINARY SCIENCES OR DEVELOPMENTAL BIOLOGY OR LIFE SCIENCES BIOMEDICINE OTHER TOPICS OR ZOOLOGY OR AGRICULTURE OR BIOTECHNOLOGY APPLIED MICROBIOLOGY OR TOXICOLOGY OR REPRODUCTIVE BIOLOGY OR WATER RESOURCES OR FISHERIES OR EVOLUTIONARY BIOLOGY OR CELL BIOLOGY OR MARINE FRESHWATER BIOLOGY)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

1 317,871
(TS=((plastic or plastics or plasticulture or macroplastic* or mesoplastic* or microplastic* or nanoplastic* or microfiber* or microfibre* or polyethylene or “polyvinyl chloride” or polypropylene or polystyrene or acrylic or polycarbonate or polylactide or “polylactic acid” or styrofoam or styrene or “acrylonitrile butadiene” or nylon or fibreglass or fiberglass or phthalate* or bisphenol*) not (fiber-optic or fibre-optic or fiberoptic or fibreoptic or prosthetic* or prosthesis or “plastic surgery” or “plastic scintillation” or “plastic scintillator” or “plastic scintillating” or metallurg* or “grain boundaries”))) AND LANGUAGE: (English)
Indexes=SCI-EXPANDED, SSCI
Timespan=2008-2019

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