Microplastics in the Environment

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ABSTRACT

Microplastics are small pieces of plastic debris less than 5 mm in diameter. They have accumulated in the environment as a consequence of: the direct release of small particles, such as those used in cosmetics; or as a consequence of wear, for example fibres released from textiles. The main source of microplastic is considered to be the fragmentation of larger items of plastics in the environment. Microplastics are widely distributed in freshwater and marine environments including remote locations such as the arctic and deep sea. A wide range of organisms are known to ingest microplastics and laboratory studies indicate the potential for harmful effects. Plastic debris can also transport co-contaminants including chemical additives and pollutants sorbed from sea water. These chemicals can be released to organisms upon ingestion, but there is little evidence that plastics provide an important pathway leading to toxicological effects in environmentally relevant scenarios. Removing microplastics from the environment is impractical and the most effective solutions are to minimise the release of plastics to the environment as litter. In this regard much could be achieved by actions to reduce the accumulation of larger items of litter such as packaging, which will eventually fragment into microplastics.

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1 Introduction

In order to understand the sources, consequences and accumulation of microplastics in the environment it is important to first set microplastics into context within the wider topic of marine litter and in particular plastic litter. Plastics are synthetic polymers that can be made into a vast range of inexpensive, lightweight and durable products that bring numerous societal benefits.[1] There are many variants, with the most common plastics including polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polystyrene (PS). The versatility of plastics has resulted in an exponential increase in global demand, from around 5 million tonnes in the 1950s to over 300 million tonnes today.[2]

Some applications of plastics have a long service life, such as PVC and PP components in vehicles or the construction industry. However, around 40% of all the plastic produced is used for packaging, which is predominantly single use.[2] These items are frequently made of highly durable polymers such as PE or PET.[3] As a consequence, end of life plastic items are now a major component of waste in managed systems and substantial quantities are accumulating as litter in the environment.[4] It is important to recognise that numerous types of material have been reported as litter but the vast majority is plastic; accounting for around 70% of the litter collected in beach clean ups, and the most abundant items are single-use plastic packaging, together with rope and netting.[5] Plastic litter has been identified as a major global problem by the United Nations Environment Assembly and in the G7 Leader's declaration 2015.[6,7]

Plastic debris has been reported across a wide range of sizes from discarded fishing nets that can be thousands of meters in length to microscopic fragments just microns in diameter. This chapter will focus on microplastic, which is widely defined as being pieces less than 5 mm in diameter.[8,9] Microplastics accumulate from primary and secondary sources. The distinction between the two is based on whether the particles were originally manufactured within the microplastic size range (primary) or whether they have resulted from the fragmentation of larger items (secondary).

While the term microplastic was first used to describe microscopic fragments of plastic in 2004[10] pieces in the currently defied microplastic size range have been reported since the 1970s and it is apparent that microplastics are a ubiquitous component of anthropogenic debris in marine and freshwater environments.[11–15] Microplastics greatly outnumber large plastic items in marine systems, but only account for a small proportion of the total mass of plastic in the ocean.[16,17] This means that even if we were able to stop the discharge of macroplastic litter into the sea today, on-going degradation of the larger litter items already at sea and on beaches would likely result in a sustained increase in microplastics for many years to come. Additionally, with an ever-increasing reliance on plastic products, their use and disposal will continue, which in the absence of improved waste management will further increase the accumulation of microplastic.[18,19]

Once in the marine environment, microplastic cannot be cost-effectively collected for recycling or successfully removed.[20] It also presents a range of negative economic and environmental consequences.[7]

This chapter will consider the definition of microplastics, and describe the sources, distribution patterns and subsequent impacts in the marine environment. We will also discuss potential solutions to reduce further accumulation of microplastics; focussing on product design, waste management, recyclability, education, policy and behaviour change.

2   Size Classifications of Plastic

Plastic debris can be defined and described in a variety of ways including by origin (*e.g.* from the land, fishing-related or sewage-related debris) size, shape, colour, polymer type or original usage. One of the commonly used classifications is according to size. Plastic can enter the aquatic environment in a wide range of sizes and have been reported from thousands of meters in length to microns in diameter.[21,22] Three categories are widely used to describe the size of plastic contamination; macroplastic (>20 mm diameter), mesoplastic (5–20 mm) and microplastic (<5 mm).[23,24] However, it is important to note that there are no universal conventions on nomenclature and this challenges inter-comparability of data.

The accumulation of macroplastic has been reported in a wide range of habitats.[15,25,26] Due to its high visibility, contamination of the environment by macroplastic may be perceived as one of the most concerning forms of plastic pollution. Clean-up campaigns typically focus on these larger items and there is wide geographical variability in abundance, which increases the difficulty of analysing potential trends. Items of macroplastic debris are often sufficiently recognisable to be categorised according to their original usage; for example, packaging, fishing or sewage related debris. Attributing sources of microplastics is more challenging.

While the upper boundary of microplastics is reasonably consistently taken to be particles less than 5 mm the lower boundary is often set by operational constraints. For example, in field studies it is the mesh size of nets used to sample surface water[27] or the sieves used in sampling beach sand[22] that primarily determine the lower-size limit of sampled microplastics. Particles as small as a few microns in diameter have been separated from an environmental matrix and identified as plastic using spectroscopy; it seems likely that even smaller nanoplastic particles also occur in the environment, but it is not currently feasible to separate and identify plastic particles of this size from complex environmental mixtures.[6,28]

3   Sources of Microplastics

Microplastics can result from the direct release of small particles (<5 mm in diameter). Such particles are described as primary microplastics, for example microbeads which are used in some cosmetics[29] (Figure 1a).
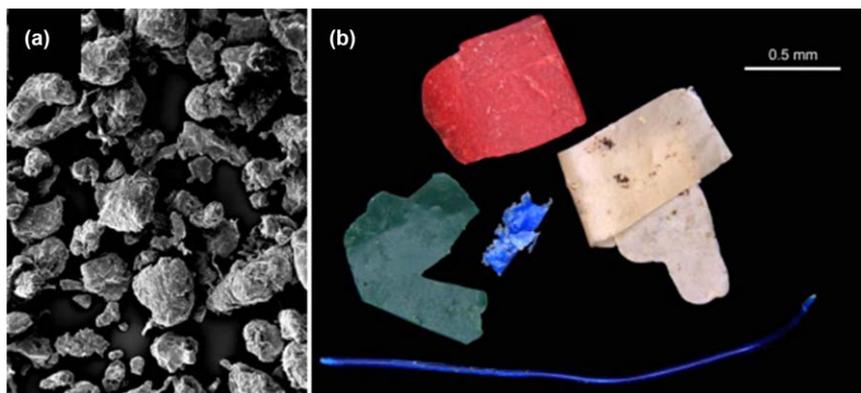
Figure 1   Pictures showing microplastics: (a) Polyethylene particles extracted from a cosmetic product. Source: Napper & Thompson, Plymouth University Electron Microscopy Suite. (b) Fragments of microplastic collected from a shoreline near to Plymouth, UK. Note: Scale bar applies to both pictures. Reproduced from ref. 32 under the terms of the Open Government Licence for Public Sector Information, http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

They can also be formed from the fragmentation of the larger plastic items once they have entered the environment and these are described as secondary microplastics (Figure 1b).

There are a wide range of potential sources and pathways that result in the accumulation of plastic in the marine environment. Much of the litter in aquatic environments enters as macroplastic from land-based actions such as general littering, dumping of waste and loss during waste collection, as well as that from inappropriately managed landfill sites.[30] Plastic waste is collected, and then contained in a waste management framework which is designed to help minimize loss to the environment. From these land-based sources, plastic litter then has the potential to end up in municipal wastewater and freshwater systems (*e.g.* from windblown litter escaping) which can then potentially move into the oceans from coastlines or rivers.[4,21,31] In industrialized countries, waste that is deposited in landfills is usually covered regularly with soil or a synthetic material, and the landfill is cordoned by a fence to prevent any debris accidentally leaving. However, in developing regions this is often not the case.[3,4]

It has been estimated that on a global scale, the input of plastic into the oceans from land based sources is in the region of 6.4 million tons per annum. Furthermore, assuming there are no improvements in waste management infrastructure, the cumulative quantity of plastic waste available to enter the marine environment from land could increase by approximately three times over the next decade.[4]

In addition, quantities of plastic are released from marine based sources such as shipping, aquaculture and commercial fishing.[20,32] Studies have indicated a significant relationship between the number of ocean-based

plastic items found on beaches and the level of commercial fishing activity.[33] Unintentional loss of in-service macroplastic products can also occur when catastrophic events, such as tsunamis,[34,35] hurricanes, or floods, carry large amounts of material of all kinds into the marine environment.[6,27,36]

The main source of microplastics in the environment is typically regarded as the fragmentation of these larger items of plastic debris; resulting in secondary microplastics.[18,21,37] This degradation occurs as a consequence of ultra-violet (UV) radiation and oxidation, which overtime can reduce the structural integrity of the plastic, resulting in fragmentation. This can be facilitated by physical forces from abrasion, wave-action and turbulence.[3,20] Depending on the chemistry of the polymer, bulk morphology and where it is exposed at, microplastics degrade at different rates in the marine environment.[38,39] However, fragmentation rates of plastic are largely unknown, and as a result little quantitative information is available on the relative contribution of secondary microplastics overall.[18,40] Given the large amount of macroplastics entering the environment, it is generally assumed that most microplastics have arisen from the fragmentation of larger items, continuously becoming smaller and smaller.[37]

Secondary microplastic can also be generated as a consequence of items such as tyres and textiles becoming abraded during life in service. Subsequently, it is clear that substantial quantities of fibres have accumulated in the environment.[41–43] For example; the washing of clothes made from synthetic materials is a direct secondary microplastic source. These microplastic fibres are released from a garment during a washing cycle and then can enter the environment *via* wastewater. Some fabrics release fibres more readily than others; research by Napper and Thompson reported that a wash load of 6 kg of acrylic clothing could release over 700 000 fibers.[47]

Primary microplastics enter the marine environment in a variety of different ways as particles that are already within the microplastic size range. These particles are produced through extrusion or grinding, either as a feed stock for manufacture of larger products or for direct use,[3] for example in cleaning products,[21] cosmetics (Figure 1a)[29,44] and as air-blasting media.[3] Compared to secondary microplastics, production volumes can be used to provide estimates of potential inputs to the environment. Some uses, such as in cosmetic products, are now beginning to be regulated.[29,45]

Plastic microbeads from facial scrubs are an example of primary microplastics used in cosmetics. After their intended use, these microbeads are likely to enter household wastewater and some will escape the waste water treatment system into the environment.[11,46] It has been estimated that 94 500 microbeads could be released from an defoliant in a single use, and this was estimated to translate to the UK alone releasing 16–86 tonnes per year.[47] Other potentially important sources are from microplastic used in medicines, drilling fluids for oil/gas exploration and in industrial abrasives (*i.e.* for air-blasting to remove paint from metal surfaces).[3,30,48]

While there has been much focus on the marine environment, a wide range of freshwater habitats are also contaminated with plastic, and rivers

provide major pathways for plastics to the ocean.[6,15,41] Microplastics have been detected at very high levels globally in rivers and lakes.[49] Rivers can transport considerable quantities of plastic (micro–macro size) to the oceans and some of this debris can travel from locations far inland. The concentrations in various parts of a river reflect different sources such as waste water treatment plants, tributaries and weirs.[50–52] Substantial quantities of plastic including microbeads from cosmetics, sanitary related items and other particles can be carried to rivers or directly to the oceans with waste water.

For any plastic that enters waste water treatment, the efficiency of capture (*i.e.*, before the effluent is discharged into the environment) depends on the particular treatment process. There is limited information on the efficiency of waste water treatment plants to capture plastic; particularly microplastics. However, some studies indicate extremely high capture rates (>95%) of plastic particles.[53] Given the large volume of influent daily, even low loss rates could result in detectable concentrations of these plastic particles in the environment.[11,13] Murphy *et al.* predicted that waste water treatment plants could release 65 million microplastic particles every day.[53] In the event of sewage overflow, wastewater and any plastic debris therein can also bypass treatment and be released directly to the environment. Even if microplastic is intercepted during wastewater treatment the resultant sewage sludge is often returned to the land as a fertilizer, hence plastic is still released into the environment. Most sources of microplastic are extremely difficult to trace back to their original source. For plastic pieces larger than around 20 µm, it is possible to identify what type of plastic polymer a particular piece of debris is made out of. For larger items of plastic debris it is often easier to identify the origin; such as fishing gear and sewage-related debris.[5]

Trends of production, consumer-use and demographics all point to a further increase in the use of plastic in the future.[49,54] Hence, there are considerable concerns that the problems of plastic pollution will escalate unless disposal practices change. Despite difficulties in identifying specific sources of microplastic sized fragments, overall the sources of marine plastic litter are mostly well known; however, there is a lack of knowledge concerning the relative importance of the different sources. Furthermore, due to the wide variety of sources and pathways, estimations for the amount of plastic in the environment are difficult to obtain and will require direct measurement of the input rates of plastic waste by wind, tidal and ocean wave transport. They will also require consistent protocols for replicable measurement of measurement of waste generation, collection rates, classification and waste disposal methods for rural areas and urban centres in countries around the world.[54,55]

4 Distribution and Abundance

Plastic debris is found in many different sizes and can accumulate in the oceans,[10] estuaries[11,17] and even in remote locations such as in arctic ice.[56]

Within these environments, microplastic has been reported at the sea surface[16] suspended in the water column[57] and in sediments, including those in the deep sea.[42,58] Plastic has also been reported in freshwater environments although there are fewer studies than in the marine environment.[13,15,51]

The concentration of microplastics recorded is directly influenced by the sampling method used, which can vary significantly between studies. A study modelling mismanaged plastic waste discharged from the land estimated annual inputs to the ocean of 4.8–12.7 million tonnes of macro-plastic items globally (10 000–27 000 tonnes in the UK).[4] An alternative approach used empirical counts of litter at sea to describe the abundance of specific types of litter, in particular environmental compartments. For example, based on data collected from net tows, Cozar *et al.* estimated there were 7000–35 000 tonnes of small (approximately 25 mm or less) debris at the sea surface,[16] while van Sebille *et al.* estimate that there was 93 000–236 000 tonnes, equivalent to 15–51 trillion small particles,[59] and Eriksen *et al.* estimated there was 270 000 metric tonnes of floating plastic in the oceans.[61] However, these estimates exclude microplastics that can pass through the plankton nets used to gather the data (Eriksen *et al.*[61]). Hence discrepancies between figures can arise from differences in the method of estimation. Different sampling matrices such as sediment or water column use different techniques and express the results in various units making inter-comparison difficult.[22] A further approach is to estimate inputs of specific categories of litter. For example, based on daily UK usage, it was estimated that a specific type of product, facial scrubs, could lead to release of 86 tonnes of microbeads to the environment per annum.[29]

There are considerable challenges in extrapolating from the very limited empirical data available to make predictions even about current patterns of spatial and temporal distribution of plastic litter and likely trends. Some of the best estimates available have uncertainty levels of over 100 fold.[59] There is also a lack of temporal data on which to base future projections. Hence, making reliable long-term future predictions is not feasible. However, assuming business as usual, Jambeck *et al.* predict a three-fold increase in the amount of plastics in the ocean between 2015 and 2025.[4]

Given the practical limitations in sampling such a diverse form of contamination, it may therefore be beneficial to link monitoring either to categories of litter where there is clear evidence of harm, or to assessing the efficacy of specific interventions. This could include monitoring the abundance of plastic items that have been the focus of specific policies re-ductions, for example the quantity of plastic bags found in the environment as a consequence of the single-use bag tax or reductions in the abundance of plastic microbeads in sewage as a consequence of legislative measures to reduce the quantity of microbeads used in cosmetics. Widespread quantification of all microplastics, while important to our understanding of encounter rates and possible harm, is likely to provide a relatively blunt tool for monitoring change. Whatever approach is used it is essential to be

explicit about the limitations of the given sampling strategy and the associated limitations of any extrapolations made in subsequent modelling studies.

Despite current uncertainties in estimating levels of contamination, it is clear that plastics have only been mass produced since the 1950s and therefore current levels of contamination reflect fairly rapid accumulation rates over just a few decades. The scale of the problem ahead is illustrated when one considers that on a global scale a similar quantity of plastics are likely to be produced in the next eight years as were produced in the whole of the 20th century, with estimates updated to the present day.[23] At the same time, it is important to recognise that the accumulation of plastics in the ocean is largely avoidable. By comparison with many other current environmental challenges, the benefits resulting from the use of plastics are not *directly* linked to the emission of plastic debris to the environment or to degradation of the environment. Hence, in theory at least, it is possible for society to retain the benefits of plastic products and at the same time reduce the quantity of plastic litter entering the environment.[19] Identification of the sources is important to gain an accurate assessment of the quantities of plastics and microplastics entering the ocean, to provide an indication of regional or local 'hot spots' of occurrence, and to determine the feasibility of introducing management measures to reduce these inputs.[37]

Estimating the distribution of microplastic based on secondary inputs is particularly difficult as it relies on accurate assessment of the distribution of macroplastics and the degradation process (which is also not well known). There is a lack of data comparing the abundance of macroplastics and microplastics at local scales. However, it is unlikely that the abundance of microplastic and macroplastics will be closely correlated as large and small objects will be influenced by environmental processes to differing degrees. For example, larger floating objects will be more prone to transport by winds than microplastics[17,60] and this is reflected in circulation models used to simulate the transport of micro- and macro-debris.[59,61]

Attention is currently being directed within the EU[24] to comparing and harmonising monitoring protocols, including those used for microplastics, to allow greater inter-comparability among data, and this topic has recently been the focus of a workshop hosted by the Ministry of the Environment in Japan as part of G7. Harmonisation of monitoring will be a key step towards increasing the accuracy and inter-comparability of spatial and temporal estimates of plastic debris. However, it is important to acknowledge the heterogeneity of plastic litter and recognise there is no current method to assess the total microplastic burden within a sample, and hence the data obtained provide an index of the quantity of microplastic rather than an absolute value. There have been some recent advances that aid plastic separation *via* oxidation of natural organic material, visualisation by staining and automation of polymer identification.[62–65]

Plastic debris has the potential to become widely dispersed and this will be influenced by the nature and location of the point of entry, as well as the

subsequent complex interactions of physical, chemical and biological processes (*e.g.* wind and currents).[26,60,66–68] At the surface of water, smaller pieces of plastic present lower rise velocities, they are less susceptible to transport by windage and are more susceptible to vertical transport.[60] Some polymers such as PVC, and PET, are denser than water and are more likely to sink, while PE, PP and PS are more likely to float. However, like any other surface immersed in water, plastic debris rapidly accumulates fouling from micro-organisms as well as sediment particles. Over time this increases their apparent density causing even some of the less dense polymers to sink.[69,70] Hence, the sea bed could be the most likely long-term place for the accumulation of plastic debris. Some of the limited data available on accumulation in the deep sea supports this hypothesis, but more work is needed to reach firm conclusions.[42,71,72] In addition, for transport *via* water bodies there is growing evidence of the importance of aeolian transport which may be particularly relevant for very small particles such as microplastics escaping from uncovered landfills,[30,41,73] or the dispersal of particles formed by wear in service, such as textile and tyre wear.[47]

5   Impacts

There is a reasonably extensive evidence base relating to the harm caused by marine litter. This can have a range of negative impacts on maritime industries, commercial fisheries, and infrastructure. It has also been found to affect a wide range of marine organisms as a consequence of entanglement and ingestion;[48,74,75] for example, over 700 species of marine organisms have been reported to encounter marine debris, the majority of these encounters are with plastic debris and around 10% of reports are for encounters with microplastics.[74] Impacts within the environment caused by plastic vary according to the type and size of the debris, and can occur at different levels of biological organization in a wide range of habitats.[76] The impacts of meso- or macroplastics have been reviewed for numerous marine species; particularly mammals, birds and turtles.[48,74,75,77] Encounters between organisms and macroplastic litter can negatively affect individuals, and a substantial proportion of some populations; for example, over 40% of sperm whales beached on North Sea coasts had marine litter including, ropes, foils and packaging material found in their gastro-intestinal tract,[78] while over 95% of the population of northern fulmars (*Fulmar glacialis*) may contain plastic litter in some European waters.[79] Even though the data on impacts form macroitems of plastic debris is relatively extensive, scaling up evidence from the impact on individuals to population-level consequences is challenging, as it is almost impossible to isolate the effects of plastic debris. For example, most species of marine turtles are red-listed by the International Union for Conservation of Nature as being (critically) endangered and frequent ingestion of macroplastics undoubtedly contributes to population decline; however, its level of contribution, as well as that of the other factors, cannot be isolated.[7]

The impact of meso- or macroplastic is more prominent by eye, therefore it is often subject to extensive scientific research and media coverage. The effects of microplastics has received less attention but is increasingly being reported and the have a variety of implications within the marine environment (Figure 2).[18,21,38,80]

Although the weight fraction of microplastics in plastic litter is relatively small, they are able to interact with a very wide variety of marine organisms, ranging from zooplankton to marine mammals.[74,81,82] There are also concerns about the potential for microplastics to transport non-native species or to act as vectors for potentially harmful chemicals in the environment.[69,83,84]

The potential for the ingestion of plastic debris is greater with pieces in the microplastic size range. Microplastics occupy the same size fraction as sediments and some planktonic organisms, they are therefore bioavailable to a wide range of organisms; including whales, fish, mussels, oysters, shrimps, copepods and lugworms.[43,74,75,81,82] For example, a study in South West England showed that of 504 fish, from 10 species, over one-third had microplastics in their digestive tract.[43] Ingestion can also depend on properties other than size including shape, density and colour. For instance, low-density (*i.e.* buoyant) microplastics are potentially more likely to be ingested by pelagic feeders and high-density microplastics by benthic feeders. As size, colour, density and shape is likely to influence whether microplastic are ingested,[85–88] it is difficult to make generic predictions about the subsequent risks of marine biota ingesting microplastics.

Organisms at lower trophic levels have been reported to ingest and accumulate microplastic particles,[10,80,89] which can then transfer between trophic levels in the food-web.[90] Additionally, with very small particles, including those in the nano-size range, there is the potential for uptake across the cell membrane, but little is known about any associated impacts.[6,28]

Floating plastics can also transfer organisms between locations. For macroplastic debris this includes the transport of species of invertebrates,[91] while microplastics have been implicated in the transfer of microorganisms.[92] For example, microplastics collected in the surface waters of the North Atlantic were colonized by a variety of organisms including bacteria, cyanobacteria, diatoms, ciliates and radiolaria.[69] As plastics have been reported to travel over long distances, they may contribute to the dispersal of non-native species.[93] However, the relative importance of plastics compared to other vectors, including natural floating debris such as logs, and transport *via* shipping, has yet to be established.

From a human health perspective, there is concern that plastic debris can support diverse microbial communities that are distinct from those found in seawater or on other floating objects. Hence the colonization, survival and transport of pathogens on polymers presents a potential risk to human health, but further investigation is needed to establish the importance of this.[92,94]

Microplastic ingestion could induce subtle effects on behaviour and ecological interactions such as the ability to escape from predators or migrate.
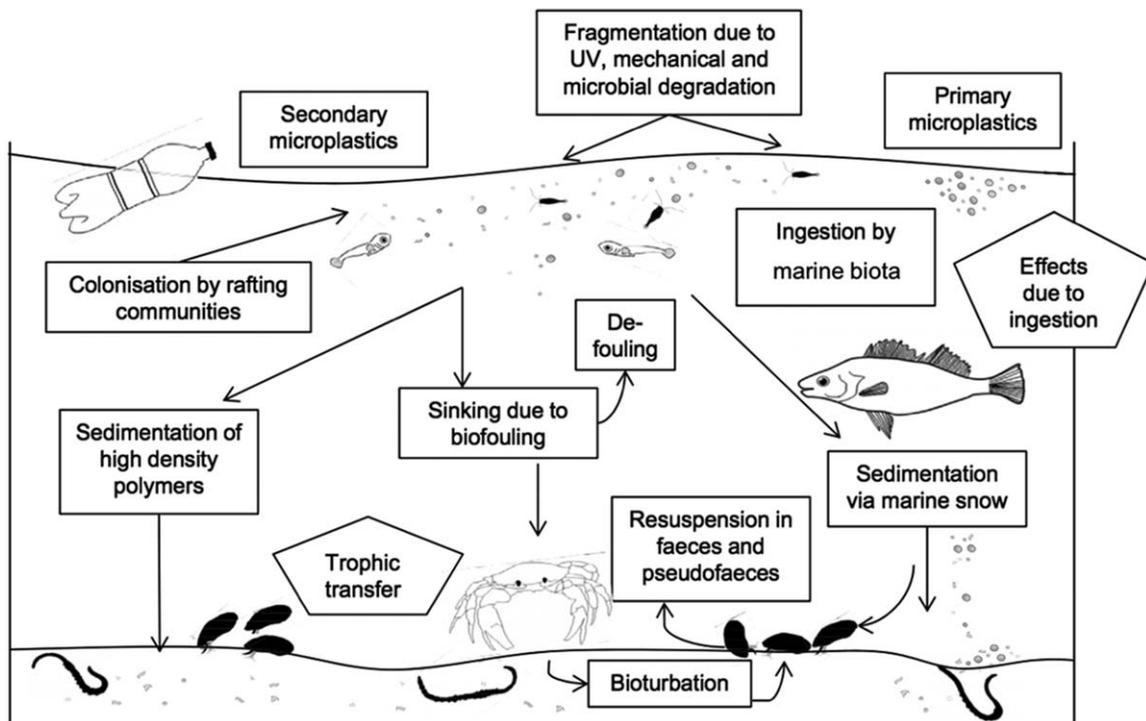
Figure 2 Potential pathways for the transport of microplastics and biological interactions. Adapted from ref. 80 with permission from Elsevier, Copyright 2013.

Fish and invertebrates are known to ingest microplastic, leading to physical effects that include physiological stress responses.[83,95,96] Other experiments have also shown that ingestion can compromise the ability of planktonic organisms to feed[81] and the ability of marine worms[96] and fish[97] to gain energy from their food.

Manipulative experiments have been used to examine the effects of microplastics and there is evidence of impacts, including effects on reproductive output, which could have associated population-level consequences.[98] However, many of the laboratory studies demonstrating effects from microplastics have used concentrations higher than those currently found in the environment.[99] While these experiments inform our understanding of thresholds in relation to future levels of contamination, they do not provide clear evidence of current environmental consequences.

Microplastics could also cause consequences at higher levels of biological organisation, including assemblages of organisms and the ecosystem services they provide. Teasing out such effects is challenging, but localised field experiments using macroplastics indicate even a single plastic carrier bag causes smothering which can alter the relative abundance of sediment-dwelling organisms as well as the ecosystem services that they provide.[100] Recent experiments in microcosms also point to the potential for assemblage-level effects of contamination with microplastics.[101,102]

There are also concerns about the potential for plastics, and in particular microplastics, to facilitate the transfer of potentially harmful chemicals to organisms. Microplastics have a larger surface area to volume ratio than macroplastics and are therefore more susceptible to contamination by co-contaminants such as persistent organic pollutants (POPs) and to some extent, metals.[103] Hydrophobic organic pollutants readily sorb onto plastics, and can accumulate at concentrations several orders of magnitude higher than in seawater.[104,105] Additive chemicals are also incorporated into plastic products at the time of manufacture. These chemicals are intentionally added during the manufacture or processing; for example, to enhance the plastics durability and corrosion resistance or act as stabilizers, plasticizers or flame retardants. Some additives, such as plasticizers, are used at high concentrations (10–50%) to ensure the functionality of the product.[106]

Therefore, there are concerns about the potential for microplastics to facilitate the transfer of chemicals to marine life directly as a consequence of ingestion or indirectly *via* release to waterbodies.[105,107] For chemicals that have sorbed to plastics from water the rate of release from the plastic is considerably enhanced in the presence of gut surfactant chemicals and increases further with temperature; such that the rate of release would be greater in a warm rather than a cold blooded organism[107] (Figure 3). Chemical uptake into tissues is determined by equilibria, and modelling estimates indicate that the sorbtion of chemicals to plastic is unlikely to offer a substantial additional pathway in the transfer of chemicals from water to biota.[108,109] One recent study modelled the potential for transfer of
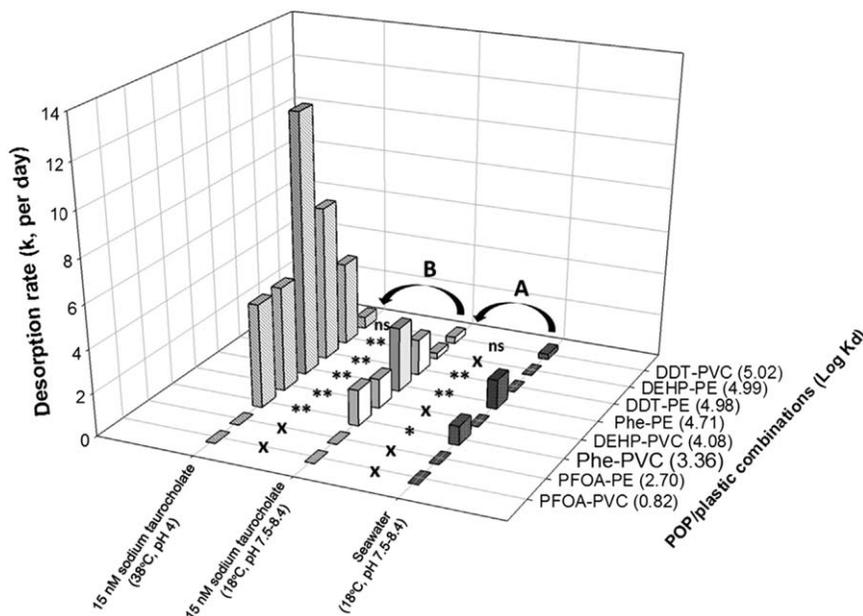
Figure 3   3D-plot of the distribution coefficients values for all plastic-POP combinations against desorption rates in seawater at 18 °C, 15 mM sodium taurocholate at seawater pH at 18 °C and in 15 mM sodium taurocholate at pH 4 at 38 °C. Arrows show, A: Effect of gut surfactant on desorption rates for a cold blooded organisms ranging from 1.2–7.3; B: effect of pH and temperature simulating a warm blooded organism with an increase in desorption rates ranging from 2.1 to 31.3, $*p < 0.05$, $**p < 0.01$, ns: not significant, those left blank: below limit of detection/not included in statistical analysis (assumed value of zero in the graph). See Bakir et al.[107] for details.
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harmful chemicals from seawater to marine organisms by several types of microplastics and then considered the consequences if these organisms were subsequently eaten by humans. The simulations predicted that microplastics were not likely to be an important factor in the transport of chemicals from seawater.[109]

Ingestion of plastic containing additives may also result in the chemicals leaching from the plastic and being transferred to the organism. Additive chemicals can be present in high concentrations[109] and it is considered that their release could provide an important pathway for chemical transfer to the biota.[110,111] However, more work will be needed to establish the potential for transfer of chemical additives, incorporated in plastic items at the time of manufacture. For example, a recent study in Korea demonstrated that potentially harmful flame retardants could be released from buoys used in an aquaculture facility, leading to elevated concentrations of flame retardants in the surrounding environment.[112]

It has been suggested in some media reports that consumption of fin-fish and shellfish that are contaminated with microplastics, and potentially chemicals, might present a threat to human health. However, the quantities of microplastics in seafood are typically low. In addition, studies of contaminated fish describe that microplastics as being present in the gut and this is typically removed before consumption. Similarly, with shellfish there is typically a depuration period prior to consumption. For organisms eaten whole, including the gut, estimates for high annual consumption of mussels indicated potential for transfer of 11 000 microplastic particles to an individual consumer.[113] Even in this fairly atypical scenario there is no evidence to indicate that the microplastic would be harmful. More work is needed to establish the potential health risks from microplastics. This would require an assessment of dietary exposure to microplastics *via* a range of foods,[6] as well as work to establish the potential consequences of such ingestion.

Subsequently, within the seafood industry there is concern that contamination by microplastic may have negative effects on consumer perceptions, affecting marketability even if there is no particular evidence of a risk to human health.[6,37] Notably potential effects have already been reported in the media and used in NGO campaigns (*e.g.*, surfrider foundation, Canada). Similar perceptual effects on marketability have been reported when stocks are identified as being contaminated with low-level radioactivity or microorganisms.[114] Hence, the actual risk of adverse effects on humans can be considerably different from the perceived risk that will affect marketability.

It is likely that there are also a range of sub-lethal effects that have not yet been recognized. While further research is needed to fully understand the environmental risks presented by microplastics, it is considered that because these small particles are readily available to organisms *via* ingestion and can be mistaken for prey, that they are likely to present different types of hazards to larger items. Summarising all of the evidence, the EU Marine Strategy Framework Directive (MSFD) expert group on marine litter recently concluded that plastics [including microplastics] present a "large scale and serious threat to the welfare of marine animals".[7]

From a risk assessment perspective, more work is needed to model the probability as well as the severity of encounters. With macroplastic debris this has recently been performed for encounters between turtles and abandoned fishing nets in waters to the north of Australia.[115] However, the wider ability to construct models of this type is limited, not only by a lack of understanding about some of the specific types of harm caused by different types of plastic debris, but also a lack of detailed empirical data on the current distribution of plastic; this is especially true for microplastic distributions, which are particularly troublesome to quantify.

6 Solutions

It is clear that substantial quantities of litter are entering aquatic habitats daily.[4,31,51] A combination of ineffective waste capture and ineffective sewage

treatment, together with product designs, that do not reflect end-of-life scenarios all contribute to the release of plastics into the environment. In this context, waste can be defined as something of little or no value and hence the problem may be exacerbated by the inexpensive nature of most plastics, which facilitates short-lived applications and can also present an obstacle to the viability of recycling. Therefore, it must be recognized that the accumulation of plastic in the oceans is actually a symptom of a wider and more systemic problem of linear use of materials and the rapid accumulation of waste. Hence, the overarching solutions to the problem of marine litter lie on land.[19] Even in the absence of complete information on distribution and impacts, it is clear that the key action must be to reduce the quantity of litter entering the oceans from the land.

The potential threats to aquatic ecosystems presented by plastic debris, particularly microplastic, has been identified as a major global conservation issue and a key priority for research.[6,37,116] To fully understand the sources and scale of this contamination would require an internationally coordinated effort with comparable sampling and microplastic extraction techniques, as well as standardized recording methodologies to map and evaluate distribution.[22,117]

There are some management strategies and policies in place to reduce plastic contamination.[6,19,118] Banning microbeads in cosmetics is an example of such legislation.[119] However, based on the levels of concern and the scale of problems outlined in this chapter it would appear that the measures currently in place are insufficient. In some cases, there are difficulties associated with enforcement; for example, the regulation of dumping at sea (MARPOL) is extremely difficult to enforce. Even in economically developed countries with robust waste management infrastructure, there are unnecessary obstacles to recycling, including the lack of availability of collection points, contamination of recycling feedstock, and the limited marketability of some recycled material.[19,120]

The benefits of citizen focused activities, such as beach cleaning are well recognized for their educational value as well as in terms of the litter removed.[5] Annual clean-up operations are now organized in many countries[3] and are often run by voluntary organizations.[5] They can remove substantial quantities of litter from beaches and the coastline. Volunteer involvement in two of the largest clean up schemes in the UK (Marine Conservation Society Beach Watch and Keep Scotland Beautiful National Spring Clean) has been estimated to provide a value of approximately £119 500 in term of cleaning, which suggests that the total cost of actions to remove marine litter is considerable.

Due to the size of microplastics and their abundance worldwide, their entire removal by clean-up is not feasible. Additionally, current rates of entry for litter into the marine environment far exceed the potential for removal by clean-up. Therefore, the main priority must be to focus on preventing litter entering the oceans in the first place and a better understanding of the behaviours that lead to littering, as well as those that lead to engagement in recycling.[121,122]

Most plastics are inherently recyclable, yet many single-use items are not compatible with recycling. A key challenge therefore is to ensure end-of-life disposal *via* recycling is appropriately considered at the design stage.

There are also some potential distractions to the key solutions; such as altering the carbon source used to make plastics by utilizing plant based carbon rather than fossil carbon from oil and gas. While this utilizes a renewable and hence a more sustainable carbon source, it will not reduce the generation of waste nor the accumulation of litter. Biodegradable plastics are another potential distraction; while products that have been designed to degrade rapidly may reduce the amount of highly visible macroscopic plastic waste, some of these items merely fragment, compromising the potential for product re-use and accelerating the production of microplastic fragments.[19,123,124] Biodegradable or compostable plastics only present a solution in very specific settings where the associated waste collection is specifically managed, provides conditions suitable for degradation and products are labelled accordingly to facilitate appropriate disposal.[19]

Education, outreach and awareness are effective ways to promote change in limiting indiscriminate disposal. However, in the past, approaches to address marine litter have mostly focused on end-of-pipe measures; in order to develop long term sustainable solutions there needs to be education and change in behaviour right along the supply chain and this could be facilitated by greater dialogue between the various stakeholders from design, through production and use, to disposal.[32] In short, what is needed is a much better stewardship so that the benefits of plastic can be realized without the accumulation of unnecessary waste in managed systems and in the environment.

7 Conclusions

Microplastics are small particulate contaminants that are widely distributed in the environment. These particles arise from a range of sources, they are persistent and accumulating. Microplastics have been reported from the surface of the sea to the deep sea and are ingested by a wide range of organisms. There is evidence that ingestion of microplastics can lead to harmful effects; these appear to be associated with the physical presence of microplastics, rather than release of chemical co-contaminants. Measures to reduce microplastic contamination should focus on minimising direct inputs of small particles, such as the microbeads used in cosmetics, but more importantly reducing the quantity of larger items of litter entering the environment as these are already widely recognised to cause negative consequences for economies and wildlife, and in addition they will ultimately fragment into microplastics.

References

1. R. C. Thompson, S. H. Swan, C. Moore and F. S. vom Saal, *Philos. Trans. R. Soc. B*, 2009, **364**, 1973–1976.

2. Plastics Europe, *Plastics the Facts 2015 An analysis of European Plastics Production, Demand and Waste Data*, Plastics Europe, Brussels, 2015.

3. D. K. A. Barnes, F. Galgani, R. C. Thompson and M. Barlaz, *Philos. Trans. R. Soc. B*, 2009, 1985–1998.

4. J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan and K. L. Law, *Science*, 2015, **347**, 768–771.

5. S. E. Nelms, C. Coombes, L. C. Foster, T. S. Galloway, B. J. Godley, P. K. Lindeque and M. J. Witt, *Sci. Total Environ.*, 2017, **579**, 1399–1409.

6. GESAMP, *Sources, Fate and Effects of Microplastics in the Marine Environment – Part Two of a Global Assessment*, 2016.

7. S. Werner, A. Budziak, J. van Franeker, F. Galgani, G. Hanke, T. Maes, M. Matiddi, P. Nilsson, L. Oosterbaan, E. Priestland, R. Thompson, J. Veiga and T. Vlachogianni, *Harm caused by Marine Litter. MSFD GES TG Marine Litter - Thematic Report*, 2016.

8. C. Arthur, J. Baker and H. Bamford, NOAA Technical Memorandum NOS-OR&R30, Proceedings of the international research workshop on the occurrence, effects and fate of microplastic marine debris, September 9–11, 2008.

9. F. Galgani, D. Fleet, J. Van Franeker, S. Katsanevakis, T. Maes, J. Mouat, L. Oosterbaan, I. Poitou, G. Hanke, R. Thompson, E. Amato, A. Birkun and C. Janssen, *Marine Strategy Framework Directive, Task Group 10 Report: Marine Litter*, European Comission Joint Research Centre, Ispra, 2010.

10. R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle and A. E. Russell, *Science*, 2004, **304**, 838.

11. M. A. Browne, P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway and R. Thompson, *Environ. Sci. Technol.*, 2011, **45**, 9175–9179.

12. E. J. Carpenter, S. J. Anderson, G. R. Harvey, H. P. Miklas and B. P. Bradford, *Science*, 1972, **178**, 749–750.

13. M. Eriksen, S. Mason, S. Wilson, C. Box, A. Zellers, W. Edwards, H. Farley and S. Amato, *Mar. Pollut. Bull.*, 2013, **77**, 177–182.

14. L. C. M. Lebreton, J. Van der Zwet, J. W. Damsteeg, B. Slat, A. Andrady and J. Reisser, *Nat. Commun.*, 2017, **8**, 15611.

15. D. Eerkes-Medrano, R. C. Thompson and D. C. Aldridge, *Water Res.*, 2015, **75**, 63–82.

16. A. Cozar, F. Echevarria, J. I. Gonzalez-Gordillo, X. Irigoien, B. Ubeda, S. Hernandez-Leon, A. T. Palma, S. Navarro, J. Garcia-de-Lomas, A. Ruiz, M. L. Fernandez-de-Puelles and C. M. Duarte, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, **111**, 10239–10244.

17. M. A. Browne, T. S. Galloway and R. C. Thompson, *Environ. Sci. Technol.*, 2010, **44**, 3404–3409.

18. K. L. Law and R. C. Thompson, *Science*, 2014, **345**, 144–145.

19. R. C. Thompson, in *Marine Anthropogenic Litter*, ed. M. Bergman, L. Gutow and M. L. Klages, Springer, Heidelberg, 2015, ch. 7, pp. 185–200.

20. A. L. Andrady, *Mar. Pollut. Bull.*, 2017, **119**, 12–22.

21. M. Cole, P. Lindeque, C. Halsband and T. S. Galloway, *Mar. Pollut. Bull.*, 2011, **62**, 2588–2597.

22. V. Hidalgo-Ruz, L. Gutow, R. C. Thompson and M. Thiel, *Environ. Sci. Technol.*, 2012, **46**, 3060–3075.

23. R. C. Thompson, C. Moore, F. S. vom Saal and S. H. Swan, *Philos. Trans. R. Soc. B*, 2009, **364**, 2153–2166.

24. MSFD GES Technical Subgroup on Marine Litter, *Marine Litter Technical Recommendations for the Implementation of MSFD Requirements*, Joint Research Centre – Institute for Environment and Sustainability, Luxembourg, 2011.

25. M. A. Browne, M. G. Chapman, R. C. Thompson, L. A. A. Zettler, J. Jambeck and N. J. Mallos, *Environ. Sci. Technol.*, 2015, **49**, 7082–7094.

26. P. G. Ryan, C. J. Moore, J. A. van Franeker and C. L. Moloney, *Philos. Trans. R. Soc. B*, 2009, **364**, 1999–2012.

27. K. L. Law, S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner and C. M. Reddy, *Science*, 2010, **329**, 1185–1188.

28. A. A. Koelmans, E. Besseling and W. J. Shim, in *Marine Anthropogenic Litter*, ed. M. Bergman, L. Gutow and M. Klages, Springer, Heidelberg, 2016, pp. 325–341.

29. I. E. Napper, A. Bakir, S. J. Rowland and R. C. Thompson, *Mar. Pollut. Bull.*, 2015, **99**, 178–185.

30. K. Duis and A. Coors, *Environ. Sci. Eur.*, 2016, **28**, 1–25.

31. C. Schmidt, T. Krauth and S. Wagner, *Environ. Sci. Technol.*, 2017, **51**, 12246–12253.

32. GoScience, *Future of the Sea: Plastic Pollution*, Government Office for Science, London, 2017.

33. C. A. Ribic, S. B. Sheavly, D. J. Rugg and E. S. Erdmann, *Mar. Pollut. Bull.*, 2010, **60**, 1231–1242.

34. M. Kamachi, Y. Ishikawa, H. Kawamura, N. Maximenko, J. Hafner and A. MacFadyen, *Modeling the Drift of Japan Tsunami Marine Debris (JTMD) An application of High Computing Simulation and Data Assimilation*, IEEE, 2016, pp. 599–602.

35. L. C. M. Lebreton and J. C. Borrero, *Mar. Pollut. Bull.*, 2013, **66**, 53–58.

36. R. Thompson, C. Moore, A. Andrady, M. Gregory, H. Takada and S. Weisberg, *Science*, 2005, **310**, 1117.

37. GESAMP, *Sources, fate and effects of microplastics in the marine environment: a global assessment*, IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, 2015.

38. A. L. Andrady, *Mar. Pollut. Bull.*, 2011, **62**, 1596–1605.

39. M. R. Gregory and A. L. Andrady, in *Plastics and the Environemnt*, ed. A. L. Andrady, John Wiley and Sons, New Jersey, 2003, pp. 379–397.

40. A. A. Koelmans, T. Gouin, R. C. Thompson, N. Wallace and C. Arthur, *Environ. Toxicol. Chem.*, 2014, **33**, 5–10.

41. R. Dris, J. Gasperi, V. Rocher, M. Saad, N. Renault and B. Tassin, *Environ. Chem.*, 2015, **12**, 592–599.

42. L. C. Woodall, A. Sanchez-Vidal, M. Canals, G. L. J. Paterson, R. Coppock, V. Sleight, A. Calafat, A. D. Rogers, B. E. Narayanaswamy and R. C. Thompson, *R. Soc. Open Sci.*, 2014, **1**, 140317.

43. A. L. Lusher, M. McHugh and R. C. Thompson, *Mar. Pollut. Bull.*, 2013, **67**, 94–99.

44. V. Zitko and M. Hanlon, *Mar. Pollut. Bull.*, 1991, **22**, 41–42.

45. A. G. Anderson, J. Grose, S. Pahl, R. C. Thompson and K. Wyles, *Mar. Pollut. Bull.*, 2016, **113**, 454–460.

46. A. van Wezel, I. Caris and S. A. E. Kools, *Environ. Toxicol. Chem.*, 2016, **35**, 1627–1631.

47. I. E. Napper and R. C. Thompson, *Mar. Pollut. Bull.*, 2016, **112**, 39–45.

48. J. G. B. Derraik, *Mar. Pollut. Bull.*, 2002, **44**, 842–852.

49. H. S. Auta, C. U. Emenike and S. H. Fauziah, *Environ. Int.*, 2017, **102**, 165–176.

50. M. Claessens, S. De Meester, L. Van Landuyt, K. De Clerck and C. R. Janssen, *Mar. Pollut. Bull.*, 2011, **62**, 2199–2204.

51. T. Mani, A. Hauk, U. Walter and P. Burkhardt-Holm, *Sci. Rep.*, 2015, **5**, 17998.

52. S. Klein, E. Worch and T. P. Knepper, *Environ. Sci. Technol.*, 2015, **49**, 6070–6076.

53. F. Murphy, C. Ewins, F. Carbonnier and B. Quinn, *Environ. Sci. Technol.*, 2016, **50**, 5800–5808.

54. R. Geyer, J. R. Jambeck and K. L. Law, *Sci. Adv.*, 2017, **3**, e1700782.

55. K. L. Law and R. Annual, in *Annual Review of Marine Sciences*, 2017, vol. 9, pp. 205–229.

56. R. W. Obbard, S. Sadri, Y. QiWong, A. A. Khitun, I. Baker and R. C. Thompson, *Earth's Future*, 2014, **2**, 315–320.

57. G. L. Lattin, C. J. Moore, A. F. Zellers, S. L. Moore and S. B. Weisberg, *Mar. Pollut. Bull.*, 2004, **49**, 291–294.

58. L. Van Cauwenberghe, A. Vanreusel, J. Mees and C. R. Janssen, *Environ. Pollut.*, 2013, **182**, 495–499.

59. E. van Sebille, C. Wilcox, L. Lebreton, N. Maximenko, B. D. Hardesty, J. A. van Franeker, M. Eriksen, D. Siegel, F. Galgani and K. L. Law, *Environ. Res. Lett.*, 2015, **10**, 124006.

60. T. Kukulka, G. Proskurowski, S. Moret-Ferguson, D. W. Meyer and K. L. Law, *Geophys. Res. Lett.*, 2012, **39**, L07601.

61. M. Eriksen, L. C. M. Lebreton, H. S. Carson, M. Thiel, C. J. Moore, J. C. Borerro, F. Galgani, P. G. Ryan and J. Reisser, *PLoS One*, 2014, **9**, e111913.

62. T. Maes, R. Jessop, N. Wellner, K. Haupt and A. G. Mayes, *Sci. Rep.*, 2017, **7**, 44501.

63. G. Erni-Cassola, M. I. Gibson, R. C. Thompson and J. A. Christie-Oleza, *Environ. Sci. Technol.*, 2017, **51**, 13641–13648.

64. A. S. Tagg, J. P. Harrison, Y. Ju-Nam, M. Sapp, E. L. Bradley, C. J. Sinclair and J. J. Ojeda, *Chem. Commun.*, 2017, **53**, 372–375.

65. L. Frere, I. Paul-Pont, J. Moreau, P. Soudant, C. Lambert, A. Huvet and E. Rinnert, *Mar. Pollut. Bull.*, 2016, **113**, 461–468.
66. F. Faure, C. Saini, G. Potter, F. Galgani, L. F. de Alencastro and P. Hagmann, *Environ. Sci. Pollut. Res.*, 2015, **22**, 12190–12197.
67. P. G. Ryan, *Environ. Res. Lett.*, 2015, **10**, 084019.
68. F. M. C. Fazey and P. G. Ryan, *Mar. Pollut. Bull.*, 2016, **110**, 371–377.
69. E. R. Zettler, T. J. Mincer and L. A. Amaral-Zettler, *Environ. Sci. Technol.*, 2013, **47**, 7137–7146.
70. F. M. C. Fazey and P. G. Ryan, *Environ. Pollut.*, 2016, **210**, 354–360.
71. F. Galgani, J. P. Leaute, P. Moguedet, A. Souplet, Y. Verin, A. Carpentier, H. Goraguer, D. Latrouite, B. Andral, Y. Cadiou, J. C. Mahe, J. C. Poulard and P. Nerisson, *Mar. Pollut. Bull.*, 2000, **40**, 516–527.
72. F. Galgani, T. Burgeot, G. Bocquene, F. Vincent, J. P. Leaute, J. Labastie, A. Forest and R. Guichet, *Mar. Pollut. Bull.*, 1995, **30**, 58–62.
73. M. C. Rillig, *Environ. Sci. Technol.*, 2012, **46**, 6453–6454.
74. S. C. Gall and R. C. Thompson, *Mar. Pollut. Bull.*, 2015, **92**, 170–179.
75. E. L. Kuhn, R. Bravo and J. A. Fvan Franeker, in *Marine Anthropogenic Litter*, ed. M. Bergman, L. Gutow and M. Klages, Springer, Heidelberg, 2015, pp. 75–116.
76. M. A. Browne, A. J. Underwood, M. G. Chapman, R. Williams, R. C. Thompson and J. A. van Franeker, *Proc. R. Soc. B*, 2015, **282**, 20142929.
77. D. W. Laist, in *Marine Debris: Sources, Impacts and Solutions*, ed. J. M. Coe and B. D. Rogers, Springer, Berlin, 1997, pp. 99–141.
78. B. Unger, E. L. B. Rebolledo, R. Deaville, A. Grone, L. L. Ijsseldijk, M. F. Leopold, U. Siebert, J. Spitz, P. Wohlsein and H. Herr, *Mar. Pollut. Bull.*, 2016, **112**, 134–141.
79. J. Van Franeker, E. L. Kuhn and R. Bravo, *Fulmar Litter EcoQO Monitoring in the Netherlands – Update 2015*, Wageningen Marine Research, 2016.
80. S. L. Wright, R. C. Thompson and T. S. Galloway, *Environ. Pollut.*, 2013, **178**, 483–492.
81. M. Cole, P. Lindeque, E. Fileman, C. Halsband and T. S. Galloway, *Environ. Sci. Technol.*, 2015, **49**, 1130–1137.
82. M. Cole, P. Lindeque, E. Fileman, C. Halsband, R. Goodhead, J. Moger and T. S. Galloway, *Environ. Sci. Technol.*, 2013, **47**, 6646–6655.
83. C. M. Rochman, E. Hoh, T. Kurobe and S. J. Teh, *Nat. Sci. Rep.*, 2013, **3**, 3263.
84. C. M. Rochman and M. A. Browne, *Nature*, 2013, **494**, 169–171.
85. R. G. Santos, R. Andrades, L. M. Fardim and A. S. Martins, *Environ. Pollut.*, 2016, **214**, 585–588.
86. M. L. Moser and D. S. Lee, *Colonial Waterbirds*, 1992, **15**, 83–94.
87. J. L. Lavers and A. L. Bond, *Mar. Environ. Res.*, 2016, **113**, 1–6.
88. H. R. Cousin, H. J. Auman, R. Alderman and P. Virtue, *EMU*, 2015, **115**, 6–11.
89. M. A. Browne, A. Dissanayake, T. S. Galloway, D. M. Lowe and R. C. Thompson, *Environ. Sci. Technol.*, 2008, **42**, 5026–5031.

90. A. J. R. Watts, M. A. Urbina, S. Corr, C. Lewis and T. S. Galloway, *Environ. Sci. Technol.*, 2015, **49**, 14597–14604.

91. M. R. Gregory, *Philos. Trans. R. Soc., B*, 2009, **364**, 2013–2026.

92. I. V. Kirstein, S. Kirmizi, A. Wichels, A. Garin-Fernandez, R. Erler, M. Loder and G. Gerdts, *Mar. Environ. Res.*, 2016, **120**, 1–8.

93. D. K. A. Barnes, *Nature*, 2002, **416**, 808–809.

94. A. Keswani, D. M. Oliver, T. Gutierrez and R. S. Quilliam, *Mar. Environ. Res.*, 2016, **118**, 10–19.

95. M. A. Browne, S. J. Niven, T. S. Galloway, S. J. Rowland and R. C. Thompson, *Curr. Biol.*, 2013, **23**, 2388–2392.

96. S. L. Wright, D. Rowe, R. C. Thompson and T. S. Galloway, *Curr. Biol.*, 2013, **23**, 1031–1033.

97. T. Cedervall, L. A. Hansson, M. Lard, B. Frohm and S. Linse, *PLoS One*, 2012, **7**, e32254.

98. R. Sussarellu, M. Suquet, Y. Thomas, C. Lambert, C. Fabioux, M. E. J. Pernet, N. Le Goic, V. Quillien, C. Mingant, Y. Epelboin, C. Corporeau, J. Guyomarch, J. Robbens, I. Paul-Pont, P. Soudant and A. Huvet, *Proc. Natl. Acad. Sci. U. S. A.*, 2016, **113**, 2430–2435.

99. R. Lenz, K. Enders and T. G. Nielsen, *Proc. Natl. Acad. Sci. U. S. A.*, 2016, **113**, E4121–E4122.

100. D. S. Green, B. Boots, D. J. Blockley, C. Rocha and R. Thompson, *Environ. Sci. Technol.*, 2015, **49**, 5380–5389.

101. D. S. Green, *Environ. Pollut.*, 2016, **216**, 95–103.

102. D. S. Green, B. Boots, N. O'Connor and R. C. Thompson, *Environ. Sci. Technol.*, 2017, **51**, 68–77.

103. L. A. Holmes, A. Turner and R. C. Thompson, *Environ. Pollut.*, 2012, **160**, 42–48.

104. Y. Mato, T. Isobe, H. Takada, H. Kanehiro, C. Ohtake and T. Kaminuma, *Environ. Sci. Technol.*, 2001, **35**, 318–324.

105. E. L. Teuten, J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P. Viet, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha and S. Takada, *Philos. Trans. R. Soc. B*, 2009, **364**, 2027–2045.

106. A. L. Andrady and M. A. Neal, *Philos. Trans. R. Soc. B*, 2009, **364**, 1977–1984.

107. A. Bakir, S. J. Rowland and R. C. Thompson, *Environ. Pollut.*, 2014, **185**, 16–23.

108. A. A. Koelmans, E. Besseling, A. Wegner and E. M. Foekema, *Environ. Sci. Technol.*, 2013, **47**, 7812–7820.

109. A. Bakir, I. A. O'Connor, S. J. Rowland, A. J. Hendriks and R. C. Thompson, *Environ. Pollut.*, 2016, **219**, 56–65.

110. K. Tanaka, H. Takada, R. Yamashita, K. Mizukawa, M. Fukuwaka and Y. Watanuki, *Mar. Pollut. Bull.*, 2013, **69**, 219–222.

111. J. Oehlmann, U. Schulte-Oehlmann, W. Kloas, O. Jagnytsch, I. Lutz, K. O. Kusk, L. Wollenberger, E. M. Santos, G. C. Paull, K. J. W. Van Look and C. R. Tyler, *Philos. Trans. R. Soc. B*, 2009, **364**, 2047–2062.

112. N. A. Al-Odaini, W. J. Shim, G. M. Han, M. Jang and S. H. Hong, *Sci. Total Environ.*, 2015, **505**, 290–298.

113. L. Van Cauwenberghe and C. R. Janssen, *Environ. Pollut.*, 2014, **193**, 65–70.

114. G. Parsons, A. Morgan, J. Whitehead and T. Haab, *Agricultural and Resource Economics Review*, 2006, **35**, 348–356.

115. C. Wilcox, B. D. Hardesty, R. Sharples, D. A. Griffin, T. J. Lawson and R. Gunn, *Conservation Letters*, 2013, **6**, 247–254.

116. W. J. Sutherland, M. Clout, I. M. Cote, P. Daszak, M. H. Depledge, L. Fellman, E. Fleishman, R. Garthwaite, D. W. Gibbons, J. De Lurio, A. J. Impey, F. Lickorish, D. Lindenmayer, J. Madgwick, C. Margerison, T. Maynard, L. S. Peck, J. Pretty, S. Prior, K. H. Redford, J. P. W. Scharlemann, M. Spalding and A. R. Watkinson, *Trends in Ecology & Evolution*, 2010, **25**, 1–7.

117. M. Fisner, A. P. Majer, D. Balthazar-Silva, D. Gorman and A. Turra, *Environ. Sci. Pollut. Res.*, 2017, **24**, 13732–13740.

118. G. O. Thomas, W. Poortinga and E. Sautkina, *J. Environ. Psychol.*, 2016, **47**, 126–135.

119. D. Xanthos and T. R. Walker, *Mar. Pollut. Bull.*, 2017, **118**, 17–26.

120. J. Hopewell, R. Dvorak and E. Kosior, *Philos. Trans. R. Soc., B*, 2009, **364**, 2115–2126.

121. S. Pahl, K. J. Wyles and R. C. Thompson, *Nature Human Behaviour*, 2017, **1**, 697–699.

122. S. Pahl and K. J. Wyles, *Anal. Methods*, 2017, **9**, 1404–1411.

123. Defra, *Assessing the Environmental Impacts of Oxo-degradable Plastics Across Their Life Cycle*, London, 2010.

124. P. K. Roy, M. Hakkarainen, I. K. Varma and A. Albertsson, *Environ. Sci. Technol.*, 2011, 4217–4227.