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Interactions of microplastic debris throughout the marine ecosystem

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Marine microscopic plastic (microplastic) debris is a modern societal issue, illustrating the challenge of balancing the convenience of plastic in daily life with the prospect of causing ecological harm by careless disposal. Here we develop the concept of microplastic as a complex, dynamic mixture of polymers and additives, to which organic material and contaminants can successively bind to form an 'ecocorona', increasing the density and surface charge of particles and changing their bioavailability and toxicity. Chronic exposure to microplastic is rarely lethal, but can adversely affect individual animals, reducing feeding and depleting energy stores, with knock-on effects for fecundity and growth. We explore the extent to which ecological processes could be impacted, including altered behaviours, bioturbation and impacts on carbon flux to the deep ocean. We discuss how microplastic compares with other anthropogenic pollutants in terms of ecological risk, and consider the role of science and society in tackling this global issue in the future.

Research reporting the presence of plastic debris in the oceans has been in the literature since the 1970s[1], when mass production methods first started to increase the scale and scope of plastic use. Fast-forward to the present day and plastics have become a ubiquitous feature of modern life and a dominant material in the consumer marketplace, with global production figures currently in excess of 300 million tonnes per year[2]. Around 50% of plastic items are used just once before being discarded, resulting in a growing burden of plastic waste, enough, it has been suggested, to leave an identifiable imprint in the geochemical fossil record[3]. An estimated 4.8–12.7 million tonnes of plastic was discharged into the oceans in 2010[4], and models have conservatively estimated over 5 trillion pieces of plastic are floating in the world's oceans[5]. Tiny plastic fragments, fibres and granules, termed microplastic (one micrometre to five millimetres in diameter) are the predominant form of ocean plastic debris[6]. Microplastic includes items manufactured to be small, such as exfoliating microbeads added to cosmetics, synthetic particles used in air blasting and antifouling of boats, and microspheres used in clinical medicine for drug delivery (ref. [7] and references therein). Secondary microplastic forms via fragmentation of plastic debris in the environment through photooxidation, mechanical action and biodegradation[8,9]. The timescale and scope of fragmentation is uncertain; in the cold, oxygen-limiting conditions found in marine waters and sediments it could take over 300 years for a 1 mm particle to reach a diameter of 100 nm (ref. [10]).

Microplastic is a concern because its small size is within the optimal prey range for many animals within the marine food web[11]. Microplastic is ingested by filter, suspension and detritus feeders living in the water column and bottom sediments, and has been found in the guts of invertebrates, fish, turtles and other larger animals, including species intended for human consumption or those playing critical ecological roles[12]. Modern plastics are typically a complex cocktail of polymers, residual monomers and chemical additives. Absorbed organic matter[13], bacteria[14] and chemical contaminants[15] add to their complexity. The transfer of these substances to animal tissues increases their potential to cause harm, since many plastic additives and persistent waterborne chemicals are endocrine disruptors, capable of activating hormone signal transduction pathways in target tissues and altering metabolic and reproductive endpoints[15,16]. The current consensus drawn from laboratory experiments, quantitative assessments and modelling studies is that the net contribution of plastics to bioaccumulation of hydrophobic contaminants by marine animals is likely to be small in comparison with uptake of contaminants directly from water[15]. Instead, it is the selective nature of the compounds transferred and the ways in which they are presented to tissues and cell receptors that pose a novel risk[13].

There have been calls for microplastic to be reclassified as hazardous[17], but regulation to restrict the mass flow of plastic debris into the oceans has been hampered by a lack of knowledge of how impacts on individual organisms might lead to ecological harm. This is confirmed by a recent systematic review of 245 studies in which biological impacts of marine debris were reported, identifying that the majority of studies were at the sub-organismal or individual level, with few, if any, able to demonstrate ecological harm at higher levels of biological organization[18]. What, then, are some of the main areas for ecological concern? How do we extrapolate from the effects on individuals to the ecological processes most likely to be impacted? How does microplastic compare with other anthropogenic stressors threatening ocean life?

The dynamic nature of microplastic

A key issue in understanding the ways in which microplastic interacts with the surrounding environment is its dynamic nature (Fig. 1). The size, shape, charge and other properties of microplastic are constantly changing, altering its biological fate and bioavailability. The vast majority of microplastic in the oceans is believed to originate from weathering of larger items[8], through mechanical action and degradation, driven largely by UV-radiation-induced photooxidation, releasing low-molecular-weight polymer fragments such as monomers and oligomers, and forming fragments of increasingly smaller size[9]. A mismatch in the expected size distribution of microplastic in ocean surface field surveys highlights the plausibility that millimetre-scale debris may be fragmenting to form nanoplastic[19]. Although measuring plastic of this minute size in the oceans presents technical challenges that have not yet been met, recently a solar reactor was used to illustrate that nanoplastic could

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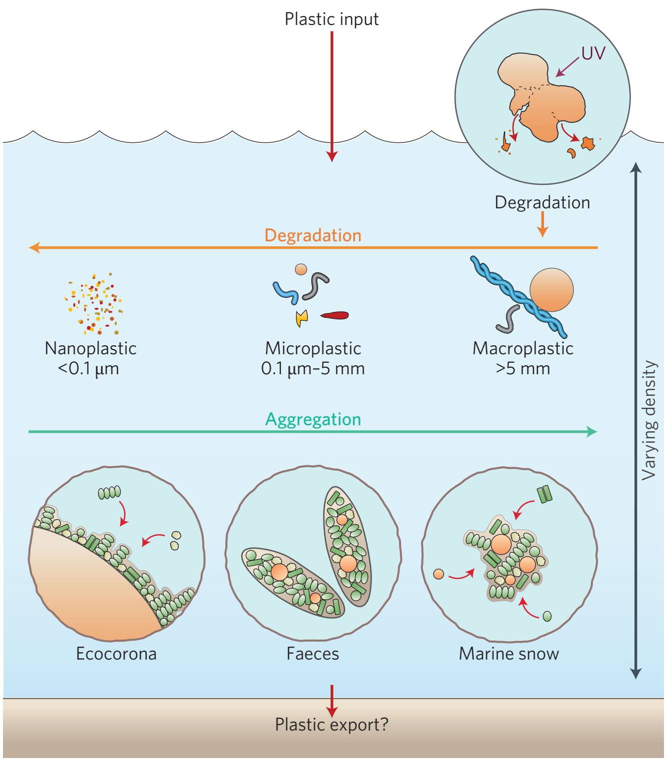

Figure 1 | Schematic illustration of the dynamic changes experienced by microplastic in the water column. Plastic entering marine ecosystems from terrestrial and maritime sources is vulnerable to photooxidation by ultraviolet (UV), mechanical and biological degradation resulting in fragmentation to smaller sizes. Adherence of macromolecules and microorganisms to the surface of micro- and nanoplastic result in the formation of an ecocorona. Interactions with biota and marine aggregates repackage microplastic into faeces and marine snows. These biological processes increase the relative size, chemical signature and density of the plastic particles. The density of a plastic particle will affect its position within the water column, potentially resulting in export to the seafloor.

form from the fragmentation of weathered polyethylene and polypropylene microplastic collected from marine waters[20]. The nanoplastic consisted of smaller (<50 nm) spherical particles and larger, uneven fractal fragments, likely to exhibit differences in diffusion properties and porosity.

The presence of nanoplastic is important from an ecological context because its microscopic size allows it to pass across biological barriers and to enter cells, whilst high surface area to volume ratios enhance its reactivity[21]. In addition, the atoms located at the surface of a nanoplastic have fewer particles around them, compared with micrometre-scale particles, and this leads to a lower binding energy per atom with decreasing particle size. Nanoparticles hence have a tendency to aggregate with other particles, natural colloids and suspended solids[22]; for example, 30 nm nanopolystyrene rapidly formed millimetre-sized aggregates in seawater with high attachment efficiencies[23]. Since aggregates will have a higher density than dispersed particles, their settling rate through the water column will be increased. Settling of micro- and nanoplastic through the water column varies depending on the type of polymer, surface chemistry and the extent of biofouling by microbial biofilms and rafting organisms[24]. Microplastic will settle until it reaches the often variable density of surrounding seawater, allowing it to remain adrift and potentially to move long distances through the action of ocean currents[19]. The timescale for these processes remains unknown; although plastics can disperse rapidly across the ocean surface, particles may take many weeks or years to reach the ocean floor[25].

Particle surfaces, the absorbsome and the ecocorona

The surface properties of microplastic play an important part in determining its ecological impacts. Plastics characteristically have smooth, hydrophobic surfaces that have no net charge, but this changes rapidly in seawater (Fig. 2). Substances from the water column or sediment are rapidly accumulated, including organic matter, nutrients, hazardous hydrophobic contaminants and bacteria, the latter attracted by the nutritious content of organic material.

A better understanding of the factors that can influence absorption onto the surface of microplastic can be gleaned from the literature relating to the protein corona that forms on nanoparticles from biological fluids such as serum and cytoplasm. According to this paradigm, the surface of nanomaterials in biological fluids rapidly becomes coated with proteins and biomolecules, which strongly influence the interaction of nanoparticles with cells and tissues, and ultimately their persistence, bioavailability, toxicity[26,27] and ecotoxicity[28]. The protein corona concept recognizes a tightly adhered 'hard corona' which remains strongly bound to the particle as it moves between compartments, and a 'soft corona' made up of more loosely bound proteins in dynamic exchange with surrounding molecules[29]. Importantly, of the many thousands of proteins present in serum, only a limited number of around 125 proteins selectively bind to particle surfaces, and these are not always the most abundant ones. This so-called absorbome forms in layers, with some proteins recognizing the nanoparticle surface directly, and others associating with the already coated particle through protein-protein interactions[30]. Why this happens is unknown, but may relate to the propensity for certain extracellular proteins (for example, lipoproteins) to form nanoscale biomolecule clusters. Hence, the nanoparticles act like scaffolds and in turn may alter the conformation of the absorbed proteins, changing their epitope recognition and/or modifying interactions with cellular receptors[13]. The corona can also contain other biomolecules such as carbohydrates, which tend to be multivalent and the net effect is to engage the nanoparticle surface with multiple, varied receptors on the cell surface, enhancing or sometimes inhibiting their internalization into cells[31].

A parallel concept for understanding the behaviour and ecological impacts of micro- and nanoplastics is that of the ecocorona[13]. Natural waters contain natural organic macromolecules (NOM) that typically host high amounts of humic and fulvic acids, excreted waste products and exuded lipids and polysaccharides, proteins and macromolecules, all forming a complex polymeric mixture that varies seasonally and spatially. The way in which NOM interacts with particle surfaces in the aquatic environment mirrors the formation of the protein corona in biological fluids. Components of NOM can be absorbed by particles in layers, varying in thickness from flat monolayers to multilayers, consistent with the notion of the hard and soft protein corona[32]. This means that microplastic could retain a record of its environmental progress into different compartments, in much the same way as nanoparticles do in serum and when moving into different cellular locations. For example, it has been shown[33] that microplastic ingested by planktonic copepods were egested within faecal pellets along with high concentrations of organic matter. Under these circumstances, the microplastic may retain an ecocorona composed of macromolecules absorbed from biological fluids that will subsequently exchange and interact with organic materials, minerals and other components of marine snows in their new environment. This could explain why microplastic behaves differently to other inert materials such as clay when it is ingested, often being retained for longer in the gut[34].

The idea of absorbed layers also supports the notion of microplastic contributing towards a Trojan horse effect for pollutants, in which particles contribute towards the flux of contaminants acquired from the surrounding environment and released into the gut fluids, tissues or cells of the ingesting organism[35]. Contaminants bound onto microplastic in layers could be more bioavailable to

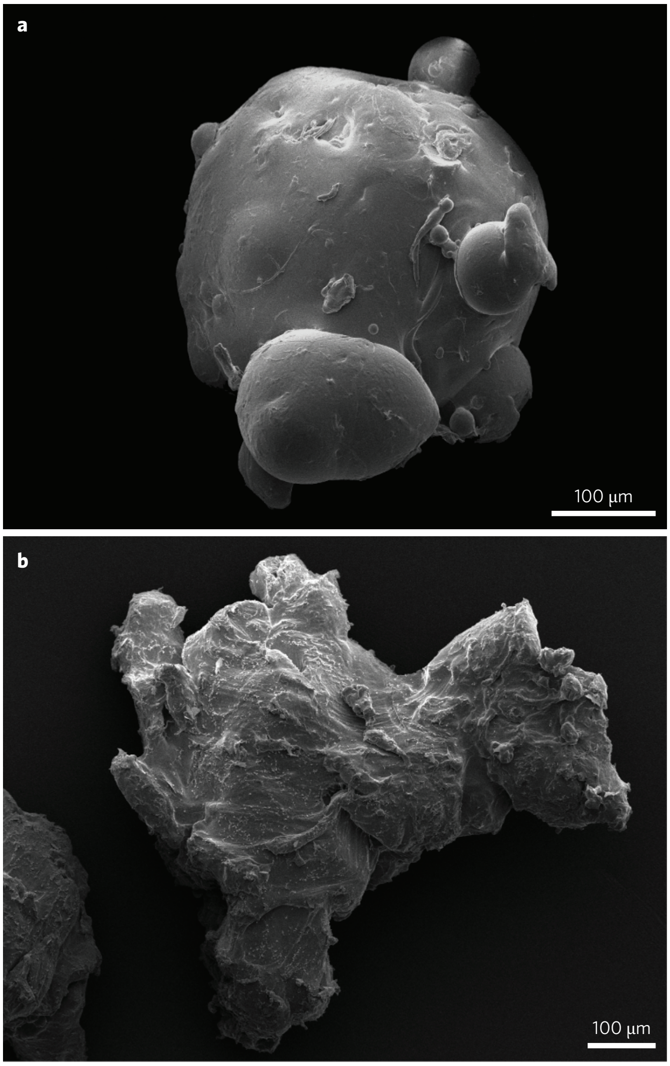

Figure 2 | Scanning electron microscopy images of microplastics. **a**, Polyethylene microbead purified from a facewash. **b**, Polyethylene fragment collected from beach litter. Images: A. Watts.

organisms if absorbed via an ecocorona layer rather than directly to the surface of the plastic[35]. This concept supports a study of the bioavailability of silver to zebrafish (*Danio rerio*), which was reduced when fish were presented with microplastic to which silver was already absorbed, compared with co-exposure to plastic and silver at the same time[36].

Ecocorona components could also influence the movement and behaviour of microplastic. Humic substances are weak acids and are negatively charged under environmental pH conditions. Their propensity to bind to particles in marine waters is borne out by the finding that virtually all weathered microplastic isolated from seawater has a negative charge[37]. Once absorbed to particles, the charge and flexibility of humic substances will tend to stabilize and disperse particles into the water column, which could enhance their bioavailability for filter-feeding and suspension-feeding organisms. Exopolymeric substances are exuded by unicellular and multicellular organisms including bacteria and phytoplankton and consist largely of long-chained polysaccharides that can form rigid, fibrillar chains. Exopolymeric substances can link to form gels, mucilage and slime aggregates, which play an essential role in nutrient cycling[38]. When absorbed to microplastics such substances are likely to encourage aggregation, increasing the density, sinking rate and bioavailability of microplastic to detritus feeders on the ocean floor.

Infochemicals

Perhaps of most interest in considering the ecological interactions of microplastic is the concept of selective binding of secretory molecules. The protein corona formed in biological fluids contains a significant proportion of proteins involved in transport and signalling, including immunoglobulins and albumins[30]. Natural organic matter likewise contains many molecules that are deliberately excreted or exuded to perform specific biological functions for marine animals. Chemical sensing is a ubiquitous means of communication and allows for many inter- and intra-species interactions, including symbiosis, mate detection and predator–prey cues. A core selection of chemical cues drives complex foraging cascades across multiple trophic levels, from behavioural attractions in locating foraging zooplankton to global scale impacts on climate[39]. These 'infochemicals' include dimethylsulfide (DMS), a sulfur-containing compound produced by phytoplankton, which induces foraging activity in a wide range of animals. Experimental studies using polypropylene and polyethylene, both abundant in marine debris, showed that both could acquire an active DMS signature after less than a month of exposure in the ocean. Responsiveness to DMS can occur at concentrations as low as 10^{-12} M and a positive relationship was found between DMS responsiveness and plastic ingestion using data from over 13,000 seabirds[40]. These results provide compelling evidence to explain the high rates of ingestion of plastic debris by seabirds and also support the notion of an ecocorona showing selective binding of an important marine infochemical.

In another study of predator–prey cues, *Daphnia magna*, small crustaceans central to aquatic food webs, were exposed to nanopolystyrene preconditioned in water from neonate cultures. The toxicity of the nanopolystyrene was enhanced and the particles were retained for longer in the animals' guts. *Daphnia* show profound changes in feeding, reproduction and other traits in response to predator 'kairomones' (interspecies pheromones) and inspection of the particle surface confirmed the presence of a protein layer that was exchanging and rearranging over time[41].

These results support the notion that a secreted protein ecocorona can form on microplastic and can mediate its ingestion in both microfauna and macrofauna. Thus the ecocorona concept could help to explain the high rates of ingestion of microplastic reported in so many animals across multiple trophic levels[34], by enhancing the attractiveness of microplastic as a food item.

Microbial communities and marine snows

The ecorona could additionally modulate the absorption of bacteria. Analysis of weathered microplastic debris collected from the sea surface revealed a diverse microbial community of colonizing bacteria, including heterotrophs, autotrophs, predators and symbionts[14]. Opportunistic bacteria form biofilms on any available surface, gaining access to nutritious matter, protection and enhanced dispersal. Microplastic biofilms appear distinct compared with those on other marine substrata and are shaped by spatial and seasonal factors[42]. *Vibrio* are ubiquitous marine bacteria frequently reported in plastic-associated biofilms[43] and some species, such as *Vibrio crassostrea* are associated with pathogenic infections in oysters. Colonization of microplastics by *V. crassostrea* is enhanced when the microplastic was already coated by a layer of marine aggregates containing a multispecies natural assemblage, that is, they are secondary[44] rather than primary colonizers showing chemotactic attraction to the particle surface. The layering of primary and secondary colonizing bacteria provides further support for the concept of a layered ecocorona documenting the movement of particles through different environmental compartments over time.

The tendency for microplastic to become incorporated into excreted and egested organic materials[33] and marine aggregates is an important observation[45]. The sinking of organic and inorganic aggregated matter (marine snow) from the surface is crucial for removal of

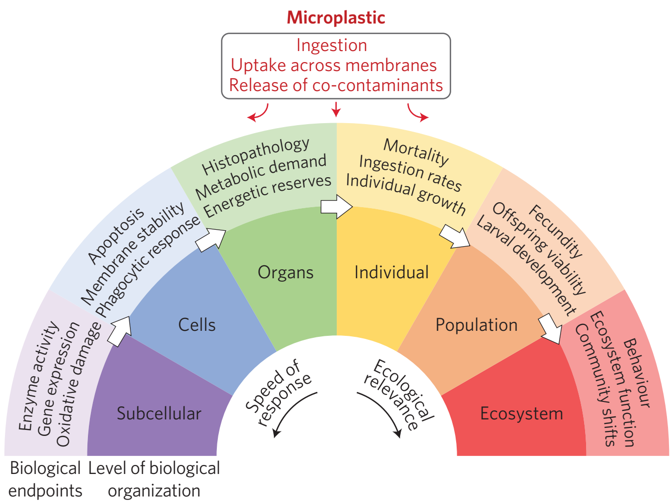

Figure 3 | Simplified scheme illustrating potential impacts of exposure to microplastic across successive levels of biological organization.

inorganic photosynthetically fixed carbon and the cycling of essential nutrients to the deep ocean, and marine snows contain diverse microbial communities that degrade organic matter during the sinking process. Hence they secrete a wide range of hydrolytic enzymes for degrading proteins, lipids and other macromolecules associated with these complex particles. The attached microbial communities at depth appear to be 'inherited' from the microbial communities found at the ocean surface, that is, they are carried there with the sinking particles[46]. This is intriguing, since sinking microplastic could host a different portfolio of microorganisms to those found on marine snow particles. Microbial communities are highly concentrated in marine snows, reaching concentrations 10,000 times higher than in surrounding waters and this enhances the release of quorum sensors by marine snow communities[47]. Quorum sensors are signalling molecules released by bacteria in response to cell density that control many metabolic processes including the hydrolysis of complex organic materials. It is an interesting speculation that such quorum-sensing regulators could, in doing so, favour the formation of communities capable of degrading hydrocarbon polymers, allowing in time for degradation and mineralization of the plastics themselves.

Characterizing the relationship between microplastic, marine aggregates, the microbial communities associated with them and the extent to which both microplastic and microbial communities change as they sink to the ocean floor is likely to be a fruitful and important future research priority.

Biological effects to individuals

Microplastic poses a risk to organisms across the full spectrum of biological organization from cellular to population level effects (summarized in Fig. 3)[48]. Understanding the potential impacts of microplastic across all biological levels is key for the development of effective risk assessments, for example using the adverse outcomes pathway (AOP) approach, common in chemical regulation[49]. Most studies have focused on individual level effects of microplastic ingestion in adult organisms, often combined with effects of microplastics at the cellular and sub-cellular level. For example, negative impacts of polystyrene microbead ingestion by rotifers on adult growth rate, fecundity and lifespan has been observed[50]. They then used *in vitro* tests to relate these effects to activation of antioxidant-related enzymes and mitogen-activated protein kinases (MAPK) signalling pathways associated with inflammation and apoptosis. Sub-cellular oxidative stress responses to polystyrene microbead (2–6 μm) ingestion have also been reported[51] in mussels exposed to 2,000 particles per ml seawater.

Microplastic ingestion rarely causes mortality, with few significant impacts on survival rate. As a result, LC_{50} values (the concentration required to cause lethality in 50% of the population) are rarely reported. Notable exceptions include: 100% mortality of common goby following 96 h exposure to polyethylene with 200 μg l^{-1} pyrene[52]; 0% survival of Asian green mussels exposed to 2,160 mg l^{-1} polyvinylchloride (PVC) for 91 days[53]; and 50% survival of *Daphnia magna* neonates after 14 days exposure to 100,000 particles ml^{-1} of polyethylene[54]. In all such cases, concentrations far exceeded environmental relevance.

An emerging paradigm is that chronic exposure to microplastic is associated with reduced ingestion of natural prey, resulting in shortfalls in energy and reduced growth and fecundity[55]. Reduced food consumption following ingestion of microplastic is associated with reductions in: metabolic rate, byssus production and survival in Asian green mussels[53]; fecundity and survival in copepods[56]; growth, development and survival in *Daphnia*[54]; nutritional state and growth in langoustine[57]; and energetic reserves in shore crabs and lugworms[58,59]. However, impacts on feeding are not always evident, with a number of suspension-feeding (for example, oyster larvae, urchin larvae, European flat oysters, Pacific oysters)[60–63] and detritivorous (for example, isopods, amphipods)[64,65] invertebrates showing no indication of impaired ingestion when exposed to microplastics.

Reproductive output is a particularly sensitive endpoint, with energetic depletion resulting from microplastic exposure affecting fecundity and fertility. In adult Pacific oysters (*Crassostrea gigas*), an eight-week exposure to polystyrene microbeads across a reproductive cycle resulted in reduced sperm motility, oocyte numbers (fecundity) and size (energetic investment per oocyte). Following fertilization, larval yield and growth were also significantly reduced without any further microplastic exposure as a carryover from the adult exposures[63]. Similar effects have been observed with the copepods *Tigriopus japonicus*[66] and *Calanus helgolandicus*[56], and rotifer *Brachionus koreanus*[50], with reduced fecundity, egg size, hatching success and survival of progeny. These findings suggest that the physical presence of microplastic particles where there should otherwise be food, and the longer gut passage times of these non-nutritious particles is associated with adverse biological impacts.

From individuals to ecological processes

A general paradigm of ecotoxicology is that the impact of a pollutant cascades through levels of biological organization such that biochemical changes at subcellular levels precede changes to cells and tissues, which in turn affect physiological functions and individual fitness (that is, populations) and ultimately ecosystems[49] (Fig. 3). Directly linking sub-organism-level impacts to the ecosystem level is hugely challenging for any environmental pollutant, yet it is the ecosystem-level impact of a contaminant that is of ultimate concern. An individual's behaviour forms an important link between physiological and ecological processes and is a sensitive measure of response to environmental stress or pollutants[67]. Hence behavioural changes can serve as early warning signs for ecosystem level effects[68]. Understanding how the presence of microplastic changes complex behaviours such as predator–prey interactions, burrowing and orientation are essential to understanding its ecological impact[67].

Behaviour

A handful of studies have considered altered behaviour, such as motility, hiding responses and predator–prey interactions, resulting from microplastic exposure. The predatory performance of juvenile gobies (*Pomatoschistus microps*) in catching prey (*Artemia* spp.) was reduced by 65% and feeding efficiency by 50% in laboratory bioassays when fish were simultaneously exposed to polyethylene microspheres of a similar size and abundance to prey[69]. *Artemia* are highly mobile, raising the possibility that the stationary microplastic reduced the discrimination of the fish for their prey. Beachhoppers show characteristic behaviours including distinctive jumping, a highly energy-dependent process, and shelter relocation post disturbance, driven largely by hygrokinetic (favouring movement towards humid conditions) and intraspecific interactions[70]. Exposure of the Australian beachhopper *Platorchestia smithi* to beach sediments containing 3.8% by weight polyethylene microspheres led to reduced jumping, whilst the time taken to return to shelters post disturbance was not changed[71]. Beachhoppers that ingested microplastic were significantly heavier, with an increase in gut retention times. Similarly, in the freshwater crustacean *D. magna*, ingestion of 1-μm polyethylene particles from the water column caused immobilization in a dose- and time-dependent manner[72]. Weight gain may contribute directly to reduced motility, but motility may also be affected indirectly as a result of reduced energy uptake from the diet. Reduced energy reserves[34,56], for example, could influence a wide range of behaviours, including those associated with risk versus benefit decisions in feeding behaviour. Studies in social vertebrates (for example, birds and fish) show how individuals will accept a greater risk of predation to obtain food with increasing hunger or energy deficit[73–75]. The internal state of animals can significantly determine their choice between alternative behavioural tactics[76], providing an interesting hypothetical mechanism by which microplastic ingestion may influence complex behaviour and species interactions.

Bioturbation

The reworking of sediments by plants and animals contributes towards ecosystem functioning by modifying benthic seascapes, increasing nutrient flux across the benthic boundary layer and altering habitat structure for other benthic organisms. Hence it can link individual physiology with ecosystem function. Throughout coastal and shelf seas benthic environments, the burrowing activities of meiofaunal and macrofaunal invertebrates such as polychaete worms, brittlestars and amphipods, whose biomass in continental shelf sediments can be up to 200 g dry weight per m^2 (ref. [77]), influences the physical and chemical properties of the sediment where they live. When the large deposit feeding polychaete worm *Arenicola marina* was chronically exposed for a month to sediment containing 5% by weight PVC, there was a significant reduction in feeding activity and the gut passage time of sediments was 1.5 times longer[34]. Extrapolation of this data to the Wadden Sea predicted this level of contamination would lead to 130 m^3 less sediment being turned over annually for that population alone. A subsequent study suggested that exposure of *A. marina* to polyethylene and PVC in sediments would reduce the surface area available for sediment–water exchange, and hence the release of inorganic nutrients, by 10–16% (ref. [78]).

The feeding behaviour of *A. marina*, and other bioturbators such as brittlestars, could alter the distributions of microplastics at the water/sediment interface, enhancing mixing of particles deeper into the sediments (Fig. 4) making them bioavailable for other meiofauna. Benthic filter feeders such as mussels and sea squirts process large volumes of seawater per hour through their siphons. Expelled waste water and pseudofaeces could draw down microplastics from the water column to the benthic boundary layer, leading to incorporation into sediments by burrowing species. Hence, microplastics may impact feeding rates of key species, whilst the same feeding activities may impact the fate of microplastics within the marine environment.

Zooplankton feeding and carbon export

Altered feeding behaviour in zooplankton in the presence of microplastics may contribute towards larger scale effects due to their important role within pelagic ecosystems. For example, prey selection by zooplankton can have a disproportionate impact on both the biogeochemistry and the timing of food presence in pelagic food webs[79]. Microplastic ingestion reduced the energetic intake of the copepod *Calanus helgolandicus* by 40% in laboratory exposures, even when the abundance of microplastic was an order of magnitude less than that of prey[56].

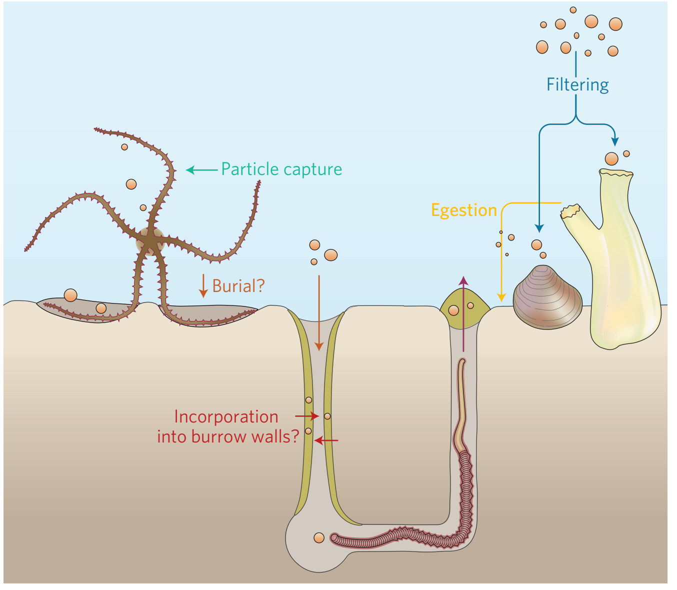

Figure 4 | Mechanisms by which benthic organisms could influence the partitioning of microplastics between the water column and sediments. The filter-feeding action of benthic mussels and sea squirts can draw down microplastic from the water column towards the benthos, increasing its bioavailability to sediment-dwelling organisms. Bioturbating species such as brittlestars and deposit-feeding polychaetes may then incorporate microplastic into sediments to varying depths through burrowing behaviour.

If similar reductions in consumption are observed across entire zooplankton communities as a result of microplastic ingestion this could have knock-on effects for pelagic ecosystems. However, whilst zooplankton ingestion of microplastic has been reported for naturally caught animals[80], we know little of the extent of microplastic consumption within communities in their natural settings, let alone how it might influence the dynamics of mixed species assemblages. Zooplankton not only influence planktonic assemblages via their feeding behaviour and prey selection but contribute to carbon transport to deeper waters through excretion of ingested organic matter[81–83]. In laboratory exposure studies copepods egested micropolystyrene-laden faecal pellets of reduced density and integrity and which had a 2.25-fold reduction in sinking rate[33]. Extrapolating these results to the average depth of the ocean would hypothetically result in faecal pellets taking on average 53 days longer to sink to the benthos. Polyethylene and polypropylene microplastics, which are very common in surface waters of oceanic regions, may have an even more pronounced effect on faecal pellet sinking speed, because they are less dense than the polystyrene used in these experiments. Given the importance of zooplankton faecal material in driving carbon export from surface waters, such reductions in density and sinking rates could potentially contribute to global scale alterations in carbon flux if zooplankton across the oceans are indeed consuming microplastic particles in sufficient quantities[25].

Conclusions and future directions

What emerges from this account are the varied ways in which the influx of microplastic into the oceans could plausibly be impacting ecological processes. Microplastic represents a novel matrix, providing an alternative surface for pollutants, bacteria and other types of organic matter to absorb, interact, and be transported. Its

Table 1 | Comparison of microplastic against the criteria proposed for classification of pollutants as persistent organic pollutants under the Stockholm Convention and against the criteria for recognition as a planetary boundary threat.

Classifications and criteria	Criterion met?
Persistent organic pollution*	
Environmentally persistent	Yes
Transported over large distances	Yes
Bioaccumulate through the food web	Yes
Cause adverse health effects	Yes
Planetary boundary threat†	
Disruptive effect on vital Earth system processes of which we are ignorant	Uncertain
Disruptive effect is not discovered until the associated impacts manifest at a global scale	Uncertain
Impacts are poorly reversible as the pollutant cannot be readily reduced in the environment	Yes

*Data from refs [91,92]. †Data from refs [86,93].

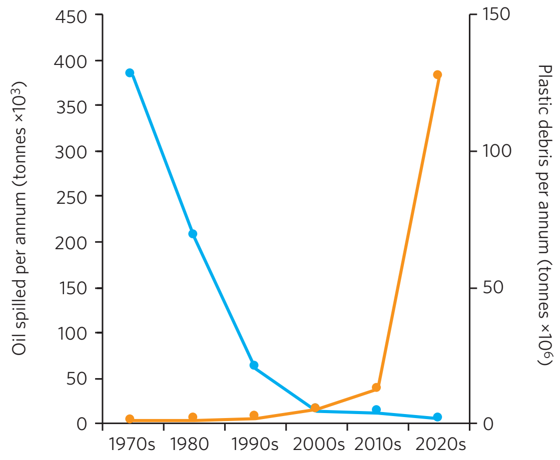

Figure 5 | Graph showing global statistics for the amount of crude oil spilled at sea compared with the increase in terrestrial plastics export into the oceans, as a function of time. The blue line shows global spillages of crude oil compiled by the International Tanker Owners Pollution Federation[87]. The orange line shows estimated amount of plastic debris discharged to the oceans, extrapolated from refs [4,90].

bioavailability to marine animals appears to be rarely lethal, but chronic exposures can evidently alter feeding, energy assimilation, growth and reproductive output. Extrapolating these impacts to the ecosystem level challenges our current abilities to measure and model relevant processes on a global scale, but we can deduce that potential impacts include behavioural changes to predator–prey relationships, bioturbation, and perturbations to carbon cycling. How do we respond to these observations and what can we do to mitigate them? How does microplastic compare with other anthropogenic stressors and can we use existing tools for monitoring and remediation?

Is microplastic a persistent pollutant?

A wide range of policy documents and procedures are in place to assess and restrict the release of chemical pollutants, including international treaties, for example, the Montreal Convention, Stockholm Convention, Minamata Convention, and diverse national legal instruments. In general, chemicals are assessed and controlled according to their persistence, bioaccumulation potential and toxicity and controlled accordingly[84]. It could be argued that since these measures have been so successful in controlling other persistent pollution threats, such as organochlorine pesticides and polychlorinated biphenyls, they should also be sufficient to curtail microplastic pollution. An immediate problem is presented by the observation that a microplastic is not an individual entity, but consists of a complex mixture of polymers, additive chemicals, absorbed organics and living substances. The assessment of each substance individually is unlikely to reflect the net sum of their action or to adequately assess their bioavailability to organisms[85]. Despite this limitation, comparison of microplastic against the criterion for classification as a persistent organic pollutant under the Stockholm Convention shows the concept of including them to be worthy of discussion (Table 1).

Is microplastic a planetary boundary threat?

Another way of viewing microplastic could be as a planetary boundary threat. Chemical pollution has been identified as one of the anthropogenic impacts of such magnitude that it threatens to exceed global resilience, alongside stressors such as climate change, biodiversity and ocean acidification[86]. By identifying these science-based planetary threats, we can theoretically encourage boundaries to be set at a global scale to allow humanity to flourish without causing unacceptable global change. Assessing microplastic against the criteria of planetary boundary threats could therefore be one way of encourage global action towards remediation and control (Table 1).

Is microplastic a marker of the Anthropocene?

Microplastic could also be viewed as a new anthropogenic material, alongside the products of mining, waste disposal and urbanization, identified as geological materials displaced by human activity with the potential for long term persistence[3]. According to this view, the massive increase in the production and release of plastics is mirrored by several other substances, including aluminium, concrete and synthetic fibres for which hundreds of thousands of tonnes are manufactured each year, sufficient to leave an imprint of population growth and industrialization in the fossil record. By defining these products as markers of a new geological epoch, the Anthropocene, the authors argue that this places the impetus on human society to acknowledge the consequences of its own actions.

The opportunity for change and remediation is not outside the realms of possibility. Figure 5 shows how global action has been successful in reducing the amount of spilled oil reaching the oceans each year as a result of concerted global action to improve tanker safety[87]. Statistical data for global emissions of hazardous waste is hard to come by, but systematic data gathered by the US Environmental Protection Agency on chemical waste emissions by US industries revealed impressive reductions, from some 278 million tonnes of hazardous waste generated by chemical plants in 1991, to just 35 million tonnes in 2009[88]. This latter improvement was brought about through an industry-led move towards green chemistry, which aimed to redesign chemical processes to make them cleaner, safer and more energy efficient. Polymers make up around 24% of the output of chemical industries worldwide[89], raising the possibility that concerted action to improve current chemical management and disposal practices for polymers is a real possibility that could lead to a similar positive reduction in waste.

Meeting the challenges posed by microplastic requires us, as a society, to actively engage and consider our role in patterns of consumption and careless disposal. Industry can play its role by reassessing the integrated management of chemical production. Finally, we have a golden opportunity as scientists to find innovative ways of rising to the multidisciplinary global challenge posed by the vast tide of marine microplastic debris which threatens to engulf our oceans, before it causes irreversible harm.

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