CHAPTER 11

Microplastics in Marine Food Webs

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11.1 INTRODUCTION

A multitude of food webs exist in the world's oceans, are made up of a wide variety of organisms that occupy distinct niches, and possess different behavioral and feeding strategies. So far, only a small fraction of these taxa have been included in studies concerning microplastic debris in marine ecosystems. Microplastics (microscopic plastic debris, 100 nm to 5 mm diameter) are now widely recognized as a pollutant of international concern (Galgani et al., 2013; GESAMP, 2016). Understanding the potential impacts this prolific contaminant can have on marine life and food webs has become of intense interest, with an exponential increase in research being conducted in recent years. In this chapter, we explore how microplastics enter marine food webs and consider the complex, iterative relationship between microplastics, biota, and biologically mediated ecological processes. Microplastic ingestion has been documented in animals throughout the marine food web, including zooplankton (Desforges et al., 2014), fish (Bellas et al., 2016; Lusher et al., 2013), marine mammals (Lusher et al., 2015a; Bravo Rebolledo et al., 2013), turtles (Nelms et al., 2016), and seabirds (Tourinho et al., 2010). We explore the factors affecting microplastic consumption and infiltration into marine food webs, with consideration given to spatial overlap, predator-plastic ratios, the properties of microplastic debris, and the life history and feeding strategies of biota demonstrated to consume plastic. At the individual level, microplastics pose a risk to the health of the organism; indeed, a growing number of experimental studies have demonstrated that at critical concentrations, microplastics can adversely affect feeding, energetic reserves, reproduction, growth, and survival in invertebrate and vertebrate species, including calanoid copepods (Cole et al., 2015; Lee et al., 2013), polychaete worms (Wright et al., 2013b; Green et al., 2016), fish (Rochman et al., 2015), and oysters (Sussarellu et al., 2016). The latest evidence suggests that microplastics could also affect higher levels of biological organization, with population shifts and altered behavior impacting upon the ecological function of keystone species (Galloway et al., 2017). While the risks microplastics pose to individual biota are explored in greater detail in other chapters of this book, here, we focus on how plastics have the potential to affect food webs and marine

ecosystems as a whole. Furthermore, we consider how trophic interactions and ecological processes can change the microplastics themselves.

11.2 THE OVERLAP BETWEEN PLASTICS AND BIOTA

Perhaps the most important variable affecting the flux of microplastic particles into marine food webs is their abundance and distribution in the environment and physical overlap with biota.

11.2.1 Geographical Overlap

In recent years, there has been a concerted effort to identify the different habitats polluted with plastic debris and ascertain the concentrations of microplastics across a wide range of aquatic ecosystems. Microplastics are ubiquitous in the world's oceans, and their presence in remote locations, including the Arctic (Lusher et al., 2015b), Antarctic (Waller et al., 2017), mid-oceanic atolls (Do Sul et al., 2014), and oceanic depths (Woodall et al., 2014), have highlighted their widespread distribution. However, accurately determining the concentrations and type of microplastics present in seawater and sediments has proved a challenge. Adaptations to traditional sampling techniques (e.g., trawls and sediment grabs; see review by Hidalgo-Ruz et al., 2012) have proved invaluable for collecting samples; however, isolating and identifying microplastics have required a more novel approach (see Box 11.1). In recent years, a wide range of methodologies have been

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BOX 11.1 Methodological Approach

Although microplastics are a relatively new topic in the environmental sciences, researchers have been able to learn from the experimental approaches and understanding gleaned from the fields of ecotoxicology, marine biology, and aquatic chemistry. Basic mechanisms of feeding and energy transfer in marine food webs are well understood, and this knowledge has been useful in understanding observed interactions between microplastics and biota. Lessons learnt from nanoparticle research have been of particular relevance to microplastic exposure studies, particularly with respect to uptake mechanisms and mechanisms underpinning observed health effects and developing sound ecological risk assessment (Syberg et al., 2015; Hüffer et al., 2017). In contrast, collecting field data on the distribution and quantity of microplastics in different ecological compartments (water surface, water column, seafloor habitats, and strandline) has turned out to be a significant challenge, requiring novel approaches, method development, and optimization (Hidalgo-Ruz et al., 2012; Lusher et al., 2017). An ongoing issue facing microplastic researchers is the absence of harmonized sampling or sample analysis protocols, and a forward challenge for the field is to work toward methodological standardization.

suggested for extracting and analyzing plastics (see reviews by Lusher et al., 2017; Miller et al., 2017); however, the variety of methods employed can often result in incomparable datasets. Analyzing such data is further confounded by the heterogeneous distribution and temporal variability in microplastic concentrations.

Global sampling efforts have helped to identify "hot spots" of plastic (Eriksen et al., 2014; Cózar et al., 2015; Van Sebille et al., 2015). For example, the North Pacific, South Pacific, and North Atlantic subtropical oceanic gyres, which amass flotsam from throughout the oceanic basins, have all been highlighted as accumulation zones for microplastic debris (Moore et al., 2001; Law et al., 2010; Eriksen et al., 2013). Oceanic gyres are largely oligotrophic and therefore relatively devoid of marine life; however, for biota that can survive in the gyres, interactions with microplastic will be commonplace. For example, in the North Pacific gyre, Moore et al. (2001) observed a 6:1 plastic-to-plankton ratio, and Goldstein and Goodwin (2013) identified that 33% of gooseneck barnacles (*Lepas* spp.) had consumed between 1 and 30 items of microplastic. However, our understanding of the numbers and distribution patterns of microplastics in marine environments is far from complete. This was pointed out already in the study dataset of >330 μm particles from surface water tows, which showed smallest particles to be most prevalent, but only down to a certain size group (1 mm) after which the concentrations decreased (Cozar et al., 2015). This absence of smaller plastic may result from difficulties in identifying very small particles or might be explained by biotic or abiotic degradation or movement of these plastics.

Enclosed and semienclosed seas like the Mediterranean Sea and the Baltic Sea have also been noted for their high microplastic concentrations (Collignon et al., 2012; Setälä et al., 2016b; Gewert et al., 2017) and thus have been proposed to accumulate plastic debris in greater amounts than open oceans (Fossi et al., 2016). As increasing concentrations inevitably increase the exposure of organisms at the base of the food webs, this may be the case also at higher trophic levels. In the Mediterranean Sea, stomach analyses from large pelagic predators (swordfish and tuna) revealed that 18.5% of the fish examined contained microplastics. The reported concentrations of microplastics from the surface waters of another highly polluted semienclosed sea basin, the Baltic Sea, show how the microplastic concentrations in surface waters may significantly differ spatially (Setälä et al., 2016b; Gewert et al., 2017) and may reach high concentrations (up to $4.7 \times 10^5 \ \text{km}^{-2}$) close to highly populated urban areas with low water exchange, or as was found by Gorokhova (2015), in deep water layers separated by a halocline. In the Baltic Sea, the field observations of microplastics in the food web have mainly related to fish, herring being the most studied fish species. Bråte et al. (2017) analyzed the data from various studies on microplastics in fish from these Nordic waters; in the analyzed dataset consisting of 1425 individuals of Atlantic and Baltic herring, microplastic ingestion varied between 0% and 30%. Ogonowski et al. (2017) reported that approximately 50% of herring individuals had ingested plastics along the Swedish coast in the Baltic Sea,

although the numbers of microplastics on individual fish were low (0–1 per fish), reflecting great variability between samples. In comparison, very low numbers of particulate microplastics (fibers were excluded) were also found in a recent study containing over 500 herring individuals from the open sea areas of the northern Baltic Sea (Budimir et al., 2018). The reported share of herring with ingested microplastic particles varies greatly between these studies and may at least partly be explained by spatial differences in the overlap of microplastics and herring. Differences in methods used for extracting microplastics from fish tissue makes comparisons between studies difficult and conclusions vague.

A recent study predicts the greatest overlap between microplastics and marine life will occur in coastal regions (Clark et al., 2016). Coastal waters and estuaries have relatively high biological productivity owing to their shallow, protected waters and fresh nutritional inputs from rivers, which are valued by aquaculture and fisheries, and encompass important nursery grounds for commercially exploited marine taxa. It is postulated that their proximity to sources of anthropogenic pollution (e.g., maritime industry, urban areas, and riverine inputs) puts them at high risk of microplastic pollution. Microplastic sampling in coastal regions is problematic owing to the density of organic material in these waters (Cole et al., 2014); nevertheless, recent studies have highlighted the overlap between plastics and biota in coastal waters. In the English Channel, a 36.5% incidence of microplastic ingestion in demersal and pelagic fish species has been observed (Lusher et al., 2013), while 70% of brown shrimps (*Crangon crangon*) sampled from the coastlines of European countries along the English Channel have been shown to consume microplastic (Devriese et al., 2015). More recently, Steer et al. (2017) identified the ratio of microplastics to fish larvae ranged from 27:1 nearest Plymouth (United Kingdom) to 1:1 35 km from the shoreline.

11.2.2 Habitats

Microplastics consist of a wide range of polymers which have their own special characteristics that affect their distribution in the water, and thereby which organisms and habitats are prone to plastic exposure. Local wind conditions, water currents, and geomorphology all affect the distribution of microplastics in water and their spatial accumulation (Barnes et al., 2009). The vast amounts of anthropogenic debris washing up on beaches across the globe (Browne et al., 2011) provide visual evidence of the efficiency with which floating plastic debris can be transported on the sea surface. Approximately half of marine plastic debris is initially buoyant (e.g., polystyrene, polyethylene, and polypropylene), while denser plastic (e.g., polyvinylchloride and nylon) readily sinks in seawater. As observed from numerous sampling campaigns, microplastics can permeate throughout the water column, with plastic and microplastic debris, including low-density polymer plastic, widely evident in benthic ecosystems (Miller et al., 2017).

Laboratory exposures have been used to demonstrate that biotic interactions including biofouling (Fazey and Ryan, 2016; Kaiser et al., 2017), egestion (Cole et al., 2013, 2016), and bioturbation (Näkki et al., 2017), as well as physical processes such as fragmentation (Andrady, 2017), can affect the properties and movement of plastics; it is hypothesized that these processes could result in changes to the distribution of microplastics within marine ecosystems where biota and plastics overlap (Fig. 11.1; Clark et al., 2016). In these waters, we might expect a downward flux of plastic debris, resulting in an accumulation of microplastics on the seafloor (Barnes et al., 2009; Woodall et al., 2014). However, it is important to recognize that vertical flux should be considered a redistribution of plastics, and not a "removal" mechanism. Benthic ecosystems can be highly biologically productive habitats, supporting a diverse array of life that play vital roles in the oceanic carbon pump (Turner, 2015), reef formation (Beck et al., 2011), and bioturbation (Cadée, 1976). Environmental sampling has identified plastic pollution in every benthic habitat investigated, including highly remote areas such as both Arctic (Bergmann et al., 2017) and Antarctic (Munari et al., 2017) polar regions and the deep sea (Woodall et al., 2014; Bergmann et al., 2017). Plastic concentrations in sediments are highly variable, due in part to different sampling and extraction methodologies and also to the natural heterogeneity of sediments. Concentrations of up to 6600 microplastics per
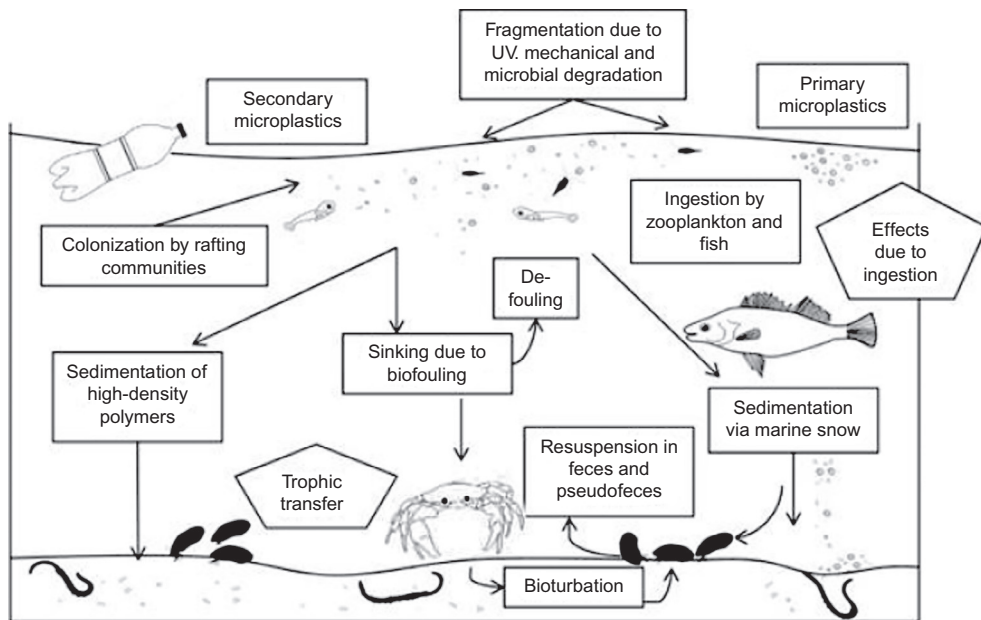

Fig. 11.1 Potential pathways for the transport of microplastics and its biological interactions. *Courtesy of Wright, S.L., Thompson, R.C., Galloway, T.S., 2013a. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492.*

kg have been reported in Arctic sediments (Bergmann et al., 2017), and in a study of 42 sites around the Australian coastline (Ling et al., 2017), a regional average of 3400 microplastics per L was reported, with the highest individual sample yielding 12,500 plastics per L. Laboratory exposures have shown that benthic invertebrates readily consume plastic, and this can have a detrimental impact on their health and functionality. A reduction in energy reserves (Wright et al., 2013a), reproduction (Sussarellu et al., 2016), metabolism, and bioturbation activity (Green et al., 2016) has been reported in benthic organisms, with potential impacts to ecosystem functioning (Volkenborn et al., 2007).

11.3 ENCOUNTERING AND DETECTION OF MICROPLASTICS

Compared with the dynamic interactions between a predator/grazer and their natural prey, the relationships between an animal and microplastic are somewhat simplified. The feeding mode and life history of an organism will affect both its encounter and ingestion rate of microplastic. Organisms may actively select microplastics from the environment in search of prey, or they may ingest them accidentally while feeding on food particles or animals that contain plastic.

11.3.1 A Passive Particle

Microplastics are passive: freely floating on the water surface, suspended or slowly sinking in the water column, or deposited on or within the seabed. Encounter rate (i.e., the commonality with which a predator comes into contact with its prey) is a crucial factor affecting the ingestion rate of that prey (e.g., Evans, 1989). Primarily, encounter rate is influenced by the relative abundance of predator/grazer and prey; for microplastic ingestion to occur, there would need to be a significant spatial overlap between biota and plastic and a substantial amount of plastic present for a likely encounter to occur.

Classic work on feeding efficiencies has shown how changes in prey density affect the ingestion rates of predators. Ingestion increases with an increasing prey density up to a saturation point, whereby the predator cannot process more prey even though the prey density still increases, as described by Solomon (1949) and Holling (1959). This has also been shown in laboratory studies with virgin microplastics and various invertebrate taxa: the more particles the organisms were offered, the more they were ingested, even when working with the relatively high concentrations used in laboratory settings (Fig. 11.2) (e.g., Cole et al., 2013; Setälä et al., 2016a). Gelatinous organisms (e.g., jellyfish and ctenophores) may feed without reaching a saturation level. This means that even in very high concentrations of prey, they continue capturing them but start to egest/vomit prey that they are unable to process. However, it has been observed that jellyfish ingested relatively low numbers of microplastics compared with other filter feeders (e.g., copepods)
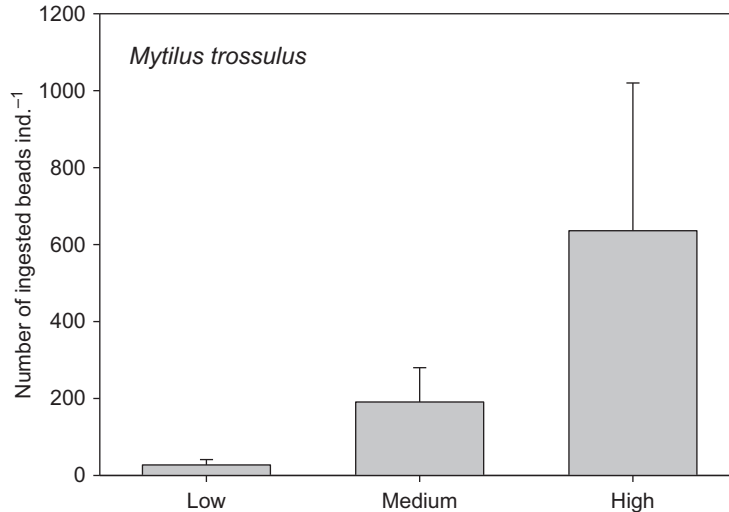
Fig. 11.2 The number of ingested 10 μm spheres (mean ± SD) in *blue* mussel (*Mytilus trossulus*) at three different bead concentrations (low, 5; medium, 50; and high, 250 beads mL^{-1}). *Data from Setälä, O., Norkko, J., Lehtiniemi, M., 2016. Feeding type affects microplastic ingestion in a coastal invertebrate community. Mar. Pollut. Bull. 102(1), 95–101.*

in the South China Sea (Sun et al., 2017). The classical Holling-type ingestion patterns may also be affected by clogging of feeding appendages. In such cases, a high concentration of microplastics (fibers) may decrease feeding activity, resulting in lower ingestion rates.

Active, motile predators (e.g., cruising predators) will encounter prey, and we therefore assume plastic, more readily as they move through the water or sediment. Nonmotile animals will encounter microplastics the same way they come into contact with suspended or deposited prey (i.e., water currents bringing particles close enough for capture or generating localized currents to draw suspended particles to the organism). Sessile organisms are also not able to avoid exposure to microplastics and are subjected to all particles present in the suspension they are feeding in. However, passively floating and sessile organisms and ambush predators can compensate for reduced encounter rates through high efficient filtering activity (Green et al., 2003).

11.3.2 Detecting Microplastics

Animals detect prey using visual or chemical cues or hydromechanical signals when identifying motile prey moving through the water. Organisms relying upon visual detection may mistake microplastics as prey. For example, ocean-foraging Fulmars travel vast distances across the North Atlantic, relying on visual cues to select prey floating near the ocean surface; dissections of Fulmars beached along European coastlines have routinely

identified that the seabirds' stomachs are full of plastic (Van Franeker et al., 2011). Researchers often note that microplastic debris comes in a wide range of shapes, size, and color; however, it is currently unclear whether these attributes have any influence on its likelihood of being consumed by animals relying on visual detection.

The swimming activity and speed of motile prey affect their encounter rate, with numerous studies establishing that actively moving prey are detected more frequently and encountered more often (Gerritsen and Strickler, 1977; Gerritsen, 1984; Tiselius et al., 1993). As microplastics are passive particles, they cannot be detected using hydro-mechanical signals, and we would therefore expect them to be encountered less frequently than motile prey at similar concentrations. For example, in pelagic communities, the swimming activity of the predator is affecting the encounter rate of microplastic particles in addition to their density and overall distribution. However, as plastic particles are nonmotile, they make easy targets for predators and may therefore be ingested (if not actively rejected) more readily than natural prey that can incite escape responses (e.g., Green et al., 2003) and may require an active capturing process.

Chemical cues play a significant but variable role in the prey selection of marine organisms from invertebrates to mammals. For example, fish have diversely developed olfactory organs (Hara, 1975) for detecting signals related to reproduction and feeding. Some marine species possess highly developed chemosensory organs (e.g., sharks), while in some others, they may be poorly developed (e.g., visual predators like pike) (Hara, 1975). Crustaceans, such as copepods are generally considered to be selective feeders that display flexibility in their feeding behavior (Koehl and Stickler, 1981); discrimination between prey can be based on size (Frost, 1972), motility (Atkinson, 1995), or chemical signals (Cowles et al., 1988). Not all chemicals are sensed; what is important is that in order for an organism to receive chemical stimuli, the chemical itself should be soluble in water. Chemical signals can assist in the selection for high-quality food, determined by protein content (Cowles et al., 1988), or be used to avoid unsuitable prey (e.g., harmful algae containing toxic compounds like saxitoxin). However, active avoidance of unsuitable or toxic prey by copepods is most likely a result of a common history, that is, coevolution of the prey and predator (Colin and Dam, 2002).

Field-collected data and exposure experiments show that plastic particles floating in the water and embedded in the sediment are rapidly colonized by rich microbial communities comprising prokaryotic and eukaryotic organisms, like bacteria and algae (Oberbeckmann et al., 2014; Harrison et al., 2014). So far, there is very little information on how the formation of biofilm actually affects the ingestion of microplastics. Recent studies show that the effects of biofouling are most likely taxon- or even species-specific. Vroom et al. (2017) identified that biofouling of polystyrene beads promoted ingestion by planktonic crustaceans, although this was somewhat dependent on taxon, size, and stage of the grazers. For two of the three copepod species studied (*Acartia longiremis* and *Calanus finmarchicus*, excluding the adult females of the latter), it was shown that

> **BOX 11.2 Experimental Work**
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> Most of the information that has so far been produced on the parameters affecting microplastic ingestion by marine organisms come from simplified laboratory experiments. Results from experimental work should not be directly applied to natural conditions where confounding factors exist. When conducting environmentally relevant experimental work on ingestion and effects of microplastics in food webs, the concentration, size, and type of the used particles should be adjusted to correspond to natural conditions. At the moment, there is still a mismatch between "reality" and laboratory experiments. So far, most experiments are run with microplastic concentrations higher than those commonly found in the environment and with virgin particles of uniform size and shape that fail to accurately represent the conditions in the field (Phuong et al., 2016). This inconsistency is likely to influence our understanding of the marine microplastic problem as Ogonowski et al. (2016) showed in laboratory experiments comparing the effects of primary and secondary microplastics. They showed that secondary microplastics have more negative effects on feeding in a cladoceran, *Daphnia magna*, compared with primary microplastics commonly used in the previous studies. The reason why experimental laboratory studies have not used microplastic concentrations commonly observed in marine environment is not only their "low" concentrations but also the uncertainty in assessing their concentrations. Microplastic concentrations found in marine environments vary significantly between areas and habitats but seem to be low when compared with the numbers of the real prey, which makes environmentally relevant exposure studies difficult. Long-lasting exposure experiments in mesocosms mimicking natural conditions would be needed to more accurately assess the relationships between microplastics and their potential predators.

in most cases, the fouled microplastics were ingested by more individuals and at higher rates than the unfouled plastics. However, one copepod species, *Pseudocalanus* spp., did not ingest any of the microplastic particles offered. Contradictory results were reported by Allen et al. (2017) who studied the ingestion of weathered, fouled, and unfouled pre-production pellets (polystyrene (PS), low–density polyethylene (LDPE), and high-density polyethylene (HDPE)), by a scleractinian coral species known to use chemosensory cues for feeding. Their results showed that the corals ingested different types of plastics, consuming significantly more unfouled than fouled microplastics that were taken up (Box 11.2).

11.4 INTO THE FOOD WEBS

The ingestion, entanglement, or inhalation of microplastic by marine organisms can be viewed as an entry point into marine food webs. Owing to their small size, microplastics are bioavailable to a wide range of marine organisms and can be both selectively and accidentally ingested (Schuyler et al., 2012). The ingestion of microplastic particles is affected

by their concentration, size, shape, distribution, and chemical character (i.e., density and chemical signal) and the animal's feeding habits. In animals with developed organs for prey detection, plastic polymers may thus not be selected, or they may be rejected if they are recognized as being unfavorable or if a more preferable prey is available.

11.4.1 Filter Feeding

Filter-feeding organisms are prevalent throughout marine food webs, from small planktonic invertebrates and benthic taxa to megafauna, where they feed on suspended organic material, such as algae, zooplankton, fish larvae, and detritus. The size range of particles that can be ingested by a grazer depends on the feeding mode (e.g., filter feeding or raptorial), gape size, and specific feeding mechanisms of the grazer/predator. For filter feeders, the actual size limits for the ingested prey are set by the structure and function of the filtering apparatus used for trapping particles from the suspension (Riisgård and Larsen, 2010). Filtering devices in suspension–feeding organisms are not simple sieves that mechanically clean the water from suspended particles. The structures of filtering apparatus found in unicellular, invertebrate, or vertebrate organisms differ greatly, both between and among taxa, with varying levels of adaptability and sensory capability. Particle capture depends on particle type (e.g., shape, size, and density), particle concentration, water viscosity, the quantity of water that is filtered, and filtering efficiency. Besides direct contact, the capturing mechanisms may also involve other factors, such as chemo- and mechanoreception (Riisgård and Larsen, 2010). Moreover, experimentally measured clearance rates of plankton have been found to vary also depending on temperature, salinity, and the type of prey that has been offered (e.g., Kiørboe et al., 1982; Garrido et al., 2013). Daily clearance rates of marine invertebrates can vary from microliters (unicellular organisms, like ciliates) to milliliters (copepods), liters (bivalves), hundreds of liters (gelatinous zooplankton), or more (baleen whales).

Two parameters are commonly used to estimate the efficiency and outcome of filter feeding: ingestion and clearance rate. The ingestion rate denotes the number of prey particles ingested per predator in a time unit. Ingestion rate can be experimentally estimated directly, through observations of ingested prey particles inside the organism, or indirectly, as the disappearance of prey from the experimental media over time. In the past, inert plastic particles (spheres) have been used as surrogates for natural prey to estimate feeding parameters in planktonic organisms (Huntley et al., 1983; Borsheim, 1984; Nygaard et al., 1988). These historical studies with *Calanus* and related copepod genera have demonstrated a preference for algae over polystyrene beads, alongside size selectivity (Fernandez, 1979; Donaghay and Small, 1979; Huntley et al., 1983). However, observations for such preferences do not necessarily hold for all developmental stages, which further complicates things, that is, when exposure studies are being conducted. Clearance rate is a derivative of ingestion rate and is calculated by dividing the latter by prey

concentration. The clearance rate thus measures the water volume that an individual organism can clear of food particles in a time unit. To understand the probability of any suspended particle to be ingested by a filter-feeding organism, both the clearance rate and the concentration of suitable prey should be taken into account.

From the viewpoint of a small filter-feeding organism under natural conditions, microplastic concentrations may be too low for routinely encountering a plastic particle. However, in waters containing high concentrations of microplastics, the situation is different even for a small organism with a relatively low clearance rate and efficiency, such as a copepod. As an example, the experimentally defined daily clearance rates of common copepods may vary between ~10 and <200 mL (Frost, 1975; Engström et al., 2000; Setälä et al., 2009). In theory, a copepod feeding, for example, with a high clearance rate of 144 mL/day (Frost, 1975), at a concentration of 9200 plastics per m^3 as has been observed from the Pacific Ocean (Desforges et al., 2014), a single microplastic would be ingested by every 0.7 copepods, assuming all particles are edible and the animals are solely undertaking passive ingestion without rejection of plastic. Assessments based on animals collected from the field have also confirmed the role of zooplankton as entry points for microplastics to food webs. The study of Desforges et al. (2015) which was based on the analysis of the number of ingested microplastics from subsurface-collected zooplankton and the overall distribution of these species from the Northeast Pacific Ocean, identified encounter of microplastics by zooplankton as 1 particle per every 34 copepods and 1 particle per every 17 euphausiid. The authors further estimated that both the juvenile salmon and adult returning fish would be affected daily with ingested microplastics through their zooplankton prey.

Invertebrates with a capacity for filtering larger quantities of water and with a longer life span (e.g., bivalves) or large filter feeders (such as whales) may encounter microplastics far more frequently than zooplankton. Bivalves are one of the key organisms when entry points of microplastics to marine food webs are assessed. They are efficient suspension-feeding animals that form links between the pelagic and benthic ecosystems and are a key source of prey for many marine fish, birds, and mammals. In the Baltic Sea, it has been assessed that within 1 year, the blue mussel beds would, in theory, filter a water volume equivalent to the whole sea basin (Kautsky and Kautsky, 2000). The numbers of microplastics found in bivalves vary significantly ranging from <0.5 particles (Eastern Atlantic and Baltic Sea) to over 100 particles (Western Atlantic) per animal (Mathalon and Hill, 2014; Vandermeersch et al., 2015; Railo, 2017). Exposure of large filter feeders to microplastics has been shown by Fossi et al. (2014) after examining concentrations of phthalates and organochlorine compounds of a basking shark and a baleen whale. The authors concluded that microlitter is ingested by these large filter feeders together with their neustonic prey. A comparative study carried out in two semienclosed basins, the Mediterranean Sea and the Sea of Cortez in the Gulf of California (Fossi et al., 2016), gives supporting information indicating that fin whales in highly polluted areas are

> ## BOX 11.3 Microplastics, an Issue of Size
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> "Microplastic" is typically used to describe plastic particles smaller than 5 mm in diameter, with a lower size limit of 100 nm; plastics larger than 5 mm are considered "macroplastics," while plastics smaller than 100 nm in size are termed "nanoplastic" (Cole et al., 2011). Using these size classifications, the largest microplastic particles (5000 μm) have a diameter 50,000 times larger than the smallest microplastic (0.1 μm). Moreover, when we consider volume and surface area, these differences become even more apparent. Imagine a spherical shaped microplastic particle, like the ones used in experimental studies, or the plastic microbeads commonly used in exfoliating personal care products: a 5 mm-diameter bead is 1.25×10^{14} times greater in volume and 2.50×10^{9} larger by area than a 100 nm-diameter bead. Of course, most of the weathered microplastic particles that are found in the marine environment are not uniform in shape, with fibrous, planar, and irregularly shaped plastic being most prevalent. Nevertheless, differences in a particle's dimensions will have a significant impact on the risk they pose to marine life. For example, microplastics of different sizes may differ in their behavior under marine conditions (i.e., buoyancy), biological availability, and capacity to incite biological effects. Furthermore, the larger surface-area-to-volume ratios associated with smaller particles greatly increase the plastic's capacity for adsorbing (and potentially desorbing) waterborne pollutants (e.g., persistent organic pollutants and hydrophobic organic contaminants) (Koelmans et al., 2016), up to 1 million times greater than that found in the surrounding seawater (Mato et al., 2001).

exposed to major health hazards due to microplastics and their cocontaminants. Considering the vast amounts of water these animals filter (5893 m^3 day^{-1}; Fossi et al., 2014), this conclusion is more than relevant (Box 11.3).

11.4.2 Respiratory Intake

Ventilation has also been identified in exposure experiments as a means by which microplastics can be concentrated from the surrounding water. Watt et al. (2014) identified that the shore crab (*Carcinus maenas*) was able to respire polystyrene microbeads, which accumulated on the surface of their gills. Blue mussels (*Mytilus trossulus*) and Baltic clams (*Macoma balthica*) have also been shown to accumulate microplastic particles to their gills after 24 h incubations; however, the bead concentrations were much higher in the digestive tracts of the same animals (Setälä et al., 2016a).

11.4.3 Entanglement

Numerous organisms have been shown to entangle with fibers or larger plastics (e.g., Laist, 1997; Cole et al., 2013; NOAA, 2014; Taylor et al., 2016). They may be found in the swimming or feeding appendages of invertebrates and in the valve gapes of bivalves or entangled

around larger animals. Entanglement with fibers in field–collected animals has been observed even in remote areas such as the deep seas, where fibers were found on sea pens and hermit crabs (Taylor et al., 2016). When these organisms are eaten by higher trophic level predators, the plastics adhered to external surfaces of the organisms will be eaten as well.

11.4.4 Trophic Transfer

Once ingested, microplastics will be either egested or retained by the organism. If a predator consumes an organism that has retained microplastic, the predator will be indirectly consuming this plastic as part of its diet, in a process referred to as "trophic transfer." The trophic transfer of plastic has been documented in predatory Norway lobsters (*Nephrops norvegicus*) that consumed polypropylene rope fibers embedded in fish (Murray and Cowie, 2011), shore crabs (*C. maenas*) that indirectly ingested fluorescent polystyrene 0.5 and 10 μm microspheres present in common mussels (*M. edulis*) (Farrell and Nelson, 2013; Watt et al., 2014), mysid shrimps (*Neomysis integer*) that consumed fluorescent polystyrene 10 μm spheres previously taken up by mesozooplankton (Setälä et al., 2014), and fish (*Gasterosteus aculeatus*) that consumed an insect larvae containing microbeads in a mesocosm experiment (Lehtiniemi and Setälä, unpublished). The trophic transfer of microplastics and associated POPs from *Artemia* nauplii to zebra fish (*Danio rerio*) was also verified in a laboratory experiment (Batel et al., 2016), and microplastic debris found in fecal pellets of predatory seabirds (great skuas, *Stercorarius skua*) was greatest when correlated with the remains of surface-feeding Northern fulmars (*Fulmarus glacialis*) (Hammer et al., 2016).

For trophic transfer to occur, microplastic must be consumed alongside the prey. This includes plastic adhered to algae (Bhattacharya et al., 2010; Gutow et al., 2015) or the external surfaces of an animal (e.g., entrapped in the setae of a copepods' appendages; Cole et al., 2013) or retained indefinitely within the organism itself. Plastics are commonly observed in the intestinal tract of marine animals, including seabirds (Van Franeker and Law, 2015), fish (Lusher et al., 2013), invertebrates (Murray and Cowie, 2011), and turtles (Nelms et al., 2016); this occurs where larger plastics or coalesced polymeric fibers cause a gut blockage, preventing the plastic from being shifted via peristaltic action. In the common shore crab (*C. maenas*), polystyrene microspheres have been observed to lodge between the microvilli that line the stomach, resulting in prolonged gut retention times. In copepods, starvation has been observed to increase gut retention times, with 10 μm polystyrene microspheres remaining in the intestinal tracts of *C. helgolandicus* for up to 7 days, far exceeding the typical gut passage times of just 2 h (Cole et al., 2013). In the common mussel (*M. edulis*), 3.0–9.6 μm polystyrene microspheres have been demonstrated to translocate into the circulatory fluid (hemolymph), where they can remain for in excess of 48 days (Browne et al., 2008; von Moos et al., 2012). Owing to their small size, nanoplastics (<100 nm diameter) have the capacity to cross epithelia and therefore have the capacity to enter tissues and circulatory fluids, for example, in dendritic cells that transport small particles (e.g., bacteria) across gut epithelial cell walls (Rescigno et al., 2001). Microplastic transfer has also
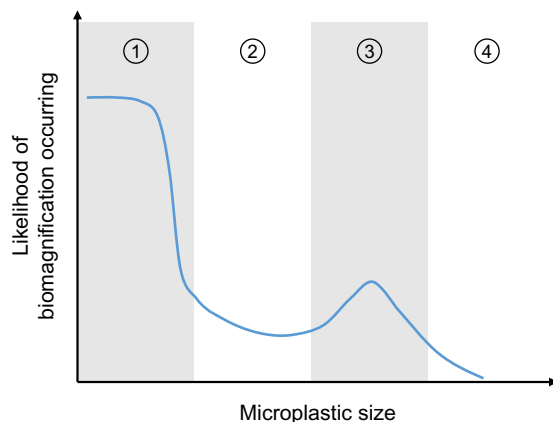
Fig. 11.3 Considering how microplastic size might influence the probability of biomagnification of plastics occurring in a food chain. (1) Very small (i.e., nano) plastics are readily absorbed by the gut and are retained within the circulatory fluid and/or tissues; (2) moderately sized plastics are ingested, are present within the organism during gut transit, and are then readily egested; (3) larger and fibrous plastics are ingested but, owing to their size, remain in the intestinal tract; (4) the largest microplastics are inedible to organisms at the base of the food chain.

been documented in a top marine predator, where the presence of microplastics in captive gray seal scats was attributed to trophic transfer from the wild-caught mackerel they were fed upon (Nelms et al., 2018).

In numerous aquatic ecosystems, persistent chemical pollutants (i.e., PCBs, PAHs, and methyl mercury) have been shown to biomagnify as they pass up the food chain (reviewed by Blais et al., 2007). The increasing body burdens of such pollutants in higher trophic organisms arise from the hydrophobicity of these chemicals, resulting in their accumulation within fatty tissues of prey species. So far, there have been no quantitative measures of microplastics passing up the food chain, and it therefore remains unclear whether plastics will biomagnify in marine food webs. Biomagnification will largely depend upon the transience of plastics in an organism, with biomagnification only occurring where plastics are readily ingested and retained. Retention of plastics can be influenced by food availability (Cole et al., 2013; Watt et al., 2014) and shape (Murray and Cowie, 2011) but will be predominantly governed by the size of the plastic (Galloway, 2015). In Fig. 11.3, we predict how the size of a plastic particle is likely to relate to the probability of that microplastic biomagnifying up the food chain.

11.5 ALTERATION, REPACKAGING AND TRANSPORT OF MICROPLASTICS WITHIN MARINE FOOD WEBS

In this section, we consider how marine organisms, trophic dynamics, and biologically mediated ecological processes can alter the fate of a microplastic and highlight how microplastics might impinge on biota, food webs, and marine ecosystems.

11.5.1 Biological Transport of Microplastic

Microplastics consumed, respired, or adhered by an organism will be subject to passive, biologically mediated transportation, with both vertical and lateral movement to be expected across a variety of habitats (e.g., water column and sediments). The distances by which microplastics can be transported via a biological vector will largely depend on the movement, migratory routes, and gut transit times of the individual organism (Fig. 11.4).

Diel vertical migrations, a synchronous daily migration of a wide range of taxa, have been highlighted as a potential route by which microplastics could be transported from the sea surface to deeper waters (Cole et al., 2016; Clark et al., 2016). Organisms may ingest plastics while feeding at the surface at night, which can then be egested hundreds of meters below the surface. For example, a large (2–3 mm) copepod swimming at speeds of between 30 and 90 m h^{-1} (Enright, 1977), with a gut evacuation time of approximately 2 h (Cole et al., 2013), could vertically transport microplastic to depths of 60–180 m. Lusher et al. (2016) identified that 11% of mesopelagic fish caught in the Northeast Atlantic had microplastics in their digestive tracts, and although it was unknown at what depth these plastics were consumed, the majority of the species identified undergo diel vertical migration and follow their zooplankton prey to the surface to feed; it is therefore plausible to suggest that ingestion of the microplastics may have occurred at the surface while feeding and egested at depth.
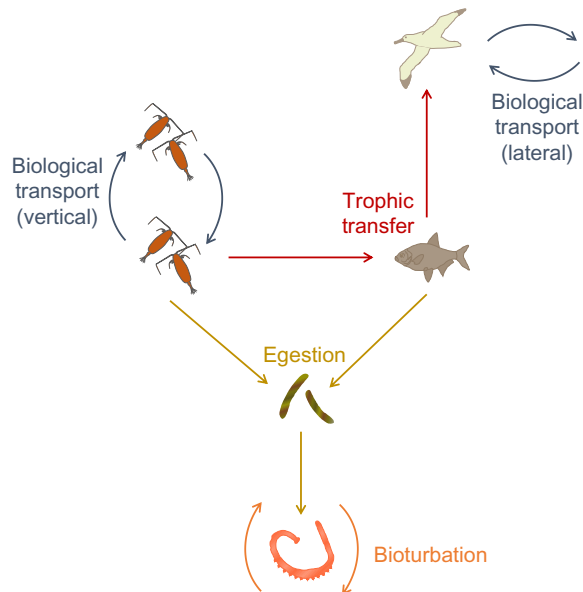

Fig. 11.4 How biota transport microplastics within marine ecosystems. *Image by Matthew Cole (original content).*

The geographic distribution of marine plastic has largely been considered from a physical perspective, with abiotic processes (i.e., wind, rivers, and oceanic currents) expected to be the dominant factors in distributing this pervasive pollutant (Sherman and Van Sebille, 2016). We consider that migratory species could also facilitate the transport of plastics. Migratory species have been widely demonstrated to play a vital role in the long-range transport of persistent pollutants (e.g., PCBs, DDT, and methyl mercury; Blais et al., 2007). For example, migratory fish (e.g., trout and salmon) have been shown to accumulate persistent organochlorines in their tissues while feeding in marine habitats, which are released in their eggs during spawning at otherwise pristine freshwater sites (Krümmel et al., 2003; Mu et al., 2004). Numerous migratory species, including turtles (Nelms et al., 2016), ocean-foraging seabirds (Van Franeker and Law, 2015), and cetaceans (Lusher et al., 2015a), are routinely sampled with plastics in their intestinal tracts. These animals undertake large-scale annual migrations; for example, the gray whale (*Eschrichtius robustus*) travels 6000 km annually from the coast of Mexico to the Chukchi Sea, and the Arctic tern (*Sterna paradisaea*) migrates 19,000 km from Greenland to the Antarctic each year (Alerstam et al., 2003). The egestion of plastic within feces, scat, or guano; the regurgitation of plastics by seabirds when feeding their young (Sileo et al., 1990); or the death of the animal will all contribute to the deposition of plastic in terrestrial, freshwater, or marine habitats far from the waters where such plastic was ingested.

11.5.2 Incorporation of Microplastics Into Biological Matrices

Within the marine environment, microplastics are rapidly colonized by "biofilms," made up of microorganisms, plants, and epibionts that attach and grow on substrates. The characteristics of the biofilm that forms on a plastic will be influenced by the polymer and the biological or ecological matrix through which it has passed; as such, the microbial complex that forms on the surface of plastics may act as a tracer of the journey of a microplastic within marine compartments (Galloway et al., 2017). The development of a biofilm can change the characteristics of the plastic polymer, for example, by increasing their mass (Lobelle and Cunliffe, 2011; Zettler et al., 2013; Rummel et al., 2017) and altering their chemical signal (see Section 11.3.2). It has been postulated that biofilm formation could be enough to cause otherwise buoyant plastics to sink or oscillate within the water column, depending on the size and density of the plastic (Ye and Andrady, 1991; Kooi et al., 2017).

In bivalves, feeding or rejection of particles that are suspended in the water is the outcome of passive and active selection. The size of the particles that may be ingested depends on the filtration apparatus of the particular species. In Pacific oyster (*Crassostrea gigas*) larvae, uptake of polystyrene microbeads was size-dependent, with microplastics larger than the oral groove unable to be ingested, while smaller plastics were readily consumed (Cole and Galloway, 2015). If the size is right and prey is directed to the

specialized feeding organs (ctenidium), it may still be rejected as pseudofeces if considered unpalatable. Studies made with blue mussels have shown that the identification of unsuitable particles and their sorting in suspension-feeding bivalves take place in the lectin-containing mucus that covers feeding organs, where interaction with carbohydrates from suspension takes place (Espinosa et al., 2010). Mussels (*M. edulis*) have been visualized rejecting nanopolystyrene (Ward and Koch, 2009) and microplastic polyvinylchloride in their pseudofeces (personal observations of authors). The fate of microplastics incorporated into pseudofeces remains unclear.

Ingested microplastics will typically be passed along the intestinal tract through peristaltic action. Within the intestinal tract, microplastics will either be adsorbed across the gut lining, become entrapped in the gut (i.e., intestinal blockage causing retention of plastic), or become incorporated into the animal's feces and egested. Microplastics have been identified in the fecal pellets of copepods (Cole et al., 2013), and it is assumed that most animals that consume plastics will then egest them. Microplastics have been observed in commercially caught fish (e.g., Lusher et al., 2013), and while there are currently no data to explain the fate of plastic post ingestion, it could be assumed that the majority would pass through the gut and get packaged in fecal pellets. The repackaging of plastic into the feces of an animal will alter the properties (i.e., relative buoyancy) of the plastics within the water column (Cole et al., 2015) and represent an alternate route by which plastics can be transferred within marine ecosystems (Clark et al., 2016).

Sinking feces and marine aggregates play a vital role in the biological pump, whereby carbon and nutrients in the euphotic zone are repackaged and transported to the ocean depths (Turner, 2015). Feces from anchovies in the productive upwelling system off the coast of Peru were observed as a key contributor to downward flux in sediment traps, with fecal sinking rates averaging >1 km day^{-1} (Staresinic et al., 1983). In this scenario, any microplastics contained within these pellets may reach benthic sediments within a very short space of time. However, experimental work has documented that the incorporation of microplastics into fecal pellets (Cole et al., 2016) and marine aggregates (Long et al., 2015) will alter the buoyancy of the biological matrix. Many carbon flux studies have concluded that slowly sinking feces are unlikely to reach the seabed, instead becoming repackaged through coprophagy (i.e., the consumption of fecal matter) by larger zooplankton species (Turner, 2002), or broken down through microbial action. In feces containing microplastic, coprophagy would therefore represent a route by which plastics can reenter the marine food web. This has been demonstrated with copepods, when polystyrene microplastics ingested by the small copepod, *Centropages typicus*, were egested in their fecal pellets and subsequently ingested by the larger copepod, *C. helgolandicus* (Cole et al., 2016). The study further highlighted that microplastic-laden pellets were more prone to fragment, making them more bioavailable to detritivores during their descent through the water column.

11.5.3 The Fate of Microplastics in Benthic Ecosystems

Benthic sediments have been identified as an important sink for microplastics, including high–density plastics, which readily settle out of the water column, and lower–density plastics whose movement to the benthos is facilitated by biological matrices. Highly polluted coastal sediments may comprise 3% microplastics (Carson et al., 2011), while estimates of 4 billion bioplastic and polymer fibers per km^2 are reported in Indian seamount sediments (Woodall et al., 2014). Within sediments, microplastics become bioavailable to benthic dwelling fauna, including important commercial species such as Norwegian lobster, *N. norvegicus* (Murray and Cowie, 2011), and shellfish (Rochman et al., 2015). A number of papers having highlighted the capacity for benthic organisms, including bivalves (Sussarellu et al., 2016), echinoderms (Graham and Thompson, 2009), and polychaetes (Wright et al., 2013b; Besseling et al., 2012; Green et al., 2016) to ingest microplastics, with the potential to incite negative health effects with repercussions for their functionality (i.e., reduced bioturbation activity and reduced energetic reserves). As with pelagic organisms, it is hypothesized that benthic taxa can alter the properties of microplastics and through bioturbation move plastics from the sediment–water interface deeper into sediments. This has been evidenced in polychaetes and clams that transported microplastic fibers (polyethylene fishing line <1 mm) to depths of 1.7–5.1 cm during a 3-week mesocosm experiment (Näkki et al., 2017). However, determining the capacity for sediment-dwelling biota to redistribute plastic under natural conditions remains unknown, and it is unclear whether bioturbation can result in the permanent burial of this plastic.

11.6 CONCLUSIONS

Microplastics are under extensive research, and their complex interactions with marine food webs are becoming increasingly evident. Microplastics are pervasive, environmentally persistent particles, which have the potential to flux between the water column, seabed, and biota. Nano- and microplastics can enter marine food webs via a number of entry points and can subsequently be cycled through different biotic compartments; these biotic processes can result in changes to the properties and movement of the microplastic. Parameters governing the entrance of microplastics into food webs include the spatial overlap of microplastics and biota, the feeding strategy and motility of the organism, and the characteristics of the plastic. From the studies carried out so far, we have learned that different taxa, species, and developmental stage of a species will each process, handle, and react to microplastics in a myriad of ways. Some organisms have mechanisms that protect them from consuming anthropogenic contaminants, while others readily ingest large numbers of microplastic particles together with their natural prey. With microplastic pollution in the marine environment becoming a growing threat, the numbers of both

primary and secondary microplastics are increasing. There may therefore come a time when the exposure experiments that are carried out today and that have been criticized because of their high microplastic concentrations will be considered as "historic" research with environmentally relevant concentrations.

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