Marine microplastic debris: a targeted plan for understanding and quantifying interactions with marine life

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Microplastic debris in the oceans is a marine pollutant that threatens aquatic biota and ecosystems. Microplastics have been detected throughout the world’s oceans; however, the relative importance of different processes that control the spatial distribution and long-term fate of microplastics in the marine environment remains largely unknown. Results from laboratory and field studies indicate that interactions between microplastic debris and marine organisms may play an important role in redistributing plastic in the oceans. We provide an overview of the various mechanisms through which marine life and microplastics can interact. By considering coupled physical–biological processes, we also identify regions where these interactions are most likely to occur, and outline a new research agenda that aims to determine their prevalence in the marine environment. We hypothesize that biological interactions are key to understanding the movement, impact, and fate of microplastics in the oceans.

In the past 10 years, more than 2.6 billion metric tons (MT) of plastic have been produced globally (PlasticsEurope 2015). In 2010 alone between 4.8 and 12.7 million MT of plastic are believed to have entered the oceans from terrestrial sources (Jambeck et al. 2015). By comparison, approximately 269,000 MT of plastic – regardless of origin – are estimated to float at or near the surface of the world’s oceans (Eriksen et al. 2014). Assuming that 50% of all plastics are positively buoyant in seawater, the total load of buoyant plastic in the oceans represents only about 1–10% of the amount entering the oceans from land-based activities in 2010. This discrepancy between the amount of plastic entering the marine environment, and the amount detected in the oceans remains a mystery, and has led researchers to pose the question: “Where is the missing plastic?” (Cózar et al. 2014; Eriksen et al. 2014; van Sebille et al. 2015).

Our plastic age

Plastic is a versatile material that provides a vast range of societal benefits, with applications in industry, construction, medicine, and food preservation (Cole et al. 2011). Over the past 70 years, plastic manufacturing has grown exponentially. At the same time, inadequate waste disposal has resulted in large quantities of plastic debris entering the world’s oceans (Jambeck et al. 2015). Owing to slow rates of degradation, marine plastic can persist for years, decades, or even centuries (Andrady 2015). Consequently, marine plastic debris is now recognized as a marine pollutant of international environmental, economic, public, and political concern that poses a threat to marine life, industry, and food security (G7 2015).

Marine plastic debris includes items spanning several orders of magnitude in size. While the prevalence of large items (eg discarded fishing gear, plastic bottles and bags) has historically received the most attention (Derraik 2002), in recent years the focus has shifted to include microscopic plastic particles and fibers, collectively termed “microplastics” (<5-mm diameter; Figure 1) (Thompson et al. 2004; Cole et al. 2011). Microplastics derive from the fragmentation of larger plastics (Andrady 2015) and may also be manufactured directly, for example, as exfoliates in cosmetics (Napper et al. 2015). These plastics enter marine waters via rivers and sewage outflow (Tagg et al. 2015), or diffusely

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through anthropogenic activities (eg aquaculture, fishing, shipping, or tourism).

In marine waters, microplastic items – depending on their size, shape, and density – can be transported by a variety of different processes. Positively buoyant items will tend to accumulate near the sea surface, where they are transported by winds and surface water currents, whereas negatively buoyant items sink out of the water column to the sediments below (Van Cauwenbergh et al. 2013). As a consequence, microplastics have been detected across the globe, including the open ocean (Law et al. 2010; Cózar et al. 2014; Eriksen et al. 2014), polar icecaps (Obbard et al. 2014), deep-sea sediments (Van Cauwenbergh et al. 2013), and the beaches of remote, mid-oceanic islands (do Sul et al. 2013).

### The missing size fraction

At global scales the movement, spatial distribution, and accumulation of plastics has predominantly been studied from a physical perspective through the use of hydrodynamic models (Lebreton et al. 2012), the tracks of ocean drifters (Maximenko et al. 2012), and sampling campaigns throughout the world’s oceans (Cózar et al. 2014; Eriksen et al. 2014). Several estimates now exist for the mass of small buoyant plastics at or near the ocean’s surface. The most recent of these uses a superset of the data from two global surveys (Cózar et al. 2014; Eriksen et al. 2014), in combination with three different surface ocean transport models (Lebreton et al. 2012; Maximenko et al. 2012; van Sebille et al. 2015), and arrives at an estimate for the total load of buoyant plastic, measuring <200 mm in size, of between 93,300 and 236,000 MT (van Sebille et al. 2015).

Even when accounting for larger macroplastics (>200 mm in size, as defined by Eriksen et al. [2014]), which have been estimated to make up more than 70% of the total mass of plastic at the ocean’s surface, and dense plastic items that rapidly sink out of the water column to the seafloor, it is difficult to reconcile these pool sizes with estimates of plastic inputs to the ocean. Indeed, such calculations suggest plastics are being rapidly removed from the ocean surface by unknown processes.

Models of the expected size distribution of plastics, based on the tendency of larger items to fragment into smaller pieces as a result of photo-degradation and mechanical weathering, suggest that there is a selective removal of microplastics from the ocean (Cózar et al. 2014; Eriksen et al. 2014). Three plausible hypotheses can be invoked to explain the apparent missing size fraction. First, rates of embrittlement followed by fragmentation may be faster for smaller items, leading to the formation of smaller and smaller particles that may be missed by current sampling practices (Hidalgo-Ruz et al. 2012; Andrady 2015). Secondly, biofouling or entanglement with planktonic aggregates may produce a ballasting effect that transfers plastic away from the sea surface (Long et al. 2015). Thirdly, smaller particles may be consumed and cycled by marine organisms, leading to redistribution within the water column and contamination of the food chain (with repercussions for food security).

Below, we draw on our own work and that of others to highlight the importance of interactions between microplastics and marine life. We illustrate how ecological processes – that act in tandem with physical transport processes – can play a role in transporting microplastics away from the sea surface, with implications for both the fate of plastics in the marine environment, and the contamination of marine food chains and commercial seafood.

### Plastic distributions in the global ocean – a spatial mismatch

Large-scale oceanic models predict that buoyant particles that escape over the continental shelf edge to the
open ocean will accumulate in the subtropical gyres (Maximenko et al. 2012) – a hypothesis supported by sampling efforts in these regions (Law et al. 2010). In Figure 2a, we present a model-based estimate for the spatial distribution of small surface plastics in the North Atlantic and surrounding waters from van Sebille et al. (2015). The model was calibrated against the most comprehensive global dataset for surface plastics assembled to date. To compare the spatial distribution of plastic debris with regions of high biological activity, we show a climatology of annual mean, satellite-derived estimates of sea surface chlorophyll (Figure 2b), which is taken as a proxy for oceanic primary production. Overlain in Figure 2 are Longhurst’s Biogeographical Provinces (Longhurst 2006) for the North Atlantic, which divide the region into a small number of physical oceanographic regimes that host distinctive pelagic and benthic communities.

Source regions for plastic are largely centered around areas of anthropogenic activity and more densely populated regions. These predominantly discharge within Longhurst’s Coastal Biomes, including shelf-sea environments, which tend to be productive, dynamic regions that support a broad range of pelagic and benthic organisms. Despite constituting approximately 8% of the area of the global ocean, shallow seas overlying the continental shelf are responsible for 15–21% of global oceanic primary production (Jahnke 2010), and given their proximity to land-based sources of plastic (ie rivers, human activity [including fishing]) the potential for co-occurrence and interactions with marine life is predicted to be high.

Away from the coasts, in the open North Atlantic Ocean, plastics are observed to collect in the North Atlantic Subtropical Gyral Provinces (Figure 2a). The subtropical gyres are regions of anti-cyclonic circulation, which drive surface convergence and downwelling. In turn, downwelling depresses the thermocline (an underwater boundary characterized by a rapid change in temperature with depth) and limits the amount of nutrients supplied to surface waters. Primary production therefore tends to be low in these regions relative to regions of upwelling, such as the subpolar gyres, equatorial regions, and coastal upwelling zones (Williams and Follows 2003). When combined, these observations suggest that in the open ocean there is a spatial mismatch between regions of high production, which are rich in marine life, and regions where plastic tends to accumulate (Figures 2 and 3). That is not to say biological interactions will not occur in the subtropical gyres. Indeed, the hard surface of plastics suspended in a relatively stable environment may be readily colonized by marine microbes (Amaral-Zettler et al. 2015) and biota reliant on flotsam for transport or oviposition (Goldstein et al. 2012). However, given the low levels of biological activity in the subtropical gyres (Figure 2b; Figure 3), the probability of interactions occurring is predicted to be low.

Like much of the world’s oceans, Longhurst’s Coastal Biomes are undersampled with respect to microplastics (van Sebille et al. 2015), and the frequency of interactions between microplastics and marine life in these regions remains largely unknown. Because collecting, isolating, and identifying microscopic particulates from vast volumes of water is very complex, most of the existing sampling effort has focused on surface waters using relatively coarse nets (typically 333-μm meshes); this allows for long, uninterrupted sampling transects, which minimize the collection of biological material that can greatly reduce sampling efficiency and mask the presence of plastics (Hidalgo-Ruz et al. 2012; Cole et al. 2014). Data pertaining to larger, buoyant microplastics have proven essential in modeling the risks posed to surface foraging seabirds (Wilcox et al. 2015). Currently, however, there is a lack of data on microplastics within the prey size range of suspension feeding organisms, and on plastics present within the water column where most pelagic animals feed.

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**Figure 2.** (a) Surface concentration of plastic debris <200 mm in size calculated by the model of van Sebille et al. (2012), and calibrated against available data (van Sebille et al. 2015). Data downloaded from https://dx.doi.org/10.6084/m9.figshare.1613256. (b) A climatology of annual mean (1997–2010), satellite-derived estimates of sea surface chlorophyll for the North Atlantic Ocean at 1/12° resolution (SeaWIFS data downloaded from the NASA ocean-color website: http://oceancolor.gsfc.nasa.gov/cms). Thick black lines within the ocean basin show Longhurst Biogeographical Provinces (Longhurst 2006) for the North Atlantic (Version 4, available online: http://marineregions.org). Image created using the matplotlib plotting library, version 1.2.
Consumption of plastics by marine life

The widespread consumption of plastics by marine organisms has been confirmed by biomonitoring studies in which the gut contents of wild marine animals – including foraging seabirds (Wilcox et al. 2015), pelagic and demersal fish (Boerger et al. 2010; Lusher et al. 2012), estuarine crustaceans (Murray and Cowie 2011), and intertidal shellfish (Van Cauwenberge and Janssen 2014) – have been inspected. These studies revealed that ingestion of microplastic particles and fibers is commonplace. For instance, 34% of gooseneck barnacles living on flotsam in the North Pacific Subtropical Gyre (Goldstein and Goodwin 2013), 52% of blue whiting and red gurnard in the English Channel (UK) (Lusher et al. 2012), and 83% of Norwegian lobsters in the Clyde estuary (UK) (Murray and Cowie 2011) were found to have ingested microplastics. These studies also revealed that ingestion of microplastic particles and fibers is commonplace. For instance, 34% of gooseneck barnacles living on flotsam in the North Pacific Subtropical Gyre (Goldstein and Goodwin 2013), 52% of blue whiting and red gurnard in the English Channel (UK) (Lusher et al. 2012), and 83% of Norwegian lobsters in the Clyde estuary (UK) (Murray and Cowie 2011) were found to have ingested microplastics. These studies also revealed that ingestion of microplastic particles and fibers is commonplace. For instance, 34% of gooseneck barnacles living on flotsam in the North Pacific Subtropical Gyre (Goldstein and Goodwin 2013), 52% of blue whiting and red gurnard in the English Channel (UK) (Lusher et al. 2012), and 83% of Norwegian lobsters in the Clyde estuary (UK) (Murray and Cowie 2011) were found to have ingested microplastics.

Marine biota and the sequestration of microplastics to the seafloor?

An interesting case study is provided by the ingestion of polystyrene microplastics by marine copepods. Copepods are prolific within aquatic ecosystems throughout the globe, and play pivotal roles in marine food webs and nutrient cycling. We have shown that...
Suspension feeding copepods can readily consume microplastics (Figure 4a), a process that affects both the organism and the plastic (Cole et al. 2013). Under normal feeding conditions, gut transit times for microplastics are rapid. Our observations show microplastics are bound up with undigested prey items in the hindgut (Figure 4b) and subsequently egested within compact fecal pellets (Figure 4c). Furthermore, plastic consumed by copepods, or present within their fecal pellets, can be trophically transferred to coprophagous animals (Cole et al. 2016).

Because they feed near the surface, copepods will be more susceptible to ingesting polypropylene, polyethylene, or polystyrene, which have densities below that of seawater (~1.02 g cm⁻³; Figure 4d). Incorporation into fecal pellets, which have densities above that of seawater (Turner 2015), provides a mechanism by which plastics can be transported from surface waters to the sediments below (Cole et al. 2016). However, laboratory experiments have demonstrated that at sufficient concentrations, low-density plastics (e.g., polystyrene) can reduce the density and sinking velocity of copepod-egested fecal pellets (Figure 4c; Cole et al. 2016). These studies show that interactions between plastics and marine life can have two-way feedbacks, including impacts on the distribution of plastics in the marine environment, and on the organisms with which they interact.

When we consider the role that copepods – with their diel vertical migrations and rapidly sinking fecal pellets – play in the biological carbon pump and the sequestration of organic material to the seafloor (Turner 2015), it is logical to consider that this transport pathway may also represent an important sink for microplastics. Likewise, microplastics may be vertically transported via the fecal matter of salps, fish, and other pelagic biota; sinking carcasses; and marine aggregates, typically made up of living or dead cells, held together by a polysaccharide mucus (Long et al. 2015).

Plastic contamination of sediments is widespread, although the impacts are unclear (Van Cauwenberghe et al. 2013). While bioturbating benthic organisms may have a role in mixing microplastics deeper into the sediment locking them away from the water column, microplastics at environmentally relevant 5% weight/weight concentrations can limit the functionality of sediment-dwelling biota (Wright et al. 2013). In shallow shelf-sea environments, plastics sequestered to the sediments may become resuspended due to the action of winds, tides, or waves, and subsequently redistributed within the water column (Latrin et al. 2004). In deeper waters, sediments may become a permanent sink for plastics that either sink out of the water column directly, or are transported over and down the continental slope.

**Key questions**

We hypothesize that biological interactions are responsible for the apparent missing size fraction of plastic in the oceans (Figure 3). To assess the prevalence of biological interactions with microplastics in situ and the role that biota play in cycling plastics within the marine environment, we argue that research programs and sampling strategies will be required to consider a broad range of physical and biological processes. We advocate that such a research effort be undertaken and structured around the following hypotheses:

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**Figure 4.** Laboratory experiments illustrate how marine copepods and 20-μm polystyrene microplastics can interact. (a) Fluorescent microplastics in the intestinal tract of the copepod *Calanus helgolandicus*. (b) Microplastics aggregated with undigested prey prior to egestion. (c) A copepod fecal pellet containing fluorescent microplastics. (d) The densities of four plastics (blue bars) commonly identified in marine samples – polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyamides (PA) – and copepod fecal pellets (FP; light green bar) per literature-derived values; *experimental data (from Cole et al. [2016]; dark green bars) showing the density of copepod (*C. helgolandicus*) fecal pellets with and without polystyrene microplastics; dashed vertical line denotes density of seawater (~1.02 g cm⁻³). Error bars represent standard error of the mean.
• $H_i$: Biological interactions with plastics predominantly occur in regions of high productivity, close to sources of microplastic pollutants (e.g., rivers, sewage outflows, and coastal cities);

• $H_2$: Microplastics accumulate within the marine food web, including commercially exploited species of fish and shellfish destined for human consumption; and

• $H_3$: Marine microplastics are actively consumed and cycled by a variety of marine organisms, including pelagic mesozooplankton and mesopelagic fish. These organisms facilitate the sequestration of plastic to deeper waters and marine sediments.

### Solving the puzzle

A major challenge for improving the management and protection of the oceans is clearly to develop multiscale, targeted monitoring programs to quantify the frequency and effects of interactions between microplastics and various forms of marine life. The probability of interactions occurring will be highest when high concentrations of plastic coincide in both space and time with high concentrations of marine life (Figure 3). Recent comparisons between the modeled spatial distribution of plastic floating at sea and the geographic range of 186 avian species have improved estimates of the risk of plastic ingestion by foraging seabirds (Wilcox et al. 2015). Surprisingly, the area with the greatest expected impact on biodiversity was identified at the Southern Ocean boundary in the Tasman Sea, which is not one of the main open-ocean accumulation zones identified in modeling studies (e.g., van Sebille et al. 2015). Furthermore, oceanic fronts (boundaries between distinct water masses) have been highlighted as a region of concern for sea turtles, in which ingested plastic can cause lacerations, intestinal injury, dietary dilution, malnutrition, and poor health outcomes (Nelms et al. 2015).

Conducting similar studies for ocean-dwelling organisms (e.g., mesopelagic fish, zooplankton) interacting with microplastics will be challenging, and will require a combination of modeling supported by laboratory and observational studies. In these investigations, it will be important to consider: (1) the physical transport of plastic away from known source regions, (2) plastic fragmentation rates and buoyancy changes, (3) the biogeographic range of various species known to ingest or otherwise interact with marine plastic, (4) species feeding patterns, and (5) the impact on both the organism and the plastic.

For different species of wildlife, interaction frequencies and the fate of the microplastic will depend on several key organismal traits. In the case of zooplankton, these frequencies will be determined by the relative size of the organism as compared to that of plastic particles and natural prey items, by its feeding mode, and by prey ingestion rates (Kierboe 2011). Marine ecological and food web models are beginning to make use of such traits in their construction (e.g., Litchman et al. 2013), and these may represent a promising means of synthesizing the large amounts of data necessary to establish reliable budget estimates for microplastics. Such models must be combined with physical transport models that are able to simulate realistic spatial and temporal patterns in the abundance of plastic and zooplankton. However, before the output from these models can be relied upon for inference they must first be built, parameterized, and tested using available laboratory and field data.

The identification of Longhurst’s Subtropical Gyral Provinces (oceanic gyres) as accumulation zones for surface plastic highlights these regions as areas of potential risk for marine life; notably, 33% of planktivorous fish sampled within the North Pacific Subtropical Gyral Province were found to have microplastics in their stomachs (Boerger et al. 2010). However, because Longhurst’s Coastal Biomes are associated with higher levels of biological production (Figure 2b; Figure 3) and coincide with major source regions of plastic, we hypothesize that interactions here will be more frequent. At present this hypothesis remains untested, and further work is required to identify interaction hotspots for different organisms (Cole et al. 2014).

Smaller microplastics are currently unaccounted for in most monitoring programs and there is a dearth of data for regions of high biological productivity. Increased attention should be given to sampling microplastics and nanoplastics – that is, smaller size fractions (<333 μm in diameter) of plastics that are edible to copepods, mesopelagic fish, and filter-feeding bivalves (Cole et al. 2013; Van Cauwenberghie and Janssen 2014; Koelmans et al. 2015). Kang et al. (2015) found the highest-ever concentration of plastic (15,600 items per cubic meter) in Geoje Bay (South Korea) by using hand nets and on-board pumps to sample microplastics >50 μm. Such sampling could be conducted at a variety of depths to assess the vertical distribution of plastics in the water column. Furthermore, by sampling biota and sinking organic matter (e.g., zooplankton fecal pellets, marine aggregates), it may be possible to determine the propensity for microplastic sequestration and trophic transfer in situ (Cole et al. 2016).

As the human population expands and rates of plastic production grow further, plastic and microplastic litter are expected to pose an increasing risk to marine ecosystems. The global nature of this risk is illustrated by the specific inclusion of marine debris in the G7 summit Strategic Development Goals (SDG target 14.1), which aim to reduce marine pollution of all kinds. In addition, the United Nations Environment Programme has recognized this emerging issue and adopted a resolution to address marine debris and microplastics by encouraging improvements to legislation, waste management, and
social education (UNEP 2016). To respond to these calls, we need to develop better tools to identify impacted or vulnerable areas or species and to track remedial efforts. We hypothesize that interactions with marine life are key to understanding the ultimate fate of microplastics in the marine environment, and that these interactions will be more frequent in regions of high biological productivity and shelf seas that are adjacent to densely populated coastal towns and cities. Developing an understanding of these interactions is an urgent research goal for improving the management and protection of our oceans from the emerging hazards posed by marine litter.

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