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Review

The present and future of microplastic pollution in the marine environment

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A B S T R A C T

Recently, research examining the occurrence of microplastics in the marine environment has substantially increased. Field and laboratory work regularly provide new evidence on the fate of microplastic debris. This debris has been observed within every marine habitat. In this study, at least 101 peer-reviewed papers investigating microplastic pollution were critically analysed (Supplementary material). Microplastics are commonly studied in relation to (1) plankton samples, (2) sandy and muddy sediments, (3) vertebrate and invertebrate ingestion, and (4) chemical pollutant interactions. All of the marine organism groups are at an eminent risk of interacting with microplastics according to the available literature. Dozens of works on other relevant issues (i.e., polymer decay at sea, new sampling and laboratory methods, emerging sources, externalities) were also analysed and discussed. This paper provides the first in-depth exploration of the effects of microplastics on the marine environment and biota. The number of scientific publications will increase in response to present and projected plastic uses and discard patterns. Therefore, new themes and important approaches for future work are proposed.

1. Introduction

In 1972, E. J. Carpenter and K. L. Smith became the first researchers to sound the alarm on the presence of plastic pellets on the surface of the North Atlantic Ocean. In their publication in *Science*, they stated: "*The increasing production of plastic, combined with present waste-disposal practices, will probably lead to greater concentrations on the sea surface… At present, the only known biological effect of these particles is that they act as a surface for the growth of hydroids, diatoms, and probably bacteria*". Not surprisingly, only months later, the ingestion of those same polyethylene pellets by fish was reported (Carpenter et al., 1972). The prediction by Carpenter and Smith (1972) is the focus of the scientific community that is studying the smallest plastic debris pollution sizes (Moore, 2008; Barnes et al., 2009; Thompson et al., 2009; Ryan et al., 2009; Andrady, 2011). Several million tonnes of plastics have been produced since the middle of the last century (more than two hundred million tonnes annually) (Barnes et al., 2009; Thompson et al., 2009; Andrady, 2011). Speculation exists over how much of this plastic will end up in the ocean, where it suffers degradation and fragmentation (Barnes et al., 2009; Andrady, 2011). In the environment, microplastic debris (<5 mm) proliferates, migrates and accumulates in natural habitats from pole to pole and from the ocean surface to the seabed; the debris is also deposited on urban beaches and pristine sediments (Moore, 2008; Barnes et al., 2009; Thompson et al., 2009; Ryan et al., 2009). This type of pollution is ubiquitous and persistent in the world's oceans and openly threatens marine biota.

Plastic means "malleable" or "flexible". Indeed, these synthetic materials can be moulded into virtually any shape (Moore, 2008). Plastics are versatile materials that are inexpensive, lightweight, strong, durable and corrosion-resistant. They have high thermal and electrical insulation values (Thompson et al., 2009) and are incredibly practical. Plastics are formed by long chains of polymeric molecules that are created from organic and inorganic raw materials, such as carbon, silicon, hydrogen, oxygen and chloride; these materials are usually obtained from oil, coal and natural gas (Shah et al., 2008). Currently, the most widely used synthetic plastics are low- and high-density polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET). Altogether, these plastics represent ~90% of the total world production (Andrady and Neal, 2009). Thus, it is widely

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accepted that the majority of the items polluting coastal and marine environments are comprised of these materials (Andrady, 2011; Engler, 2012).

Most synthetic polymers are buoyant in water (e.g., PE and PP). Consequently, substantial quantities of plastic debris that are buoyant enough to float in seawater are transported and eventually washed ashore (Thompson et al., 2009; Andrady, 2011; Engler, 2012). The polymers that are denser than seawater (e.g., PVC) tend to settle near the point where they entered the environment; however, they can still be transported by underlying currents (Engler, 2012). Additionally, microbial films rapidly develop on submerged plastics and change their physicochemical properties (i.e., surface hydrophobicity and buoyancy) (Lobelle and Cunliffe, 2011). If these fragments sink, then the seabed becomes the ultimate repository for the plastics (including those that were initially buoyant) (Barnes et al., 2009).

Polymers are rarely used as pure substances. Typically, resins are mixed with additives to enhance their performance (Andrady and Neal, 2009; Teuten et al., 2009). Considerable controversy exists over the extent to which additives that are released from plastic products (e.g., phthalates and bisphenol A) adversely affect animals and humans (Andrady and Neal, 2009; Thompson et al., 2009; Teuten et al., 2009; Lithner et al., 2009, 2011). More information is available from Thompson et al. (2009) and Cole et al. (2011), among others.

Additionally, the hydrophobic pollutants available in seawater may adsorb onto plastic debris in ordinary environmental conditions (Thompson et al., 2009; Cole et al., 2011). The majority of these pollutants are persistent, bioaccumulative and toxic; thus, they are of particular concern for human and environmental health (Engler, 2012). Plastics not only have the potential to transport contaminants, but they can also increase their environmental persistence (Teuten et al., 2009). This highlights the importance of plastic as vehicles of pollutants to marine biota and humans (Teuten et al., 2009; Tanaka et al., 2013).

Small plastics enter the environment directly, whereas larger items are continuously fragmenting (Barnes et al., 2009). Primary-sourced microplastics (Arthur et al., 2009) are directly released to the environment in the form of small (μm) pellets that are used as abrasives in industrial (shot blasting) (Gregory, 1996) and domestic applications (e.g., Fendall and Sewell, 2009); they can also be released by spilling virgin plastic pellets (mm) (Thompson et al., 2009). Facial cleansers that are used by millions of people, especially in developed countries, contain PS particles (μm) that directly enter sewage systems and adjacent coastal environments (Zitko and Hanlon, 1991; Gregory, 1996; Fendall and Sewell, 2009). Moreover, laboratory experiments using *Sphaeroma quoianun* indicated that isopods can produce millions of PS fragments, which resemble plastic pellets, when incrusted in buoys in the Pacific Ocean (Davidson, 2012).

Larger plastics eventually undergo some form of degradation and subsequent fragmentation, which leads to the formation of small pieces (Shah et al., 2008; Costa et al., 2010; Andrady, 2011). Degradation is a chemical change that reduces the average molecular weight of polymers (Andrady, 2011). The most-used polymer types (i.e., PE and PP) have high molecular weights and are non-biodegradable (Shah et al., 2008). However, once in the marine environment, they start to suffer photo-oxidative degradation by UV solar radiation, followed by thermal and/or chemical degradation. This renders plastics susceptible to further microbial action (i.e., biodegradation) (Shah et al., 2008; Andrady, 2011). The light-induced oxidation is orders of magnitude higher than other types of degradation (Andrady, 2011). Any significant extent of degradation inevitably weakens the plastic, and the material become brittle enough to fall apart into powdery fragments (Andrady, 2011) when subjected to sea motion. This process essentially occurs forever (Barnes et al., 2009), including on the molecular level (Andrady, 2011).

Reports of plastics have spread rapidly in terms of geography, marine habitat and biota influenced (Barnes et al., 2009; Ryan et al., 2009). It was hypothesised that microplastics accumulate in the centres of subtropical gyres, but their means of movement and transport in the sea are largely unknown (Hidalgo-Ruz et al., 2012), especially along the vertical axis. Environmental microplastics are available to every level of the food web, from primary producers (Oliveira et al., 2012) to higher trophic-level organisms (Wright et al., 2013). Individuals who ingest microplastics may suffer physical harm, such as internal abrasion and blockage. Impacts at the population-level are also possible, but largely unknown (Wright et al., 2013). Plastic pellets are also used as ovipositon sites by insects, such as *Halobates micans* and *H. sericeus*, which can affect their abundance and dispersion (Majer et al., 2012; Goldstein et al., 2012). In the western Atlantic, 24% of the pellets ($N > 1000$) had eggs attached to their surface, most with viable embryos. In the North Pacific Ocean, the numbers of adults, juveniles and eggs (*H. sericeus*) were significantly correlated with microplastic abundance. Although it is still risky to conclude the magnitude of this problem (i.e., transport of fouling species), it is fair to consider plastics as potential vectors that transport species to previously unknown mobility levels (Barnes et al., 2009).

As predicted (e.g., Carpenter et al., 1972), microplastic pollution became widespread with significant implications for ecosystems and organisms in a variety of forms. Supporting evidence has been published in peer-reviewed journals from the 1971 benchmark paper by Buchanan (1971) to the present. In this context, the present work aims to sort, critically analyse, and synthesise the recent literature regarding microplastics at sea, as well as highlight the risks to and effects on the marine biota. The Arthur et al. (2009) definition of microplastics was adopted (fragments and primary-sourced plastics that are smaller than 5 mm) as the main criteria for discerning a specific size class of plastic pollution. A periodic critical assessment of this issue is essential, especially because the problem is mounting and will persist for centuries, even if pollution is immediately stopped (Barnes et al., 2009).

2. Results

Results from the scientific literature were classified according to the main focus of each work: (1) the presence of microplastics in plankton samples; (2) the presence of microplastics in sandy and muddy sediments; (3) the ingestion of microplastics by vertebrates and invertebrates; (4) microplastics' interactions with chemical pollutants (see the supplementary content in Tables S1, S2, S3, S4 and S5). Papers in each category were analysed for their most relevant findings to improve and advance discussions on microplastics at sea.

One hundred and one documents from various sources fulfilled the review criteria (Table 1). Two works were included in more than one category: Carpenter et al. (1972) and Thompson et al. (2004). Fourteen literature reviews, from 2008 to 2013, on microplastics in the marine environment were also consulted. Research related to the development of new sampling or laboratory methods and/or analytical procedures, the (bio)degradation of plastics and other relevant issues were used when appropriated. Approximately 80% of the articles were published in the last 15 years, and more than 60% of the articles were published in the last 5 years.

2.1. Plankton samples and floating microplastics

The notion of using surface plankton samples to diagnose pelagic areas in relation to the presence and amount of floating

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Table 1
The main focuses of the publications, the number of reviewed papers and the peer-reviewed journal with the most publications in each category. [dotted box] = works deal with the ingestion of microplastics by marine biota. See the Supplementary content for details.

Main focus	Number of papers	Journal with the most contributions
Microplastics on plankton samples	25	*Marine Pollution Bulletin*
Microplastics in sediments	22	*Marine Pollution Bulletin*
Ingestion of microplastics by vertebrates	26	*Marine Pollution Bulletin*
Ingestion of microplastics by invertebrates	11	*Environmental Science and Technology*
Interactions of microplastics with pollutants	17	*Marine Pollution Bulletin*

plastics is well-established (Carpenter and Smith, 1972; Carpenter et al., 1972; Morris and Hamilton, 1974; Wilber, 1987; Ryan, 1988) (Table S1). While sampling the pelagic sargassum community in the early 1970s, Carpenter and his team observed high quantities of polystyrene plastic pellets (1–2 mm) on the sea surface of the western North Atlantic Ocean. Most pellets had hydroids and diatoms attached to their surfaces (Carpenter and Smith, 1972). Previously, the only evidence of synthetic microplastic fibres were reported in membrane-filtered water samples from the North Sea (Buchanan, 1971). Archived plankton samples from the North Atlantic Ocean, which are regularly obtained with a continuous plankton recorder (CPR) between Aberdeen and the Shetlands and from Sule Skerry to Iceland, also revealed the presence of microplastics in the 1960s (Thompson et al., 2004). Furthermore, these samples indicated a significant increase in the abundance of microplastics (mainly fibrous and 20 μm in length) during the 1960–1970s and 1980–1990s (Thompson et al., 2004).

In the western North Atlantic Ocean and Caribbean Sea, a wide-range ship-survey dataset (~6100 tows) also reported the quantities and characteristics of pelagic plastics (Law et al., 2010). Plastic fragments, 88% of which were smaller than 10 mm, were sampled between 22 and 38°N. This finding reflects the presence of a large-scale subtropical convergence zone. Chemical analysis revealed that 99% of the particles were less dense than seawater: high- and low-density PE, PP (Law et al., 2010) and plastic pellets. Using a subset of these samples (Law et al., 2010), Kukulka et al. (2012) developed a theoretical model that indicates that the plastics obtained from surface tows are dependent on wind speed (i.e., tows in high wind conditions tend to capture fewer plastic pieces) because plastics are vertically distributed in the mixed layer due to wind (Kukulka et al., 2012). Around the Saint Peter and Saint Paul archipelago in the equatorial Atlantic Ocean, plastic fragments (N = 71; ~85% smaller than 5 mm) were retained near the seamount, as well as reef fish and semi-terrestrial decapod larvae (Ivar do Sul et al., 2013). Despite its isolation, the archipelago is not free of autochthonous and allochthonous sources of plastics, which may be ingested by the biota.

In the North Atlantic Ocean (11–44°N, 55–71°W), more than 18,000 archived surface net tows were analysed, which allowed researchers to investigate the spatial and temporal trends (1991–2007), as well as the visual characteristics, of pelagic microplastics (Morét-Ferguson et al., 2010). Sixty per cent of the fragments were 2–6 mm. Apparently, the densities (g ml^{-1}) of the plastic pellets decreased, but the quantities of the fragments increased 18% over the time period (Morét-Ferguson et al., 2010). The microplastics were sampled significantly higher at 30°N, the subtropical convergence zone. Furthermore, neustonic samples collected in the Mediterranean Sea indicated that the closed basin is also threatened by microplastic pollution (Collignon et al., 2012). Ninety per cent (N = 40) of the samples contained plastics (0.3–5 mm), which were mostly fibres, PS fragments and films. The microplastic concentrations were 5 times higher before a strong wind event than after the event. Researchers suggested that wind stress might redistribute plastics in the upper layers of the water column and prevent them from being sampled by the surface tows (Collignon et al., 2012). Recently, the occurrence of suspended plastic pellets and fibres was reported in the Jade System of the southern North Sea. The pellets were associated with a paper recycling plant, whereas the fibres were most likely sewage-related (Dubaish and Liebezeit, 2013).

In the Pacific Ocean, plankton tows performed in the 1980s revealed high amounts of coloured microplastic fragments (Shaw and Day, 1994). The North Pacific Central Gyre (NPCG) was sampled for the first time at the turn of the XXIst Century (Moore et al., 2001). The surface tows collected plastic fragments, thin films and monofilament lines, the majority of which were smaller than 5 mm. A large plastic to plankton ratio was reported. However, the NPCG is not an area of high biological productivity, and the extrapolation of these findings to other oceanic areas is somewhat limited.

Surface plankton tows were carried out in southern California's coastal waters (Moore et al., 2002). Higher quantities of plastics (mainly small fragments) were sampled after a storm event, which resulted in a high plastic to plankton ratio (Moore et al., 2002). Plastics were also sampled throughout the water column (surface, middle and bottom) in Santa Monica Bay, California, before and after a storm (Lattin et al., 2004). Unexpectedly, the densities of the plastics were not the highest at the surface, but instead were the highest near the bottom. Higher amounts were sampled after a storm, especially close to the shore, which reflects the inputs from land-based runoff and re-suspended sediments (Lattin et al., 2004). In another study, microplastics were collected on the surface, rather than at subsurface layers, of the North Pacific Ocean (the Bering Sea and off the coast of southern California). The authors emphasise that microplastics (fragments, fishing lines/fibres and virgin plastic pellets) were concentrated near the surface due to their buoyancy in seawater (Doyle et al., 2011).

In the western Pacific Ocean, particularly in the Kuroshio Current (30–34°N, 133–139°W), plastic and PS fragments were identified in surface plankton tows (Yamashita and Tanimura, 2007). Seventy-two per cent of the sampled stations contained fragments, many of which measured ~3 mm. Plastic pellets represented <1% of the total sampled items. The surface microlayers (50–60 μm) and subsurface layers (1 m) around Singapore were also reported to be contaminated by PE, PP and PS microplastics (Ng and Obbard, 2006).

The Southern Hemisphere is likely contaminated by floating plastic debris, as predicted by a recent mathematical computational model (Maximenko et al., 2012). Based on these findings, Eriksen et al. (2013) conducted a specific surface survey in the South Pacific Subtropical Gyre (SPSG), where 96% of the samples revealed the presence of plastics. The majority of the plastics (88.8% of the total weight) were microplastic fragments (1–5 mm) that were collected between 97 and 111°W. The total amount of sampled plastics was lower than that in the NPCG (Moore et al., 2001), but both gyres contained similar sized fragments. A possible inverse relationship exists between plastic counts (or weight) and the sea conditions (Kukulka et al., 2012; Collignon et al., 2012).

2.2. Sandy and muddy sediments

Microplastics on sandy beaches were first reported in the form of plastic pellets in New Zealand, Canada, Bermuda and Lebanon (Gregory, 1977, 1978, 1983; Shiber, 1979) (Table S2). In New Zealand, the pellets were translucent, 2–5 mm in size and related to accidental spillages at the major ports (Gregory, 1977, 1978). These characteristics were also observed for PE pellets sampled on beaches in Canada, Bermuda and Lebanon. Many of the pellets showed deterioration due to weathering (Gregory, 1983). Plastic pellets have also been reported on beaches at the Gulf of Oman, the Arabian Gulf (Khordagui and Abu-Hilal, 1994) and the Maltese coast of the Central Mediterranean (Turner and Holmes, 2011). On the Arabian coast, large numbers of stranded pellets and the presence of entire bags indicated that a massive spill most likely occurred during shipping. Some of the PE pellets observed in the Mediterranean were embedded in tar. Recently, Fotopoulou and Karapanagioti (2012) investigated the superficial characteristics of plastic pellets; they revealed that the surfaces of virgin pellets are smooth and uniform, whereas the surfaces of stranded and eroded PS and PP pellets are rough and uneven. The PS pellets found in the environment had enlarged surface areas and were more polar, which indicates that they more efficiently interact with a variety chemical compounds compared with virgin pellets (Fotopoulou and Karapanagioti, 2012).

It seems that plastic resin pellets were already distributed worldwide in the 1970s (Hidalgo-Ruz et al., 2012). Nowadays, other types of microplastics are also reported globally (Browne et al., 2011). Microplastics are reportedly present on six continents, and higher amounts are commonly related to densely populated areas. In a study of the types (mostly fibres) and materials (frequently polyester and acrylic) of microplastics, Browne et al. (2011) suggested that the plastics were produced by sewage effluents, including wastewater from washing machines.

By analysing sediments from 18 beaches around the UK, Thompson et al. (2004) most often observed polymers in the form of fibres. Microplastics (<1 mm) were also present in sediment samples from the Tamar Estuary, UK (Browne et al., 2010). PVC, polyester and polyamide comprised ~80% of the total sampled fragments and were generally more common at downwind sites.

On the Belgium coast, the sediment from beaches, harbours and sub-littoral habitats were found to be contaminated with microplastics (38 μm–1 mm). In general, plastic fibres were more common than pellets, except in harbour areas (Claessens et al., 2011). The sediment cores from sandy beaches revealed that microplastic deposition tripled over the last 20 years (Claessens et al., 2011). In the North Sea, microplastics were quantified on beach and tidal flat habitats on the East Frisian Islands (Liebezeit and Dubaish, 2012). Pellets (<100 μm) and fibres were present, but plastic fragments and PS pellets were completely absent. The tidal flats were more contaminated, mostly by pellets, than the sandy beaches.

At the Lagoon of Venice, Italy (Vianello et al., 2013), 10 different polymers that measured 30–500 μm were successfully identified by μFT-IR (Harrison et al., 2012). PS and PP were prevalent. Spatially, microplastic particles tend to accumulate in low hydrodynamism sites (such as the inner lagoon) in a similar manner to fine sediment fractions (Vianello et al., 2013).

The presence of small-sized plastics on Hawaiian beaches is expected because the archipelago is located in the NPCG. All of the sediment samples from the islands were contaminated, primarily by plastic fragments (87%) but also by resin pellets (11%) (McDermid and McMullen, 2004). The strand line was significantly more contaminated when compared to the berm. The samples measured 2.8–5 mm; however, on remote beaches, such as Cargo Beach in the Midway Atoll, the majority of the sampled plastics were even smaller. Another heavily polluted beach in the Hawaiian Archipelago is Kamilo Beach, where plastic fragments mostly occur (95%) in the top 15 cm of the sediment cores (Carson et al., 2011). Artificial sediment cores were constructed, and they indicated that higher amounts of fragments increase the permeability of the sediment and change its maximum temperature, which causes the sediments to warm more slowly. This can affect the sex of temperature-determinant organisms, such as sea turtles (e.g., a reduction in the number of females) (Carson et al., 2011).

In the Pacific Ocean (Chile), a volunteer survey revealed that microplastic fragments (1–4.75 mm) occurred in 90% of the beach samples ($N = 39$), including those from Easter Island. There, higher abundances of smaller fragments were registered (Hidalgo-Ruz and Thiel, 2013).

Near the Sea of Japan (Kusui and Noda, 2003), plastic fragments and pellets were reported on Japanese beaches. However, plastic resin pellets were absent from Russian beaches. The presence of buried fragments indicates that surveys might underestimate the quantities of stranded microplastics on sandy beaches (Kusui and Noda, 2003). In the Indian Ocean, the presence of microplastics and other materials in coastal sediments were reported in India (Reddy et al., 2006) and Singapore (Ng and Obbard, 2006). Polyurethane, Nylon, PS and polyester were identified in inter-tidal environments on the western coast of India (Reddy et al., 2006). In Singapore, microplastics, mostly with secondary sources, were prevalent on tourist beaches (east coast) (Ng and Obbard, 2006) (Table S2).

In the western South Atlantic Ocean, plastic pellets have been present on the continental shores for many years (e.g., Ivar do Sul and Costa, 2007). The occurrence of plastic fragments was documented over the last three decades, but not systematically. The studies were usually related to macro categories of plastic debris. Currently, the research focuses on microplastic debris (Ivar do Sul et al., 2009; Costa et al., 2010; Fisner et al., 2013). Microplastics (mostly hard fragments) were reported on the beaches of Fernando de Noronha Archipelago (3°S, 32°W). Virgin plastic pellets have only been spotted on windward beaches, which highlights their oceanic origins. Microplastics pose a serious risk to the resident and migrant biota, especially endemic species (Ivar do Sul et al., 2009). At Boa Viagem Beach (8°S), an important tourist destination in the region, primary- and secondary-sourced microplastics were present (Costa et al., 2010). The authors emphasised that beach cleaning services cannot target this size category. Thus, the only abatement method is to reduce the amount of microplastics that enter the marine and coastal environments. New methods and techniques aimed at improving microplastic research and the standardisation of sampling protocols are continually being developed (e.g., Imhof et al., 2012; Claessens et al., 2011; Harrison et al., 2012).

2.3. Ingestion of microplastics

The ingestion of microplastics has been documented for vertebrate and invertebrate marine species (Tables S3 and S4). The interactions between microplastics and marine vertebrates were discovered and primarily reported from opportunistic sampling. However, for invertebrates, the research is somewhat restricted to controlled laboratory experiments (Table 2).

2.4. Vertebrates

The ingestion of microplastics by teleost fish was discovered many years ago (Carpenter et al., 1972; Hoss and Settle, 1990). In the early 1970s, Carpenter et al. (1972) reported the presence of plastics (<5 mm) in larvae and juvenile *Pseudopleuronects flounder* in the North Atlantic Ocean. Adults (*Morone america* and *Pronotus evolans*) were also found to ingest plastic pellets. Furthermore, controlled laboratory experiments were performed (Hoss and Settle, 1990) in which six different species of fish in early life stages were fed 100–500 μm pellets; all of the fish ingested the microplastics. These early works were the first to detect and report this level of interaction between microplastics and the marine biota.

Recently, concerns over the ingestion of microplastics emerged when synthetic fragments were found in the gastrointestinal content from 35% ($N = 670$) of the planktivorous fish in the NPCG (Boerger et al., 2010; Table S3). Quantitatively, the average number of plastic pieces ingested (1–2.79 mm) increased with the fish size. The colours of the plastics collected in the marine environment during sampling revealed similar percentages to those of the ingested plastics (Boerger et al., 2010). This similarity may indicate that there is no colour-based selectivity by lantern fish (Myctophidae) during feeding. Pelagic and demersal fish inhabiting the coastal waters around the UK were also found with synthetic and semi-synthetic plastics from sewage sources in their digestive tracts. Thirty-six percent ($N = 504$) mostly ingested fibres (68%) and microplastic fragments (Lusher et al., 2013).

In the North Pacific, mesopelagic fish (9%; $N = 141$), including Myctophidae, were also contaminated with microplastic fragments (~2.2 mm) and fibres (Davison and Asch, 2011). Lantern fish were also found with plastics in their stomach contents (~40%) at the Mariana Islands (Philippines Sea). Unlike the NPCG, the Marianna Islands are not a hotspot of microplastic debris, which illustrates the magnitude of the problem (Van Noord, 2013).

It is well-established that estuarine environments around the world are affected by microplastic pollution (Browne et al., 2011), and their resident fish are at risk of interacting with this pollutant. In a small estuary in the western South Atlantic Ocean, catfishes (Ariidae), estuarine drums (Sciaenidae) and mojarras (Gerreidae) have been reported to have synthetic polymers in their digestive tracts (Possatto et al., 2011; Dantas et al., 2012; Ramos et al., 2012; Table S3). All of the studied species are benthophagous, which feed on or just below the sediment surface. These species most frequently ingest blue nylon threads. For catfishes ($N = 182$), the ingestion of plastic debris appeared to vary according to the ontogenetic phase (except for *Cathorops agassizii*) (Possatto et al., 2011). Approximately 8% ($N = 569$) of the estuarine drums (adults) ingested plastic threads during the late rainy season and in the middle estuary, when higher water fluxes and intense fishery activities occurred (Dantas et al., 2012). Among mojarras, 13.4% ($N = 425$) were contaminated with synthetic threads. The sources of microplastics are related to the ingestion of contaminated prey (e.g., polychaetes), the ingestion of threads during normal suction feeding, and the active ingestion of plastics with biofilm. The possible transference of the plastics to the species predators at higher trophic-levels in the estuarine and coastal food webs was highlighted (Ramos et al., 2012).

Table 2
The main differences in the ingestion of microplastics between vertebrate and invertebrate marine species based on the retrieved literature ($N = 37$ works). See the Supplementary content for details.

Group	Type of study	Number of organisms examined	Plastic size range
Vertebrates	Field campaigns	Dozens to hundreds	~1 mm to several cm
Invertebrates	Controlled laboratory experiments	Units to dozens	Few μm to few mm

Seabirds have long been known to interact with marine plastic pollution and have been used to monitor the quantities and composition of plastic ingestion for at least four decades (e.g., Day et al., 1984; Fry et al., 1987; Van Franeker and Bell, 1988; Barnes et al., 2009; Colabuono et al., 2009, 2010). The majority of the ingested fragments were identified by the naked eye, and macroplastics (>5 mm) and microplastics are commonly reported together. Plastic pellets were identified in migratory petrels, shearwaters and prions in the 1980s and 2000s in the Atlantic and south-western Indian oceans (Ryan, 2008). Surprisingly, the proportion of pellets decreased significantly in all five species that were investigated over the last 20 years. However, because the total loads of ingested plastics did not vary significantly between decades, the author attributed this change to the enhancement of secondary-sourced plastics (i.e., fragments) (Ryan, 2008).

Plastic fragments and pellets were identified in two *Fulmarus glacialis* colonies in the Canadian Arctic. More than 80% of the fulmars ingested fragments (Provencher et al., 2009). This species was monitored in several regions in the North Sea and the Netherlands for at least three decades (Table S3). As previously observed by Ryan (2008), the industrial plastic pellets found in stomachs decreased by half over 20 years, but the plastic fragments tripled (Van Franeker et al., 2011). An important finding is that juveniles ate more plastics than adults (Kühn and van Franeker, 2012) and that higher quantities of ingested plastics were reported near highly industrialised areas directly related to fishing and shipping (Van Franeker et al., 2011). Further north in Iceland, *Fulmarus glacialis* were contaminated (Kühn and van Franeker, 2012). Fragmented plastics were much more common than virgin plastic pellets, which illustrates the wide-ranging distribution of these pollutants (Kühn and van Franeker, 2012). However, the percentage of contaminated birds (79%, $N = 58$) was low compared to that of birds inhabiting lower latitudes, most likely because more fragments are available. This hypothesis was previously suggested by Provencher et al. (2010) when they were studying *Uria lomvia* in Nunavut, Canada. There, 11% ($N = 186$) of the murres ingested plastic fragments, some of which were too small to be identified by the naked eye. The authors emphasised that because murres feed below the sea surface, they are not likely to ingest floating plastics. Nonetheless, the magnitude of plastic pollution in the marine environment is still a concern (Provencher et al., 2010). Fulmars throughout the eastern North Pacific Ocean are also highly susceptible to plastics (Avery-Gomm et al., 2012). More than 90% of samples were found to be contaminated by microplastics, mostly fragments.

At the Canary Islands, eastern North Atlantic Ocean, fledgling cory shearwaters (*Calonectris diomedea*) contained plastics (83.5%, $N = 85$) in their guts. Because these chicks never feed in the marine environment, the plastics were certainly regurgitated during parental feeding (Rodríguez et al., 2012). Ingested items (nylon threads) were directly related to commercial fishery activities because the Canary Islands are one of the most important fishery grounds in the world. Along the United States east coast, boluses ($N = 589$) from *Larus glaucescens* were collected from an environmentally protected area to study plastics consumption. Twelve per cent of the boluses were identified as contaminated, mostly by films (<1 cm) derived from supermarket plastic bags (Lindborg et al., 2012). In the North Pacific Ocean, albatrosses obtained as by-catch from fisheries near the Hawaiian Islands were also contaminated. *Phoebastria immutabilis* ($N = 18$; 83.3%) had a higher frequency of ingested plastic than *P. nigripes* ($N = 29$; 52%). Ordinary plastic fragments and fishing lines comprised the majority of the ingested items (Gray et al., 2012). Twenty seabirds and other aquatic bird species that were sampled between British Columbia, Canada, and Washington contained low contamination rates. Among the common murres, for example, only 2.7% were found with ingested plastics. However, many species had small samples, so definitive conclusions could not be drawn (Avery-Gomm et al., 2013).

The transference of organic pollutants adsorbed onto marine plastic fragments to vertebrates via ingestion was detected with *Calonectris leucomelas* and *Puffinus tenuirostris* (Teuten et al., 2009; Tanaka et al., 2013). Streaked shearwater chicks were fed with pellets that were contaminated by significant amounts of PCBs. After 7 days, the identification of lower chlorinated congeners of PCBs, which can be regarded as a sensitive tracer to detect the contribution from plastic-derived PCBs, verified the transference of this contaminant from ingested plastics to the biological tissues of the seabirds (Teuten et al., 2009). Similarly, Tanaka et al. (2013) measured the concentrations of PBDEs from ingested plastic fragments in the natural prey of birds (fish) and in their adipose tissues. Two PBDEs congeners were not found in their prey, but were adsorbed onto the plastics, which indicate the transfer of plastic-derived chemicals to the seabird (Tanaka et al., 2013).

For marine mammals, research related to the ingestion of microplastics is restricted. By analysing fur seal (*Arctocephalus tropicalis* and *A. gazella*) scats collected on Macquaire Island, Eriksson and Burton (2003) identified pellet and plastic fragment (2–5 mm) contamination. The authors related the ingested plastics to the animal's prey, *Electrona subaspera*, which had previously ingested plastics from seawater (Eriksson and Burton, 2003). Recently, scats collected from *Phoca vitulina* in The Netherlands did not contain microplastics. However, 107 stomachs and 100 intestines that were analysed were contaminated (11% and 1%, respectively), mostly by sheets and threads (Rebolledo et al., 2013). To our knowledge, only a single study investigated the impacts of microplastics on cetaceans (Fossi et al., 2012). The authors suggested that fin whales (*Balaenoptera physalus*) ingest microplastics because of the concentration of phthalates in their blubber, which are linked to the pollutants measured on marine microplastics sampled in the same area of the Mediterranean Sea where the whales live and feed (Fossi et al., 2012) (Table S3).

2.5. Invertebrates

After identifying plastics in plankton samples and sedimentary habitats, Thompson et al. (2004) investigated whether invertebrates ingest microplastics in the environment. The authors observed that amphipods (*Orchestia gammarellus*), lugworms (*Arenicola marina*) and barnacles (*Semibalanus balanoides*) ingested microplastics within a few days of exposure. This was the first of a series of works on the ingestion of microplastics by marine invertebrates (mainly molluscs, crustaceans, annelids and echinoderms) using controlled laboratory experiments (Table 2).

Among the well-established model organisms, *Mytilus edulis* is the most commonly studied in terms of microplastic ingestion (Table S4). These mussels ingested and accumulated microplastics (<1 mm) within 12 h of the experiment start time (Browne et al., 2008). High quantities of microplastics (mostly <3 μm) were found in the hemolymph until the 12th day. Recently, the presence of HDPE (≤80 μm) in gills and inside the digestive system of *M. edulis* was also investigated (von Moos et al., 2012). The authors observed microplastics in the gills, that were trapped directly from the water column. Microplastics were also in the intestines, which suggests that particles were ingested via ciliar movements and then transferred to this organ (von Moos et al., 2012). Moreover, mussels ingested even smaller (30 nm) fragments. The experiment results indicated that nanoplastics were also ingested by *M. edulis,* which triggered the production of pseudofeces and reduced their filtering activities (Wegner et al., 2012). The authors emphasised the risks to humans when eating blue mussels. In fact, the transference of microplastics from *M. edulis* to higher trophic levels (*Carcinus maenas*) has already been registered (Farrell and Nelson, 2012). Microplastics can even translocate to the hemolymph and tissues of the crabs. Therefore, the implications are evident for the rest of the food web (Farrell and Nelson, 2012), including for humans (Wegner et al., 2012). Braid et al. (2012) opportunistically found another mollusc, a cephalopod, which has ingested microplastics. Humboldt squids (*Dosidicus gigas*), observed during a mass stranding, ingested pellets and fishing lines (26%; $N = 30$). This exemplifies the growing concern over the accumulation of plastics in the marine environment (Braid et al., 2012).

Another animal group that has been studied in terms of microplastic ingestion is Holothuria (Graham and Thompson, 2009). Deposit-feeding and suspension-feeding sea cucumbers selectively ingest nylon and PVC fragments (0.25–15 mm) over sediment grains. Because plastics concomitantly collected in the study area (USA) were contaminated with organic pollutants, the ingestion of plastics could initiate a new pathway of PCB exposure and cycling within the marine communities (Graham and Thompson, 2009), which could possibly reach human populations.

Studies concerning microplastic ingestion by benthic crustaceans are limited (Thompson et al., 2004; Murray and Cowie, 2011; Ugolini et al., 2013). In the Clyde Sea, eighty-three per cent of the sampled lobsters ($N = 120$) contained microplastics, mainly filaments in the form of balls, in their stomachs (Murray and Cowie, 2011). A visual analysis revealed that the material of these balls is the same (PP) found on the ropes used by the fishing industry for catching *Nephrops*. In the laboratory, lobsters also ingested plastic seeds in the first 24 h after exposure (Murray and Cowie, 2011). *Talitrus saltator* was found to ingest PE and PP microplastics on sandy shores in Pisa (Italy). In the laboratory, experiments confirmed they are able to ingest microplastics when feeding and expel the plastic within one week (Ugolini et al., 2013).

Thirteen zooplankton taxa, mainly crustaceans (Copepoda, Euphausiacea and Decapoda) and Tunicata, Cnidaria and Mollusca, ingested microplastics (1.7–30.6 μm) under laboratory conditions (Cole et al., 2013). Among copepods, the presence of microplastics significantly reduced feeding, which illustrates the negative impacts of microplastics on zooplankton communities (Cole et al., 2013).

Information concerning the uptake of microplastics and its implications for polychaetes also exist (Thompson et al., 2004). In a laboratory experiment, *Arenicola marina* ingested PS microplastics (400–1300 μm); the authors established a positive relationship between the microplastic concentration in the sediment and the ingestion of plastics and the weight loss by the lugworm (Besseling et al., 2013). Feeding activity was also reduced. Despite these physical impacts, the microplastics did not accumulate in their digestive tracts during the experiment (28 days). The ingestion of PS (small doses) by *A. marina* was associated with higher concentrations of PCBs in their tissues (Besseling et al., 2013).

2.6. Adsorption of pollutants onto microplastic particles

PP resin pellets collected along the Japanese coast were enriched with polychlorinated biphenyls (PCBs), organochlorines (DDE) and nonylphenols (NP) absorbed from seawater (Mato et al., 2001; Ogata et al., 2009) (Table S5). The concentrations were comparable to those found in suspended particles and bottom sediments collected in the same area. Plastic additives and/or their degradation products were most likely the major source of NP (Mato et al., 2001). Individual analysis of PCBs revealed that concentrations are highly variable among individual pellets and locations along the Japanese coast (Endo et al., 2005; Ogata et al., 2009). Additionally, discoloured (weathered) pellets generally exhibited higher concentration of PCBs than coloured pellets.

Near Lisbon, along the Portuguese coast, black, white, coloured and aged pellets were analysed separately for PCBs, polycyclic aromatic hydrocarbons (PAHs) and DDTs (Frias et al., 2010). The black pellets exhibited higher concentrations of PCBs than aged pellets, possibly because they have higher adsorption rates (Frias et al., 2010). Latitudinal surveys revealed that organic chemical pollutants were present along the entire Portuguese coastline (Ogata et al., 2009; Mizukawa et al., 2013). The concentrations of PCBs adsorbed onto the pellets were one order of magnitude higher around the major cities of Porto and Lisbon and were directly related to industrial and urban discharges. In less-developed cities, PCBs are most likely airborne from industrialised areas (Mizukawa et al., 2013). Similarly, beaches in the Saronikos Gulf near Athens had higher contamination levels (Karapanagioti et al., 2011) than other beaches around the world (e.g., Ogata et al., 2009). Organic compounds and metals accumulate on PE plastic pellets in the coastal and marine environments (Ashton et al., 2010).

Microplastics and associated pollutants were investigated in the South Atlantic Ocean (Ogata et al., 2009). On South African beaches, long-term surveys of PE pellets indicated that the mean average concentrations of all of the persistent organic pollutants (POPs) decreased from the 1980s to 2000s (Ryan et al., 2012). The concentrations of these contaminants likely decreased in the South African coastal waters as well. In the western Atlantic Ocean, plastic pellets were systematically sampled as deep as 1 m in the sediment of a sandy beach at Santos Bay, which is a long-term and densely industrialised region (Fisner et al., 2013). Higher concentrations of $\sum$-total PAHs were found in the surface layer (0–10 cm), whereas $\sum$-priority PAHs were found in higher concentrations in the 60–70 cm layer. Petrogenic and pyrolytic sources were introduced to the area (Fisner et al., 2013).

Laboratory experiments tested the kinetic distribution of plastic pellets from different materials (PP, PE, polyoxymethylene (POM) and eroded pellets) (Karapanagioti and Klontza, 2008). Phenanthrene adsorption occurs through diffusion onto the plastic pellets for all materials, except for PP. For this material, diffusion is most likely dependent on salinity (more so than for the other materials). For eroded pellets, the distribution coefficient ($Kd_{FW} = 1400\ \mathrm{L\ kg^{-1}}$) is higher due to the weathering in the environment, and diffusion occurs more slowly (Karapanagioti and Klontza, 2008).

Near the NPCG and California coast, the presence of PCBs, PAHs from combusted fossil fuels, and DDTs from pesticides was reported in plastic pellets and microplastic fragments (80–90% PP) (Rios et al., 2007). Recently, plankton samples from the same area indicated that PP fragments were still contaminated by organic pollutants. Several samples exhibited high concentration levels (similar to those from marine sediments), which demonstrates that plastics actually adsorb and accumulate pollutants once in the marine environment (Rios et al., 2010).

Using a thermodynamic approach, Gouin et al. (2011) suggested that hydrophobic organic chemicals will adsorb onto PE plastics if the plastics are available in large quantities and the natural organic matter is limited. In addition, the transport of microplastics may enhance the mobility of the hydrophobic compounds that have limited transport potential (Gouin et al., 2011).

To assess the relationships between mass-produced plastic polymers and organic contaminants, Rochman et al. (2013) carried out a controlled experiment that exposed PE, PP, PET and PVC fragments over a 12-month period to environmental concentrations of PCBs and PAHs at San Diego Bay, California, where POPs were already known to contaminate beached plastic debris (Van et al., 2012). The concentrations of PAHs and PCBs that adsorbed onto HDPE, LDPE, and PP were consistently greater than those adsorbed onto PET and PVC fragments (Rochman et al., 2013). The authors suggested that products made from HDPE, LDPE, and PP pose a greater risk to marine animals than those products made from PET and PVC if the fragments are ingested.

The possible differences amongst the most often used and released types of plastics (i.e., PE, PP, PVC) have been tested in sedimentary habitats. PE, which has larger volumes of the internal cavities, adsorbed more phenanthrene than PP and PVC (Teuten et al., 2007). Again, the authors suggested that microplastics would increase the accumulation of PAHs when ingested by lugworms (*A. marina*). However, in the environment, chemical compounds normally occur as mixtures, not single solute systems (Bakir et al., 2012). In the laboratory, in a bi-solute system with phenanthrene and 4,4′-DDT, the DDT did not exhibit significantly different sorption behaviour (using PE and PVC 200–250 μm) than single solute systems. However, the DDT did appear to interfere with the sorption of phenanthrene onto plastics, which indicates an antagonistic effect (Bakir et al., 2012) (Table S5).

3. Discussion

It is well-established that plastics will fragment in the marine environment and form micro and nano pieces (Andrady, 2011); however, no long-term studies have been undertaken to estimate the actual residence time of these fragments (Roy et al., 2011; Hidalgo-Ruz et al., 2012). Moreover, if these fragments are not completely mineralised (i.e., biodegraded) within relatively short periods of time, their potential harmful effects must be addressed (Figs. 1 and 2) (Roy et al., 2011). Scientific evidence of the fate and consequences of microplastics rapidly emerged in the literature, although crucial investigations remain uncompleted or overlooked (Fig. 3).

Microplastics have a larger surface area to volume ratio than macroplastics and are more susceptible to contamination by a number of airborne pollutants (i.e., manufactured POPs and to some extent, metals) (Table S5). Because plastics are made of highly hydrophobic materials, the chemical pollutants are concentrated in and/or onto their surfaces, and microplastics act as reservoirs of toxic chemicals in the environment. Plastic pellets have been successfully studied to assess the worldwide quantities of POPs in a platform called the “International Pellet Watch” (e.g., Ogata et al., 2009). With these data, it was possible to identify geographical ‘hotspots’ (Table S5). More importantly, scientists can continuously and systematically monitor contaminated pellets and determine the temporal patterns of various pollutants, which effectively aids decision-makers (Fig. 3). Recently, laboratory studies showed that weathering significantly changes the superficial characteristics of virgin plastic pellets. Additionally, coloured plastics and different types of polymers (i.e., PP and PE) may adsorb POPs from the

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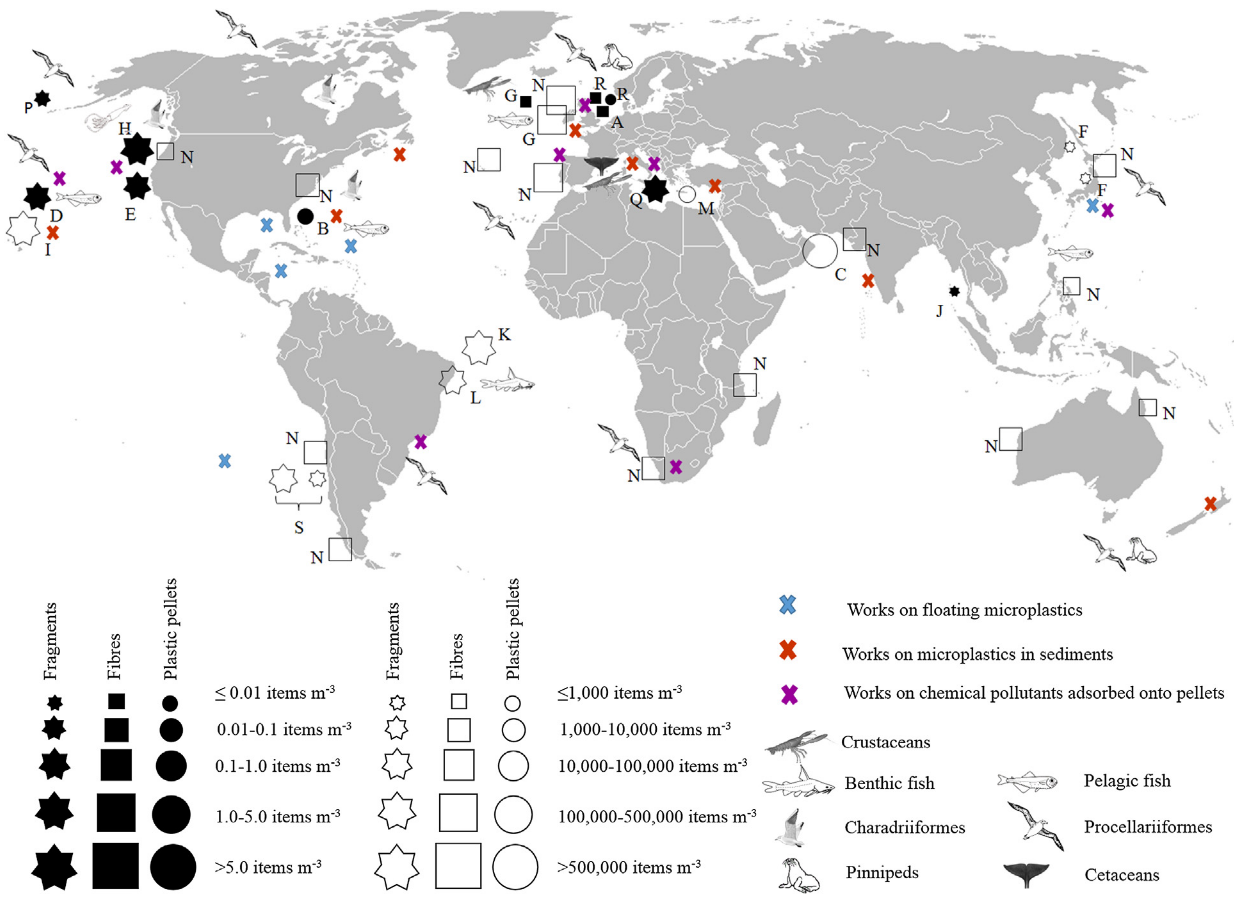

Fig. 1. Reports on the amount and occurrence of microplastics in the marine environment and their interactions with the marine biota in the wild. Stars, squares and circles represent the average number of items per cubic meter of seawater (black symbols) or sediment (open symbols) observed and/or estimated. (A) Buchanan, 1971; (B) Carpenter et al., 1972; (C) Khordagui and Abu-Hilal, 1994; (D) Moore et al., 2001; (E) Moore et al., 2002; (F) Kusui and Noda, 2003; (G) Thompson et al., 2004; (H) Lattin et al., 2004; (I) McDermid and McMullen, 2004; (J) Ng and Obbard, 2006; (K) Ivar do Sul et al., 2009; (L) Costa et al., 2010; (M) Turner and Holmes, 2011; (N) Browne et al., 2011; (P) Doyle et al., 2011; (Q) Collignon et al., 2012; (R) Dubaish and Liebezeit, 2013; (S) Hidalgo-Ruz and Thiel, 2013. The crosses represent works that registered microplastics outside of the scale used here.

environment differently. These findings must be considered and validated in future work and monitoring projects (e.g., Frias et al., 2010), including in the assessment of microplastic fragments (Hirai et al., 2011).

Microplastics transport pollutants over large oceanic areas (Zarfl and Matthies, 2010) and contaminate the marine biota when ingested (Teuten et al., 2007, 2009; Tanaka et al., 2013). By eating the contaminated microplastics, individuals are susceptible to physical damage and to doses of pollutants that were not previously accessible in other tangible matrices, such as seawater and sediments. Organisms at every level of the marine food web ingest microplastics (Fig. 2), but those inhabiting industrialised areas are exposed to higher amounts and may be more contaminated. However, the speculated quantities (μg g^{-1}; ng g^{-1}) of contaminants vary significantly among fragments within the same area; consequently, the toxicity of pollutants and incorporation into bodily tissues varies for each biological species. Some groups (e.g., holothurians) apparently ingest microplastics with specific colours and shapes; if those polymers adsorb higher quantities of pollutants, the consequences are most likely greater. Therefore, population level effects, including the mechanisms to explain the transference of ingested plastics and their adsorbed contaminants along marine food webs, are merely speculative. Primary producers are known to incorporate microplastics and organic pollutants (Oliveira et al., 2012); therefore, bioaccumulation to top predators, including larger species (Mysticetidae) (Fossi et al., 2012), or among primary and secondary consumers may occur (Eriksson and Burton, 2003; Farrell and Nelson, 2012) (Fig. 2).

Potentially, microplastics with low and high densities are ingested when present in the marine environment (Fig. 2) and tend to float on the sea surface. There, they are available to a wide range of organisms that may ingest microplastics passively or actively. Until recently, only hypotheses and weak evidence for the ingestion process were available (e.g., Day et al., 1984; Boerger et al., 2010; Ramos et al., 2012). If the polymer is denser than the seawater or becomes covered by biological films, then it tends to sink (eventually reaching the seabed) or becomes neutrally buoyant (e.g., Lattin et al., 2004).

Higher amounts of buoyant microplastics were reported in the North Pacific Ocean, particularly the NPCG, than in other ocean basins (Fig. 1). This region is currently referred to as the "eastern garbage path" (Moore et al., 2001, 2002; Lattin et al., 2004; Rios et al., 2010). Microplastics were mainly related to fishing activities (oceanic sources) in the gyre, but on the coast, they were related to continental discharges at highly industrialised low latitudes. In the North Atlantic Ocean, contamination patterns at the sea surface are generally two orders of magnitude lower than in the NPCG (Fig. 1). Fibres were prevalent in the North Sea, whereas hard plastic fragments were more common in the Caribbean Sea; however, the sampling methods varied between the locations (Table S1). The corresponding subtropical gyres in the Southern Hemisphere were less contaminated, most likely because there are

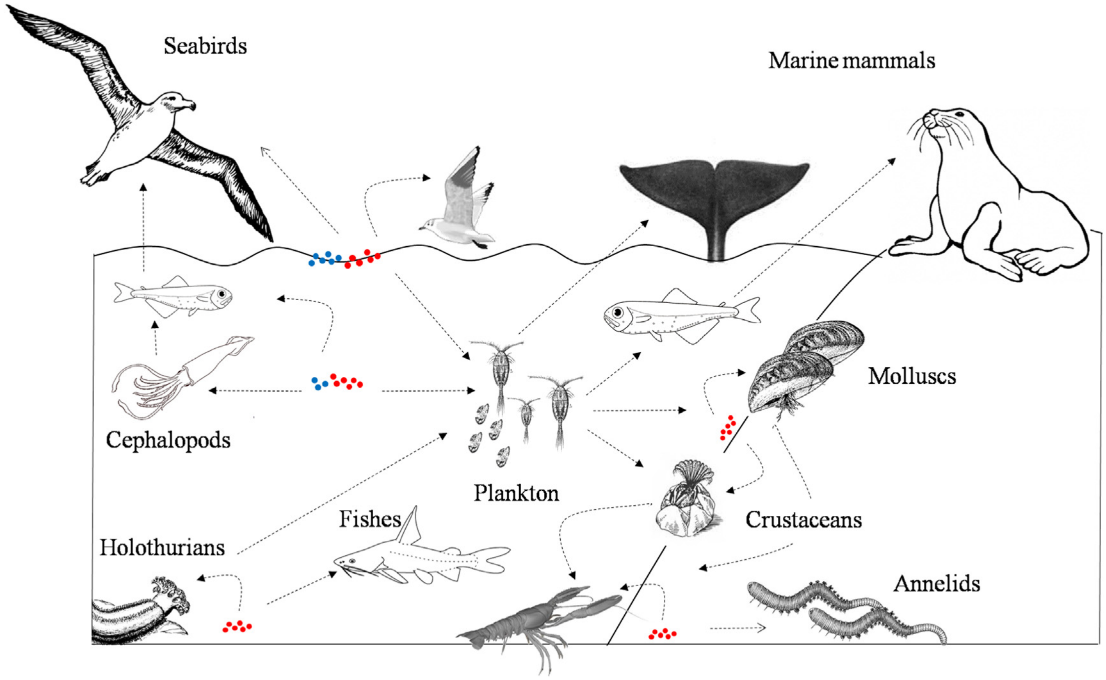

Fig. 2. A conceptual model of the potential trophic routes of microplastics across marine vertebrate and invertebrate groups. The blue dots are polymers that are less dense than seawater (i.e., PE and PP) and the red dots are polymers that are more dense than seawater (i.e., PVC). The dashed arrows represent the hypothesised microplastic transfer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

less land masses and the region is less developed than the highly industrialised Northern Hemisphere. The 300 μm mesh size is most commonly used to sample microplastics at sea (Hidalgo-Ruz et al., 2012). However, additional mesh sizes were also applied, which produce large variations in the quantity of microplastics collected (e.g., Cole et al., 2011).

Surface-feeding petrels, shearwaters and albatrosses, including fledgling chicks, appear to be the most impacted by floating microplastics (up to 90% of samples). Scientific reports are widespread, from the Antarctic to the Canadian Arctic, and throughout all of the ocean basins (Fig. 1 and Table S3). As expected, ingested amounts of plastics decreased towards the high latitudes; plastic

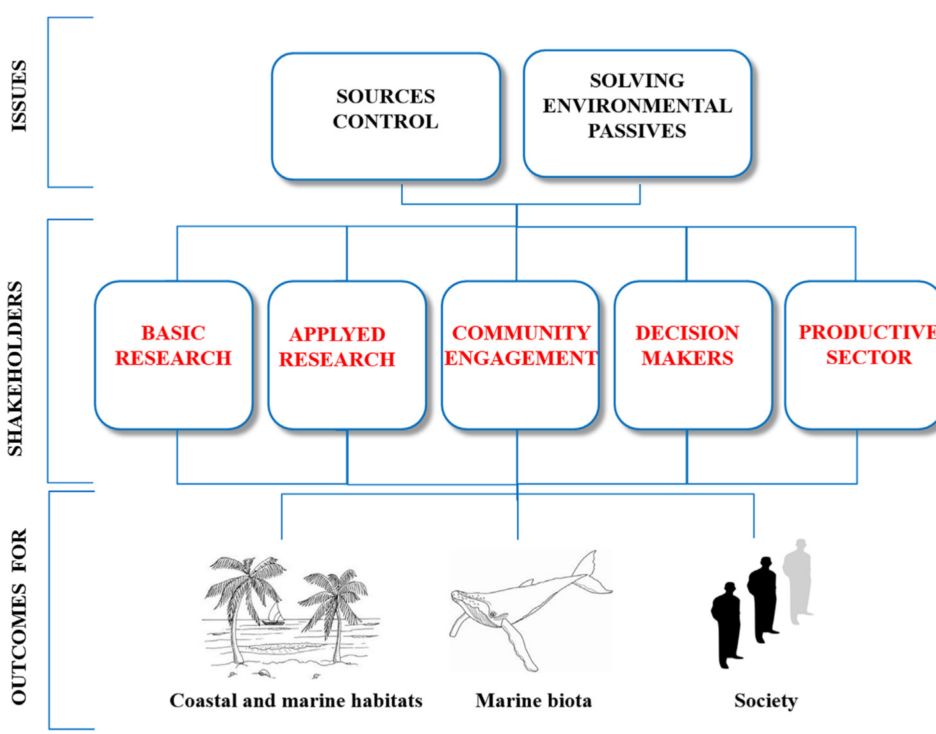

Fig. 3. Various issues regarding microplastic pollution at sea will need the cooperation of different stakeholders. The integration of their actions will encourage positive outcomes for coastal and marine environments, marine biota and society.

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fragments are now prevalent over pellets as observed from the long-term field work in the Atlantic Ocean (e.g., Morét-Ferguson et al., 2010). Therefore, seabirds can be considered sensitive monitors of small plastics at sea (Ryan, 2008). Ingested plastics significantly vary in size, and studies now need to quantify the magnitude and characteristics of smaller sizes (<1 mm) of microplastics. Procellariiformes do not regurgitate plastics, which is one explanation for the high amount of plastics observed in their stomachs. However, POPs from the microplastics in their digestive tracts can eventually enter the bloodstream, reach other organs and possibly result in physiologic damage. Seabirds may eat pelagic microplastics when feeding, but they likely also ingest planktivorous fish and squids that had previously ingested microplastics from seawater (similar to the observations of other top predators, such as fur seals) (Table S3). Likewise, pelagic fish and squids may ingest microplastics with plankton or ingest them actively (most of the ingestion processes are largely speculative). The extent of the problem is huge; fish (Myctophidae) reported in various geographic regions with microplastics comprise more than half of the world oceans' total fish biomass. Furthermore, because fish excrete ingested plastics (Hoss and Settle, 1990), sub-lethal effects are a very likely hypothesis.

The shores on six continents are contaminated with microplastics (Fig. 1). Fibres (μm) are prevalent in the eastern North Atlantic and the North Sea due to continental effluent discharges. Microplastic fragments and virgin plastic pellets are more common when the size limitation of their detection is on the order of millimetres (i.e., the eastern and western coasts of South America). However, fibres are most likely also spread throughout these sediments, mostly around urban areas (Browne et al., 2011). Oceanic islands were also reportedly contaminated by microplastic fragments. In estuaries, which are potential sources of these contaminants, studies are nearly non-existent. Moreover, the presence of microplastics in terrestrial ecosystems and the soil are completely absent from the literature (Rillig, 2012). The presence of microplastics in coastal sediments resulted in unexpected consequences, such as changes in the physical proprieties of beaches and associated problems (e.g., Carson et al., 2011).

Additionally, benthic species ingest microplastics in highly developed areas and in small estuarine ecosystems (Fig. 1; Table S3). Threads from fisheries (ropes and nets) were positively identified in the digestive tracts of benthic fish and lobsters. Microplastics, and consequently POPs, are possibly remobilised (bioturbation) in the sediment–water interface (Besseling et al., 2013). Ingestion events were described for several groups of invertebrates through laboratory experiments, but there is still a lack of research on the ingestion of microplastics by invertebrates in the marine environment, possibly because these studies are time-consuming and require more advanced technology (Table S4).

4. Conclusion and suggestions

With knowledge comes greater responsibility. Historical and recent findings regarding microplastic pollution in coastal and marine environments, as described by review papers, need to be coalesced to provide guidelines for all stakeholders concerned with the life cycle of plastic. Two major issues are prevalent: how to proceed with source control and methods to address the enormous environmental passives that were built over the last 60 years (since plastics became largely expendable) (Fig. 3). Source control has been preached by every paper, official and un-official document on marine plastics debris for decades. However, technical evidence and published opinion have failed to effectively introduce it into the DNA of the plastic production, use and re-use industries. Source control has only been a priority for very close and restricted circles where the 3Rs (or the 5Rs: Refuse, Reduce, Reuse, Recycle, Rethink) are the norm rather than the exception. Source control would have to integrate and prioritise Rethink (choose other materials and techniques) and Refuse (reduce the production of all single use plastic items) into society and the production sectors. Specific actions targeted to primary and secondary sources of microplastics are required to control pellets and to stop large items from reaching the sea (where they decay). Unfortunately, based on present trends, animals and humans will continue to be at risk and accidents will occur before these goals are achieved.

Tackling the environmental passives is a different story. Microplastics cannot be sieved from sands or filtered out of seawater. Collecting all of these microparticles would take forever, and even so it would not be effective. Microplastics will continue their slow, intricate paths towards the bottom of the ocean and ultimately become buried in sand and mud for centuries. However, rather than despair, scientists should propose solutions that can be considered by academia, society and industry. Each group of stakeholders (academia, the community, decision-makers and industry) is responsible for various tasks (Fig. 3) including communicating results to other stakeholders. Several knowledge gaps need to filled: standardising size definitions; establishing the relative importance of primary and secondary sources; rescuing information on pelagic plastics that is stored in plankton samples; adding microplastics as a routine survey variable in river basins and oceans; assessing microplastic pollution in the Antarctic and Arctic; creating and continuously improving experimental methods to quantify microplastics.

Applied research, which is performed by many societal sectors, has the potential to introduce new techniques to assess microplastics pollution and new materials, designs and facilities that will ultimately prevent plastics from reaching the environment. Some suggestions include performing laboratory tests on microplastic ingestion and necropsies for verification of physical harm, ingestion of contaminated microplastics (POPs) and confirmation of transference/damage by histology and chemical characterisation of pelagic and benthic microplastics to confirm its composition.

The community, although aware of the problem, must be guided by the public sector to search for local alternatives to excessive packaging, safely deposit their inevitable plastic rubbish and make better and more informed choices as consumers. Additionally, independent world conferences on microplastics would coalesce knowledge and actions, integrate research from countries where primary plastics are produced/exported and help define the temporal patterns of chemical pollutants (e.g., International Pellets Watch).

These suggestions will require implementation of educational programs, the cooperation of urban and rural facilities and, above all, persuasion through practical examples of environments that easily and directly exhibit proper control of waste. Decision-makers, mostly in the public sector, have intelligent and technically sound regulations to issue in the future, in addition to existing issues already enforced. State polices can be formed to direct the control of the sources of primary plastics and calculate environmental value losses (fish stocks, gas exchange, beach erosion) by microplastic pollution. Additionally, a complete cradle-to-grave approach to plastics would reduce the amount that reaches the sea and reduce our carbon footprint. Plastics are a branch of the oil and gas industry (8% of the oil produced is used in plastic production). Therefore, both sectors must meet to collaborate as soon as possible.

In addition to the petrochemical and plastics moulding units, industry as a whole must be prepared for the need to produce and use less plastic. Fiscal incentives for technologies that resolve environmental passives need to be established. The intention is not to face this sector as an arch-enemy, but rather to start a collaborative process that will steadily progress from controlling pellet pollution to effectively and dutifully applying reverse logistics to tackle the environmental passives caused by plastics on land and at sea.

The outcomes of such rationales are expected to be far-reaching. First, coastal and marine habitats will regain their lost aesthetic values, ecological functions and services. Secondly, the risks posed to the marine biota will be reduced. Ultimately, these outcomes would create a less plastic-addicted and more nature-centred society in which the greatest values, based on science and experience, are life and environmental preservation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2013.10.036.

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