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Review

Plastic waste in the marine environment: A review of sources, occurrence and effects

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HIGHLIGHTS

- The annual production of plastic has increased 200-fold from the 1950s to 2014
- Macroplastics and microplastics pose a risk to organisms
- Microplastics can lead to absorption of hydrophobic contaminants
- Recommendations are made to minimise plastic pollution in the environment

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ABSTRACT

This review article summarises the sources, occurrence, fate and effects of plastic waste in the marine environment. Due to its resistance to degradation, most plastic debris will persist in the environment for centuries and may be transported far from its source, including great distances out to sea. Land- and ocean-based sources are the major sources of plastic entering the environment, with domestic, industrial and fishing activities being the most important contributors. Ocean gyres are particular hotspots of plastic waste accumulation. Both macroplastics and microplastics pose a risk to organisms in the natural environment, for example, through ingestion or entanglement in the plastic. Many studies have investigated the potential uptake of hydrophobic contaminants, which can then bioaccumulate in the food chain, from plastic waste by organisms. To address the issue of plastic pollution in the marine environment, governments should first play an active role in addressing the issue of plastic waste by introducing legislation to control the sources of plastic debris and the use of plastic additives. In addition, plastics industries should take responsibility for the end-of-life of their products by introducing plastic recycling or upgrading programmes.

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1. Introduction

Plastic contamination in the natural environmental has attracted much attention from both researchers and the general public. Organisms can ingest the plastic or become entangled in it; plastic waste is therefore hazardous to the entire ecosystem (Stefatos et al., 1999; Sutherland et al., 2010). Plastics are synthetic or semi-synthetic organic polymers that are cheap, lightweight, strong, durable and corrosion-resistant (Derraik, 2002; Thompson et al., 2009). They tend to become brittle, break down into small pieces, and eventually degrade further when exposed to UV radiation either under direct sunlight or in seawater (Moore, 2008). However, the actual time that it takes for plastic to completely degrade in the marine environment remains unknown (Andrady, 2005). Many types of plastic debris, such as fishing nets, ropes and plastic bags, occur in the natural environment. It is estimated that 50% of plastic products, including utensils, plastic bags and packaging, are intended to be disposable (Hopewell et al., 2009). Therefore, the annual production of plastic has increased significantly from 1.5 million t in the 1950s to an estimated 299 million t in 2013 (PlasticsEurope, 2015). The most commonly used and abundant polymers are high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP) and polyethylene terephthalate (PET) (Table 1), which together account for approximately 90% of the total plastic production worldwide (Andrady and Neal, 2009). As a result, these polymers are also the most commonly found plastics in the environment, especially in aquatic environments (Andrady, 2011; Engler, 2012). Due to their corrosion-resistant properties, most plastics are regarded as "hard-to-degrade" materials, which will persist in the environment for up to a century (Cole et al., 2011). Large plastic items, known as macroplastics, have been reported in the marine environment since the early days of production (Derraik, 2002). Microplastics (<5 mm), which are smaller, have recently drawn attention because they not only make their way into the marine environment but are also more easily ingested by marine organisms; they may thus act as vectors for the chemical transfer of pollutants within the food chain (Teuten et al., 2009). This article reviews the sources of both macroplastic and microplastic debris found in water bodies and beach sediments, and their occurrences are summarised in tables. The physical and chemical effects and the fate of the plastic debris are then evaluated. Finally, various recommendations are proposed to control the amount of plastic entering the natural environment and raise public awareness of the effects of plastic debris.

Table 1
Types of plastic commonly found in the natural environment. (Halden, 2010; Andrady, 2011; Ghosh et al., 2013).

Type	Specific gravity	Use/application	Health effects
Polyester (PES)	1.40	Fibers, textiles	Cause eye and respiratory-tract irritation and acute skin rashes (Ecology Center, 1996).
Polyethylene terephthalate (PET)	1.37	Carbonated drinks bottles, peanut butter jars, plastic film, microwavable packaging, tubes, pipes, insulation molding	Potential human carcinogen (Ecology Center, 1996).
Polyethylene (PE)	0.91–0.96	Wide range of inexpensive uses including supermarket bags, plastic bottles	
High-density polyethylene (HDPE)	0.94	Detergent bottles, milk jugs, tubes, pipes, insulation molding	Release estrogenic chemicals resulting in changes in the structure of human cells (Ecology Center, 1996)
Polyvinyl chloride (PVC)	1.38	Plumbing pipes and guttering, shower curtains, window frames, flooring, films	Lead to cancer, birth defects, genetic changes, chronic bronchitis, ulcers, skin diseases, deafness, vision failure, indigestion, and liver dysfunction (Ecology Center, 1996).
Low-density polyethylene (LDPE)	0.91–0.93	Outdoor furniture, siding, floor tiles, shower curtains, clamshell packaging, films	
Polypropylene (PP)	0.85–0.83	Bottle caps, drinking straws, yogurt containers, appliances, car fenders (bumpers), plastic pressure pipe systems, tanks and jugs	
Polystyrene (PS)	1.05	Packaging foam, food containers, plastic tableware, disposable cups, plates, cutlery, CD, cassette boxes, tanks, jugs, building materials (insulation)	Irritate eyes, nose and throat and can cause dizziness and unconsciousness. Migrates into food and stores in body fat. Elevated rates of lymphatic and hematopoietic cancers for workers (Ecology Center, 1996).
High impact polystyrene (HIPS)	1.08	Refrigerator liners, food packaging, vending cups, electronics	
Polyamides (PA) (nylons)	1.13–1.35	Fibers, toothbrush bristles, fishing line, under-the-hood car engine moldings, making films for food packaging	Lead to cancer, skin allergies, dizziness, headaches, spine pains and system dysfunction (Ecology Center, 1996)
Acrylonitrile butadiene styrene (ABS)	1.06–1.08	Electronic equipment cases (e.g., computer monitors, printers, keyboards), drainage pipe, automotive bumper bars	Airborne ultrafine particle (UFP) concentrations maybe generated while printing with ABS, which leads to oxidative stress, inflammatory mediator release, and could induce heart disease, lung disease, and other systemic effects (Card et al., 2008).
Polycarbonate (PC)	1.20–1.22	Compact discs, eyeglasses, riot shields, security windows, traffic lights, lenses, construction materials	Bisphenol-A could be leached from polycarbonate products, which leads to liver function alternation, changes in insulin resistance, reproductive system and brain function (Srivastava and Godara, 2013).
Polycarbonate/acrylonitrile butadiene styrene (PC/ABS)		A blend of PC and ABS that creates a stronger plastic. Used in car interior and exterior parts and mobile phone bodies	

1.1. Macroplastics

Macroplastic pollution is a global issue and is perceived as one of the most severe forms of pollution in shorelines, oceans and freshwater bodies. The problem has been widely reported since the 1990s (Shomura and Godfrey, 1990), and macroplastic litter has been subjected to much study. More recently, this issue has drawn greater public attention and is now covered by several international regulations. Anthropogenic macroplastic debris surveys and clean-up campaigns have usually focused on the larger plastic items found on beaches, and there is wide geographical variability in the level of pollution, which increases the difficulty of analysing potential trends. Macroplastics are generally defined as having a size >25 mm (Romeo et al., 2015), but, despite their larger size, it has been reported that they are regularly ingested and retained by various marine species including seabirds, fish and cetaceans (Derraik, 2002, Teuten et al., 2007).

1.2. Microplastics

1.2.1. Primary microplastics

According to Cole et al. (2011), primary microplastics are defined as plastics manufactured to have a microscopic size. Most primary microplastics in the environment are generated from industrial and domestic products (Betts, 2008; Moore, 2008) and are mainly used in air-blasting media (Gregory, 1996), in facial cleansers and cosmetics (Zitko and Hanlon, 1991) and in medicine as drug vectors (Patel et al., 2009). For example, blasting acrylic, melamine or polyester microplastic scrubbers (0.25–1.7 mm) is used to remove rust and paint (Browne et al., 2007). Although modern wastewater treatment facilities can remove up to 99% of microplastics, microplastics released thru effluents are still significant due to their sheer amount (Rochman et al., 2015). Thus, microplastics readily enter the marine environment and may accumulate in seas and freshwater bodies (Thompson et al., 2007). One of the most widely discussed types of primary microplastics consists of scrubbers, which are used in exfoliating hand cleansers and facial scrubs. In the 1980s, the use of the microplastic scrubbers increased significantly following the patenting of these products by cosmetic companies. The size, shape and composition vary according to the cosmetic (Fendall and Sewell, 2009), for example, polyethylene and polypropylene granules (<5 mm) and polystyrene spheres (<2 mm) have all been found in a single cosmetic product.

Browne et al. (2011) catalogued microplastic pollution at the shorelines of 18 sites worldwide, representing six continents from the poles to the equator. It was found that one of the most significant sources of microplastics in the marine environment was sewage polluted by fibres from washing clothes. It was concluded that the polyester (78%) and acrylic (22%) fibres on the studied shores were mainly from washing machine discharges rather than the fragmentation of plastic cleaning tools because the proportions of polyester fibres found in the wastewater and marine sediment were similar to those used for textiles (Oerlikon, 2009). Moreover, there was a positive relationship between the abundance of microplastics and human population density (Oerlikon, 2009).

1.2.2. Secondary microplastics

Secondary microplastics are derived from the fragmentation of large plastics into smaller debris, both at sea and on land (Ryan et al., 2009). The longevity of plastics is estimated to range from months to thousands of years (Zheng et al., 2005; Barnes et al., 2009), although this figure is still uncertain because conventional plastics have only been mass-produced for approximately 60 years. However, there are many reports stating that the fragmentation of plastic items is occurring in the environment as a result of various physical, biological and chemical processes that reduce the structural integrity of plastic debris (Browne et al., 2007).

Weathering is the most important process causing the breakdown of plastics (Arthur et al., 2009). According to Corcoran et al. (2009), beaches are the optimal settings for plastic fragmentation due to the presence of both chemical and mechanical weathering. Another important process is photodegradation caused by sunlight. The ultraviolet radiation in sunlight causes oxidation of the polymer matrix, resulting in chemical bond breakage (Barnes et al., 2009). Compared to the cold temperatures of the marine environment, plastic debris on beaches is degraded more quickly due to the higher oxygen availability and direct exposure to sunlight, resulting in the loss of structural integrity (Browne et al., 2007). Finally, plastic particles are vulnerable to fragmentation from a combination of mechanical forces, for example, abrasion, wave action and turbulence (Barnes et al., 2009). The introduction of biodegradable plastics is also a source of microplastics. Biodegradable plastics are composed of traditional synthetic polymers plus starch and vegetable oils and are designed to reduce the degradation time (Derraik, 2002; Thompson et al., 2004; O'Brine and Thompson, 2010). However, if the plastics are inappropriately disposed of, the synthetic polymer, which is not biodegradable, will accumulate and fragment in the environment (Fig. 1).

2. Sources of plastic debris

2.1. Land-based debris

Land-based sources of plastic debris contribute 80% of the plastic debris in the marine environment, with densely populated or industrialised areas being the major sources due to littering, plastic bag usage and solid waste disposal, for example (Derraik, 2002). A study by Lee et al. (2013) found that the majority of floating and beached plastic debris originated from coastal recreational activities and land-based sources in the northern South China Sea. Other researchers found that large quantities of plastic debris derived from raw manufacturing materials were transported onto beaches following accidental spillage during handling and other processes (Redford et al., 1997). Other land-based sources include wastewater effluent and refuse site leachate (Browne et al., 2010). Plastics are transported from their sources by river systems and wastewater treatment works to the marine environment (Browne et al., 2010; Cole et al., 2011). In addition, extreme weather events (e.g., hurricanes or flooding) increase the transfer of land-based debris to the sea (Barnes et al., 2009). Research has found that the abundance of microplastic in Californian waters increased from 10 to 60 plastic particles m^{-3} after a storm and that increased river water volume resulted in litter being deposited at greater distances from the estuary (Moore et al., 2002).

2.2. Ocean-based debris

Ocean-based sources account for the remaining 20% of marine plastic debris, to which commercial fishing is the major contributing human activity. In 1975, the sinking of a fishing fleet resulted in the deposition of 135,400 t of plastic fishing gear and 23,600 t of synthetic packaging material into the sea (Cawthorn, 1989). Currently, the amount of fishing gear lost to the environment has quadrupled: an estimated 640,000 t of discarded fishing gear are added into the ocean every year, which amounts to approximately 10% of the total marine debris (Good et al., 2010). These discarded fishing items, including monofilament lines and nylon netting, float at specific depths within the sea, which results in "ghost fishing" and may cause the entanglement of aquatic organisms (Lozano and Mouat, 2009). There is a significant relationship between the number of ocean-based plastic items found on beaches and the level of commercial fishing (Walker et al., 1997; Cunningham and Wilson, 2003; Ribic et al., 2010). Edyvane et al. (2004) also highlighted this relationship by demonstrating a probable link between the reduction of ocean-based plastic debris over 10 years and a documented decline in specific inshore fisheries. Overall, these studies suggest that

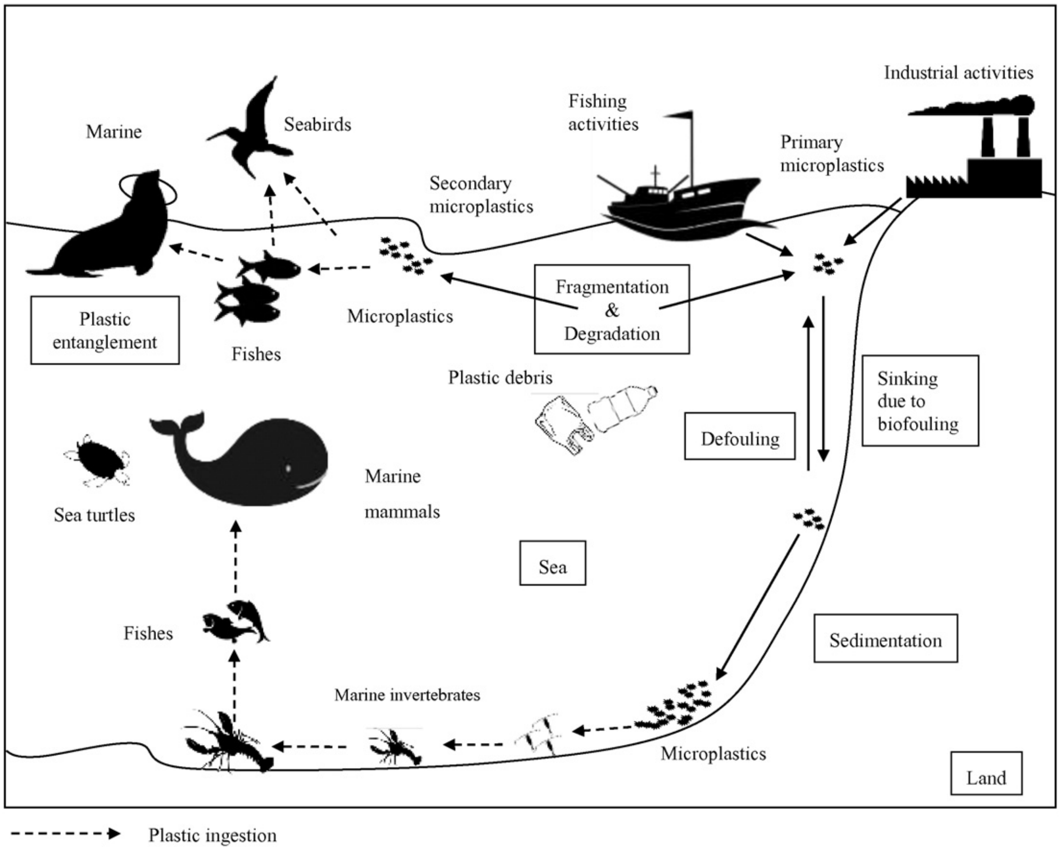

Fig. 1. Potential pathways of plastic debris transportation and its biological interactions (Wright et al., 2013; Ivar do Sul and Costa, 2014).

the level of fishing activity contributes to the amount of plastic debris in the ocean.

3. Occurrence in water bodies and beach sediments

3.1. Water bodies

Floating plastic particles have been reported in the Northern Hemisphere subtropical gyres, particularly in the North Atlantic, since the early 1970s. Many publications have reported that plastic debris is the most serious marine litter worldwide; as detailed in Table 2, plastic debris is found globally in multiple seas. The distribution of plastic debris in the sea depends on various mechanisms, including winds, currents, coastline geography and human factors such as urban areas and trade routes (Barnes et al., 2009). For example, Table 2 shows that the density of plastic debris in the Mediterranean Sea and Atlantic Ocean is very high, attributed to both natural and human factors. With regard to the natural factors, the densities might exceed 1000 pd. ha^{-1} along the coast, especially next to large cities and offshore canyons because the waste is trapped in zones with high sedimentation rates, and these rates are a regular occurrence where sea floors are flat (Galgani et al., 2000). In addition, coastal areas with industrial activity are regarded as plastic hotspots: an estimated 100,000 plastic particles m^{-3} were found in a harbour area near a PE production plant in Sweden (Noren and Naustvoll, 2010).

In addition, accumulation zones of plastic debris are also found in the open sea far from any waste sources, for example, 320 km off the Danish coast (Galgani et al., 2000). Gyres are particular hotspots for both macroplastic and microplastic accumulation (Lebreton et al., 2012; Eriksen et al., 2013b): the plastic debris, originating from both sea- and land-based sources, is transported into the subtropical gyres (Lebreton et al., 2012) and thus forms accumulation zones of particles. Eriksen et al. (2013b) reported 26,898 particles km^{-2}, ranging in size from 0.355 mm to over 4.750 mm, in the South Pacific subtropical gyre. The high abundance of plastic debris in the South Pacific subtropical gyre might be due to the occasional transfer of particles from the shores of Indonesia and Ecuador via the boundary currents (Eriksen et al., 2013b). Another study conducted by Moore et al. (2001) measured the plastic pollution in the contrasting region, the North Pacific subtropical gyre. >33.000 particles km^{-2} were reported that ranged in size from 0.355 mm to over 4.760 mm, including fragments, Styrofoam pieces, pellets, polypropylene and thin plastic films. This phenomenon may be explained by the influence of hydrodynamics (Moore et al., 2001) and might be related to the location of strong currents in the upper parts of canyons with overall reduced water movements. Sedimentation factors may also explain this situation: an area with very low turbulence (Jegou and Salomon, 1991) that coincides with the convergence zone of seabed sediment movements (Open University, 1993) will favour sedimentation, producing an accumulation zone. In addition to the natural factors affecting the plastic accumulation zones in the ocean, human activities such as fishing also contribute to the density and distribution of plastic in the marine environment (Kanehiro et al., 1995). Other anthropogenic factors, such as tourism and the presence of large metropolitan areas, are important in terms of the abundance and distribution of plastic debris (Galgani et al., 2000).

There have been many recent studies of the microplastic pollution in water bodies (Eriksen et al., 2013a; Reisser et al., 2013; Desforges et al., 2014). Plastics can be buoyant because they are composed of multiple polymers (Cole et al., 2011). The buoyancy of plastic is highly related to its specific gravity. Generally, plastic with a specific gravity <1 (Table 1) is buoyant. Microplastic abundance has been found to be higher in coastal areas compared with offshore regions because anthropogenic activities are the major source of microplastics in the marine environment (Barnes et al., 2009; Ribic et al., 2010; Doyle et al., 2011; Collignon et al., 2012; Dubaish and Liebezeit, 2013). Eriksen et al. (2013a) calculated the levels of plastic pollution in the surface water

Table 2
Occurrence of plastic debris found in water bodies.

Location	Regions	Water bodies	Water column	Debris load	Unit	Plastic type	Plastic sizes	Plastic (%)	Reference
Baltic Sea	Baltic Sea	Marine	Surface water	1.3 ± 0.8	Items/Ha	Macroplastics	>20 mm mesh	35.7%	Galgani et al. (2000)
Atlantic Ocean	North Sea	Marine	Surface water	1.6 ± 0.4	Items/Ha	Macroplastics	>20 mm mesh	48.3%	Galgani et al. (2000)
	Channel East	Marine	Surface water	1.2 ± 0.1	Items/Ha	Macroplastics	>20 mm mesh	84.6%	Galgani et al. (2000)
	Bay of Seine	Marine	Surface water	1.7 ± 0.1	Items/Ha	Macroplastics	>20 mm mesh	89%	Galgani et al. (2000)
	Celtic Sea	Marine	Surface water	5.3 ± 2.5	Items/Ha	Macroplastics	>20 mm mesh	29.5%	Galgani et al. (2000)
	Rio de la Plata	River and estuary	Coastal area and river bottom	0–15.1	Items/Ha	–	–	74%	Acha et al. (2003)
	Offshore, Ireland	Marine	Surface water	2.5	Item/m^3	Macroplastics and microplastics	<1.25 mm to >10 mm	94%	Lusher et al. (2014)
	Portuguese coast	Marine	Surface water and depth range of 25 m in the water column	0.02–0.04	Item/m^3	Microplastics	–	43.8–91.7%	Frias et al. (2014)
	Gioana estuary, Brazil	Estuary	Surface and bottom water	0.3	Item/m^3	Microplastics	2.23 ± 1.65 mm	–	Lima et al. (2014)
Mediterranean Sea	Gulf of Lion	Marine	Surface water	1.4 ± 0.2	Items/Ha	Macroplastics	>10 mm mesh	70.5%	Galgani et al. (2000)
	East Corsica	Marine	Surface water	2.3 ± 0.7	Items/Ha	–	–	45.8%	Galgani et al., 2000
	Adriatic Sea	Marine	Surface water	3.8 ± 2.5	Items/Ha	Macroplastics	>20 mm mesh	69.5%	Galgani et al. (2000)
	Greece Gulfs	Marine	Seafloor	0.7–4.4	Items/Ha	–	–	56%	Koutsodendris et al. (2008)
Pacific Ocean	North Pacific Central Gyre	Marine	Surface water	334,271	Item/km^2	Macroplastics and microplastics	0.355 to >4.76 mm	98%	Moore et al. (2001)
	Waters around Australia	Marine	Surface water	4256.4	Item/km^2	Macroplastics and microplastics	0.4 to 82.6 mm	80%	Reisser et al. (2013)
	Tokyo Bay	Marine	Surface water	1.9–3.4	Items/Ha	–	–	48.3–58.9%	Kuriyama et al. (2003)
	North Pacific offshore, surface	River	Surface water	0.4–2.2	Item/m^3	–	–	–	Moore et al. (2005)
	North Pacific central gyre	Marine	Surface water	0.02	Item/m^3	Macroplastics and microplastics	1–10 mm	–	Carson et al. (2013)
	North Pacific, inshore, surface	River	Surface water	5.0–7.3	Item/m^3	–	–	–	Moore et al. (2005)
	Eastern China Sea	Marine	Seafloor	–	Items/Ha	–	–	<5%	Lee et al. (2006)
	South Sea of Korea	Marine	Seafloor	–	Items/Ha	–	–	<10%	Lee et al. (2006)
	The South Pacific subtropical gyre	Marine	Surface water	26,898	Item/km^2	Macroplastics and microplastics	0.355 to >4.75 mm	88.8%	Eriksen et al. (2013b)
	NE Pacific Ocean	Marine	Surface water	8–9180	Item/m^3	Microplastics	64.8 μm to 5810 μm	75%	Desforges et al. (2014)
	Geoje Island, South Korea	Marine	Surface water	16,000	Item/m^3	Microplastics	<50 μm to >1000 μm	–	Song et al. (2014)
Southwest England	Tamar Estuary	Estuary	Surface water	0.03	Item/m^3	Microplastics (82%) and macroplastics (19%)	< 1 mm to >5 mm	82%	Sadri and Thompson (2014)
The United States	Laurentian Great Lakes	Lake	Surface water	43,000	Item/km^2	Macroplastics and microplastics	0.355–0.999 mm (81%), 1.000–4.749 mm (17%), >4.75 mm (2%)	90%	Eriksen et al. (2013a)

of lakes and reported an average abundance of 43,157 plastic particles km^{-2}, 81% of which had a size of 0.355–0.999 mm. The majority of these plastics originate from heavily populated areas with heavy commercial and industrial activity, such as coal-burning power plants (Stamper et al., 2012) and sandblasting media (Eriksen et al., 2013a). Reisser et al. (2013) found that the surface waters around Australia are polluted by microplastics from the degradation of larger polyethylene and polypropylene objects. There was a high prevalence of plastic particles smaller than 5 mm. Similarly, it was assumed that the sources of these microplastics consisted mainly of populated regions such as the cities of Sydney and Brisbane (Reisser et al., 2013).

Furthermore, plastic debris is found throughout the water column. Table 2 shows the density of the most common plastic types found in the natural environment. Plastics with a specific gravity > 1, for example, PS, PET and PVC, usually sink to the benthos, whereas LDPE and PP appear in the surface water. However, the density of individual plastic items can be altered once in the marine environment, for example, low density plastic can also be found on the seafloor. One of the major reasons for this alteration is that plastic debris in the aquatic environment can acquire a microbial biofilm on its surface, leading to colonisation by algae or invertebrates, which produces an increase in density (Andrady, 2011). A study conducted by Lobelle and Cunliffe (2011) investigated the development of biofilms on plastic bags. The authors discovered that a biofilm developed on the surface of the plastic after just 1 week and that microbial density increased dramatically after 3 weeks. When plastic reaches a certain density, some of it sinks to the seafloor, and some remains suspended within the water column due to turbulence (Cole et al., 2011).

3.2. Beaches, sediments and shorelines

In addition to water bodies, the beach is another important environment suffering from plastic pollution. Table 3 illustrates the contamination by plastic debris of beaches worldwide (Velander and Mocogni, 1999; Santos et al., 2009; Martins and Sobral, 2011; Dekiff et al., 2014). The highest abundance, 258,408 items m^{-2}, was found at Fan Lau Tung Wan, Hong Kong (Fok and Cheung, 2015). Over 90% of the collected samples were classified as microplastics (<5 mm), with 92% of the microplastics being expanded polystyrene. The high abundance of expanded polystyrene found on beaches in Hong Kong may be attributable to the high population density and the lifestyle of the people of Hong Kong, for example, the use of insulated boxes for takeaway food or food transportation (Fok and Cheung, 2015). Claessens et al. (2011) investigated beach sediment along the Belgian coast and found that the average microplastic concentration was 92.8 particles kg^{-1} dry sediment, with fibres constituting over 88% (82.1 particles kg^{-1}) of the total collected plastic debris. It is assumed that the analysed fibres were nylon, polyvinyl alcohol and polypropylene, which are mainly derived from fishing nets, carpets and ropes. It was also stated that microplastic concentrations along the Belgian coast are increasing. Claessens et al. studied the change in the plastic concentration with time by investigating vertical sections of beach sediment and showed that the microplastic concentration on the beach at Groenendijk increased three times over the period from 1993 to 1996 to 2005–2008, with estimated concentrations of 54.7 $\pm$ 8.7 and 156.2 $\pm$ 6.3 particles kg^{-1}, respectively.

In addition to anthropogenic factors, natural factors such as rainstorms may also result in a high accumulation of plastic debris on beaches. A study conducted by Lee et al. (2013) investigated the abundance of plastic in different seasons and found that the accumulation of plastic, especially microplastic, in beach sediment after the rainy season was higher than that before the rainy season. Additionally, the directions of the wind and ocean currents are important determinants of the level of plastic contamination on beaches. A greater abundance of plastic items was observed on windward beaches compared to leeward beaches (Ivar do Sul et al., 2009); for example, the windward beaches of Fernando de Noronha Island, which has no plastic industry or fishing activity, had higher levels of contamination with plastic pellets (Ivar do Sul et al., 2009). This observation implies that plastic debris is mainly transported to windward beaches by surface currents or winds (Debrot et al., 1999; Ivar do Sul et al., 2009). Similar findings have been reported for non-industrial remote locations in Tonga, Rarotonga and Fiji (Gregory, 1999); the Pitcairn Islands (Benton, 1995); the Hawaiian Islands (Corcoran et al., 2009); and Chile (Hidalgo-Ruz and Thiel, 2013).

4. Effects on organisms

4.1. Plastic ingestion

Fig. 1 shows the pathway of plastic ingestion by different organisms. Plastic debris has been found in multiple species worldwide, including seabirds, turtles, crustaceans and fish (Derraik, 2002; Ryan et al., 2009;

Table 3
Occurrence of plastic debris found in beach sediment.

Location	Occurrence	Plastic type	Plastic sizes	Reference
Edinburgh coast, UK	Average density of 0.8 items m^{-2}	–	–	Velander and Mocogni (1999)
Mumbai, India	Average abundance of 7.49 g and 68.83 items m^{-2}	Microplastics and macroplastic	<5 mm to 100 mm	Jayasiri et al. (2013)
Tasmania, Australia	Average abundance of 113 items or 1.69 kg of debris per beach.	–	–	Slavin et al. (2012)
Nakdong River Estuary, South Korea	Average abundances of 8205 particles m^{-2} in May and 27,606 particles m^{-2} in September	Microplastics and macroplastic	1 mm to >25 mm	Lee et al. (2013)
San Diego, California	2453 individual plastic debris	Microplastics and macroplastic	<5 mm to 50 mm	Van et al. (2012)
UK	Maximum 8 particles kg^{-1}	–	–	Thompson et al. (2004)
Hong Kong	Average abundance of 5595 items m^{-2} and maximum 258,408 items m^{-2}	Microplastic	0.315 to >5 mm	Fok and Cheung (2015)
Western coast of Portugal	Average density of 185.1 items m^{-2}	Microplastics (72%), macroplastic (18%)	50 μm to 20 cm	Martins and Sobral (2011)
Hawaii	Average weight of debris per sample was 23.38 g plastic	Microplastics and macroplastic	1–2.8 mm (43%), 2.8–4.75 mm (48%), >4.75 mm (9%)	McDermid and McMullen (2004)
Belgian coast	Average 92.8 particles kg^{-1} dry sediment	Microplastics	38 μm to 1 mm	Claessens et al. (2011)
Norderney	Mean 1.76 kg^{-1} dry sediment	Microplastics and macroplastic	<1 mm to >2 cm	Dekiff et al. (2014)
East Frisian Islands, Germany	Maximum 621 particles per 10 g	–	–	Liebezeit and Dubaish (2012)
Singapore	Maximum 3 particles kg^{-1}	–	–	Ng and Obbard (2006)
North Atlantic Coast	Average density of 0.15–12.5 items m^{-2}	–	–	Barnes and Milner (2005)
Northeast Brazilian Coast	Average density of 82.1 items m^{-2}	–	–	Santos et al. (2009)
Malta Island	>1000 particles m^{-2}	Microplastics	1.9 to 5.6 mm	Tuner and Holmes (2011)

Cole et al., 2011). Macroplastics and microplastics are physical hazards to organisms if ingested (Fendall and Sewell, 2009). The effects include blockage of the intestinal tract, inhibition of gastric enzyme secretion, reduced feeding stimuli, decreased steroid hormone levels, delays in ovulation and failure to reproduce (Azzarello and Vleet, 1987; McCauley and Bjorndal, 1999; Wright et al., 2013). Ingestion seldom leads to immediate mortality in organisms; however, sub-lethal or chronic effects have long-term consequences (Wright et al., 2013). A review by Derraik (2002) suggested that the ingestion of macroplastics and microplastics by organisms might lead to a reduction in food consumption. For example, a negative correlation was found between the fitness of seabirds and the total mass of ingested plastics (Spear et al., 1995). A study conducted by Ryan (1988) investigated and imitated the potential effects of plastic ingestion by seabirds using domestic chicks (*Gallus domesticus*). The chicks, which were fed with polyethylene pellets, had reduced food consumption due to reductions in their stomach storage volume and feeding stimuli. Other studies, however, reported that some organisms might regurgitate the ingested plastic debris, which would reduce the potential adverse effects. For example, Thompson et al. (2004) showed that polychaete worms can excrete egested plastic particles in their faecal casts.

Seabirds may be one of the most vulnerable species to plastic ingestion because seabirds seldom regurgitate undigested hard material, including plastics. The resultant accumulation of plastic in their gastrointestinal tract will eventually lead to gastrointestinal blockage or problems with feeding stimuli and activity levels (Derraik, 2002). The amount of plastic ingested by seabirds varies with their foraging practices, feeding technique and diet (Cole et al., 2011) but has remained at a high level (Fig. 2) (Lozano and Mouat, 2009; van Franeker, 2010; Trevail et al., 2015), indicating that microplastics are a new and increasing problem with regard to plastic ingestion. Plastic fragments have been reported in the guts of seabirds since the 1960s (Ryan et al., 2009). Surface-foraging species, such as gulls, shearwaters and fulmars, are vulnerable to both floating plastic entanglement and ingestion (Ryan, 1987; Moser and Lee, 1992). Table 4 shows that the occurrence of plastic debris in fulmar and shearwater species is over 65%. Zooplanktivorous species, for example, the little auk (*Alle alle*), are also susceptible to plastic ingestion because it may be difficult for them to distinguish between zooplankton, such as amphipods, copepods or euphausiids, and small neustonic plastic debris (Avery-Gomm et al., 2013).

Many studies have found that juvenile birds ingest significantly higher amounts of macroplastic and microplastic debris compared to adult birds (Codina-Garcia et al., 2013; Provencher et al., 2014; Acampora et al., 2014). Intergenerational transfer of plastic debris could explain the higher plastic ingestion by young seabirds (Carey, 2011). A study conducted by Skira (1986) reported that plastic debris is commonly found in the adult short-tailed shearwater at the beginning of its breeding period; however, the quantity of debris declined steadily as the period progressed. Moreover, microplastic ingestion by the non-breeding short-tailed shearwater is higher than that by its breeding equivalent, and the non-breeding bird suffered more from plastic pollution (Carey, 2011). Similarly, van Franeker et al. (2011) reported that the plastic loads of breeding adult northern fulmars increased until July before subsequently decreasing. This decrease in plastic ingestion may be due to the offloading of most of the ingested plastics to the offspring at the breeding grounds (Hutton et al., 2008; Carey, 2011; van Franeker et al., 2011).

In addition, macroplastic and microplastic particles have been detected in the tracts of multiple species of fish from many locations, including the Mediterranean Sea (Romeo et al., 2015), North Pacific Ocean (Boerger et al., 2010; Jantz et al., 2013), South Atlantic Ocean (Possatto et al., 2011; Dantas et al., 2012) and North Sea. Seven common species of fish (1203 individuals) in the North Sea were examined by Foekema et al. (2013), 2.6% of which contained microplastics ranging in size from 0.04 to 4.88 mm. In this study, the physical effects caused by the ingested plastic were insignificant because the amounts ingested were too low and the particle sizes too small to cause intestinal blockage or feelings of satiation. In another study, a high occurrence (36.5%) of synthetic polymers was observed in the gastrointestinal tracts of 504 fish from the English Channel (Lusher et al., 2013), with 92.4% of the ingested plastic debris categorised as microplastics and 68.3% consisting of fibres. However, Hoss and Settle (1990) suggested that digestive system blockage would occur in small organisms if high amounts of plastic

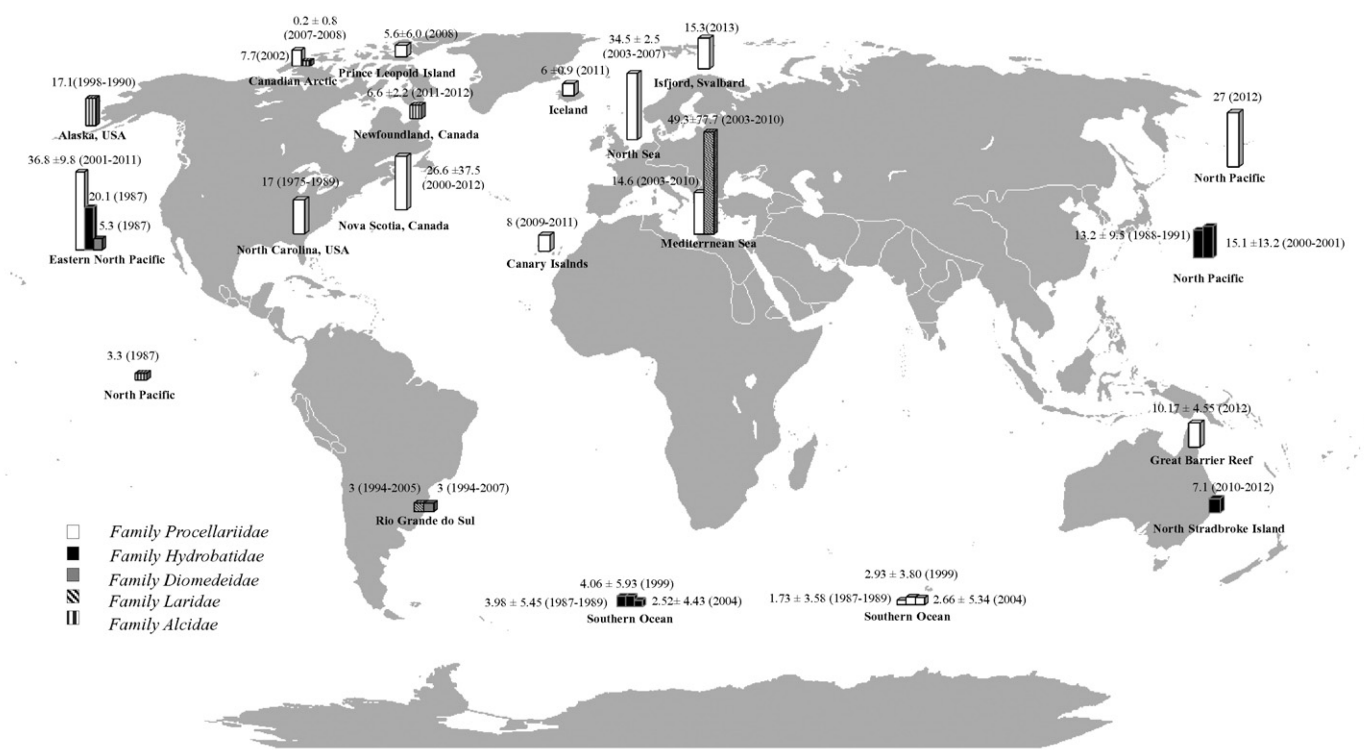

Fig 2. Occurrence (mean pieces) of plastic ingestion found in seabirds.

Table 4
Occurrence of plastic ingestion found in seabirds.

Species	Number studied	Percentage with plastic (%)	Mean number of particles per individual	Studied year	Location	Source
Family Procellariidae						
Fulmarus glacialis	44	86.4%	17	1975–1989	North Carolina, USA	Moser and Lee (1992)
Fulmarus glacialis	15	36	7.7	2002	Davis Strait, Canadian Arctic	Mallory et al. (2006)
Fulmarus glacialis	1295	95	34.5 ± 2.5	2003–2007	North Sea	van Franeker et al. (2011)
Fulmarus glacialis	67	92.5	36.8 ± 9.8	2001–2011	Eastern North Pacific	Avery-Gomm et al. (2012)
Fulmarus glacialis	58	79	6.0 ± 0.9	2011	Westfjords, Iceland	Kuhn and van Franeker (2012)
Fulmarus glacialis	176	93	26.6 ± 37.5	2000–2012	Nova Scotia, Canada	Bond et al. (2014a,b)
Fulmarus glacialis	40	87.5%	15.32	2013	Isfjord, Svalbard	Trevail et al. (2015)
Fulmarus glacialis	25	84	5.6 ± 6.0	2008	Prince Leopold Island	Provencher et al. (2009)
Fulmarus glacialoides	9	79	–	1994–2005	Rio Grande do Sul, Brazil	Colabuono et al. (2009)
Calonectris diomedea	85	83	8	2009–2011	Canary Islands, Spain	Rodríguez et al. (2012)
Calonectris diomedea	49	96	14.6	2003–2010	Catalan coast, Mediterranean	Codina-Garcia et al. (2013)
Puffinus tenuirostris	12	100	27	2012	North Pacific	Tanaka et al. (2013)
Pachyptila vittata	95	–	2.66 ± 5.34	2004	Southern Ocean	Ryan (2008)
Pachyptila vittata	86	–	2.93 ± 3.80	1999	Southern Ocean	Ryan (2008)
Pachyptila vittata	149	–	1.73 ± 3.58	1987–1989	Southern Ocean	Ryan (2008)
Ardenna pacifica	24	21%	10.17 ± 4.55	2012	Great Barrier Reef, Australia	Verlis et al. (2013)
Family Hydrobatidae						
Oceanodroma furcata	7	100	20.1	1987	Offshore, eastern North Pacific	Blight and Burger (1997)
Pelagodroma marina	15	73.3	13.2 ± 9.5	1988–1991	Offshore, North Pacific	Spear et al. (1995)
Pelagodroma marina	86	–	4.06 ± 5.93	1999	Southern Ocean	Ryan (2008)
Pelagodroma marina	5	–	2.52 ± 4.43	2004	Southern Ocean	Ryan (2008)
Pelagodroma marina	253	–	3.98 ± 5.45	1987–1989	Southern Ocean	Ryan (2008)
Puffinus tenuirostris	99	100	15.1 ± 13.2	2000–2001	Offshore, North Pacific	Yamashita et al. (2011)
Puffinus tenuirostris	129	67	7.1	2010–2012	North Stradbroke Island, Australia	Acampora et al. (2014)
Family Diomedeidae						
Thalassarche melanophris	2	100	3	1994–2007	Rio Grande do Sul, Brazil	Tourinho et al. (2010)
Phoebastria nigripes	3	100	5.3	1987	Offshore, eastern North Pacific	Blight and Burger (1997)
Family Laridae						
Rissa tridactyla	4	50	1.2	2003–2010	Catalan coast, Mediterranean	Codina-Garcia et al. (2013)
Larus melanocephalus	4	25	3.7 ± 7.5	2003–2010	Catalan coast, Mediterranean	Codina-Garcia et al. (2013)
Larus audouinii	15	13	49.3 ± 77.7	2003–2010	Catalan coast, Mediterranean	Codina-Garcia et al. (2013)
Larus glaucescens	589	12.2	–	2007–2010	Protection Island, USA	Lindborg et al. (2012)
Family Alcidae						
Aethia psittacula	208	17.1	17.1	1998–1990	Alaska, USA	Robards et al. (1995a,b)
Fratercula cirrhata	9	89	3.3	1987	Offshore, North Pacific	Blight and Burger (1997)
Uria lomvia	3	100	6.6 ± 2.2	2011–2012	Newfoundland, Canada	Bond et al. (2013)
Uria lomvia	186	11%	0.2 ± 0.8	2007–2008	Nunavut, Canada	Provencher et al. (2010)
Alle alle	65	14	1.11	2013	White Bay, Newfoundland	Fife et al. (2015)

debris accumulated in the intestine, similar to the effects caused by large plastic particles in larger organisms. Predation activities are regarded as the most common means of plastic ingestion by fish. For example, tuna find their prey in or chase their prey to shallow waters with abundant buoyant plastic debris (Romeo et al., 2015), thereby ingesting unwanted plastic particles during feeding. In addition, a carnivorous diet leads to secondary ingestion of plastic contained in the prey. Battaglia et al. (2013) suggested that microplastic ingestion by mesopelagic fish resulted in plastic accumulation within *Thunnus thynnus* in the Pacific Ocean.

The problem of plastic ingestion is not restricted to seabirds and fish: sea turtles are also vulnerable to marine plastic debris (Table 5). A recent review by Schuyler et al. (2014) estimated that plastic ingestion by green turtles increased by nearly 20% from 1985 to 2012. It is assumed that most of this debris was ingested during predation activities (Schuyler et al., 2014). Several studies reported that the ingested plastic particles were white or transparent (Bugoni et al., 2001; Da Silva Mendes et al., 2015); it is thus possible that the turtles mistake the white plastic for jellyfish (Da Silva Mendes et al., 2015). In addition to sea turtles, it was reported that at least 48 cetacean species, such as whales and dolphins, suffered from plastic ingestion between 2000 and 2010, which is 11 times higher than between 1960 and 1970. Many regulations now restrict whale or dolphin hunting to protect endangered species, and plastic debris is a new and significant hazard. The death of a West Indian manatee (*Trichechus manatus*), an endangered species, in Florida may have been due to digestive tract blockage by a huge piece of plastic (Laist, 1987). A more recent study produced similar findings regarding the death of sperm whales in the Mediterranean Sea: the death of the whales could be attributed to either starvation or gastric rupture caused by plastic debris (de Stephanis et al., 2013).

4.2. Plastic entanglement

The physical hazards posed by macroplastic debris to marine organisms, such as ingestion and entanglement, have been reported since the late 1980s (Laist, 1987). Despite this, the importance of marine plastic

Table 5
Occurrence of plastic ingestion found in sea turtle, fish and other organisms.

Species	Locations	No of sample	Occurrence	Ingested material	Plastic sizes	Plastic type	Reference
Turtle							
Green turtle (*Chelonia mydas*)	Brazilian coast	265	70%	–	–	–	Santos et al. (2015)
	South west Altantic	62	90%	–	0.5–3.0 cm	Macroplastics and microplastics	Carman et al. (2014)
	Ubatuba, Brazilian coast	20	45%	Soft plastic (54.3%), hard plastic (19%), nylon (21.4%), rubber (4.2%) and foam (1.1%)	(76%) 0–5 cm, (23%) 5–10 cm, (1%) >10 cm	Macroplastics and microplastics	Da Silva Mendes et al. (2015)
	Paranagua Estuary, Brazil	76	70%	Plastic bags (44.7%), hard plastic (38.5%), nylon (7.73%), polystyrene (5.1%) and rubber (1.1%)	–	–	Guebert-Bartholo et al. (2011)
	USA	10	70%	–	–	–	Parker et al. (2011)
Loggerhead sea turtles (*Caretta caretta*)	Adriatic Sea	54	35.2%	–	–	–	Lazar and Gracan (2011)
	Mediterranean	19	37%	–	–	–	Revelles et al. (2007)
	northern Pacific	52	35%	–	–	–	Parker et al. (2005)
	Tuscany coasts, Mediterranean Sea	31	71%	User plastics (70.4%), fragments (20.3%), and threadlike (4.3%)	–	–	Campani et al. (2013)
Chelonia mydas and *Caretta caretta*	Australia	54	65%	–	–	–	Boyle and Limpus (2008)
Fish							
Herring, gray gurnard, whiting, horse mackerel, haddock, atlantic mackerel, and cod	North Sea	566	2.6%		0.04 mm to 4.8 mm	Microplastics	Foekema et al. (2013)
Whiting, blue whiting, Atlantic horse mackerel, poor cod, John Dory, red gurnard, dragonet, redband fish, solenette and thickback sole	English Channel	504	36.5%	Semi synthetic cellulosic material rayon (58%), and polyamide (35%)	0.13 mm to 14.3 mm	Macroplastics and microplastics	Lusher et al. (2013)
Anchovy (*Stolephorus commersonnii*)	Alappuzha, India	16	37.5%		1.14 mm to 2.5 mm	Microplastics	Kripa et al. (2014)
Cololabis saira, *Hygophum reinhardtii*, *Loweina interrupta*, *Myctophum aurolaternatum*, *Symbolophorus californiensis*	North Pacific	670	35%	Fragments (94%), film (3%), fishing line (2%), and finally rope (woven filaments), Styrofoam and rubber (all <1%)	1 mm to 2.79 mm	Microplastics	Boerger et al. (2010)
Lampris sp. (*big eye*)	North Pacific	115	29%		49.1 mm (±71.1)	Macroplastics and microplastics	Choy and Drazen (2013)
Marine invertebrates							
Zooplankton	Western English Channel	15	87%	–	7.3 to 30.6 μm	Microplastic	Cole et al. (2013)
	Portuguese coastal waters	152	61%	Low density polyehtylene (98.1%)	–	Microplastic	Frias et al. (2014)
Neocalanus cristatus	Northeast Pacific Ocean	960	2.6%	–	555.5 ± 148.7 μm	Microplastic	Desforges et al. (2015)
Euphausia pacifica	Northeast Pacific Ocean	413	5.8%	–	816.1 ± 107.7 μm	Microplastic	Desforges et al. (2015)
Norway lobster (*Nephrops norvegicus*)	Clyde, U.K.	120	83	–	–	–	Murray and Cowie (2011)
Brown shrimp (*Crangon crangon*)	Belgium	110	–	fibres (95%), films (5%)	300 to1000 μm	Microplastic	Devriese et al. (2014)
Blue mussel (*Mytilus edulis*)	Belgium, The Netherlands	45	–	Fibres	300 to 1000 μm	Microplastic	De Witte et al. (2014)
Mytilus edulis	North Sea, Germany	36	–	–	5 to 25 μm	Microplastic	Van Cauwenberghe and Janssen (2014)
Gooseneck barnacles (*Lepas* spp.)	North Pacific Subtropical Gyre	385	33.5%	Fragments (99%), monofilament line (1%)	0.609 mm to 6.770 mm	Microplastic and macroplastic	Goldstein and Goodwin (2013)
Cetacean							
Franciscana dolphins (*Pontoporia blainvillei*)	Northern coast of Argentina	106	28.1%	Packaging debris (64.3%), fishery-related fragments (35.7%)	0.2 to 11.4 cm	Macroplastic	Denuncio et al. (2011)

(continued on next page)

Table 5 (*continued*)

Species	Locations	No of sample	Occurrence	Ingested material	Plastic sizes	Plastic type	Reference
True's beaked whales (*Mesoplodon mirus*)	North and west coast of Ireland	20	85%	–	0.3 mm–7.1 cm	Microplastic and macroplastic	Lusher et al. (2015)

debris has been largely neglected for three main reasons: 1) entanglement encounters are straightforward and require little investigation, 2) entanglement encounters between debris and organisms are rare, and 3) there is a distinct lack of reports to prove this overall rarity. However, in recent years, there have been many more studies focusing on entanglement encounters between debris, especially plastic debris, and marine organisms.

A recent review by Gall and Thompson (2015) summarised 340 publications related to the incidence of marine organisms ingesting or becoming entangled by marine debris. Plastics accounted for 92% of all ingestion and entanglement cases. It was also found that the occurrence of plastic entanglement (55%) was much higher than that of plastic ingestion (31%). Furthermore, the incidences of entanglement were more serious or more frequently reported than those of ingestion, as it causes direct and visible harm to animals.

Marine animals such as sea turtles, mammals, seabirds and crustaceans are vulnerable to entanglement encounters, which can lead to mortality (Gilman et al., 2009; Macfayden et al., 2009; Gilardi et al., 2010). The effects of entanglement can be summarised as drowning, suffocation, laceration, reduced fitness, a reduced ability to prey or an increased probability of being caught (Laist, 1987; Derraik, 2002; Gall and Thompson, 2015). Table 6 lists the incidence of entanglement encounters for different organisms, including sea lions, seals and seabirds. It is clear that the majority of entanglement materials are plastic, for example, packing loops and fishing materials such as fishing nets and ropes. Fishing materials, which are the most common encounter material reported, mostly originate from fishing activities or cargo ships (Kiessling, 2003; Macfayden et al., 2009; Gilardi et al., 2010). According to Macfayden et al. (2009), >6.4 t of fishing gear are abandoned or lost in the sea each year. Once unusable nets are lost, they continue to indiscriminately entangle marine organisms because most nets are made from synthetic materials, which are cheaper, more durable and more lightweight (Gilardi et al., 2010).

The entanglement incidence for a species depends on its behaviour (Derraik, 2002). Firstly, the sea turtle is regarded as the most susceptible species to 'ghost netting' because they frequently use floating objects either for shelter to avoid predation or as foraging stations (White, 2006). It was found that a larger mesh size poses greater problems because it increases the extent of animal ensnarement, especially for sea turtles (Murray, 2009; Lopez-Barrera et al., 2012; Wilcox et al., 2015). Plastic entanglement encounters have also been widely reported for seals and sea lions, which are the most vulnerable species to entanglement (Lawson et al., 2015). Materials such as packing loops may attract the interest of sea lions and seals, especially juveniles (Arnould and Croxall, 1995; Hanni and Pyle, 2000; Page et al., 2004; Boren et al., 2006); young animals may be particularly vulnerable to entanglement due to their curiosity and playfulness (Page et al., 2004). Moreover, young sea lions and seals are smaller in size and therefore become entangled in the plastic material more easily because it is easier for their necks or legs to pass through the material (Lawson et al., 2015).

Table 6
Occurrence of plastic entanglement by organisms.

Species	Location	Study period	Entangled material	Entanglement rate	Reference
Seals and sea lions					
Antarctic fur seals	Bird Island, South Georgia	1989–2013	Packaging bands (43%), synthetic line (25%) or fishing net (17%)	–	Waluda and Staniland (2013)
Antarctic Fur Seals	Subantarctic island, Bouvetøya	1996–2002	Fishing net (48.1%), polypropylene packaging strap (17.9%), rope or string (14.2%)	0.024–0.059%	Hofmeyr et al. (2006)
	Marion Island	1991–1996	Polypropylene packaging strap (39.5%), synthetic string (10 mm diameter) (10.5%), synthetic rope (>10 mm diameter) (13.2%), and fishing net (21.1%).	0.15%	Hofmeyr and Bester (2002)
	South Georgia	1988–1994	Polypropylene packing band (42%), synthetic string (21%), fishing net fragment (14%)	0.4%	Arnould and Croxall (1995)
New Zealand fur seals	Kaikoura region	1995–2005	Green trawl net (42%), and plastic strapping tape (31%)	0.6–2.8%	Boren et al. (2006)
	Cape Gantheaume, Kangaroo Island	1989–1991 and 2000–2002	Packing tape (30%), trawl netting (28%), lobster float rope (13%)	0.73%	Page et al. (2004)
Hawaiian Monk Seal	Northwestern Hawaiian Islands	1982–1998	Net, line, net and line combination, strap, ring	0.70%	Henderson (2001)
Australian fur seals	Southern Australia	1997–2012	Plastic twine or rope (50%), other plastics (20%), monofilament line (17%)	–	Lawson et al. (2015)
Steller sea lions	Southeast Alaska and northern British Columbia	2000–2007	Packing bands 54%, rubber bands (30%), net (7%), rope (7%)	0.26%	Raum-Suryana et al. (2009)
Australian sea lions	Seal Bay, Kangaroo Island	1988–2002	Monofilament netting (55%), packing tape (11%), trawl netting (11%), other rope (14%)	0.83%	Page et al. (2004)
Seabirds					
Northern gannets	Spanish Iberia and Mauritania	2007–2010	Fishing ropes (73.5%), nets (11.8%), nylon fishing lines (14.7%)	0.93%	Rodríguez et al. (2013)
American crow	Davis, California	2012–2013	Synthetic twine, string and rope (77%), plastic strips (10%)	5.6%	Townsend and Barker (2014)
Others					
Seals, sea lions, gull, fulmar and turtle	United States	2001–2005	Fishing related (91.7%) such as fishing line, fishing hook, fishing string	–	Moore et al. (2009)

Approaching the materials, their heads may become caught in the holes; the neck is therefore the most common part of the sea lion or seal to become entangled. Once they have been entangled, it is difficult for them to remove the material because their long guard hair prevents the material from slipping off easily (Raum-Suryana et al., 2009).

Birds are another group that is particularly vulnerable to entanglement. In a study conducted by Votier et al. (2011), an average of 66 birds become entangled around the legs or feet by plastic material, such as netting, each year in Grassholm, Wales, UK. A study conducted by Moore et al. (2009) investigated 31 bird species and nine marine mammal species and found that the common murre, western gull and California sea lion are the most commonly entangled species. Fishing materials are most frequently responsible for entanglement. The plunge diving fishing method of seabirds such as northern gannets (*Morus bassanus*) leads to a high rate of entanglement encounters, partly because the birds mistake floating plastic debris for fish or other food items (Rountree, 1989). This mode of feeding may be the primary reason for the entanglement encounters of seabirds. Apart from seabirds, terrestrial birds also suffer from plastic entanglement, although there are few studies of the effects of plastic debris on terrestrial animals. A recent report investigated the effect of plastic debris on the American crow (*Corvus brachyrhynchos*) in North America and found that 85.2% of the crow nests studied contained anthropogenic material, including synthetic string, twine, rope, plastic tape and plastic strips; in addition, 11 of 195 (5.6%) investigated nestlings were entangled (Townsend and Barker, 2014).

Plastic entanglement leads to the addition of materials to the bodies of organisms, which raises the energetic cost of movement and therefore increases food consumption requirements. It was discovered that the addition of over 200 g of material in northern fur seals (*Callorhinus ursinus*) produced a four-fold increase in food consumption to simply maintain daily activity levels (Derraik, 2002). The entangled seals also spent more time foraging at sea. In addition, if plastic becomes entangled around the necks of organisms, it constrains their necks and may cause injury or even death by strangling as they grow up (Raum-Suryana et al., 2009). The wounds created by entanglement materials such as fishing nets or packing bands often lead to infection or necrosis. If the lymph system lacks the ability to control these infections, the lungs might become infected, eventually leading to mortality (Angliss and DeMaster, 1998). In addition, secondary infections can occur from microbes entering the bloodstream through the wound.

Table 6 shows that the entanglement rate of seals and sea lions is below 1% on average. However, even a low entanglement rate may have important consequences for the population as a whole. Fowler (1987) reported that although the entanglement rate of northern fur seals is 0.4% and decreasing, this low entanglement rate has had adverse effects on the entire population. Similar studies of the effects of entanglement on the population of northern fur seals in the Pribilof Islands found that the percentage of entangled seals increased by 38% from 1969 to 1973. These rates of entanglement may be the cause of the population decrease at a rate of 4–6% each year, which corresponds to an estimated 40,000 fur seals killed by entanglement (Weisskopf, 1988). Furthermore, the entanglement rates may sometimes be underestimated (Page et al., 2004; Raum-Suryana et al., 2009). Firstly, it is difficult to observe all the entangled individuals within a population. The entangled animals may die at sea or on inaccessible land areas. As mentioned previously, the entanglement materials add weight to the affected animals, resulting in increased time spent at sea and reduced survival rates (Raum-Suryana et al., 2009). Secondly, it is difficult to monitor all the entangled animals that have been identified. For example, for Steller sea lions (*Eumetopias jubatus*), there are over 40 major haul-out sites and eight settlements during the breeding season and over 50 sites during the non-breeding season (Raum-Suryan et al., 2004; Pitcher et al., 2005).

4.3. Chemical effects on organisms

As mentioned previously, plastic ingestion by different organisms has been widely reported. Apart from the physical impacts discussed in earlier sections, the ingestion of plastic debris can also have chemical effects. Multiple studies have reported that marine plastic debris can be a vector for the absorption or transport of waterborne chemical pollutants from invertebrates to higher trophic levels (Gregory, 1996; Teuten et al., 2007), including polychlorinated biphenyls (PCBs) (Zarfl and Matthies, 2010), polycyclic aromatic hydrocarbons (PAHs) (Teuten et al., 2009) and organochlorine pesticides such as DDT (Ivar do Sul and Costa, 2014). These pollutants are regarded as persistent organic pollutants (POPs), which are toxic, persistent in the environment, bioaccumulative, and hydrophobic and have long-range transport potential (Zarfl and Matthies, 2010). Plastics, especially microplastics, are particularly effective at carrying airborne pollutants such as POPs because plastics are composed of highly hydrophobic materials (Ivar do Sul and Costa, 2014). For example, it was found that the concentration of PCBs held by microplastics is one million-fold higher than in the surrounding water (Betts, 2008). In addition, a deployment experiment showed that unpolluted polypropylene pellets readily accumulated or absorbed hydrophobic contaminants such as PCBs, *p*-chlorophenyl and dichlorodiphenyldichloroethylene (DDE) over a period of 7 days (Mato et al., 2001). Plastic debris contaminated with POPs has been found worldwide. PCBs and DDE have been detected on plastic resin pellets gathered along the Japanese coast (Ogata et al., 2009). In Europe, PCBs (0.02–15.56 ng g^{-1}) and DDT (0.16–4.5 ng g^{-1}) have been detected on plastic pellets from the Portuguese coast (Frias et al., 2010). Marine organisms are especially susceptible to polluted plastic via ingestion due to its ubiquity, larger surface-area-to-volume ratio and small size (Barnes et al., 2009).

The toxicity displayed by these POPs is correlated with the amount of plastic ingested because the polluted plastic debris can be a major source of these toxins (Mato et al., 2001). A positive relationship was found between the amount of ingested plastic and the concentration of PCBs in the fat tissues of great shearwaters (Ryan, 1988). A similar study by Yamashita et al. (2011) also reported that the concentration of PCBs in North Pacific pelagic seabirds is positively correlated with the amount of ingested plastic debris. After organisms ingest plastic particles, the presence of digestive surfactants enhance the bioavailability of contaminants from the plastics and significantly increase the desorption rate of the contaminants absorbed on the plastics (Voparil and Mayer, 2000; Teuten et al., 2007). A recent study conducted by Bakir et al. (2014) investigated the POP desorption rate from plastic pellets in gut conditions and in seawater and found that the desorption rate in the presence of gut surfactants (38 °C, pH 4) was higher than in seawater (38 °C, pH 7.5–8.4). The authors suggested that temperature and pH could play important roles in the desorption of POPs from plastic pellets and thus increase the bioavailability of these compounds to marine animals (Bakir et al., 2014). A high concentration of POPs such as PCBs may cause endocrine disruption, teratogenicity and toxicity of the liver and kidney (Muirhead et al., 2006; Yogui and Sericano, 2009). For example, arctic fish suffer from endocrine disruption following exposure to polychlorinated dibenzo-*p*-dioxins (PCDDs) and PCBs. These chemical toxins have also been found in seabirds, the predator at the top of the food chain. In Svalbard, exposure to POPs led to alterations in steroid hormones, thyroid hormones and prolactin in the glaucous gull (Verreault et al., 2006; Verboven et al., 2008).

Apart from POPs, plastic additives, such as brominated flame retardants, phthalates and the constituent monomer bisphenol A, may have serious consequences in the natural environment because low concentrations in the ng/L or μg/L range could have harmful effects on molluscs, crustaceans, fish and amphibians (Oehlmann et al., 2009). Plastic additives are used to reduce the chemical affinity between molecules or as monomers in polycarbonate plastic. They are unstable in the plastic and therefore leach out into the environment (Staples et al., 1997). Recently, studies have reported that plastic additives are found in the bodies of organisms and are released from the plastic once ingested (Engler, 2012; Lithner et al., 2011). Similar to POPs, the desorption rate of plastic additives, such as diethylhexyl phthalate (DEHP), in the gut is higher than the rate in seawater. According to research by Bakir et al. (2014), the DEHP desorption rate from PE is 14-fold higher in the gut than in seawater. Once the toxins have desorbed from the plastic debris, they tend to bioaccumulate in an organism, causing adverse effects. For example, polybrominated diphenyl ethers (PBDEs), including BDE-183 and BDE-209, released from ingested plastics were detected in the tissues of short-tailed shearwaters, which might cause endocrine disruption (Tanaka et al., 2013).

A high concentration of additives may result in the disruption of biological processes, for example, endocrine disruption due to molecular imitation or competition with the synthesis of endogenous hormones (Barnes et al., 2009; Lithner et al., 2009; Talsness et al., 2009). In particular, phthalates exert effects at the molecular, cellular and organ levels in marine organisms such as fish or invertebrates (Oehlmann et al., 2009). In addition, exposure to phthalates may lead to behaviour alternations in fish (Oehlmann et al., 2009). For example, the presence of 100 μg L^{-1} benzyl butyl phthalate (BBP) in water stimulated alterations in the shoaling and feeding behaviour of the three-spined stickleback (*Gasterosteus aculeate*). Other researchers have also reported that 5 mg L^{-1} diethyl phthalate (DEP) caused changes in the general behaviour of the common carp (Barse et al., 2007). Fossi et al. (2012) were the first to report the effects of DEHP and mono-(2-ethylhexyl) phthalate (MEHP) on the baleen whale, the second-largest filter feeder. The authors found that high concentrations of DEHP or MEHP may lead to endocrine disruption. Bisphenol A can have adverse effects on reproduction and metabolism, the nature of which depends on the concentration of the compound and the species of the organism (Oehlmann et al., 2009). For example, 1.75–2.40 μg L^{-1} BPA caused ovulation delays and reductions in sperm quality in brown trout (Lahnsteiner et al., 2005). However, there is little research on the effects of exposure to POPs and plastic additives on marine seabirds or mammals such as whales, dolphins, seals and sea lions. In addition, the long-term effects of exposure to these hydrophobic contaminants remain unclear (Oehlmann et al., 2009). A study by Koelmans et al. (2015) found that, although chemicals can accumulate in the plastic, the role of plastics in chemical bioaccumulation is relatively low compared to that of naturally occurring particles.

5. Fate of plastic debris in the environment

As mentioned previously, most currently used plastic polymers are highly corrosion resistant and can persist in the environment for a long time (Tamara, 2015). The occurrence of plastic debris in beach sediment and water bodies is summarised in Tables 2 and 3. The fate of plastic debris in the environment primarily depends on the degree of natural attenuation.

Firstly, the biodegradation rate of plastic debris in the natural environment depends on the properties of the debris (Guo et al., 2012). Generally, the rate of biodegradation of most plastic debris is insignificant in natural water bodies such as rivers or oceans. In principle, plastics with high molecular weight, for example, PE and PS, are regarded as biodegradation resistant; these plastics gradually fragment but will remain in the environment as smaller pieces of the same polymer. Only a few microbial strains can biodegrade non-oxidized PE (Shah et al., 2008). The polymer chains eventually reach a sufficiently low molecular weight that can be easily decomposed by microorganisms (Zheng et al., 2005). Additionally, some plastics made of biodegradable materials are vulnerable to degradation via the activities of bacteria and fungi (Gregory and Andrady, 2003). However, the actual degradation time remains unknown (Andrady, 2005). In addition, a recent study of specific biodegradable plastic bags found decomposition rates of only 4.5% after 49 days and approximately 50% after 389 days (Müller et al., 2012).

In addition to biodegradation, photodegradation is another important component of natural attenuation. This process of chemical transformation may occur directly or indirectly via a light-induced mechanism (Yousif and Haddad, 2013). Ultraviolet light from the sun provides the energetic input to begin the incorporation of oxygen atoms into the plastic (Andrady, 2011), allowing the fragmentation of the plastic into small pieces. Photodegradation is regarded as an effective mechanism for LDPE and PP degradation upon exposure to air, for example, when lying on a beach surface (Andrady, 2011). However, in seawater, the rate of photodegradation becomes insignificant because of lower temperatures and lower oxygen concentrations (Andrady, 2011). The overall degradation process is very slow: complete degradation may take over 50 years (Müller et al., 2001). However, a study found that when plastic reaches a certain depth within the sea, the high pressure facilitates the degradation of plastics (Maurizio et al., 2012). In addition, Ho et al. (1999) reported that the degradation rate of plastic debris increased with elevated temperature and humidity because these conditions increased the rates of chemical reactions. Therefore, seawater conditions may hinder plastic degradation. On sediment, biodegradation is relatively significant due to a higher exposure to UV radiation and mechanical erosion than in water (Gregory and Andrady, 2003). However, the degradation rate of plastic in sediment is still almost negligible because the chemically and mechanically labile minerals, such as feldspars and clays, are easily washed out to the ocean (Corcoran et al., 2009). Overall, natural attenuation plays only a minor role in plastic degradation. The majority of plastics are resistant to degradation and only break down into smaller pieces (microplastics), which therefore persist in the natural environment. Ironically, plastic debris in the natural environment poses an ingestion or entanglement hazard to organisms.

6. Recommendations

To commence, governments should play an important role in controlling plastic contamination in ecosystems. Microplastics have become a serious problem because they are ubiquitous in the natural environment, including in surface waters, the benthos and beach sediments (Barnes et al., 2009; Ryan et al., 2009). Microplastics have been detected not only in close proximity to areas of industrial activity but also in remote areas (Lebreton et al., 2012). Developing countries such as China, Indonesia, the Philippines, Sri Lanka and Vietnam are reportedly the major source of plastic pollution in the oceans, accounting for >50% of the plastic in the marine environment (Tibbetts, 2015). Microplastics are difficult or impossible to clean up due to their ubiquity in global waters. However, there remains a lack of legislation to control microplastic contamination (Arthur et al., 2009). Therefore, it is recommended that governments cooperate globally or nationally to regulate the major sources of microplastics, namely, industrial and domestic products (Betts, 2008; Moore, 2008). In addition to greater legislation, more resources should be allocated to research the long-term effects of plastic debris, especially microplastics, on organisms. Because microplastic pollution is still a relatively new and increasing concern, the potential impacts on ecosystems remain uncertain. According to Oehlmann et al. (2009), the long-term effects of plastic additives or POPs on different organisms are poorly understood. This gap in understanding has contributed to the lack of regulation regarding the use of toxic additives such as bisphenol A.

In addition to legislation, it is essential to increase investments in the development of plastic collection technologies. Several advanced technologies have been developed for the collection of plastics from water bodies and soil. In the past, manta trawlers, a hybrid between a fish trawler and a plankton tow, were used for plastic collection (Ryan et al., 2009). The manta trawler was usually placed behind the ship and used to skim surface waters to collect buoyant plastic debris. However, due to the high level of plastic pollution, these technologies were insufficient for the removal of oceanic plastic. Recently, an innovative technology named the “plastic-eating drone” has been proposed as a method for cleaning up oceanic plastic debris. This technology relies on an autonomous device that can tow a trapping net, which could remove plastic debris from ocean waters (Boyle, 2012). Sonic transmitters could be used to deter marine organisms from getting caught in the net. It has been suggested that this technology could be used both in ocean and freshwater systems (Sigler, 2014). Another innovative technology, “The Ocean Cleanup Array”, may be a solution for extracting the plastics accumulating in the ocean gyres by harnessing ocean currents (The Ocean Clean-Up, 2014). Solid floating booms are attached to platforms that are anchored to the ocean floor. The array is designed to allow marine organisms to float beneath the booms and to collect floating plastic along the booms at the level of the surface water (The Ocean Clean-up, 2014). An estimated 7.25 million t of plastic debris could be collected and removed from the ocean (Singh, 2013; The Ocean Clean-up, 2014).

In addition, a new technique using ellipsoid bodies has been developed to detect pixels of coloured plastic debris on beaches using photographs taken by a webcam. The technique involves generating colour references, using a uniform colour space (CIELUV), to detect plastic pixels and to remove misdetected pixels by applying a composite image method (Kataoka et al., 2012). This technique demonstrated superior performance in terms of detecting plastic pixels of various colours compared to the previous method, which instead used the lightness values in the CIELUV colour space (Kataoka et al., 2012). Webcam monitoring of plastic debris on beaches is effective because it is possible to take remote measurements of the level of plastic. In addition to monitoring debris levels, the webcam is also a potential tool for the systematic planning of beach cleanup initiatives (Kataoka et al., 2012).

Furthermore, improving public awareness of the problems produced by microplastics is an important step towards changing people's behaviour with regard to plastic consumption. It has been suggested that the aim of raising public awareness of plastic pollution should be placed on the international political agenda, primarily because the issue of plastic marine litter is not familiar to the general public. Although the dumping of plastic garbage is forbidden by the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex V, many people are unaware of the prohibition regarding the disposal of plastics into the sea. In response to this, awareness should be raised by introducing different campaigns to those stakeholders that play an important role in plastic littering, including plastics industries, marine businesses and consumers. Large multinational organisations, such as the United Nations Environment Programme (UNEP) and the International Maritime Organisation (IMO), should organise campaigns on a global scale.

Finally, plastics industries should be responsible for the end-of-life of their products under requirements similar to those of electronic equipment producers. It has been suggested that materials with a high biodegradation rate, such as starch or pullulan, should be used instead of non-degradable or standard material. Biodegradable material will be more readily degraded by bacteria and fungi, reducing the lifetime of these plastics in the natural environment (Gregory and Andrady, 2003). In addition, industries should consider recycling or upgrading their plastic waste. Recently, the tertiary recycling of plastic has become better known; the process of converting the plastic material into smaller molecules can produce feedstock for the production of new petrochemicals and plastics (Mastellone, 1999). For example, PE can be recycled into a potential feedstock for gasoline production (AL-Salem, 2009).

7. Conclusion

In summary, plastic debris is commonly found in water bodies and beach sediment and originates from two major sources, land-based and ocean-based, with domestic, industrial and fishing activities being the most important contributors. Once the plastic debris has entered the environment, it is difficult to biodegrade and only fragments into smaller pieces; it thus persists in the environment due to its long lifespan and resistance to corrosion. The presence of plastic debris in the environment has adverse effects on a wide range of organisms, predominantly via plastic entanglement or ingestion. Some marine organisms such as fish, seabirds or sea lions accumulate ingested plastic, which is often associated with hydrophobic contaminants, in their bodies; these organisms may also become entangled in the plastic, which can be harmful or fatal. Finally, it is suggested that governments play an active role in addressing the issue of plastic waste by introducing legislation to control the sources of plastic debris and the use of plastic additives. In addition, plastics industries should take responsibility for the end-of-life of their products by introducing plastic recycling or upgrading programmes.

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