Plastics in the Marine Environment: The Dark Side of a Modern Gift

Jort Hammer, Michiel H.S. Kraak, and John R. Parsons

Contents

J. Hammer (✉) • M.H.S. Kraak • J.R. Parsons
Institute for Biodiversity and Ecosystem Dynamics,
Sciencepark 904, Amsterdam 1098 XH, The Netherlands
e-mail: jorthammer@gmail.com

D.M. Whitacre (ed.), *Reviews of Environmental Contamination and Toxicology*,
Reviews of Environmental Contamination and Toxicology 220,
DOI 10.1007/978-1-4614-3414-6_1,

1 Introduction

Plastics are one of the most widely used materials in the world; they are broadly integrated into today's lifestyle and make a major contribution to almost all product areas. The typical characteristics that render them so useful relate primarily to the fact that they are both flexible and durable. These characteristics are very useful when plastics are used in everyday life. But when plastics are discarded into the environment they can persist for very long periods of time. Because of their nearly indestructible morphology and the toxins they contain, plastics can seriously affect ecosystems (UNEP 2005).

The biggest mass of plastic debris occurs in the oceans' major gyres (Moore et al. 2001). Herein, the rotation of ocean currents catches any sea debris that floats and moves it to the vortex center, where it accumulates. Currently, the plastic debris patch in the North Pacific Ocean covers an area as large as France and Spain together. This debris constitutes particles that have diameters as small as several millimeters to big plastic-filled "ghost nets" having a weight of 2,000 kg. This debris affects all ocean life, and because we are at the top of the food chain, it affects humans too.

The aim of this review is to address and answer the following questions from information sourced largely from scientific reports and the mainstream scientific literature: What are plastics actually? What happens when they are discarded? How do plastics pose a threat to organisms in marine environments, and what are the solutions to the plastic debris problem?

2 Facts About Plastics

2.1 History of Plastic

The term plastics comes from the Greek word "plastikos" meaning "fit for molding," and refers to the plasticity of these materials during their manufacture (Liddell et al. 1968). Nowadays, plastics[1] is the term applied to a wide range of synthetic organic compounds that are produced by polymerization, and these consist of many repeating units (monomers) that come together to create copolymers. The plasticity of plastics allows them to be pressed or extruded into many different shapes and forms. Because of their sometimes infinitely long molecular structures, they can be very flexible and strong.

Plastics have been developed to replace depleted natural resources since ancient times. Polymers were used in 1600 B.C. by the ancient Mesoamericans, the first to

[1]The term *plastics* refers to a large number of synthetic organic compounds that have a polymeric structure and the ability to be cast in various shapes. However, the term *plastic* only refers to the plasticity of a material.

process natural rubber, to make figurines and bands (Hosler et al. 1999). Several semisynthetic plastics like polystyrene (PS) and polyvinyl chloride (PVC) were discovered in the nineteenth century, which marks the beginning of the plastic era (Ebewele 2000). Initially, plastics could not be used in commercial products because of their often rigid and brittle structure. This changed in 1909, when the first true synthetic phenol-formaldehyde plastic material (Bakelite) was discovered and was used in many different products, from telephone handsets to engine parts (Groot 2009). Later, in 1926, the modern form, PVC, was created as a plasticized polyvinyl chloride (vinyl), and in 1933 polyvinylidene chloride (PVDC), or Saran, was introduced by Ralph Wiley (Morris 1986).

Polyurethane (PUR), a flexible foam, was invented in 1937. In 1938, polystyrene (PS) became commercially practical and was used in peanut packaging; in this same year, polytetrafluoroethylene (PTFE) or Teflon was invented by Roy Plunkett. In 1939, nylon and Neoprene were invented by Wallace Carothers. Polyethylene terephthalate (PET), also known as polyester, was introduced by John Rex Whinfield in 1941. Polyester is primarily used in the manufacture of beverage bottles (PackagingToday 2009).

World War II increased the worldwide demand for plastics because copper, aluminum, and steel became so valuable for military use. Thereafter, plastics quickly gained use as a manufacturing material, and consequently material manufacturers, machine builders, and mold-makers flourished (Beall 2009). After the Second World War ended, civilian outlets were needed for plastics to keep the factories in business. The market was rapidly overwhelmed with plastic products, which were regarded by society to be “cheap and disposable.” In 1979, the plastic production in the USA exceeded that of steel production. Hence, one could conclude that World War II changed the world and started the age of the plastic industry (Beall 2009; Morris 1986).

In 1951, high-density polyethylene (HDPE) and polypropylene (PP) were invented and were employed for use in making water jugs and hula hoops. In 1954, Styrofoam was invented. Styrofoam is a trademark for extruded polystyrene foam and weighs 30-fold less than normal polystyrene foam. Thermoplastic polyester, which is based on polybutylene terephthalate (PBT), was introduced in 1970. This thermoplastic polymer is used as a material for high-quality, highly stressed engineering parts in many industrial sectors as a result of its high strength and good stability at high temperatures (Beall 2009).

2.2 Production

Plastics are produced by the conversion of natural products or by synthesis from primary chemicals, generally from oil, natural gas, or coal (Morris 1986; Thompson et al. 2009b). After conversion by a compounder fabric, the plastics become building materials for thousands of plastic products that are used worldwide. The fabrics, which give shape to plastics and are used to produce plastic products, are called “converters.” The most economical way to ship large quantities of a solid material

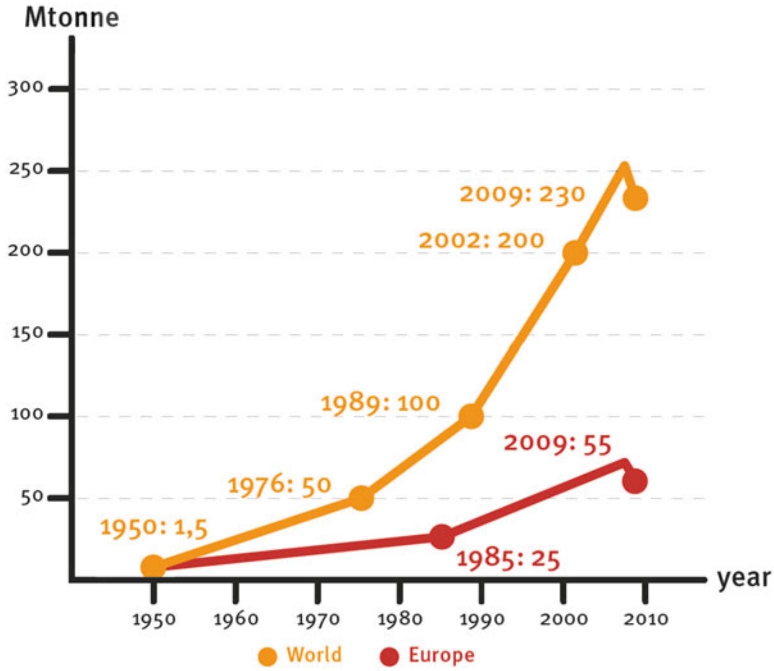

Fig. 1 World plastics production from 1950 to 2009 in millions of tons (PEMRG 2010)

from a compounder to these converters is in pelletized form (Ogata et al. 2009). Plastic-producing manufacturers utilize a form of preproduction pellets that are called “nurdles.” Nurdles are about 5 mm in diameter and weight approximately 20 mg each. After production, the nurdles are shipped to converters by rail tank cars which contain around one billion nurdles per tanker. In the USA, approximately 27 million tons of nurdles are produced annually, which constitute 1.35 quadrillion granules (EPA 1993). These preproduction nurdles can be subjected to different manufacturing processes to produce different products (Andrady 2003).

Once plastics became components of building materials that were commercially used in products and in the construction industry, their production and consumption increased significantly. The global production of plastics between 1950 and 2009 showed an average annual increase of 9%. In 1950, 1.5 million tons of plastics were produced and this has increased to 230 million tons in 2009 (Fig. 1). In 2008, the production dropped by 15 million tons as a consequence of the global financial crisis (Gioia et al. 2008). In mid-2009, there were signs of a market recovery, and in 2010 the annual production increased to 265 million tons (PEMRG 2011). The current plastic consumption per capita has grown to approximately 100 kg/year for NAFTA (North American Free Trade Agreement, including Canada, the USA, and Mexico) and Western Europe. If the growth continues, projected consumption will become 140 kg per capita in 2015. The biggest potential growth is expected from rapidly developing countries in Asia and the new European member states.

2.3 Additives

Plastics can be modified by adding a variety of chemicals (additives) that impart specific properties for the end product. Additives are specific chemical compounds that are added to a basic polymer to alter or improve its properties. The use of common plastics in today's products would not be possible without the use of such additives. PVC, for example, is very sensitive to thermal- and photo-degradation and is not useful without the addition of stabilizer additives, such as antioxidants and UV stabilizers (ACC 2010; Andrady 2003). Some of these additives, however, may cause a variety of toxic effects. For example, flame retardants (e.g., polybrominated diphenyl ethers), which are often added to plastics like PVC, can leach from food packaging's into food and are suspected to be endocrine disruptors (Hale et al. 2002). Phthalates are a widely used group of plasticizing chemicals that are primarily utilized in PVC polymers. Di-2-ethylexyl phthalate (DEHP) is the major plasticizer used in medical devices such as blood bags, catheters, and tubing (Koch and Calafat 2009). The primary building block of polycarbonate, bisphenol A, is known to be an endocrine disruptor, and is often used in food packaging (Nadal et al. 2009). Toxic metals such as lead (McIlgorm et al. 2011) and chromium (Cr) can also be present in polymers. These metals are often used in pigments that are added to plastics, and are potentially released into the environment (Omori et al. 2011). The toxicity of plastics and their additives is further discussed in Sect. 4.3.

3 Plastic Debris in the Marine Environment

3.1 Introduction

Plastics are often light, cheap, and durable materials. Because they can usually be cheaply produced, they are generally used only once and are then thrown away as litter. The fact that plastics are light and durable causes such litter to accumulate in landfills, or to be transported from source areas to sinks like the ocean. About 49% of all produced plastics are buoyant, which gives them the ability to float, and thereby travel on ocean currents to anyplace in the world (EPA 2008). As addressed below, a good understanding of the transport and fate of plastics in the ocean can be gained by categorizing and monitoring the movement of plastic debris.

3.2 Categorization of Plastic Debris

Plastic debris in the environment is routinely monitored to gain insights that concern the quantity and geography of its distribution. To this purpose, plastic debris is divided into three classes: macrodebris (>20 mm diameter), mesodebris (2-20 mm), and microdebris (<2 mm) (Galgani and Lecornu 2004; Thompson et al. 2009b), although some authors recommend other size limits (Cheshire et al. 2009).

3.2.1 Macrodebris

Macrodebris relates to the larger parts of plastic debris (>20 mm to several meters). Large-sized plastic debris may comprise plastic chairs, shoes, car/plane/boat parts, buoys, footballs, etc. Nearly any object larger than 20 mm that has ever been made from plastic is found in the oceans. An important, often found piece of macrodebris is the "ghost net." A ghost net is an abandoned or lost fishing net that roams the ocean. A ghost net travels with the currents and tides, continually catching animals and other macrodebris in its maze, and becomes filled primarily with other plastic objects. Ghost nets can grow to masses of 6 ton, and are often too heavy and too large to be removed from the ocean (CGNP 2009).

3.2.2 Mesodebris

Mesodebris often consists of plastic resin pellets, also known as nurdles. Nurdles are small granules that have the shape of a cylinder or disk, and have a maximum diameter of 5 mm. The pellets are made as raw industrial material, and are sent to manufacturers for remelting and molding into plastic products (Ogata et al. 2009). Because of their small size, nurdles are often accidentally expelled into the environment during transport and manufacturing. They then travel by surface run-off, rivers, and streams toward the ocean. Nurdles are highly persistent, and therefore are widely distributed in the ocean, and are found on beaches and water surfaces all over the world (Barnes et al. 2009; Derraik 2002; Edyvane et al. 2004; Ogata et al. 2009).

3.2.3 Microdebris

Microdebris consists of small plastic fragments <5 mm in diameter. Meso- and macro-debris can fragmentize into smaller bits from the constant movement and collisions with other plastic debris, or from the influence of UV-radiation and photo-oxidative degradation (Ng and Obbard 2006; Shaw and Day 1994). These microdebris fragments can become as small as 2 μm. Other small plastic particles, also called "scrubbers," which originate from hand cleaners, cosmetic products, and airblast cleaning media, have also contaminated the marine environment. Scrubbers are often contaminated with other chemicals (see Sect. 4.3) and can easily be ingested by filter-feeding organisms (Fendall and Sewell 2009; Gregory 1996).

3.3 Origin of Plastics in the Marine Environment

The release of plastics into the environment is a result of inappropriate waste management, improper human behavior, or incidental pollution (Barnes et al. 2009). Well-operated landfills are closed systems; they are daily covered by soil or synthetic materials and are surrounded by fences to hold wind-blown debris in place. Plastics do not biodegrade and can remain in place for centuries, until they are burned or used for recycling. The portion of plastic litter that does not reach landfills will roam the earth's surface, travelling by wind until it reaches the rivers, and eventually the sea. Improper human behavior produces such waste, when plastics are abandoned or are dumped outside licensed collection points or at sea. Incidental pollution also occurs, and includes the loss of containers at sea (Barnes et al. 2009).

In highly populated areas, land-based sources dominate the input of plastic waste into the marine environment; ship-generated debris is the major source of marine debris found on remote shores. The US Academy of Sciences estimated the total annual input of marine debris into the oceans to be approximately 6.4 million tons. Furthermore, eight million items of marine litter are estimated to enter the oceans and seas every day through various sources (UNEP 2005; 2009b).

3.3.1 Ocean-Based Sources

Nearly 5.6 million tons of marine debris every year is estimated to come from ocean-based sources, which is 88% of the total marine debris input. Daily, about five million items of solid marine debris are estimated to be thrown overboard or lost from ships (UNEP 2009b). The main ocean-based sources of such waste are as follows (Sheavly 2005; UNEP 2001; 2009b).

Merchant Ships, Ferries, and Cruiseliners

These ships are sources for marine debris in the form of household waste, sewage, cargo, and cargo hold waste (wiring straps, covering material and cargo residues), packaging material (plastic sheets, boxes), engine-room waste (oil or detergent containers), and discarded medical and sanitary equipment. The debris is intentionally dumped for lack of sufficient storage facilities or because of negligence, and sometimes is lost accidently through careless handling or bad weather.

Naval and Research Vessels

Naval and research vessels produce much of the same garbage as do the merchant ships, ferries, and cruiseliners, but military vessels may also deliberately dump military items to dispose of them. An example of this is the dumping of old military equipment in the Marsdiep by the Dutch Navy.

Pleasure Craft

From these craft, primarily household waste, sewage waste, oil containers, and recreational fishing gear (angling line and weights) are dumped from ignorance, negligence, or lack of reception facilities in local harbors.

Table 1 A summary of abandoned/discarded and lost polymer-containing fishing gear from around the world (taken from articles summarized by UNEP 2009b)

Region	Fishery/gear type	Indicator of gear loss
North Sea and NE Atlantic	Bottom-set gillnets	0.02–0.09% nets lost per boat per year
English Channel and North Sea (France)	Gillnets	0.2% (sole and plaice) to 2.11% (sea bass) nets lost per boat per year
Mediterranean	Gillnets	0.05% (inshore hake) to 3.2% (sea bream) nets lost per boat per year
Gulf of Aden	Traps	20% lost per boat per year
United Arab Emirates Sea Area	Traps	260,000 lost per year in 2002
Indian Ocean	Maldives tuna longline	3% loss of hooks/set
Australia (Queensland)	Blue swimmer crab trap fishery	35 traps lost per boat per year
NE Pacific	Bristol Bay king crab trap fishery	7,000–31,000 traps lost in the fishery per year
NW Atlantic	Newfoundland cod gillnet Fishery	5,000 nets per year
	Canadian Atlantic gillnet Fisheries	2% nets lost per boat per year
	Gulf of St Lawrence snow crab	792 traps per year
	Net England lobster fishery	20–30% traps lost per boat per year
	Chesapeake Bay	30% traps lost per boat per year
Caribbean	Guadeoupe trap fishery	20,000 traps lost per year

Offshore Oil or Gas Platforms

Drill pipes and drill pipe protectors, hard hats, cotton and rubber gloves, storage drums, oil containers household waste, discarded medical and sanitary equipment are lost from offshore platforms. The waste is usually dumped on purpose and sometimes is accidently lost from careless handling or bad weather.

Fishing Vessels

Most ocean-based marine litter is probably represented by abandoned and lost fishing gear. In areas far away from urban development, discarded fishing gear is responsible for 50–90% of the total marine debris. Table 1 shows a summary of the types of abandoned, discarded, or lost gear that reaches the oceans around the world every year. Among the different forms of discarded marine debris from fishing vessels are fishing nets, fishing lines, fish boxes, crab and lobster pots, oyster nets, strings for packaged bait, rubber gloves and of course household waste, oil containers, and sewage. There are several reasons as to why fishing gear can become marine litter (UNEP 2009b):

– *Fishing gear is abandoned*
  Some fishing gear and nets are abandoned by their owners and are never retrieved after falling into the ocean. This generally happens when fishing activities are

illegal, unregistered, and unreported; illegal gear is often abandoned because fishing vessels cannot enter a harbor and be seen with this equipment, or to avoid inspections when fishing occurs in forbidden areas. Finally, abandonment may result from the lack of time to collect all nets or traps.

– *Fishing gear is discarded*
  Fishing gear is often discarded when damaged; it is often cheaper to discard a damaged item, than to transfer the gear for onshore disposal. This occurs for many discarded and dumped marine debris items; it is cheaper and faster to dump everything overboard than to arrange for onshore disposal.
– *Fishing gear is lost*
  Accidental loss of fishing gear at sea often happens due to gear conflict (nets from different vessels become entangled with each other), misplaced gear, poor topography (nets and traps become struck on the seafloor), and extreme weather.
– *Containers are lost*
  Between 1990 and 2005, 16,625 containers worldwide were reported as lost by the Institute of Shipping Economics and Logistics (ISL 2009). Transport containers can contain several thousand pairs of shoes, televisions, or rubber ducks (Ebbesmeyer and Ingraham 1994); these are generally buoyant, and therefore the container may open and discharge contents when waterlogged. The loss of containers at sea is primarily caused by heavy weather (42%) and collisions between ships (11%). Since the fleet of container ships has grown by 140% since 1994, the chance of losing containers has increased accordingly (ISL 2009).

3.3.2 Land-Based Sources

Approximately 0.8 million tons annually of marine debris, which is 12% of the total debris input into the oceans, originates from land-based sources, and primarily consists of discarded plastic items (user plastic). In highly populated areas, marine debris comes primarily from the land. Main land-based sources of marine debris are as follows (Sheavly 2005; UNEP 2005; 2009b).

Municipal Landfills Located on the Coast

Many poorly managed or illegal landfills on the coast contribute to marine debris (solid household waste) under the influence of wind, which blows litter into the sea, or from flooding of the landfill area.

Transport of Waste by Rivers from Landfills, or Any Other Sources of Debris Along River- and Waterway Systems

Solid household waste and other items are flushed into the river after water levels rise, or from the influence of heavy rains. Debris could also be blown into rivers or illegally dumped (Moore et al. 2005). Moore et al. (2005) quantified the contribution of plastic particles from two rivers draining a large urban area (Los Angeles). Samples were taken from different depths in the rivers, and from one moderate and one heavy rain day, and one dry day. A total of 72 h of monitoring by using a net resulted in collecting a total of 2,333,871,120 (2.3 billion) plastic objects and fragments having a total weight of 30,438.52 kg (Moore et al. 2011).

Discharge of Untreated Sewage and Storm Water

In many of the world's cities, untreated sewage and storm water is discharged into the rivers and into the sea. Storm water carries solid and liquid items that are thrown onto streets and are subject to being washed away.

Industrial Facilities

The enormous amount of plastic resin pellets found in the sea today originates from industrial facilities. Also, untreated waste water from landfills delivers a large mass of solid material into the sea. Other materials, which originate from industrial facilities, are packaging material and production scrap.

Tourism

Various kinds of food packages, beverage cans and cartons, toys, and cigarettes are left at the beach by numerous tourists. This debris often blows into the sea or is taken off shore by the tide.

In summary, most plastic debris originates from ocean-based sources such as waste from cruise ships or fishing gear from the fishing industry. Land-based plastic debris is often only found near highly populated areas.

3.4 Degradation of Plastics in the Marine Environment

Most polymeric materials that enter the environment are subjected to degradation[2] that is caused by a combination of factors, including thermal oxidation, photo-oxidative degradation, biodegradation, and hydrolysis. The common plastics found

[2] Degradation implies here to the loss of useful properties following chemical changes in polymeric materials. When plastic material is technically said to be fully degraded, the polymer structure no longer exists (Andrady 1994).

in marine environments, however, do not biodegrade and primarily break down through photo-oxidative degradation. Furthermore, unlike plastics exposed on land, exposed plastics floating on the ocean's surface do not suffer from heat build-up due to absorption of infrared radiation, and therefore barely undergo thermal oxidation (Andrady 1994, 2003; Andrady et al. 1993). The degradation of negatively buoyant plastics depends on very slow thermal oxidation, or hydrolyses, as a result of most wavelengths being readily absorbed by water. Hence, plastics residing in marine environments degrade at a significantly slower rate than they do on land. Biodegradable plastics will further be discussed in Sect. 5.

Plastics primarily break down through photo-oxidative degradation, which is activated by solar radiation. The spectral energy of solar radiation reaching the earth's surface ranges between 298 nm in the ultraviolet (UV) region and 2,500 nm in the near-infrared region. Because short wavelengths contain more photonic energy than long wavelengths, short wavelengths have a stronger actinic[3] effect on materials and are capable of breaking strong bonds. Therefore, most photo-oxidative degradation occurs in the UV wavelength range of solar radiation (298–420 nm). However, regardless of the intensity, a specific wavelength can only cause damage to a surface when the material is capable of absorbing the specific wavelength. Thus, the effect of solar radiation on plastic depends on (1) the wavelength and amount of radiation a polymer is able to absorb and (2) the strength of the chemical bonds within the polymer (Andrady 2003).

The direct absorbance of solar radiation by a polymer is often determined by the presence of chromophores[4], which can absorb wavelengths longer than 290 nm. Only aromatic polymers like polyarylate (PAR) and PET contain structural chromophores capable of absorbing UV radiation. Nonaromatic (aliphatic) polymers, like polyethylene and PVC, do not contain chromophores and their UV absorbance lies below the range of the spectral energy of solar radiation. However, most aliphatic plastics contain solar UV absorbing impurities like catalyst residues, organic contaminants, and thermal oxidation products attached to the polymer chain, which makes them sensitive to photo-oxidation. A small amount of radiation absorbed by these impurities can initiate a rapid free-radical[5] chain reaction that can cause extensive photo-oxidation. This reaction causes many aliphatic polymers to be indirectly more sensitive to radiation than aromatic polymers, while the latter are able to directly absorb much more solar UV radiation (Andrady 2003; Hamidi 2000).

Two major reaction mechanisms occur by which solar radiation can degrade polymer materials: (1) a reaction is initiated by photolysis of the chromophores as a result of absorbing UV radiation, which produces a hydroxy radical, and (2) a photo-oxidative chain reaction is initiated by the energy absorbed by impurities. The radicals

[3] Actinism is the intrinsic property in radiation that produces photochemical activity.

[4] A chromophore is a chemical group capable of selective light absorption resulting in the coloration of certain aromatic organic compounds.

[5] A free-radical is a usually short-lived atom or molecule with at least one unpaired electron. Free-radicals are often highly reactive and unstable.

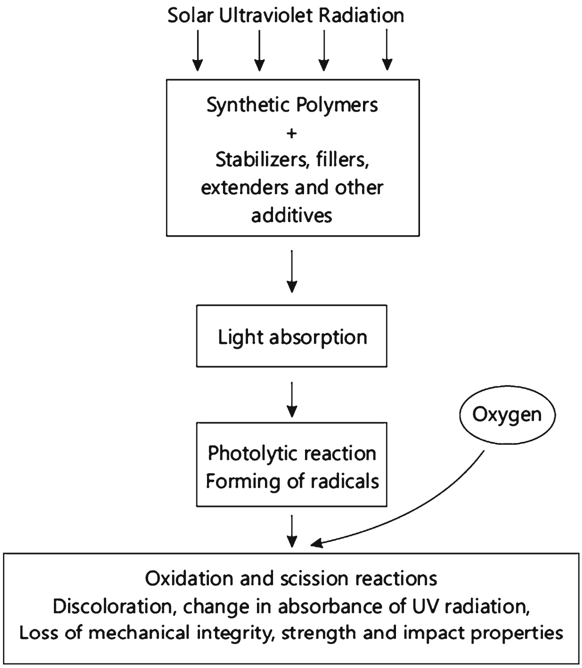

Fig. 2 A schematic diagram of polymer degradation under the influence of UV radiation (adapted from Andrady et al. 1998)

created by these two pathways react with oxygen and the polymer to produce cross-link bonds. Therefore, the polymer loses tensile strength, elasticity, and stretch; it becomes more brittle and breaks more easily (Andrady 2003; Andrady et al. 1998). Photolysis of the chromophores reduces coloration and thus causes bleaching of the polymeric material (Shaw and Day 1994) (Fig. 2). Synthetic polymers are only degraded by solar UV radiation of which the UV spectrum constitutes only 1%; therefore, degradation of polymers is a long-lasting process. Annually, ever larger amounts of plastic debris are introduced into the environment than can be degraded. Therefore, plastics are constantly accumulating in the oceans and in coastal areas.

It was shown in a recent study (Sivan 2011) that biodegradation of plastic waste could be possible with selected microbial strains. By incorporating pro-oxidants (photo sensitizers) into the polymer chain, a photochemical reaction can quickly be initiated via the catalytic activity of these oxides. This reaction causes oxidative degradation of the polymeric molar mass and forms oxygenated groups (such as carbonyl), which are then more easily metabolized by microorganisms. Although degradation of plastics would still be a long lasting process, microbes would speed up the process; e.g., after 1 year of natural weathering and 3 months of composting at 58°C. Twelve percent of the original carbon present in test samples were microbially mineralized (Sivan 2011).

3.5 Accumulation of Plastics in the Marine Environment

The persistence of plastics causes them to accumulate in the environment. The mass production of plastics started in the 1950s. Today, marine debris is dominated by plastics. It is estimated that half a century ago the amount of anthropogenic debris in the ocean would have been four orders of magnitude lower than it is today (UNEP 2005). The percentage of plastic fragments that exists in marine debris increases as the distance from the debris source increases. This characteristic is caused by the low weight and strength of plastics, which renders them easily transported further than other debris, resulting in plastic contamination, even in the most remote places on earth. Plastic objects are primarily found floating on the sea surface or along shorelines where they have been washed ashore. Research in the North Sea showed that, of all plastic debris annually dumped in the sea, 15% is floating on the surface, 15% is washed ashore, and eventually, 70% will sink to the sea bottom (Barnes et al. 2009; UNEP 2001).

3.5.1 Floating Plastic Debris

Many plastic items float, because they consist of light polymeric material, or because their shapes allow them to trap air (e.g., bottles and bags). Most plastic objects float until they either become too heavy from biota growing on their surface, or because they become waterlogged and sink.

Monitoring Floating Debris

The abundance of floating plastic at sea can be estimated by observing large plastic items or by using net trawls to collect smaller items. The success of visual observations depends on the number of observers. Rather large areas can be scanned for debris, especially when aerial observation is performed. Less subjective observations are made by using net trawls, but these are limited to sampling smaller areas. Most net trawl samples are taken with a manta trawl, a device which captures surface debris in a fine mesh net. A manta trawl has a 90-cm wide opening, with a small collection sock attached to it, which consists of a 0.333-mm mesh net. Another way to sample is with a 3-m long and 1-cm wide bongo net. This net also consists of a 0.333-mm mesh size and can be used to take samples from 10 to 100 m depths (AMRF 2010; Ryan et al. 2009).

Plastics Accumulation at Sea

Floating debris appears to particularly accumulate in oceanographic convergence areas, enclosed seas, and ocean currents. The North Pacific central gyre, an area of high atmospheric pressure with a clockwise ocean current, forces debris into a central area where winds and currents fade away. This gyre has been widely used for sampling and investigating plastic debris. Meanwhile, because of the inexorable accumulation of plastic debris, mostly meso- and micro-plastic particles, the center of the North Pacific gyre is now known as the Great Pacific "Garbage Patch" or "Pacific Trash Vortex" (Allsopp et al. 2007).

Moore et al. (2001) used a manta trawl to sample 11 random sites in the eastern area of the North Pacific central gyre. The individual plastic pieces collected were segregated by type into five categories: unidentified fragments, Styrofoam fragments, plastic resin pellets, polypropylene (sailboat) line fragments, and thin plastic film fragments. The mean abundance of plastic particles in the surveyed area was 334,271 particles/km^2 with a mass of 5,114 g/km^2. The abundance of plankton was measured to be five times higher than that of plastic, but the mass of the plastic particles was approximately six times that of plankton (Moore et al. 2001). In 2002, paired bongo nets were used to sample another area in the eastern part of the North Pacific central gyre. The nets were brought to a depth of 10 and 30 m. The samples collected at both depths contained a mean particle density of 0.017 particles/m^3, a factor 100 lower than densities found at the surface of the same sites that were sampled earlier (Moore et al. 2005).

Another undertaking to observe plastic particle density in the ocean was performed at the western side of the North Pacific gyre in the Kuroshio Current area (Yamashita and Tanimura 2007). Here, between April 2000 and April 2001, 76 locations were sampled using a manta trawl. Plastics were categorized as follows: plastic resin pellets, plastic products, fragments of plastic products, rubber, fiber, Styrofoam, plastic sheets (less than 2 mm thick), and sponge. The abundance (0–3,520,000 particles/km^2) and mass (0–153,000 g/km^2) varied among the locations. The abundance of plastic particles increased as distance from the shore increased, and the maximum abundance occurred in the area of the Kuroshio Current, which implies that this current plays a role in the transport and distribution of plastics from Japan and Indonesia over the North Pacific Ocean (Yamashita and Tanimura 2007).

The North Pacific gyre is only one of five gyres that are present on earth. The North Atlantic gyre has also been investigated and research institutions have been working on mapping their data. The Sea Education Association (SEA) monitored the North Atlantic gyre for plastics between 1986 and December 2008. More than 6,100 surface plankton net tows were conducted onboard various research vessels. Sixty-two percent of all tows contained plastics and the largest sample contained 1,069 pieces, which would equal 580,000 pieces/km. Although plastic production increased steadily after the year 2000, it is remarkable that this study showed an increase in the abundance of plastic debris only up to the year 2000, whereas the period from 2000 to 2008 showed barely any increase in plastic debris (Law et al. 2010).

The Agalita Marine Research Foundation is an institution that has sent many expeditions across the North Pacific gyre, and is planning more expeditions to other gyres like the South and North Atlantic. Nevertheless, abundance information on the incidence of floating plastic debris in the ocean is very limited. Gaining insights into the extent of such floating plastic pollution is almost impossible because of the immense surface area of the oceans. Nevertheless, the few studies that are available have produced enough information to suggest that humanity should be alarmed at the magnitude of floating plastic pollution, and the fact that it has become a serious waste problem.

In addition, as recently shown (Zarfl and Matthies 2010) plastic microdebris fragments, termed microplastics, also occur in oceans worldwide, including even Antarctica, where they are brought by ocean currents.

3.5.2 Plastic Debris Washed Ashore

Plastic debris is very commonly found on many beaches. Much of what is known about the distribution and origin of plastic debris comes from the monitoring of debris that has been stranded on beaches.

Monitoring Beach Debris

Surveys of marine debris accumulation on beaches have been used as the most common way to estimate the load of marine debris at sea, and they can also be used for public education and environmental awareness. Beach areas are easily accessible, and permit low-cost monitoring, although obtaining reliable datasets on beach pollution requires use of the same protocol and sampling methods. Therefore, the United Nations Environmental Programme and the Intergovernmental Oceanographic Commission have developed a standardized marine litter sampling protocol (Cheshire et al. 2009). This protocol includes several important specifications: beach areas to be surveyed should have a slope between 15° and 45° (shallow mudflats are not considered sample areas) and should be from 0.1 to 1 km wide. The beaches should have clear access to the sea and not be blocked by any anthropogenic structures. The surveys should be performed every 3 months throughout a period of 5 years, and the site should not be subjected to any other marine debris collecting activities. The items collected should be categorized into different classes by weight, size, and material type (Cheshire et al. 2009).

Plastic Accumulation on Beaches

Quantities of plastic debris items are highly variable over the course of any 1 year and per location, but numbers of more than 40,000 plastic items (mostly plastic pellets) per m^2 are not uncommon (Gregory 1978; Thompson et al. 2009a). The accumulation of plastic debris is greater near densely populated areas and on more frequently visited beaches; plastic litter on beaches are primarily sourced from adjoining land areas.

Ross et al. (1991) studied the sources of persistent marine litter in the Halifax Harbour, Canada, and concluded that 62% of the total litter, whereof 54% was plastics, originated from recreation and land-based sources. In contrast, at beaches far from urban areas, most plastic debris consisted of discarded fishing gear and litter. Derraik (2002) reviewed studies on the percentage of plastics in marine debris and concluded that the proportion of plastics varied between 60% and 80% of total marine debris.

A study in Singapore (Ng and Obbard 2006) showed that plastic microdebris accumulated in both seawater and in the sediment of Singapore beaches. The microdebris, containing polyethylene, polypropylene, polystyrene, nylon, polyvinyl alcohol, and acrylonitrile butadiene styrene, were derived from the physical and chemical fragmentation of larger plastic debris. The cleaning of such microscopic items from beaches is almost impossible, and moreover, photo-oxidative degradation of the debris does not occur because it becomes buried beneath beach sediments. In another study, performed along the tropical beaches of Northeast Brazil, the quantity, composition, and distribution of marine debris over a beach area of 150 km south of Salvador city, was examined. It was observed that at some locations the marine debris consisted of 90% plastics and Styrofoam. The average density of the debris was 9.1 items/m^2 being threefold higher than north of Salvador city, as a result of the southward littoral drift (Santos et al. 2009).

In 2010, the abundance of plastic particles in Belgian coastal waters and beach sediments showed a generally high distribution of microplastics (Claessens et al. 2011). Concentrations up to 390 particles/kg dry sediment were observed. The most abundant particles were plastic fibers (59%) and plastic granules (25%). The study results suggested that fresh water rivers are a potentially important source of microplastics, and showed temporal trends of increased microplastics in coastal sediments.

In a recent study, the effect of small plastic debris on water movement and heat transfer through beach sediments was investigated (Carson et al. 2011). Sediment cores from a beach known for plastic accumulation were compared with a beach where plastics were less common. The great majority (95%) of cores from the former beach contained plastic particles that were concentrated in the top 15 cm of the sediment, which sediment was also coarser grained and more permeable. Artificial cores were constructed that had different plastic-to-sediment ratios, and adding plastic significantly increased sediment permeability. Furthermore, sediments that contained plastics warmed more slowly and reached lower maximum temperatures. These changes can have a serious effect on beach organisms, including those that have temperature-dependent sex-determination, such as sea turtle eggs (Carson et al. 2011).

3.5.3 Plastic Debris on the Seabed

Marine debris is found resting or drifting on the seabed at all depths. It is estimated that in the North Sea up to 70% of marine litter ends up on the seabed.

Monitoring Debris on the Seabed

Data on the abundance of plastic debris in the benthic environments is still very limited, and is restricted by sampling difficulties and the costs of research into deep seabed ecosystems. Therefore, most scientists who have investigated seabed debris have focused their attention on continental shelves (Barnes et al. 2009). Benthic litter can be surveyed by using trawls and camera equipment towed behind a boat, or by direct visual observation by divers. The latter can only be performed in shallow waters, while trawls can also be used to probe deeper parts of the sea. When observations are made with towed equipment, like trawls, great care should be taken by researchers. Such methods can have a huge environmental impact from the by-catch of fish and the physical damage wrought on the benthic environment. A good example of this collaboration is the “Fishing for Litter” program. This program aims to reduce and survey the amount of marine debris by providing fishing boats with large bags for the deposit of marine sourced litter.

Plastics on the Seabed

In the North Sea, study results have indicated that an average of 110 pieces of debris per km^2 occurs on the seabed. If this number is extrapolated to the whole North Sea, a total of 600,000 m^3 of marine debris would be present on the seabed. In the Mediterranean, at a depth of 2,500 m, 300 million pieces of marine debris were found while surveying France and Corsica (UNEP 2001). In Dutch waters, the “Fishing for Litter” project has already collected 500 ton of debris between 2000 and 2006. This debris consisted of truck tires, fridges, large tree trunks, packaging material, lost shiploads, fishing gear, and ropes, among other things (KIMO 2010).

In 2004, the abundance and composition of marine benthic debris was investigated in the eastern Mediterranean on some coastal areas of Greece (Fig. 3). The mean total density of marine debris was estimated to be 15 items/km^2, ranging from 0 to 251 items/km^2, with plastics being the dominant form of debris (55.47%) (Katsanevakis and Katsarou 2004). In a second study conducted in the Patras and Echinadhes Gulfs of Western Greece, marine debris from fishing boat trawls was examined. The density of this debris in these two Gulfs was respectively 89 and 240 items per km^2. Again, the dominating form of debris consisted of plastic items (Stefatos et al. 1999).

3.6 Conclusions

Plastics introduced into the environment end up in different debris pools; floating on the surface, sinking to the seabed or washed ashore (Fig. 4). Floating plastics appear to accumulate in current waters and are very abundant in the world’s gyres. Approximately 70% of all floating plastic objects are believed to eventually

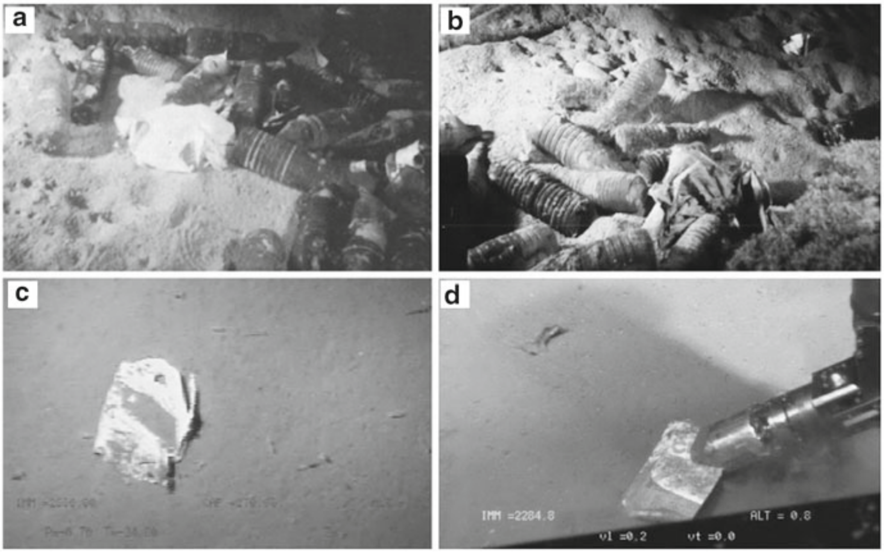

Fig. 3 Accumulation of debris at the seafloor in Mediterranean canyons (**a** and **b**; plastic bottles at 1,000 m depth in the Marseille canyon) and above the polar circle, under an ice sheet (**c** and **d**; plastic bags at 2,200–2,600 m depth at Hausgarten, Fram strait) (reprinted with permission from Barnes et al. 2009)

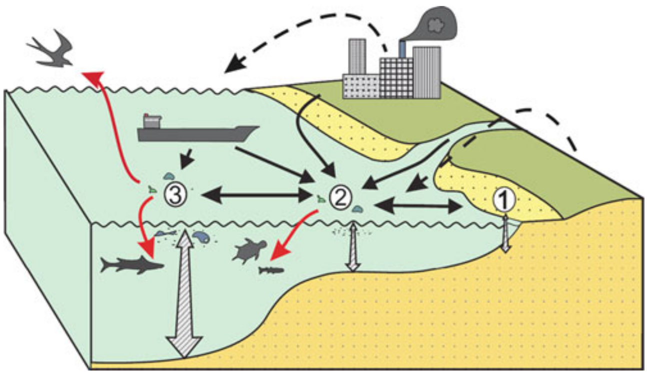

Fig. 4 A schematic diagram showing the main sources and movement pathways for plastics in the marine environment: (1) debris washed ashore on beaches, (2) debris in coastal waters, (3) debris in the open ocean, which may also sink to the seabed. *Dashed arrows* indicate wind-blown debris, *black arrows* waterborne debris and exchange between debris pools, *red arrows* effects on marine life, and *striped-gray arrows* vertical movement through the water column (adapted from Ryan et al. 2009)

sink to the seabed. Near densely populated areas, plastic debris consists primarily of user plastics. In contrast, in areas remote from human activity the debris mostly consists of abandoned, discarded, or lost fishing gear. The fishing industry is responsible for the largest input (50–90%) of total plastic marine debris to the oceans. Therefore, reducing loss and abandonment/discard by the fishing industry would significantly reduce the input of marine litter, and its effects on marine life. However, the plastic items that are present in the marine environment will fragmentize into smaller particles, microplastics, which are persistent and only slowly degrade. Recent studies showed that these microplastics occur nearly everywhere in the world's oceans including Antarctica.

4 Impact of Plastics on the Marine Environment

4.1 *Introduction*

The properties that make plastics such desirable materials for modern society can make them lethal for wildlife, when introduced into the environment. Numerous species are affected by plastic pollution, primarily because organisms become entangled in plastic nets, or plastic objects are ingested when organisms mistake plastic debris for food (Laist 1997). Another problem of plastic pollution is that it facilitates the transport of species to other regions; alien species hitchhike on floating debris and invade new ecosystems, thereby causing a shift in species composition or even extinction of other species (Aliani and Molcard 2003). Plastics also transfer contaminants to the environment or to organisms when ingested (Teuten et al. 2009). In addition to impact on marine life, plastic debris can also damage marine industries (entangling propellers and blocking cooling systems). It has been estimated that marine debris damage to the marine industry in the Asia-Pacific region costs $1.26 billion annually (McIlgorm et al. 2011).

4.2 *Mechanical Impact*

It was shown that at least 267 marine species worldwide suffer from entanglement and ingestion of plastic debris (Laist 1997). When such contacts occur, organisms are seriously affected in ways that quite often results in death.

4.2.1 Entanglement

It is very difficult to estimate what the total effect of plastic debris in the ocean is, or to predict the consequences for organisms that ingest or otherwise contact that debris, because it cannot be directly observed. By contrast, entanglement can be observed, and is the most visible effect of plastic debris on organisms in the marine environment. Laist (1997) studied and composed a comprehensive list of species that suffered from entanglement and ingestion, and estimated that a total of 136 species are being affected by marine debris entanglement (Table 2). Nevertheless, the exact extent of entanglement faced by marine organisms is difficult to quantify, because entanglement generally occurs in areas remote from human activity.

Table 2 Number and percentage of marine species that have documented entanglement and ingestion records (Reprinted with permission from Laist 1997)

Species group	Total number of species worldwide	Number and percentage of species with entanglement records	Number and percentage of species with ingestion records
Sea turtles	7	6 (86%)	6 (86%)
Seabirds	312	51 (16%)	111 (36%)
Penguins (Sphenisciformses)	16	6 (38%)	1 (6%)
Grebes (Podicipediformes)	19	2 (10%)	0
Albatrosses, Petrels, and shearwaters (Procellariiformes)	99	10 (10%)	62 (63%)
Pelicans, Boobies Gannets, Cormorants, Frigatebirds, and Tropicbirds (Pelicaniforms)	51	11 (22%)	8 (16%)
Shorebirds, Skuas, Gulls, Terns, Auks (Charadriiformes)	122	22 (18%)	40 (33%)
Other birds	–	5	0
Marine mammals	115	32 (28%)	26 (23%)
Baleen Whales (Mysticeti)	10	6 (60%)	2 (20%)
Toothed Whale (Odontoceti)	65	5 (8%)	21 (32%)
Fur Seals and Sea Lions (Otariidae)	14	11 (79%)	1 (7%)
True Seals (Phocidae)	19	8 (42%)	1 (5%)
Manatees and Dugongs (Sirenia)	4	1 (25%)	1 (25%)
Sea Otter (Mustellidae)	1	1 (100%)	0
Fish	–	34	33
Crustaceans	–	8	0
Squid	–	0	1
Species total		136	177

Entanglement can cause death by drowning, suffocation, strangulation, or starvation (Allsopp et al. 2007). Very often, birds, small whale species, and seals drown in ghost nets, lose their ability to catch food, or cannot avoid predators because of their entanglement (Derraik 2002).

Coastal and Marine Birds

Many birds in the marine environment dive for food, and thereby come into contact with plastic debris. The greatest causes of entanglement by seabirds are fishing lines and six-pack rings. Both materials are often transparent and difficult to see. If seen, they can be mistaken for jellyfish and other food (Allsopp et al. 2007).

The gannet is one marine bird species that is endangered by plastic debris. As a "plunge-diver," the gannet dives from great heights into the ocean and can thereby be caught by ghost nets or other debris. A study at the island of Helgoland in

Fig. 5 A Grey Seal inside a seal shelter at Texel, The Netherlands. The seal was entangled in a nylon thread which had cut into the flesh and damaged the backbone. It suffered from internal bleeding and symptoms of paralysis. Because of its incurable injuries the veterinarian euthanized this animal (De Wolf 2008)

Germany, which hosts a large gannet colony, showed that between 1976 and 1985, 29% of dead gannets found had become entangled in net fragments (Schrey and Vauk 1987). Helgoland is generally a safe habitat for these birds and one of the few threats is entanglement while foraging. Another study, performed in the Netherlands between 1970 and 2000, showed that, of the total number of dead gannets found (1,413), 5.9% (83) had died from entanglement by fishing nets, rope, nylon fibers, nylon line, or other unidentified plastics (Camphuysen 2001). The numbers of entangled gannets have increased over time, which may relate to the increasing amount of plastics produced in Europe. The dead gannets found on the Dutch coast were far away from their colony and were often transmigrating to other places, in contrast to the gannets from Helgoland. There is a chance that a portion of the gannets in the second study died from exhaustion, which may explain the difference in entanglement percentages. Entanglement is probably most common for gannets, albatrosses, a few gull and penguin species, and petrels (Laist 1997).

Seals

Many seal species are curious and playful, and especially young seals are attracted to plastic debris and swim with it or poke their heads through loops. Plastic rings, loops, or lines easily glide onto the seal's neck, but are difficult to remove due to the backward direction of the seal's hair. As the seal grows, the plastic collar tightens and strangles the animal or severs its arteries (Fig. 5). When foraging, many seals become entangled in submerged fishing nets, especially in the North Sea where their vision is limited. After entanglement in these nets the animals are not able to reach the water surface, and drown. Every year fykes[6] in Dutch coastal waters

[6] A fish trap consisting of a net suspended over a series of hoops, laid horizontally in the water.

causes the death of 15 gray- and harbor-seals, and in 1987, during a search for new feeding grounds, 60,000 harp seals died in stake nets in Norway (De Vleet 2010).

Hanni and Pyle (2000) studied the synthetic-material entanglement of California sea lions, northern elephant seals, steller sea lions, pacific harbor seals, and northern fur seals, between 1976 and 1998, at south-east Farallon Island, California. A total of 914 pinnipeds had indications of entanglement (32%) or displayed constrictions of past entanglement (68%) from various debris types. Most entangled pinnipeds were California sea lions (820), of which 72% had neck constrictions. A total of 68 northern elephant seals were observed to have been entangled primarily by packaging material (59% of the total entanglements) and miscellaneous synthetic materials. Of the 26 entangled Steller sea lions, 15 were observed to have salmon flashers or other hooks hanging from their jaws (Hanni and Pyle 2000).

In a second study performed at the other side of the Pacific Ocean, on the shores of Australia and New Zealand, it was estimated that 1,478 fur seals and sea lions die annually from entanglement (Page et al. 2004). In Australian coastal waters, sea lions were observed to most frequently become entangled with monofilament gillnet, which originated from the shark fishery in that region. In contrast, in New Zealand coastal waters fur seals were observed to primarily become entangled in packaging material, loops, and trawl net fragments that were suspected to originate from regional trawl fisheries (Page et al. 2004).

The material that is responsible for causing entanglement of seals often originates from local fisheries. In many cases, the area where seals forage is also used by humans for shark or trawl fishery. For example, the Farallon Islands are well-known fishing grounds for recreational fishery, and this may have caused the high percentage of flashers embedded in seals of this region.

Whales

Whales also become entangled in marine debris. However, although some whale species are incapable of freeing themselves and consequently drown, the larger size whales often drag fishing gear away with them. This latter type of entanglement can cause strangulation and can affect the feeding ability of the whale in ways that causes starvation (Fig. 6).

In 2005, a study was performed on the entanglement of large whale species in the western North Atlantic Ocean. The purpose of the study was to investigate the entanglement of 31 right whales and 30 humpback whales to determine the types of gear involved. The most common points of gear attachment on the whale's anatomy were the mouth and the tail. Further, 89% of the entanglements were determined to result from pot and gill net gear (Johnson et al. 2005). Pots and gill nets both are located on the seafloor. They are often attached in tandem to each other, and to surface buoys. Large whale species regularly become entangled in these buoy- or connection-lines. According to Johnson et al. (2005), most whale entanglements in the western North Atlantic Ocean involve ground lines. The Provincetown Centre for Coastal Studies, together with several federal agencies, is monitoring the

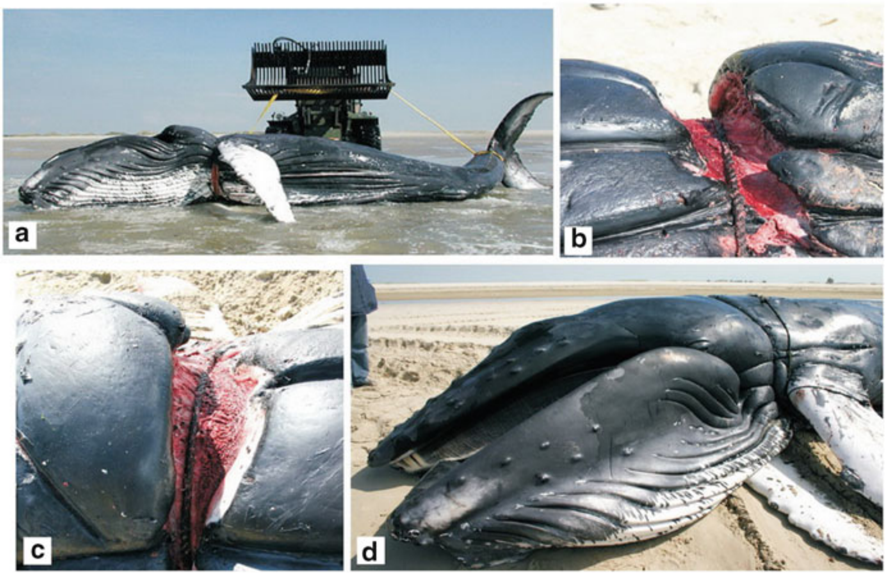

Fig. 6 In June 2004, a Humpback Whale was stranded on the coast of Vlieland an island in the north of the Netherlands. The whale was entangled in a nylon rope that was wrapped around the head. The rope had cut deeply into its body and was probably the cause of the animal's death (**b**–**d**). The specimen, a young male and approximately 8 m long, was first buried upon discovery by the Dutch Air Force, because it was stranded in a practice area. (**a**) After the photos were shown to experts, the animal was determined to be a Humpback Whale, which is a rare whale species in the North Sea (Bruin 2004)

abundance of whale entanglements in the Atlantic coastal waters of the USA and Canada. Between 1983 and 2009 there were 83 reports of entangled whales in these regions (PCCS 2010).

Fish Species and Ghost Fishing

The incidence of accidental entanglement of fish species is difficult to estimate, because certain fish are "intended" to become entangled in nets. Therefore, research emphasizes by-catch of endangered species. For example, between 1978 and 2000, 28,687 sharks were caught in nets that protected people at popular swimming beaches in KwaZulu, South Africa. Over this period, 53 sharks were found with polypropylene strapping bands around their bodies, and these sharks were evaluated as being significantly underweight (Cliff et al. 2002). Another source of entanglement of fish species is caused by ghost fishing (see Sect. 3.2.1).

Ghost fishing results from fishing gear that continues to function in the water after being discarded or lost (UNEP 2009b). Fishing nets and pots can capture marine organisms, which subsequently die if they cannot escape. In turn, these organisms attract larger predators which also become trapped. When the larger organisms die they attract smaller scavengers, and so the cycle continues. These fishing nets and pots are death traps for marine organisms, because they do not biodegrade, but rather continue to "fish" for many years (UNEP 2009b).

Sea Turtles

Sea turtles are well-known victims of plastic debris. Juvenile specimens are easily caught in discarded fishing nets, and succumb by drowning. Larger sea turtles are still able to swim with fishing gear attached to their fins or shell, but the debris often affects their ability to feed in ways that eventually results in starvation.

A study on the cause of death among sea turtles stranded at the Canary Islands, Spain, revealed that 70% had died from the influence of human activities, including entanglement by discarded fishing nets (25%). In the same study, it was demonstrated that only 27% of the turtles died from natural causes like diseases (Orós et al. 2005). Plastic debris and other human activities have a big impact on these species worldwide, because six out of seven sea turtle species are known to be affected by entanglement (Table 2) (Laist 1997). Since only 7–13% of the turtles that die from the influence of fishing are washed up on the beaches (Bugoni et al. 2001), studies of stranded turtles alone address only a small part of the total mortality that is caused by fisheries and plastic debris.

4.2.2 Ingestion

Plastic debris that pollutes the marine environment is often ingested by marine birds, mammals, turtles, and fish (Laist 1997). The ingestion of plastics primarily occurs when it is mistaken for food, but can also occur from incidental intake. The ingested material often consists of micro- and meso-debris sized fragments, which sometimes are able to pass through the gut without hurting the organism. In most cases, however, fragments become trapped inside the stomach, throat, or digestive tract and cause damage (e.g., sharp objects) or a false sense of fullness, which will result in starvation.

Coastal and Marine Birds

A high proportion of coastal and marine bird species (36% of the 312 species worldwide) ingest plastic fragments (Laist 1997). Although plastics are mainly ingested by birds because they are mistaken for food, they may also already be present in the gut of their prey, or may be passed from adult to chick by regurgitation feeding. Some species feed selectively on plastic fragments that have a specific shape or color (Moser and Lee 1992). Therefore, plastics ingestion by birds is directly related to their feeding habits and foraging techniques. For example, birds that consume fish (piscivores) are less likely to ingest small plastic fragments than are birds that primarily feed on plankton (planktivore); the latter often confuse plastic pellets with their prey (Derraik 2002). A study on the ingestion of plastic particles by sea birds in the Subarctic North Pacific Ocean showed a great variation in ingestion of plastics between species within the same area, which confirms the correlation between plastic ingestion and feeding and foraging techniques. Robarts et al. (1995) found 4,417 plastic particles in the gut contents of 1,799 birds, of which 76% consisted of plastic pellets. In comparison with an earlier study in the same area, an increasing frequency of ingested plastic particles was found over time (Robarts et al. 1995).

The Laysan albatross accumulates plastic fragments when collecting food for the feeding of its chicks. These plastics are passed on to the chicks by regurgitation. A total of 251 Laysan albatross chicks from Sand Island, Midway Atoll, were examined, and only six did not contain plastic fragments. Of the 245 chicks that carried ingested plastic, a variety of plastic items were found that included hips and shards of unidentified plastic, Styrofoam, beads, fishing line, buttons, chequers, disposable cigarette lighters, toys, PVC pipe and other PVC fragments, golf tees, dish-washing gloves, magic markers, and caylume light sticks. Most of these items were trapped, and were acting to block the stomach or digestive paths of these birds, rather than to damage their guts; such blockage eventually leads to starvation.

The northern fulmar is a planktivore bird species that is often studied for its ingestion of plastics. In 2006, fulmars obtained from fisheries as by-catch in the Davis Strait between Canada and Greenland, were examined for plastic particles; 36% of the total of 42 birds evaluated contained at least one piece of plastic (Mallory et al. 2006). In general, the number, size, and volume of plastics ingested by fulmars in the north of the North Pacific and the North Atlantic Ocean were lower than in fulmars from the southern parts of these regions. Study results from the North Atlantic Ocean disclosed an incidence of plastic ingestion by fulmars of 79–99% (Moser and Lee 1992; Van Franeker 1985; Van Franeker and Meijboom 2002) and 84–88% in the North Pacific Ocean (Andrady 2003; Robarts et al. 1995). The composition of plastic debris inside the fulmars also varied; in the David Strait 100% of ingested plastic were fragments of discarded plastic products (user plastics), whereas in the North Sea, only 50% consisted of user plastics (Mallory et al. 2006; Van Franeker 1985). Apparently there are regional differences in number, size, and volume of ingested plastics by fulmars, which can be explained by the difference in abundance of plastic debris that occurs near manufacturing centers or areas with intensive shipping traffic. The OSPAR commission, aiming to protect and conserve the North-East Atlantic Ocean, defined acceptable ecological quality as the situation in which no more than 10% of fulmars exceed a critical level of 0.1 g of plastic in the stomach (OSPAR 2008). In a recent study on the abundance of plastics in stomachs of northern fulmars from the North Sea, 1,295 dead beached fulmars were sampled from various European countries, and it was observed that 58% of the birds exceeded the critical level of 0.1 g of plastic; these amounts greatly exceeded the acceptable ecological quality critical level of 10% (Van Franeker et al. 2011).

Seals

Ingestion of plastic fragments is far more commonly reported for birds than for seals. The reason for this may also result from the small sample size prevalent in seal studies. Feces from fur seals at Macquarie Island, Australia, were examined for plastic fragments in 2003. A total of 164 plastic fragments, mostly polyethylene (93%), were found in the scat of 145 seals, which is more than one fragment per seal. All fragments consisted of user plastics. According to the otoliths, and compared to plastic ingestion by fish in other studies, these fragments were probably not directly ingested by the seals, but rather were accumulated in the fish they consumed (Eriksson and Burton 2003).

Whales

Twenty-eight of 75 whale species, including toothed whales and baleen whales, were reported to have ingested plastic debris (Baird and Hooker 2000; Laist 1997). Most whales that ingest plastic debris live in remote areas and may sink after they die. This, and the fact that most whale species are protected, makes it difficult to study the incidence of plastic ingestion by whales. The sample size is often very small, and is limited to specimens that have been washed ashore. Nevertheless, if one specimen is found to be affected by ingestion of plastic debris, it is probable that other individuals from the same species run comparable risks.

A harbor porpoise, found dead on a beach near Pictou, Canada, died from ingesting a balled up piece of plastic that measured 5 by 7 cm when stretched out. Upon examination, the plastic was found to have blocked the digestive tract, resulting in the accumulation of bones, half digested fish and intact fish in the digestive track. The harbor porpoise had died from starvation (Baird and Hooker 2000). Another report showed that the death of a Sperm whale, which had washed ashore in Texas, USA, had died from ingesting a corn chip bag, plastic sheets, a garbage can liner, and a bread wrapper. In one final example, the death of a beaked whale that washed ashore in Brazil was believed to have resulted from the ingestion of a bundle of plastic threads (Derraik 2002).

Walker and Coe (1989) reported 43 incidents of debris ingestion in 16 stranded toothed whale species. Of these incidents, 80% resulted from plastic debris, mostly plastic bags and sheeting. The authors stated that the ingestion of debris by most toothed whales occurred primarily as incidental ingestion as they were consuming benthic prey. Most reported incidents occurred on the east and west coasts of North America. Variability among these reports may have resulted from regional differences in surveys, recovery, and necropsy, rather than true geographical differences (Walker and Coe 1989).

Data from a study on the ingestion of plastics by Franciscana dolphins in Argentina indicated that 28.1% of the 106 examined dolphins had plastic debris in their stomachs. Most debris (64.3%) consisted of plastic packaging (cellophane, bags, and bands) and a lower proportion (35.7%) consisted of fishing gear fragments. A sharp increase in the occurrence of ingested plastic debris was found in younger dolphins during their weaning phase. Such dolphins may have misidentified what constituted food, or plastic debris, because they had yet to learn what is and is not edible (Denuncio et al. 2011).

Fish

Plastics ingestion by fish has received little attention, with most reports recording only incidental ingestion events. Tiger sharks are known to ingest various items of plastic debris, including plastic bottles, caps, bags, and foil (Randall 1992). Authors of a study performed in the Bristol Channel observed ingested plastic (polystyrene) fragments in the gut of 21% of the flounders examined. Similar fragments were found in 8 of 13 fish species caught along the New England coast, USA (Derraik 2002). Laboratory experiments have proven that some larval and juvenile species of mullet and spot feed on polystyrene fragments. Further, some larval and juvenile fish species in the field were found to have plastic pellets or fragments thereof in their guts. In addition, some adult species had a wide range of material in their guts, from plastic fragments to whole plastic cups. The ingestion rate of plastic particles by mesopelagic fishes at the North Pacific Subtropical Gyre was estimated to be between 12,000 and 24,000 ton/year (Davison and Asch 2011). However, little is known about the impact of plastics ingestion among fish species. This is largely because sampling has not been sufficiently frequent, and there is almost no evidence to determine if ingestion is an important cause of mortality in fish (Hoss and Settle 1990).

Sea Turtles

Sea turtles are among the marine species which are most threatened by plastic debris. Various studies showed that sea turtles do ingest plastic debris (Bugoni et al. 2001; Derraik 2002; Orós et al. 2005). Plastic debris, like bags and sheets, is often transparent and can be mistaken for jellyfish, which is a key diet item for most sea turtles. Furthermore, sea turtles are endangered species, and if plastic intake increases their mortality, the consequences for sea turtle populations around the world may be quite serious.

One turtle found in New York was reported to have ingested 180 m of heavy fishing line (O'Hara et al. 1988). In a study in southern Brazil the contents of the stomach and esophagus of 38 dead stranded Green Turtles was examined. Results were that 60.5% of the green turtles had ingested plastic debris, and this debris caused the death of 13.2% of the green turtles examined. The ingested materials were comprised mostly of plastic bags and white or colorless plastic pieces (Bugoni et al. 2001). Authors of a study in the Mediterranean Sea analyzed debris ingested by 54 juvenile loggerhead turtles. Forty-three of these turtles had ingested marine debris, of which 76% consisted of plastics. Loggerhead turtles are general predators and display little prey discrimination while foraging. This was confirmed by a large variety of plastic items of different colors and shapes found inside their digestive tracts (Tomás et al. 2002). In comparison, green turtles have a selective feeding pattern (Coyne 1994), which was reflected in the more uniform kind of debris found in these animals.

4.3 Chemical Impact and Ecotoxicology

Plastics are considered to be biochemically inert; because of their macromolecular structures, they neither react with, nor penetrate the cell membrane of an organism. However, most plastics are not pure. Besides their polymeric structure, they consist of a variety of chemicals that all contribute to a certain property of the plastics they comprise. These chemicals are called additives and they function as described in Sect. 2.3 above. Additives are mostly of small molecular size, are often not chemically bound to a polymer and are, therefore, able to leach from the plastics. Being primarily liphophilic, they penetrate cell membranes, interact biochemically, and cause toxic effects. Moreover, plastic debris in the marine environment not only contains additives, but also contains chemicals (contaminants) adsorbed from the surrounding water. The hydrophobic surface of plastics has an affinity for various hydrophobic contaminants, and these are taken up from the surrounding water and accumulate on, and in the plastic debris. This mechanism receives great attention for microdebris or microplastics, because they are easily ingested by organisms and constitute a pathway for chemicals to enter an organism (Andrady 2011).

In summary, plastic debris in the marine environment can contain two types of possible toxic contaminants: (1) additives and (2) hydrophobic chemicals that become adsorbed from the surrounding water (Teuten et al. 2009).

4.3.1 Toxic Additives: Phthalates and Bisphenol A

The release of additives into the environment changes the properties of polymers and affects living organisms. Bisphenol A (BPA) is a constructive monomer that is used in polycarbonate and as a plasticizer, stabilizer, and antioxidant in other plastics such as PVC (Yamamoto and Yasuhara 1999). There are many studies that address the leaching of BPA from polycarbonate or other plastics into the aquatic environment (FDA 2010; Sajiki and Yonekubo 2003; Yamamoto and Yasuhara 1999). Sajiki and Yonekubo (2003) reported that BPA was easily leached from polycarbonate tubes into seawater at 37°C. The leaching rate depended on the temperature of the surrounding water, which can be a concern along tropical seashores in the summertime.

Phthalates are a group of chemicals that are widely used as plasticizers, primarily in PVC polymers. Phthalates and BPA are proven endocrine disruptors. These agents disrupt the functioning of the hormone system, and have received much attention because of their ubiquitous presence in the environment and in humans (Diamanti-Kandarakis 2009; Koch and Calafat 2009; Sax 2009). Phthalates and BPA can leach into the environment, decreasing the flexibility of plastics and affecting reproduction, impairing development, and inducing genetic aberrations in a variety of organisms (Teuten et al. 2009). In a study published in 2009, the effects of phthalates and BPA were examined on several fish, crustacean, and amphibian species; results were that these chemicals affected development and reproduction of a wide range of species. The authors of this study reported alterations in the number of offspring produced, reduced hatching success, and disruption of larval development of molluscs, crustaceans, and amphibians by low concentrations of BPA and phthalates. Fish species were affected only by relatively high doses of these chemicals, and these demonstrated species-specific sensitivities to these compounds (Oehlmann et al. 2009).

4.3.2 Toxic Additives: Flame Retardants

Flame retardants are also present as additives in plastics and have been added to many common products. The majority of flame retardants are brominated molecules and are referred to as brominated flame retardants (BFRs). BFRs are widely used in plastic products because they affect material properties in only a minor way, and are very effective in preventing ignition. However, they are also present as contaminants almost everywhere in the world's environment; they exist in air, rivers, and waters up to the Arctic regions. BFRs bioaccumulate in the marine food web, including in Canadian Arctic belugas (Tomy et al. 2008) and blue mussels (Gustafsson et al. 1999). Some BFR congeners cause reproductive and carcinogenic effects (Darnerud 2003), disrupt endocrine systems, and cause neurotoxicological effects on mammals and aquatic organisms (Legler 2008).

4.3.3 Adsorption of Contaminants by Plastic Debris

In the marine environment, adsorption of contaminants by polymers is primarily studied with mesoplastic and microplastic debris. Adsorption reduces the transport and diffusion of contaminants. Hydrophobic organic contaminants have a greater affinity for plastics like polyethylene, polypropylene, and PVC, than for natural sediments (Teuten et al. 2009). Polychlorinated biphenyls (PCBs) are a group of organic compounds that once were used as insulating fluids and coolants, as plasticizing and stabilizing additives in PVC, as flame retardants (before the introduction of BFR as a flame retardant), electronic components, and much more. Although PCBs have been banned since 1977 in the USA, and since 1985 in the Netherlands, they have been spread throughout the environment by leakage, dumping, and leaching (EPA 2010), and are present in waters all over the world. Figure 7 shows the PCB concentrations in plastic pellets that were washed ashore. The concentrations in plastics were highest in samples taken along the coasts of the USA, followed by Japan and Europe. Such differences are caused by a differences in PCB usage and production; of the total global PCB production, the USA produced more than half, whereas Africa, Australia, and tropical Asia contributed only minimal amounts (Teuten et al. 2009). In 2001, results of a study on the adsorption of toxicants by plastic pellets along the Japanese coast showed that pellets adsorb PCBs from the surrounding seawater. Virgin polypropylene pellets were used in a 6-day field experiment and increased PCB concentrations were observed throughout the experiment. Moreover, different plastics were observed to have different adsorption capacities; polyethylene pellets adsorbed four times more PCBs than did polypropylene pellets (Mato et al. 2000).

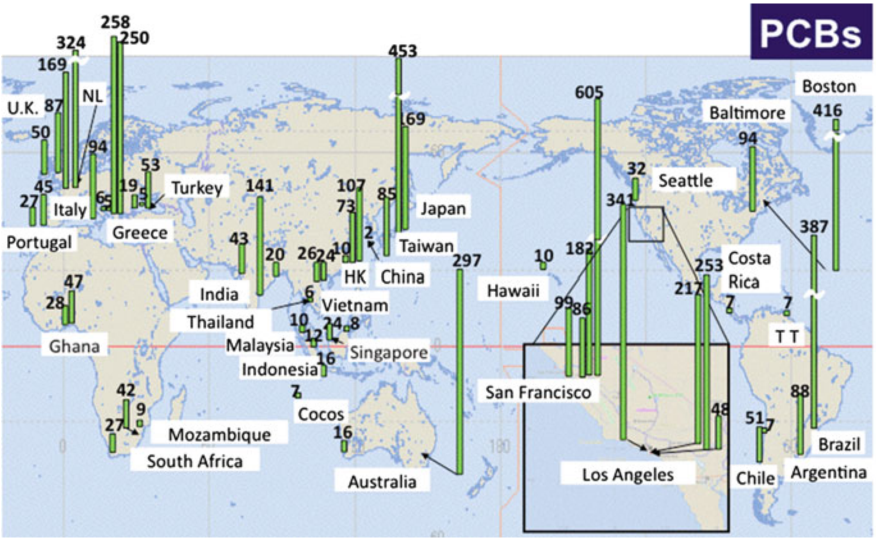

Fig. 7 The concentrations of PCBs that exist in plastic pellets washed ashore. The USA is responsible for half of the world's total PCB production. Therefore, the highest concentrations were found along the US coasts (reprinted with permission from International Pellet Watch 2010)

In addition to PCBs, plastic pellets also adsorb other chemicals, including the pesticides hexachlorocyclohexane (HCH), dichloride diphenyl trichlorethane (DDT) and its metabolites DDE and DDD, and the polycyclic aromatic hydrocarbons (PAHs) that are produced during the burning of fuels. Many of these contaminates are carcinogenic, mutagenic, and/or teratogenic. Adsorption of contaminants can also reduce contaminant biodegradation. Thus, plastics not only adsorb and transport contaminants, but may also increase their environmental persistency (Teuten et al. 2009).

International Pellet Watch (IPW) is a global monitoring program for persistent organic pollutants (POPs). IPW uses plastic resin pellets to monitor the concentrations of contaminants in pellets that are washed ashore. The types and concentrations of chemicals found in these pellets are then used to calculate the concentration of contaminants in the water. This sampling approach is relatively cheap compared to water, sediment, and biological sampling-monitoring approaches and can be used to build maps such as the one that is presented in Fig. 7 (IPW 2010) .

4.3.4 Transfer of Contaminants from Plastics to Organisms

Most marine organisms obtain contaminants from plastics by ingesting plastic debris. Adsorbed contaminants can leach into digestive fluids and can be transferred to other tissues. Toxicants may bioaccumulate in the tissues to produce high tissue toxicant concentrations. Toxicant concentrations may also increase through transfer within a food web (biomagnification). Higher trophic level organisms are exposed to enriched concentrations of contaminants via their prey. However, researchers have shown that some contaminants, like PAHs, do biomagnify less with increasing trophic level (Takeuchi et al. 2009). Notwithstanding, these contaminants are found in marine organisms at high trophic levels (De Laender et al. 2011; Mato et al. 2001).

Results of a study performed in 1988 showed a positive correlation between ingesting plastics and PCB concentration in fat and eggs of 20 female great shearwaters (Ryan et al. 1988). Results from a 2008 feeding experiment proved that PCBs were transferred from contaminated plastics to streaked shearwater chicks. Chicks fed fish laced with polyethylene pellets that were contaminated by PCBs contained PCB residues that were threefold higher than that of the control group (Teuten et al. 2009). These results confirmed that POPs (including PCBs) are transferred to organisms through plastics. However, the authors of a recent study stated that the relative importance of this uptake route is limited compared to other exposure pathways (Gouin et al. 2011). Nevertheless, according to some studies, the ingestion of plastics could play a significant role in the accumulation of contaminants by marine organisms.

In recent years, microplastics have received increasing attention because they are easily ingestible and thereby form a pathway for chemicals to enter organisms, including plankton species (Andrady 2011; Zarfl et al. 2011). As plankton species form the foundation of every food web, any threat to them can have serious effects. The transfer of contaminants within food webs is prevalent everywhere in the marine food web and may even affect nonmarine species such as polar bears (De Laender et al. 2011) and humans (Bocio et al. 2007).

4.4 Use of Plastic Debris by Marine Organisms

Floating natural debris, e.g., trunks from trees or volcanic rocks, have always provided a way for organisms to be transported around the world's oceans. However, because large amounts of plastics have been introduced into the marine environment during the last decades, an increase in marine rafting has been reported. Organisms like algae, mussels, covered with marine organisms have been found floating in the Pacific Ocean, and often wash ashore (Aliani and Molcard 2003; AMRF 2010). Most natural debris is heavy and driven by currents. In contrast, plastic rafts are light weight objects, and are often driven by wind when not totally submerged. Therefore, the species that attach themselves to these plastic items can travel in all directions to colonize new areas. In a study on hitch-hiking of organisms on floating debris, it was reported that an exotic barnacle (*Elminius modestus*) had attached itself to plastic debris found near the Shetland Islands (Barnes and Milner 2005). The incidence of anthropogenic debris more than doubled the rafting opportunities for organisms and is a serious threat to global biodiversity (Barnes 2002).

4.5 Conclusions

Entanglement and ingestion of plastics in plastic debris are the two main causes of mortality in marine organisms. Approximately 267 marine species are known to be affected by entanglement and/or ingestion. The number of affected species may be much higher, since many organisms live in areas remote from human activity. Marine mammals, turtles, and plunge-diving bird species suffer most from entanglement; they get stuck in nets, six-pack rings, or fishing lines and die from starvation, suffocation, or strangulation. For seal species, these harmful plastics often originate from local fisheries that exist in their foraging area. Seals and small whale species and turtles drown from entanglement in (ghost) nets or old fishing gear. The larger whale species drag nets with them, and then suffer from strangulation and starvation as the debris prohibits their ability to catch food.

Marine bird species and turtles are most affected by the ingestion of plastics. They mistake plastics for food and some selectively feed on plastic items. Most marine mammals accumulate plastics in their bodies by feeding on fish that have ingested plastic fragments. There are also cases of ingestion by whales, although the sample size is small for this species (as for other aquatic mammalian species), and often is only based on specimens that have accidentally washed ashore.

In addition to the physical impact of plastics, plastic debris in the marine environment can also leach chemical contaminants into the waters that are absorbed by marine species. Most plastics contain additives such as phthalates, bisphenol A, and BFRs, all of which can leach into the environment. Plastic debris is also known to adsorb contaminants from the surrounding water. Polymers often have an affinity for apolar molecules because they have hydrophobic surfaces. Contaminants leach from the plastics and, when ingested, may cause a variety of toxic effects. Recently, microplastics have received increasing attention because they are easily ingested and form a pathway for contaminants to enter organisms as small as plankton. This causes a threat to the basis of the marine food web and can have serious and far-reaching effects, even on nonmarine species such as humans.

5 Reduction, Prevention, and Clean-up of Plastic Debris in the Marine Environment

5.1 Introduction

Although plastic debris is one of the most widespread forms of marine pollution, it is also among the most soluble of all pollution problems that affect the world's oceans. Notwithstanding, the extent and impact of plastic debris in the marine environment is often underestimated, and therefore the prevention, reduction, and control of plastic debris require much more attention, both from governments and from manufacturers. Because of the nature of the plastic debris problem, a wide variety of approaches and strategies is needed to produce a significantly cleaner and safer marine environment (UNEP 2009a).

5.2 *Prevention*

The plastic debris problem in the marine environment results from the lack of global and regional strategies adequate to prevent the introduction of waste into the environment (UNEP 2009a). Only at the end of the 1960s and early 1970s were the first concerns expressed about accumulating plastic debris and its consequences for wildlife (Kenyon and Kridler 1969; Syrek 1975). Since then a number of countries have taken legislative measures at the national level to regulate the marine litter problem. Most importantly, the cooperation among countries has taken regulatory and preventive measures to an international level.

5.2.1 Legislation

MARPOL 73/78

In 1983, a United Nations agency, the International Maritime Organization (IMO), introduced the Marine Pollution (MARPOL) convention, an international protocol to prevent and reduce pollution from ships. The protocol is referred to as MARPOL 73/78, from the fact that the convention was signed in 1973 and the protocol was added in 1978. The protocol has been approved by 169 countries, which together are responsible for 98% of the world's total shipping transport by weight. The protocol consists of several measures attendant preventing pollution in the marine environment by ships. Annex V of MARPOL 73/78 regulates pollution by preventing ships to release garbage, and totally prohibits the disposal of plastics anywhere into the sea. Further, it obligates governments to keep terminal facilities and harbors clean of garbage. According to the terms of this agreement, every ship having a weight over 400 t and able to carry more than 14 persons is obligated to maintain a Garbage Record Book, in which records of all disposal operations will be kept. Information required includes the date, time, position of the ship, and description and estimated amounts of garbage that is incinerated or discharged. In addition to maintaining a Garbage Record Book, mariners are asked to prepare a Garbage Management Plan that gives procedures for collecting, storing, and processing onboard waste (IMO 2010).

The Regional Seas Programme

In 1974, the United Nations Environmental Programme (UNEP) initiated the Regional Seas Programme, which aimed to address the accelerating degradation of the world's oceans and coastal zones. The program seeks to create sustainable management and use of the marine and coastal environments by engaging involved countries and creating a plan of action. All Action Plans have a similar approach, but are shaped by each government according to their own needs and environmental challenges.

Today, the program covers 18 coastal and sea areas and has more than 140 participating countries (UNEP 2010). Nevertheless, the legislation is still widely ignored and it is estimated that ships dump 6.5 million tons of plastic into the world's oceans every year (UNEP 2009b). This flagrant disregard of the dumping rules questions whether this regulatory approach is adequate to deal with such a problem. Although this program may help over the long term, the current continuing extent of the plastic dumping problem demands drastic changes in mankind's behavior.

The Marine Strategy Framework Directive

The Marine Strategy Framework Directive (MSFD) introduced in Europe in July 2008 aims at achieving or maintaining a good environmental status (GES) by 2020 (MSFD 2011). This means that EU member states must develop action plans and activities to achieve this "GES." This includes a legislative framework that allows for managing human activities that have an impact on the marine environment, and also integrating concepts of environmental protection and sustainable use. The criteria and methodological standards on GES of marine waters have been set up by the MSFD and are based on existing obligations and developments within the EU legislation. However, some criteria are fully developed and operational while others require further refinement. Therefore, more scientific knowledge on the marine environment is required to develop a better understanding and achieve the Directive's goal (Zarfl et al. 2011).

5.2.2 Alternatives for Plastics

Another way to prevent the input of persistent plastics into the marine environment is to introduce biodegradable plastics. Biodegradable plastics are made of renewable sources, and consist of polymers that are capable of undergoing decomposition into carbon dioxide, water, methane, inorganic compounds, or biomass. Biodegradation of these polymers is achieved by the use of microorganisms that have the ability to catabolize these polymers into less environmentally harmful material (BioPlastics24 2010). The residue of degraded polymers is often used as plant fertilizer and these plants can serve as a new source for manufacturing biodegradable polymers. Recently, progress has been made in developing biodegradable plastics that possess characteristics similar to those of oil-based polymers (Song et al. 2009). Biodegradable plastics, or bioplastics, often have inferior performance compared to traditional plastics because they eventually become permeable to water. Therefore, bioplastic materials are used as disposable items, such as packaging material. The biodegradable polymers that are used are of diverse types. Bioplastics that are based on polylactic acid (PLA) and Plastarch material (PSM) are two of the most commonly used ones in current commercial practice.

Polylactic Acid

PLA is made from starch-rich substances like maize, wheat, or sugar. The bioplastic made from PLA is biodegradable and can, under ideal composting conditions, degrade in less than 60 days. PLA was discovered in 1890, but has only recently entered the market as a biodegradable plastic. Today, PLA is still more expensive to produce than are many traditional plastics, but the price is decreasing as the demand for bioplastics increases (BioPlastics24 2010).

Plastarch Material

PSM is a thermoplastic polymer composed of starch, from corn, that is combined with other biodegradable materials. PSM is one of the few plastics that can withstand high temperatures (up to 125°C). Apart from the fact that it is biodegradable, the material has similar characteristics to those of polyethylene. After serving its useful life, PSM can be incinerated to produce both a nontoxic smoke and a residue that can be used as a plant fertilizer (BioPlastics24 2010).

Bioplastics are renewable and are easily degradable. Although they have existed for as long as traditional oil-based plastics, the market for them is now expanding as a direct result of the high price of oil. There are only a few producers of bioplastic products. NatureWorks LLC is the largest producer of PLA in the world. They use corn to create PLA food packaging, bottles, and shirts. The Indian company Earthsoul uses the biodegradable polymer Master-Bi to produce various products, although they are focused primarily on products for agriculture. In 2002, the US Department of Agriculture (USDA) found a way to use animal waste for bioplastic production. They used the protein in chicken feathers from poultry production as a building block to make plastic. These feather-derived plastics have high strength and are fully biodegradable (USDA 2009). Sony is one of the giants of electronic production that uses NatureWorks' PLA plastic for their famous Walkman®; moreover, the packaging for their Playstation is made from extendable polystyrene, which is recycled from orange peels (JapanFS 2009). Another company, NEC Electronics, has produced a biodegradable mobile phone, which will biodegrade if buried in soil, and importantly, it does not form toxic gasses when burnt. NEC electronics is also developing a biodegradable laptop computer casing that utilizes PLA, with fibers added to improve strength and heat resistance (Bio-Plastic 2009).

5.3 Recycling

Recycled polymeric materials can be reused, which saves production energy and prevents the dumping of materials into the environment. During the last decade, the mechanical recycling industries have showed an encouraging trend, i.e., a 7% annual growth in western Europe (Thompson et al. 2009a). Unfortunately, the recycling rate varies regionally and globally, and only a small percentage of total plastic waste is

Table 3 Plastics production, recovery and disposal in the USA in 2005 (thousands of metric tons) for polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and other plastics

Plastic type	Generation of plastics in municipal solid waste	Recovery	Discards
PET	2,600	491	2,109
HDPE	53.55	473	4,882
PVC	1,491	0	1,491
LDPE	5,864	173	5,691
PP	3,636	9	3,681
PS	2,355	0	2,355
Other	4,982	355	4,981
Total	26,282	1,500	24,782

Data show that only a small proportion of plastics is being recycled. Plastic material from construction and agricultural sectors are not included (Reprinted with permission from Barnes et al. (2009))

currently being recycled (Table 3). In most countries, the form of plastic that are recycled is largely limited to bottles and drink containers (Barnes et al. 2009). Most consumers are keen to recycle, and support for recycling is often very high in most western countries. However, the difference in symbols (SPI Resin Identification Code) printed on different forms of plastic to describe recyclability of the object vary considerably among countries or regions, and is often an obstacle to convenient recycling. This is why, in most countries, all kinds of plastic waste is collected together and is sorted at special stations before being recycled.

Plastic waste often consists of a mixture of different types of plastics, which makes it difficult for recyclers to work with; this problem is caused, in part, because manufacturers and recyclers neither communicate, nor make agreements. The recycling of plastic items is therefore more difficult than the recycling of paper or glass (i.e., three types only—transparent, green, or brown). For example, plastic drinking bottles may consist of a HDPE body, fitted with a polypropylene cap and a steel ring. The variation of forms or components that compose plastic items can be limitless. Therefore, most recyclers collect all kinds of plastics together, melt it down or grind it up and turn it into a new plastic product.

Tie-Tek LLC is a company that produces railroad ties from vehicle tires, plastic bottles, and plastic bags. One mile of railroad made from these ties (3,300 ties) is composed of the equivalent of nine million plastic bags, two million plastic bottles, and 10,000 vehicle tires. Agri-Plas is another recycling company that collects agricultural plastics and turns them into new plastic items for use in agricultural; hence, the plastics from this company form a circle of production and recycling that is continuous.

5.4 Clean-up

Efforts to render new plastics more environmentally friendly, or legislation to reduce persistent polymer input into the environment do not address the burdens of plastic debris that are already present in our oceans. The clean-up of existing marine debris often falls to local authorities, nongovernmental organizations, and to volunteers. Clean-up costs can be very high, and great efforts are required to motivate a sufficient number of people to assist in clean-up efforts. For example, the Korean government recently removed derelict fishing gear from the deep seabed of the East Sea by bottom trawling with heavy hooks (50–80 kg) and ropes. A total of 207.8 and 252.2 ton of marine debris was removed from the seabed in 2009 and 2010, respectively; most of the debris was comprised of derelict fishing gear. The total cost of this 2-year project was $ US2.3 million. The use of bottom trawls is dangerous because they are performed by fishing vessels during closed seasons, when the weather is often stormy and typhoons occur. Such clean-up projects have already led to the loss of one ship and five crew members in 2009 (Cho 2011).

There are many projects that aim to prevent, control, or clean-up marine debris. In addition to debris clean-up, most projects also endeavor to educate the community on the importance of reducing marine pollution. Such education includes distributing brochures or giving lectures at local schools. The effort to educate school age children is important because it instills good habits, and establishes a basis for these children to spread their knowledge to others. In addition, there are some projects that go further, by organizing local or general clean-up of marine debris.

One of the largest organizations in Europe that has an international scope, and deals with marine pollution is Kommunenes Internasjonale Miljøorganisasjon (KIMO). KIMO has the aim of contributing to a steady reduction of marine pollution in Europe's seas. One of their projects is called "Fishing for Litter." This project provides fishing boats with large bags for use in the disposal of marine-sourced debris. When full, these bags are collected for disposal. The Fishing for Litter project has successfully removed debris from the sea and has reduced the volume of debris that is washed ashore. Another environmental program is called Clean Up the World. Clean Up the World is held in conjunction with UNEP, and mobilizes 35 million volunteers from 120 countries to positively improve local environments. They organize activities such as the clean-up of coastal areas, education campaigns for local populations and tree planting. The organization Provincetown Centre for Coastal Studies (PCCS) monitors the abundance of whale entanglements in the Atlantic coastal waters of the USA and Canada. In addition to monitoring programs, the organization is also focused on the removal of entangling material from whales.

5.5 Conclusions

The most effective and efficient response to the plastic debris problem in the marine environment is to ban the input of plastics into the oceans. Therefore, several different prevention measures have been implemented. These include (1) legislation that obligates consumers to pay attention to the waste they generate and (2) the introduction and use of alternatives such as biodegradable plastics. Recycling is another option to reduce input of plastics to the marine environment. It not only prevents the discard of plastics, but also saves material and energy. Removal of the current bulk of plastic debris that is present in the oceans is also needed. Many environmental organizations contribute to this, or have produced action plans to clean beaches and other coastal areas of plastic debris. These organizations also are capable of contributing to the education of communities by drawing inhabitant's attention to the plight marine species face as a result of plastic debris. Education is particularly important, because it is the basis for teaching the next generation to be aware of and address the consequences of discarding plastics and other debris into the world's oceans.

6 Summary

Plastics are cheap, strong, and durable and offer considerable benefits to humanity. They potentially can enhance the benefits that both medical and scientific technology will bestow to humankind. However, it has now been several decades since the use of plastics exploded, and we have evidence that our current approach to production, use, transport, and disposal of plastic materials has caused, and is still causing serious effects on wildlife, and is not sustainable.

Because of frequent inappropriate waste management practices, or irresponsible human behavior, large masses of plastic items have been released into the environment, and thereby have entered the world's oceans. Moreover, this process continues, and in some places is even increasing. Most plastic debris that now exists in the marine environment originated from ocean-based sources such as the fishing industry. Plastics accumulate in coastal areas, at the ocean surface and on the seabed. Because 70% of all plastics are known to eventually sink, it is suspected that ever increasing amounts of plastic items are accumulating in seabed sediments. Plastics do not biodegrade, although, under the influence of solar UV radiation, plastics do degrade and fragment into small particles, termed microplastics. Our oceans eventually serve as a sink for these small plastic particles and in one estimate, it is thought that 200,000 microplastics per km^2 of the ocean's surface commonly exist.

The impact of plastic debris has been studied since the beginning of the 1960s. To date, more than 267 species in the marine environment are known to have been affected by plastic entanglement or ingestion. Marine mammals are among those species that are most affected by entanglement in plastic debris. By contrast, marine birds suffer the most from ingestion of plastics. Organisms can also be seriously affected from contact with plastics-associated contaminants. Such contaminants are absorbed by floating plastic debris, or the contaminants may derive from plastic additives that are leached to the environment. Recent studies emphasize the important role of microplastics as they are easily ingestible by small organisms, such as plankton species, and form a pathway for contaminants to enter the food web. Contaminants leached from plastics tend to bioaccumulate in those organisms that absorb them, and chemical concentrations are often higher at higher trophic levels. This causes a threat to the basis of every food web and can have serious and far-reaching effects, even on nonmarine species such as polar bears and humans, who consume marine-grown food. Therefore, resolving the plastic debris problem is important to human kind for two reasons: we are both creator, and victim of the plastic pollution problem.

Solutions to the plastic debris problem can only be achieved through a combination of actions. Such actions include the following: Legislation against marine pollution by plastics must be enforced, recycling must be accentuated, alternatives (biodegradable) to current plastic products must be found, and clean-up of debris must proceed, if the marine plastic pollution problem is to eventually be resolved. Governments cannot accomplish this task on their own, and will need help and initiative from the public. Moreover, resolving this long-standing problem will require time, money, and energy from many individuals now living and those of future generations, if a safer and cleaner marine environment is to be achieved.

Acknowledgements We would like to thank Salko de Wolf and Dirk Bruin for providing some very useful photos.

References

ACC (2010) How is plastic made? American Chemistry Council, Plastics Division, the Chlorine Chemistry Division, and the Chemical Products and Technology Division

Aliani S, Molcard A (2003) Hitch-Hiking on floating marine debris: macrobenthic species in the Western Mediterranean Sea. Hydrobiologia 503(1):59–67

Allsopp M, Walters A, Santillo D, Johnston P (2007) Plastic debris in the World's oceans, Greenpeace

AMRF (2010) The Algalita Marine Research Foundation. http://www.algalita.org/

Andrady AL, Pegram JE, Tropsha Y (1993) Changes in carbonyl index and average molecular weight on embrittlement of enhanced-photodegradable polyethylenes. J Polym Environ 1(3):171–179

Andrady AL (1994) Assessment of environmental biodegradation of synthetic polymers. J Macromol Sci, Part C: Polym Rev 34(1):25–76

Andrady AL, Hamid SH, Hu X, Torikai A (1998) Effects of increased solar ultraviolet radiation on materials. J Photochem Photobiol B: Biol 46(1–3):96–103

Andrady AL (2003) Plastics and the Environment, Wiley, New York

Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62(8):1596–1605

Baird RW, Hooker SK (2000) Ingestion of plastic and unusual prey by a juvenile harbour porpoise. Mar Pollut Bull 40(8):719–720

Barnes DKA (2002) Biodiversity: invasions by marine life on plastic debris. Nature 416(6883): 808–809

Barnes DKA, Milner P (2005) Drifting plastic and its consequences for sessile organism dispersal in the atlantic ocean. Mar Biol 146(4):815–825

Barnes KA, Galgani F, Thompson RC, Barlaz M (2009) Accumulation and fragmentation of plastic debris in global environments. Philos Trans Royal Soc Lond B: Biol Sci 364(1526): 1985–1998

Beall G (2009) By Design: World War II, Plastics, and Npe. http://www.plasticstoday.com/imm/articles/design-world-war-ii-plastics-and-npe

Bio-Plastic (2009) Development of Kenaf fiber-reinforced bioplastic for mobile phones. http://www.bioplastic-product.com/?p=369

BioPlastics24 (2010) …How Plastics Are Made from Plants! http://www.bioplastics24.com/index.php

Bocio A, Domingo JL, Falcó G, Llobet JM (2007) Concentrations of Pcdd/Pcdfs and Pcbs in Fish and Seafood from the Catalan (Spain) market: estimated human intake. Environ Int 33(2): 170–175

Bruin D (2004) Aanspoelen Bultrug Op De Vliehors. Vlieland, The Netherlands

Bugoni L, Krause L, Virgínia Petry M (2001) Marine debris and human impacts on sea turtles in Southern Brazil. Mar Pollut Bull 42(12):1330–1334

Camphuysen K (2001) Northern Gannets *Morus Bassanus* found dead in the Netherlands, 1970–2000. Dutch Seabird Group, Netherlands Institute for Sea Research (NIOZ)

Carson HS, Colbert SL, Kaylor MJ, McDermid KJ (2011) Small plastic debris changes water movement and heat transfer through beach sediments. Mar Pollut Bull 62(8):1708–1713

CGNP (2009) Carpentaria Ghost Nets Programme. www.ghostnets.com.au

Cheshire AC, Adler E, Barbière J, Cohen Y, Evans S, Jarayabhand S, Jeftic L, Jung RT, Kinsey S, Kusui ET, Lavine I, Manyara P, Oosterbaan L, Pereira MA, Sheavly S, Tkalin A, Aradarajan S, Wenneker B, Westphalen G (2009). Unep/Ioc guidelines on survey and monitoring of marine litter, UNEP regional seas reports and studies. Vol. IOC Technical Series No. 83+ 120

Cho D-O (2011) Removing derelict fishing gear from the deep seabed of the East Sea. Mar Policy 35(5):610–614

Claessens M, Meester SD, Landuyt LV, Clerck KD, and Janssen CR (2011) Occurrence and distribution of microplastics in marine sediments along the Belgian Coast. Mar Pollut Bull 62(10): 2199–2204

Cliff G, Dudley S, Ryan PG, Singleton N (2002) Large sharks and plastic debris in Kwazulu-Natal, South Africa. Mar Freshw Res 53:575–581

Coyne MS (1994) Feeding ecology of subadult green sea turtles in South Texas waters, University of Florida

Darnerud PO (2003) Toxic effects of brominated flame retardants in man and in wildlife. Environ Int 29(6):841–853

Davison P, Asch RG (2011) Plastic ingestion by mesopelagic fishes in the north pacific subtropical gyre. Mar Ecol Prog Ser 432:173–180

De Laender F, Hammer J, Hendriks AJ, Soetaert K, Janssen CR (2011) Combining monitoring data and modeling identifies PAHs as emerging contaminants in the Arctic. Environ Sci Technol 45(20):9024–9029

De Vleet (2010) Zee in Zicht. http://www.zeeinzicht.nl/vleet

De Wolf S (2008) Zeehond Met Zwerfvuil. www.salkodewolf.nl

Denuncio P, Bastida R, Dassis M, Giardino G, Gerpe M, Rodríguez D (2011) Plastic ingestion in Franciscana Dolphins, Pontoporia Blainvillei (Gervais and D'orbigny, 1844), from Argentina. Mar Pollut Bull 62(8):1836–1841

Derraik JGB (2002) The pollution of the marine environment by plastic debris: a review. Mar Pollut Bull 44(9):842–852

Diamanti-Kandarakis E (2009) Endocrine-disrupting chemicals: an endocrine society scientific statement. Endocr Rev 30(4):293–342

Ebbesmeyer CC, Ingraham WJ (1994) Pacific toy spill fuels ocean current pathways research. Eos Trans AGU 75(37):425

Ebewele RO (2000) Polymer science and technology, 2nd edn. Prentice Hall College Div, Upper Saddle River, NJ

Edyvane KS, Dalgetty A, Hone PW, Higham JS, Wace NM (2004) Long-term marine litter monitoring in the remote Great Australian Bight, South Australia. Mar Pollut Bull 48(11–12): 1060–1075

EPA (1993) Plastic pellets in the aquatic environment, sources and recommendations. Washington, DC, United States Environmental Protection Agency Oceans and Coastal Protection Division, Marine Debris Section: 130

EPA (2008) Municipal solid waste generation, recycling and disposal in the United States: facts and figures for 2008, United States Environmental Protection Agency

EPA (2010) Hudson River Pcbs. U.S. Environmental Protection Agency. http://www.epa.gov/hudson/background.htm

Eriksson C, Burton H (2003) Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. AMBIO: J Human Environ 32(6):380–384
FDA (2010) Update on bisphenol a for use in food contact applications. http://www.fda.gov/newsevents/publichealthfocus/ucm197739.htm
Fendall LS, Sewell MA (2009) Contributing to marine pollution by washing your face: microplastics in facial cleansers. Mar Pollut Bull 58(8):1225–1228
Galgani F, Lecornu F (2004) Debris on the Sea Floor at Hausgarten: In the Expedition Arktis Xix/3 of the Research Vessel Polarstern in 2003. Berichte Polar, Meeresforsch, 488
Gioia R, Nizzetto L, Lohmann R, Dachs J, Temme C, Jones KC (2008) Polychlorinated biphenyls (Pcbs) in air and seawater of the Atlantic Ocean: sources, trends and processes. Environ Sci Technol 42(5):1416–1422
Gouin T, Roche N, Lohmann R, Hodges G (2011) A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. Environ Sci Techno 45(4): 1466–1472
Gregory MR (1978) Accumulation and distribution of virgin plastic granules on New Zealand beaches. N Z J Mar Freshw Res 12:399–414
Gregory MR (1996) Plastic 'scrubbers' in hand cleansers: a further (and minor) source for marine pollution identified. Mar Pollut Bull 32(12):867–871
Groot R (2009) Amsterdam bakelite collection. http://www.amsterdambakelitecollection.com/history.php
Gustafsson K, Björk M, Burreau S, Gilek M (1999) Bioaccumulation kinetics of brominated flame retardants (polybrominated diphenyl ethers) in Blue Mussels (*Mytilus Edulis*). Environ Tox Chem 18:1218–1224
Hale RC, La Guardia MJ, Harvey E, Matt Mainor T (2002) Potential role of fire retardant-treated polyurethane foam as a source of brominated diphenyl ethers to the US environment. Chemosphere 46(5):729–735
Hamidi SHHA (2000) Handbook of polymer degradation. CRC, Boca Raton, FL
Hanni KD, Pyle P (2000) Entanglement of pinnipeds in synthetic materials at South-East Farallon Island, California, 1976–1998. Mar Pollut Bull 40(12):1076–1081
Hosler D, Burkett SL, Tarkanian MJ (1999) Prehistoric polymers: rubber processing in ancient Mesoamerica. Science 284(5422):1988–1991
Hoss DE, Settle LR (eds) (1990) Ingestion of plastics by teleost fishes. Proceedings of the second international conference on marine debris. Honolulu, Hawaii
IMO (2010) International convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating Thereto (Marpol). http://www.imo.org/Conventions/contents.asp?doc_id=678&topic_id=258#garbage
IPW (2010) International pellet watch. http://www.pelletwatch.org
ISL (2009) Institute of Shipping Economics and Logistics. http://www.isl.org
Japan FS (2009) Sony Launches Veggie-Based Plastic "Walkman." http://www.japanfs.org/en/pages/025157.html
Johnson S, Kenney R, Kraus L, Clapham (2005) Fishing gear involved in entanglements of right and humpback whales. ROYAUME-UNI, Blackwell, Oxford
Katsanevakis S, Katsarou A (2004) Influences on the distribution of marine debris on the seafloor of shallow coastal areas in Greece (Eastern Mediterranean). Water Air Soil Pollut 159(1): 325–337
Kenyon KW, Kridler E (1969) Laysan albatrosses swallow indigestible matter. Auk 86:339–343
KIMO (2010) Fishing for Litter, Kommunenes Internasjonale Miljoorganisasjon, Local Authorities International Environmental Organisation
Koch HM, Calafat AM (2009) Human body burdens of chemicals used in plastic manufacture. Philos Trans Royal Soc B: Biol Sci 364(1526):2063–2078
Laist DW (1997) Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe JM, Rogers DB (eds) Marine debris: sources, impacts, and solutions. Springer Series on Environmental Management, pp 99–139

Law KL, Morét-Ferguson S, Maximenko NA, Proskurowski G, Peacock EE, Hafner J, Reddy CM (2010) Plastic accumulation in the North Atlantic Subtropical Gyre. Science 329(5996): 1185–1188

Legler J (2008) New insights into the endocrine disrupting effects of brominated flame retardants. Chemosphere 73(2):216–222

Liddell HG, Scott R, Jones HS, Barber EA (1968) A Greek-English Lexicon compiled by Henry George Liddell and Robert Scott. The Clarendon, London

Mallory M, Robertston G, Moenting A (2006) Marine plastic debris in Northern Fulmars from Davis Strait, Nunavut. Oxford, ROYAUME-UNI, Elsevier, Canada

Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, Kaminuma T (2000) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ Sci Technol 35(2):318–324

Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, Kaminuma T (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ Sci Technol 35(2):318–324

McIlgorm A, Campbell HF, Rule MJ (2011) The economic cost and control of marine debris damage in the Asia-Pacific region. Ocean Coastal Manage 54(9):643–651

Moore CJ, Leecaster MK, Moore SL, Weisberg SB (2001) A Comparison of plastic and plankton in the North Pacific Central Gyre. Mar Pollut Bull 42(12):1297–1300

Moore CJ, Lattin GL, Zellers AF (2005) Density of plastic particles found in zooplankton trawls from coastal waters of California to the North Pacific Central Gyre, Algalita Marine Research Foundation

Moore CJ, Lattin GL, Zellers AF (2011) Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. J Integrated Coastal Zone Manage 11(1):65–73

Morris PJT (1986) Polymer pioneers: a popular history of the science and technology of large molecules. Philadelphia, Center for history of chemistry polymer project

Moser ML, Lee DS (1992) A fourteen-year survey of plastic ingestion by Western North Atlantic Seabirds. Colon Waterbirds 15(1):83–94

MSFD (2011) Marine strategy framework directive. http://ec.europa.eu/environment/water/marine/ges.htm

Nadal A, Alonso-Magdalena P, Soriano S, Quesada I, Ropero AB (2009) The pancreatic [beta]-cell as a target of estrogens and xenoestrogens: implications for blood glucose homeostasis and diabetes. Mol Cell Endocrinol 304(1–2):63–68

Ng KL, Obbard JP (2006) Prevalence of microplastics in Singapore's coastal marine environment. Mar Pollut Bull 52(7):761–767

O'Hara K, Iudicello S, Bierce R (1988) A citizen's guide to plastics in the ocean: more than a litter problem. Center for Marine Conservation, Washington, DC

Oehlmann J, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk KO, Wollenberger L, Santos EM, Paull GC, Van Look KJW, Tyler CR (2009) A critical analysis of the biological impacts of plasticizers on wildlife. Philos Trans Royal Soc B: Biol Sci 364(1526):2047–2062

Ogata Y, Takada H, Mizukawa K, Hirai H, Iwasa S, Endo S, Mato Y, Saha M, Okuda K, Nakashima A, Murakami M, Zurcher N, Booyatumanondo R, Zakaria MP, Dung LQ, Gordon M, Miguez C, Suzuki S, Moore C, Karapanagioti HK, Weerts S, McClurg T, Burres E, Smith W, Velkenburg MV, Lang JS, Lang RC, Laursen D, Danner B, Stewardson N, Thompson RC (2009) International pellet watch: global monitoring of persistent organic pollutants (Pops) in coastal waters. 1. Initial phase data on Pcbs, Ddts, and Hchs. Mar Pollut Bull 58(10):1437–1446

Omori K, Guo X, Yoshie N, Fujii N, Handoh IC, Isobe A, Tanabe S (2011) Toxic metals in polyethylene plastic litter. TERRAPUB interdisciplinary studies on environmental chemistry (Marine Environmental Modeling & Analysis) pp 271–277

Orós T, Calabuig P, Déniz S (2005) Diseases and causes of mortality among sea turtles stranded in the Canary Islands, Spain (1998–2001). Dis Aquat Organ 63:13–24

OSPAR (2008) Background document for the Ecoqo on plastic particles in stomachs of seabirds, Biodiversity Series, London. OSPAR Commission, 18 pp

PackagingToday (2009) An introduction to the history of plastics. http://www.packagingtoday.com/

Page B, McKenzie J, McIntosh R, Baylis A, Morrissey A, Calvert N, Haase T, Berris M, Dowie D, Shaughnessy PD, Goldsworthy SD (2004) Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after government and industry attempts to reduce the problem. Mar Pollut Bull 49(1–2):33–42

PCCS (2010) The centre for coastal studies. http://www.coastalstudies.org

PEMRG (2010) Plastics – the facts 2010: an analysis of European plastics production, demand and recovery for 2009, PlasticsEurope Market Research Group

PEMRG (2011) Plastics – the facts 2011: an analysis of European plastics production, demand and recovery for 2010, PlasticsEurope Market Research Group

Randall JE (1992) Review of the biology of the tiger shark (Galeocerdo Cuvier). Aust J Mar Freshwater Res 1992(43):21–31

Robarts MK, Piatt JF, Wohl KD (1995) increasing frequency of plastic particles ingested by seabirds in the Subarctic North Pacific. ROYAUME-UNI, Elsevier, Oxford

Ross JB, Parker R, Strickland M (1991) A survey of shoreline litter in Halifax Harbour 1989. Mar Pollut Bull 22(5):245–248

Ryan PG, Conella AD, Gardner BD (1988) Plastic ingestion and Pcbs in seabirds: is there a relationship? Mar Pollut Bull 19(4):174–176

Ryan PG, Moore CJ, van Franeker JA, Moloney CL (2009) Monitoring the abundance of plastic debris in the marine environment. Philos Trans Royal Soc B: Biol Sci 364(1526):1999–2012

Sajiki J, Yonekubo J (2003) Leaching of bisphenol a (Bpa) to seawater from polycarbonate plastic and its degradation by reactive oxygen species. Chemosphere 51(1):55–62

Santos I, Friedrich A, Ivar do Sul J (2009) Marine debris contamination along undeveloped tropical beaches from Northeast Brazil. Environ Monit Assess 148(1):455–462

Sax L (2009) Polyethylene terephthalate may yield endocrine disruptors. Environ Health Perspect 118:445–448

Schrey E, Vauk GJM (1987) Records of Entangled Gannets (Sula Bassana) at Helgoland, German Bight. Mar Pollut Bull 18(6 (Suppl 2)):350–352

Shaw DG, Day RH (1994) Colour- and Form-Dependent Loss of Plastic Micro-Debris from the North Pacific Ocean. ROYAUME-UNI, Elsevier, Oxford

Sheavly SB (2005) Marine debris - an overview of a critical issue for our oceans. Sixth meeting of the UN open-ended informal consultative processes on oceans & the Law of the sea

Sivan A (2011) New perspectives in plastic biodegradation. Curr Opin Biotechnol 22(3):422–426

Song JH, Murphy RJ, Narayan R, Davies GBH (2009) Biodegradable and compostable alternatives to conventional plastics. Philos Trans Royal Soc B: Biol Sci 364(1526):2127–2139

Stefatos A, Charalampakis M, Papatheodorou G, Ferentinos G (1999) Marine debris on the seafloor of the mediterranean sea: examples from two enclosed gulfs in Western Greece. Mar Pollut Bull 38(5):389–393

Syrek D (1975) California litter: a comprehensive analysis and plan for abatement. The Institute for Applied Research, Sacramento, CA

Takeuchi I, Miyoshi N, Mizukawa K, Takada H, Ikemoto T, Omori K, Tsuchiya K (2009) Biomagnification profiles of polycyclic aromatic hydrocarbons, alkylphenols and polychlorinated biphenyls in Tokyo Bay elucidated by [Delta]13c and [Delta]15n isotope ratios as guides to Trophic web structure. Mar Pollut Bull 58(5):663–671

Teuten EL, Saquing JM, Knappe DRU, Barlaz MA, Jonsson S, Björn A, Rowland SJ, Thompson RC, Galloway TS, Yamashita R, Ochi D, Watanuki Y, Moore C, Viet PH, Tana TS, Prudente M, Boonyatumanond R, Zakaria MP, Akkhavong K, Ogata Y, Hirai H, Iwasa S, Mizukawa K, Hagino Y, Imamura A, Saha M, Takada H (2009) Transport and release of chemicals from plastics to the environment and to wildlife. Philos Trans Royal Soc B: Biol Sci 364(1526):2027–2045

Thompson RC, Moore CJ, vom Saal FS, Swan SH (2009a) Plastics, the environment and human health: current consensus and future trends. Philos Trans Royal Soc B: Biol Sci 364(1526):2153–2166

Thompson RC, Swan SH, Moore CJ, vom Saal FS (2009b) Our plastic age. Philos Trans Royal Soc B: Biol Sci 364(1526):1973–1976

Tomás J, Guitart R, Mateo R, Raga JA (2002) Marine debris ingestion in Loggerhead Sea Turtles, Caretta Caretta, from the Western Mediterranean. Mar Pollut Bull 44(3):211–216

Tomy GT, Pleskach K, Arsenault G, Potter D, McCrindle R, Marvin CH, Sverko E, Tittlemier S (2008) Identilication of the novel cycloaliphatic brominated flame retardant 1,2-dibromo-4-(1,2-dibromoethyl)cyclohexane in Canadian Arctic Beluga (*Delphinapterus Leucas*). Environ Sci Technol 42:543–549

UNEP (2001) Marine litter - trash that kills, United Nations Environment Programme

UNEP (2005) Marine litter, an analytical overview. United Nations Environment Programme, Nairobi

UNEP (2009a) Marine Litter: A Global Challenge. United Nations Environment Programme, Nairobi, 232

UNEP (2009b) Abandoned, lost or otherwise discarded fishing gear. United Nations Environment Programme, Food and Agriculture Organization of the United Nations, Rome

UNEP (2010) United Nations Environmental Programme, the Regional Seas Programme. http://www.unep.org/regionalseas/

USDA (2009) Biodegradable plastic derived from feathers. http://www.ars.usda.gov/is/pr/2009/090908.htm

Van Franeker JA (1985) Plastic ingestion in the North Atlantic Fulmar. Mar Pollut Bull 16(9): 367–369

Van Franeker JA, Meijboom A (2002) Marine litter monitoring by Northern Fulmars (a pilot study). Wageningen, Alterra, Alterra-rapport 401, 72 pp

Van Franeker JA, Blaize C, Danielsen J, Fairclough K, Gollan J, Guse N, Hansen P-L, Heubeck M, Jensen J-K, Le Guillou G, Olsen B, Olsen K-O, Pedersen J, Stienen EWM, Turner DM (2011) Monitoring plastic ingestion by the Northern Fulmar Fulmarus Glacialis in the North Sea. Environ Pollut 159(10):2609–2615

Walker WA, Coe JM. (eds.) (1989) Survey of marine debris ingestion by odontocete cetaceans. Proceedings of the second international conference on marine debris. Honolulu, Hawaii

Yamamoto T, Yasuhara A (1999) Quantities of bisphenol a leached from plastic waste samples. Chemosphere 38(11):2569–2576

Yamashita R, Tanimura A (2007) Floating plastic in the kuroshio current area, Western North Pacific Ocean. Mar Pollut Bull 54(4):485–488

Zarfl C, Matthies M (2010) Are marine plastic particles transport vectors for organic pollutants to the arctic? Mar Pollut Bull 60(10):1810–1814

Zarfl C, Fleet D, Fries E, Galgani F, Gerdts G, Hanke G, Matthies M (2011) Microplastics in oceans. Mar Pollut Bull 62(8):1589–1591