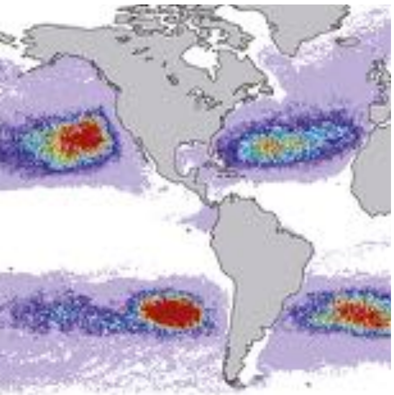
Plastic Debris in the Ocean

The Characterization of Marine Plastics and their Environmental Impacts, Situation Analysis Report

Florian Thevenon, Chris Carroll and João Sousa (editors)



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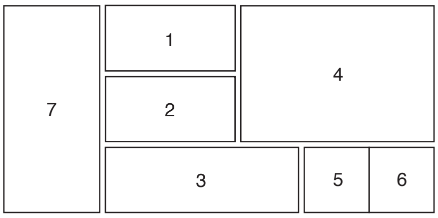

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Fishermen in India © Florian Thevenon.

FOREWORDS

The present report, conducted by the Global Marine and Polar Programme of the International Union for the Conservation of Nature (IUCN) within the framework of the "Action for an Ocean Free of Microplastics" project, with the participation of the Race for Water Foundation and the support of Svenska Postkodlotteriet, aims to provide to economic actors, policy makers and the public at large, a comprehensive overview of the current state of knowledge of the effects of plastics on marine environments, organisms and ecosystems.

As recently evidenced by scientific research investigations, there is an urgent need to increase public awareness about the adverse effects of plastic pollution on marine organisms, to foster a sense of individual responsibility and to encourage government action and public initiatives for a reduction of the most severe impacts. The implementation of action plans to reduce the input of marine plastic around the world needs to involve different stakeholders from the plastic, tourism and fishing industries, the research community, NGOs, local authorities and national governments. Only this way can socio-economic and environmental issues resulting from plastic pollution be effectively and globally addressed.

The awareness of this growing threat to individual marine organisms, species and ecosystems is now recognized by the international community as one of the main priority issues for the protection of the marine environment in the forthcoming years. With the present report, the IUCN Global Marine and Polar Programme aims to address its partner and member organizations' need to have up-to-date and reliable information about this issue, and to build a coalition to raise awareness and identify policy options.

Carl Gustaf Lundin

Director, IUCN Global Marine and Polar Programme

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The authors of this report would like to thank Felippe de Alencastro (Ecole Polytechnique Fédérale de Lausanne, EPFL), François Galgani (Institut Français de Recherche pour l'Exploitation de la Mer, IFREMER) and Pascal Hagmann (OceanEye) for their constructive comments and advice concerning the extent of the plastic pollution and the related toxicological impacts. These reviewers are also gratefully acknowledged for sharing their knowledge about the sampling, sorting and analysis of the microplastics found in aquatic environments. François Simard (IUCN) is acknowledged for his support and stimulating discussions during the compilation of the report. Helen Fox and Sylvie Rockel (IUCN) reviewed a draft of this report and their comments for improving the text are gratefully acknowledged. Special thanks to Fabiano Prado Barretto (Global Garbage) for support with recent scientific literature on marine plastics and for photos of marine litter in Brazil. For images, we also thank the Algalita Marine Research Foundation (AMRF) and the National Oceanic and Atmospheric Administration (NOAA).

ABBREVIATIONS, ACRONYMS AND UNITS USED

BPA	bisphenol A	PCB	polychlorinated biphenyls
DDT	dichlorodiphenyltrichloroethane	PE	polyethylene
H_2O_2	Hydrogen peroxide	PET	polyethylene terephtalate
km	kilometre	POP	persistent organic pollutant
m	metre	PP	polypropylene
m^2	square metre	PS	polystyrene
mm	millimetre	PVC	polyvinyl chloride
NaCl	sodium chloride	SEM	Scanning Electron Microscopy
PAH	polycyclic aromatic hydrocarbons	μm	micrometre

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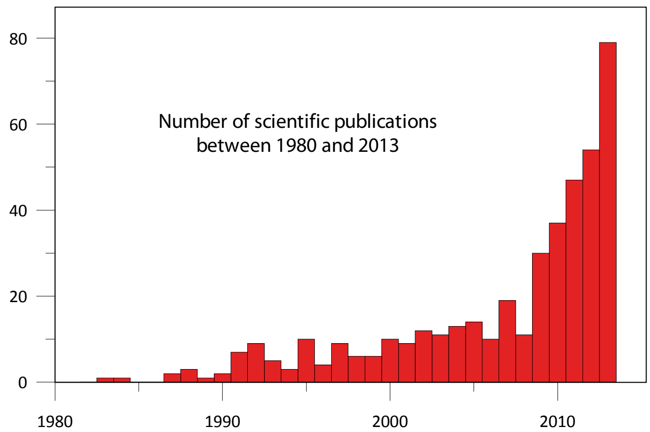
ABSTRACT

Plastic debris has now become the most serious problem affecting the marine environment, not only for coastal areas of developing countries that lack appropriate waste management infrastructures, but also for the world's oceans as a whole because slowly degrading large plastic items generate microplastic (particles smaller than 1 to 5 mm) particles which spread over long distances by wind-driven ocean surface layer circulation.

Growing scientific and public awareness is fuelling global concern regarding the impact of plastic ingested by marine species and the accumulation of plastics in coastal and remote areas of oceans (in trash vortexes or gyres). Private and public initiatives, such as the volunteer beach cleanups and campaigns for removing beach debris, represent the major source of information concerning the amounts and types of marine litter. The regular cleaning by municipalities and public authorities to maintain beaches attractive to tourists engenders major economic costs.

It is now well recognized that drifting plastic debris has several adverse effects on marine species and ecosystems. However, there is still a lack of precise knowledge about the quantity, sources, transport, accumulation and fate of plastics in the oceans. The most visible and disturbing impact of marine plastic pollution is the ingestion, suffocation and entanglement of hundreds of marine species. Floating plastics, which are presently the most abundant items of marine litter, also contribute considerably to the transport of non-indigenous (alien) marine species thereby threatening marine biodiversity and the food web. These floating particles accumulate toxic pollutants on their surface during their long-residence time in polluted seawater and can therefore represent a concentrated source of environmental pollution, or serve as a vector for toxic pollutants that accumulate in the food webs (bio-accumulation of contaminants).

The globally emerging environmental, economic and health risks related to plastic pollution require immediate international attention. It is time to take regional- and global-level actions against the entry of plastics into the ocean. There is also an urgent need to monitor the type and quantity of marine plastics using standardized methodologies as well as to better assess the impacts of plastic pollution on marine environments, species and ecosystems. Environmental monitoring data will help to set up local and global action programmes that need to be effective from a long-term perspective so as to reduce the entry of marine plastic litter and their redistribution within the world's oceans.



This figure shows the increasing number of scientific publications during the last decade dedicated to the impacts of marine plastic debris. In 2013, 79 peer-review articles containing the words marine, plastic, and debris were published (Data Source: Web of Knowledge).

1. Plastics in the marine environment

Florian Thevenon, IUCN Global Marine and Polar Programme (Gland, Switzerland) and Scientific Advisor at Race for Water Foundation (Lausanne, Switzerland)

INTRODUCTION

Plastic pollution has now become a global concern as plastic debris have reached all the oceans of the world with adverse effects on marine organisms and biodiversity as well as on human livelihoods and economy. Marine plastics result from inadequate waste disposal infrastructure and management but also a lack of public knowledge about their environmental impacts. The economic impact of marine plastics on coastal communities is also considerable, especially for fisheries and municipalities that regularly need to remove the beach litter to maintain tourism revenues. Moreover, the low-density plastic particles which float on the sea surface concentrate the hydrophobic contaminants from the surrounding polluted seawater, and release their intrinsic toxic chemicals (plastic additives) while they break down into smaller particles that will persist for decades to centuries in the marine environment due to their high resistance to natural degradation. There is therefore an urgent need to assess the environmental impacts of the plastic debris that accumulate in coastal areas close to large urban centers and popular tourist destinations, but also to a lesser extent at remote islands and in the deep sea such as in convergence zones that are formed by the wind-driven ocean's surface currents.

Left page: © Florian Thevenon.

1.1. Sources and characteristics

Plastics are synthetic organic polymers (i.e. they contain carbon as an essential element along their chains), which are long and high molecular-weight molecules consisting of repeating units called monomers. It is estimated that around 4% of the world's annual petroleum production is converted to plastics while a similar amount of petroleum is used to provide the energy for plastic manufacturing. The annual global production of plastics highly increased since the development of synthetic polymers in the middle of the 20th century and has doubled in the last 15 years, being in the order of 280 million tons per year (PlasticsEurope, 2010). It has been estimated that plastics account for around 10% by weight of the municipal waste stream (Barnes *et al*., 2009) with less than 10% of the plastic produced being recycled and about 50% of the 25 million tons of plastic produced in the European Union alone sent to landfills, most of it packaging (COM, 2013). Plastics are ideally suited for a variety of applications in transport, telecommunications, clothing and packaging because of light weight, low cost, strong and potentially transparent material. In Europe, more than a third of plastics produced each year is used to make disposable items of packaging or other short-lived products that facilitate the transport of a wide range of food, drinks and other goods which are discarded within a year of manufacture (Hopewell *et al*., 2009) (Fig.1.1). The average plastic consumption per capita in North America and Western Europe reached approximately 100 kg per year in 2005 and was expected to increase to 140 kg by 2015. The potential growth is highest in Asian countries where the current individual consumption of about 20 kg per year per person is estimated to increase to 36 kg by 2015 (PlasticsEurope 2009). In 2008, Europe used 49.5 million tons of plastic with almost 75% of the demand coming from four major sectors: packaging, construction, automotive and electrical/electronics (Fig. 1.1).

Packaging represents more than a third of European plastic consumption and consists of products which have a very short life span. Several broad classes of plastics are used in packaging, including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephtalate (PET) and polyvinyl chloride (PVC).

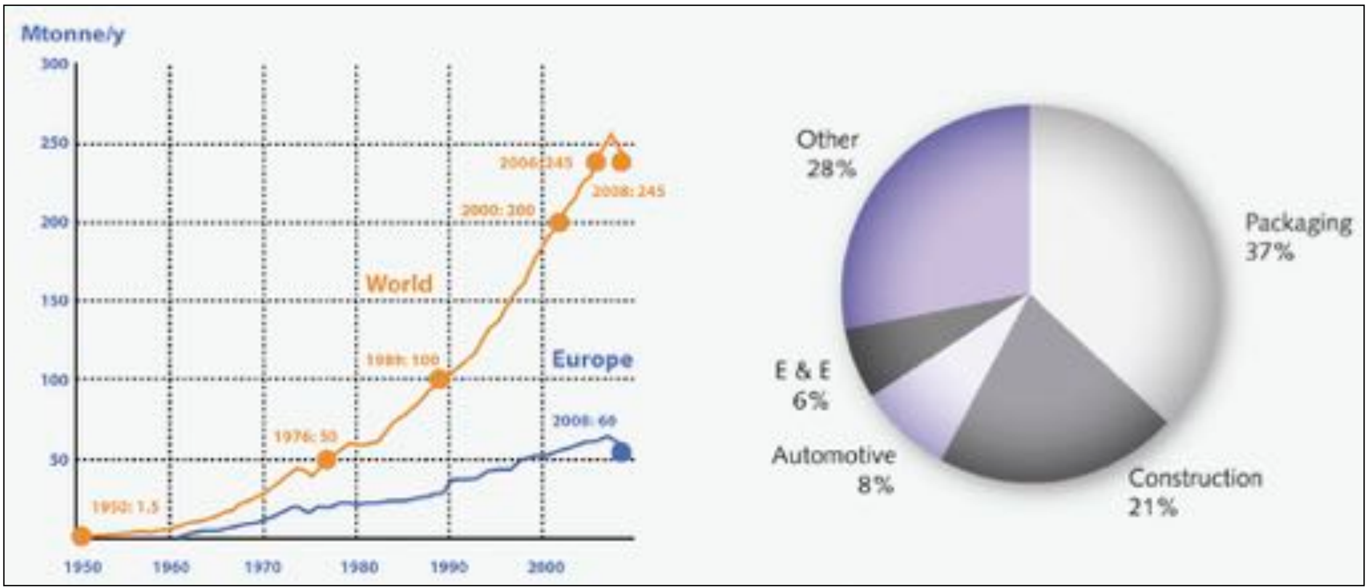


Figure 1.1: (left) Growth in world plastics production for 1950-2009, showing a continuous growth and a drop of production in 2008 due to economic downturn. About 25% of the world production takes place in Europe. (right) European plastic consumption for 2006 (total of 49.5 million of tons) according to application. (Source: PlasticsEurope 2008 and 2010).

Table 1.1: Classes of plastics that are commonly encountered in the marine environment (Source: Andrady, 2011).

Plastic Class	Specific Gravity	Percentage production*	Products and typical origin
Low-density polyethylene (LDPE LLDPE)	0.91–0.93	21%	Plastic bags, six-pack rings, bottles, netting, drinking straws
High-density polyethylene (HDPE)	0.94	17%	Milk and juice jugs
Polypropylene (PP)	0.85–0.83	24%	Rope, bottle caps, netting
Polystyrene (PS)	1.05	6%	Plastic utensils, food containers
Foamed Polystyrene			Floats, bait boxes, foam cups
Nylon (PA)		<3%	Netting and traps
Polyethylene terephthalate (PET)	1.37	7%	Plastic beverage bottles
Polyvinyl chloride (PVC)	1.38	19%	Plastic film, bottles, cups
Cellulose Acetate (CA)			Cigarette filters

* Fraction of the global plastics production in 2007

Generally, the plastic polymers are mixed with various additives to improve performance, such as carbon and silica to reinforce the material, plasticizers to render the material pliable, thermal and ultraviolet stabilizers, flame retardants and coloring. Some additive chemicals are potentially toxic and there is a particular concern about the extent to which additives released in the environment from plastic products of high production volume and wide usage (e.g. phthalates, bisphenol A (BPA), bromine flame retardants, UV screens and anti-microbial agents) have adverse effects on animal or human populations (Thompson *et al.*, 2009), while a recent study estimated that the direct ingestion of microplastics by some aquatic species is a negligible pathway for exposure to nonylphenol and BPA (Koelmans *et al.*, 2014).

Although limited in terms of mass compared to the other plastic sources, the wide use of microplastic scrub beads (especially polyethylene and polypropylene particles; Fig. 1.2) as abrasives in personal care products (e.g. facial cleaners and some toothpastes) has been only recently identified as potential contributor to marine pollution (Fendall and Sewell, 2009). However, these microplastic particles that are generally smaller than 1 millimeter in size may be a major source of microplastic pollution for aquatic environments, because they are designed to be washed down the drain and they are usually not captured by treatment screens in wastewater plants (generally larger than 1 to 6 mm). As a result, the worldwide use of microplastic-containing products directly releases huge amounts of microbeads via sewage discharge into the aquatic environment. These insoluble particles can be ingested by planktonic and filter-feeding organisms at the base of the aquatic food-chain. Surface water sampling in the Laurentian Great Lakes of the United States in 2012 revealed a great abundance of these multi-colored spheres suspected to be microbeads from consumer products (Eriksen *et al.*, 2013).

Figure 1.2: Left: The insoluble material obtained after sieving three facial and body scrub products. Right: A zoom showing the polyethylene colored microbeads with a graduated measuring scale **(**millimeter graduations) (Source: Florian Thevenon).

The United Nations Environment Program (UNEP) and the European Commission define marine litter as **"**any persistent**,** manufactured or processed solid material discarded**,** disposed of or abandoned in the marine and coastal environment" (UNEP, 2005; Galgani *et al.*, 2010). The average proportion of plastics varies between 60 to 80% of total marine debris and can reach as much as 90 to 95% of the total amount of marine litter (Derraik, 2002). Table 1.1 shows the main classes of plastics that are commonly encountered in the marine environment and Figure 1.3 presents the results of the top ten marine debris items removed during the 2012 International Coastal Cleanup, the world's largest volunteer effort to collect information on the amounts and types of marine debris. In 2012, more than half a million volunteers participated, collecting more than 5 thousand tons of trash and covering a distance of nearly 30 000 km. Many of the most commonly found pieces of trash include items we use every day from food wrappers and beverage containers to plastic bags (Fig. 1.3). The statistics provided by the Ocean Conservancy about marine debris collected in 2010 along California's coastline also indicate that 54.3% of the million debris collected was associated with shoreline and recreational activities, 4.4% with smoking, 3.2% with ocean/waterway activities, 1.5% with dumping, and 0.5% with medical/personal hygiene (Ocean Conservancy, 2010). These numbers are certainly underestimations of the real quantity of debris because beach surveys and volunteer-based cleanups which provide the most valuable data about the quantity and type of plastics present in coastal environment, do not take into account the buried debris and the small fragments (Ryan *et al.*, 2009; Barnes *et al.*, 2009). In order to gain an accurate and meaningful assessment of marine plastics distribution and movement, large-scale and long-term monitoring is needed across countries and marine environments, not only on beaches but also in the water column, seafloor and sediments; and across a wide range of debris sizes which has to include microplastics particles (smaller than 1 to 5 mm) (EPA 2011). Multi-criteria evaluation system based on statistical analyses of standardized spatial and temporal monitoring data can be eventually used to link the observed results to sources of marine litter and to identify indicators for the achievement of good environmental status (Schulz *et al.*, 2013).

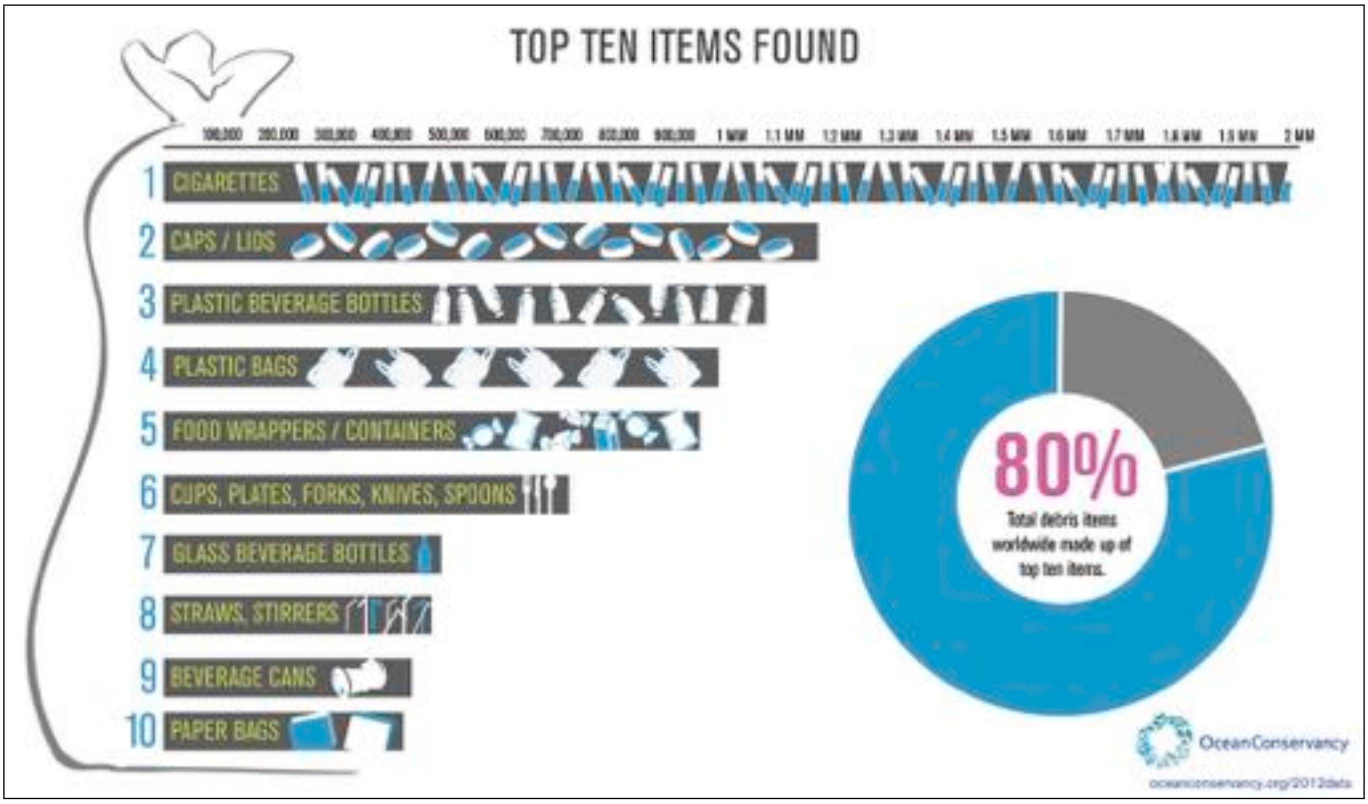


Figure 1.3: Top ten marine debris items removed from the global coastline and waterways during the 2012 International Coastal Cleanup (Source: OceanConservancy.org).

1.2. Distribution in coastal and open oceans

The sources for plastic fragments in the ocean are mainly the discharge of wastewater and runoff water by river systems, including in the vicinity of outfalls from wastewater treatment plants, and the fragmentation of discarded plastic products from landfills (domestic and industrial wastes) (Morritt, *et al.*, 2014). A significant part of the manufactured plastics is buoyant in water and plastic debris currently represents the main part (50-80%) of shoreline debris (Barnes *et al.*, 2009). Their presence was detected from the deep sea (including sediments) to shorelines (including remote islands) of the six continents from the poles to the equator, with more plastic material in popular tourist destinations and densely populated areas, where sewage contains microplastics in the form of contaminated fibers from washing clothes (Browne *et al.*, 2011). In general, it is difficult to identify the ultimate sources of marine plastics due to the fragmentation and degradation of the debris in small and heterogeneous assemblages. Moreover, the observation of the tiny microplastics floating just below the surface of the seawater is not possible by flight observations or satellite, and there is no precise information concerning the global plastic input to the ocean and about the part that ultimately sinks to the ocean floor. Although more precise information is required about plastic inputs, transport dynamics, and potential accumulation areas and sinks (scavenging in the water column and burial in sediment), it is considered that the majority of marine plastics come from land-based sources including urban and storm runoff, sewer overflows, beach visitors, inadequate waste disposal and management, industrial activities, construction and illegal dumping (Gordon 2006; Jayasiri *et al.*, 2013). The rest (ocean-based source) principally derives from the fishing industry, nautical activities and aquaculture (Fig. 1.4).

In fact, the abundance of plastics in the marine environment primarily varies spatially as a function of the distance to coastal populated areas and popular tourist destinations, as well as with the occurrence of heavy rain and flood events, but also with the speed and direction of the surface current which control the transport pathway and accumulation of plastic debris (oceanographic conditions) (Kukulka *et al.*, 2012; Desforges *et al.*, 2014). Backwards models using drifter trajectories arriving at the sampling location of plastic items can furthermore provide indications about the directions that the collected plastics could have taken and therefore possible information about the source of contamination (Fig. 1.5)

(Reisser *et al.*, 2013). There are many unknowns about the sources, spatial distribution, and pathways of marine plastics in coastal and oceanic regions, but also regarding the influences of the chemical and biological processes controlling the vertical movement of plastics through the water column. Indeed, according to their density or to the organism and sediment fouling that adds weight to the particles, plastic debris can sink relatively quickly within the water column to the seafloor where they are incorporated to sediment deposits. This is also the case with biodegradable plastics that generally have densities higher than 1 g/cm^3 and tend to sink relatively rapidly to the sea floor, where their degradation will principally depend of the microbial activity, the organic and geochemical properties of the sediment (Tosin *et al.*, 2012; Weber *et al.*,

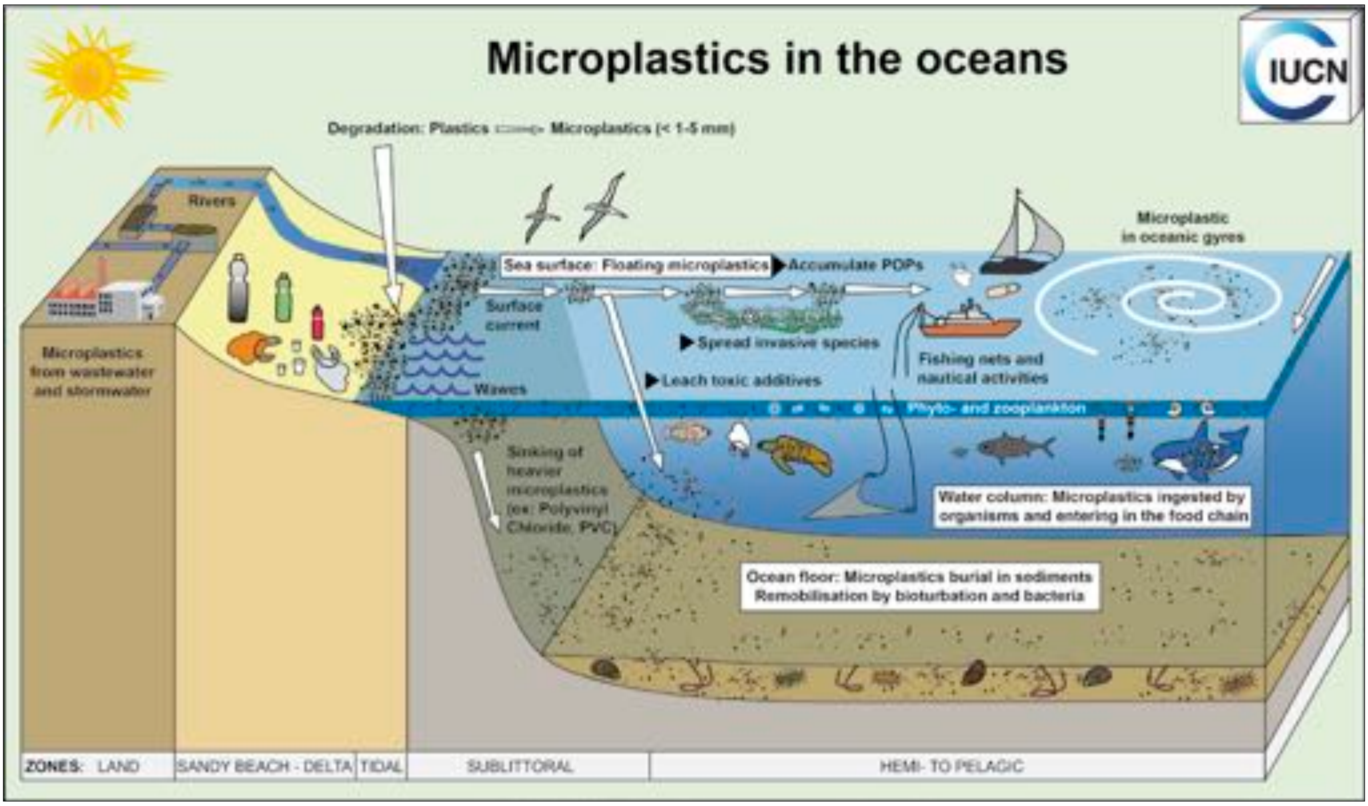


Figure 1.4: Schematic drawing showing the main sources and movement pathways for plastics debris in the oceans (Source: Florian Thevenon).

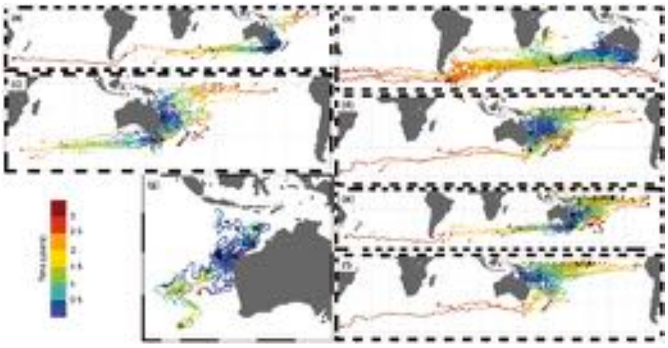


Figure 1.5: The inferred drifter pathways arriving at 57 net stations around Australia. The purple dots indicate net station and asterisks indicate drifter release areas (Source: Reisser *et al.*, 2013).

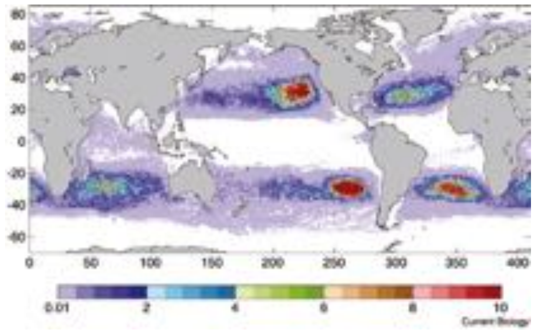


Figure 1.6: A model simulation of the possible distribution of marine litter in the ocean after ten years showing the plastic debris converging in the 5 major ocean gyres (Source: IPRC 2008).

2006), and the time to completely bury the plastic fragment below the surface sediments (local sedimentation rate). These parameters are closely related to the oxygen availability (oxic versus anoxic conditions) that controls the chemical gradients in the different marine habitats (littoral to deep-sea sea floor) and to the input (or deposition rate) of aquatic and terrigenous organic and mineral particles.

The other part of the plastics that are neutrally to positively buoyant remains close to the ocean surface where their long-range transport and accumulation are strongly influenced by the surface ocean circulation driven by regional or large-scale air-sea heat flux patterns. Computer model simulations suggest that plastic debris tends to accumulate in limited sub-tropical convergence zones or gyres where they may stay for many years (Fig. 1.6). However, there is a relative absence of field data for some of these remote areas, and a lack of parameters reflecting the properties and fate of the plastic particles that may change with time; as well as an absence of precise data about the source, transport and sinking of microplastics in the pelagic regions (Ryan 2013). Despite the general awareness and concern about the abnormal presence of microplastics in remote pelagic areas (generally lower than 1 plastic particle per km^2), and especially in the Great Pacific Garbage Patch (also known as Pacific Trash Vortex), the public should keep in mind that plastic pollution is not only restricted to distant parts of the ocean, as demonstrated for example by the substantial amounts of microplastics found along the Californian shorelines as well as in remote islands (Stevenson, 2011); whereas a high abundance of plastic debris (~ 1 plastic particle per m^2) is also found in shelf stations in the Mediterranean Sea (Collignon *et al.*, 2012).

Concerning tropical coastal ecosystems, the experimental release of selected tagged plastic items in a mangrove forest in Brazil demonstrates a rapid accumulation but for long periods (months-years) of plastic retention that varied among habitats, depending on characteristics such as hydrodynamics (i.e. flow rates and volume transported) and relative vegetation height and density, but also types of plastic items (PET bottles, plastic bag) (Ivar do Sul, 2013). The study of plastic debris entrapped in sediments of intertidal mangroves of Singapore also points to the prevalence of microplastics as a consequence of the degradation of marine plastic litter accumulating in the mangroves (Nor and Obbard *et al.*, 2014).

The microplastic pollution does not only concern the marine environment but also the continental surface freshwater resources (lakes and rivers) that supply a significant part of drinking water to humans, as demonstrated by some recent investigations in the largest surface freshwater system on Earth (the Great Lakes, United States; Eriksen *et al.*, 2013), in the largest freshwater lake of Western Europe (Lake Geneva, Switzerland; Faure *et al.*, 2012), and in some French rivers where 12% of the collected wild gudgeons (*Gobio gobio*) were contaminated with small plastic particles (Sanchez *et al.*, 2013). Although plastic waste is of increasing concern for aquatic environments, there is a considerable lack of knowledge about the extent of the contamination of freshwater ecosystems that may represent a significant sink and source for plastic debris (Imhof *et al.*, 2013; Morritt *et al.*, 2014).

The distribution and abundance of marine debris are strongly affected by transport mechanisms such as storm water, flood events, streams and river inputs in coastal areas, as well as by wind-driven ocean current in near-surface zones of pelagic areas (Desforges *et al.*, 2014). The model developed by Martinez *et al.* (2009) to predict the accumulation of marine debris in subtropical gyres suggests that the accumulation of plastics in convergence zones is reduced during El Niño years due to a decrease or reversal of the trade winds. Conversely, the accumulation of plastics in the convergence zone is greater during La Niña years, which are characterized by stronger trade winds. Despite such regional effects due to seasonal climate variations, there is no long-term trend change in plastic accumulation related to climate changes. Moreover, the sinking and the (low-rate) biodegradation of plastics in the world oceans do not account for a net carbon sink because the carbon from petroleum-based plastics is of fossil origin. Recycling or valorization (incineration of plastic wastes with energy recovery) nevertheless provides an opportunity to reduce oil usage and resource depletion, carbon dioxide greenhouse gas emission as well as the quantity of waste requiring disposal in landfills (Hopewell *et al.*, 2009). Recycling or valorization of plastic materials are also the most important actions currently available for reducing the environmental impacts of open landfills and

Figure 1.7: From left to right and top to bottom: Household waste disposal (dumping and open-air burning) of plastic packaging items in a coastal area of India. Plastic debris causes navigational hazards for vessels by fouling their propellers, and additional costs associated to plastic litter removal from fishing nets (Portugal). Regular beach cleanups to maintain beaches attractive for tourists generate immense economic costs (Portugal) (Source: Florian Thevenon).

open-air burning that are often practiced in developing countries to manage domestic wastes (Fig. 1.7), or when municipal incinerators plants are not equipped with appropriate filters. Both these practices release large amounts of hazardous chemicals (e.g. PCBs, dioxins, HAP) to the air, surface waters and soils from where they can enter the food-chain and be of concern to human health.

1.3. Socio-economic impacts

Plastic marine debris generates substantial economic impacts to coastal communities and governments. According to UNEP (2009), the increasing pollution from coastal urban centers creates environmental problems which threaten the sustainable development of the cities themselves. Half the world's population is presently living within 60 km of the sea and three-quarters of the largest cities are located on coasts. To date, very little information has been reported on the economic impacts of marine litter, but plastic debris causes aesthetic problems and presents a hazard to maritime activities including fishing and tourism (Gregory, 2009). Plastic pollution is of particular concern for coastal cities because marine litter can reduce the area's attractiveness to local residents and tourists while immense economic costs are incurred for regular beach cleanups. Despite environmental measures to reduce plastic pollution in these areas, municipalities throughout the Northeast Atlantic region continue to face high costs associated with the removal of beach litter, with approximately €18 million spent each year by English municipalities (approximately €10 million per year in the Netherlands and Belgium), which represents a 37% increase in cost over the past 10 years (KIMO, 2010). Figure 1.8 illustrates the pollution in two famous touristic sites (Hawaii and Maldives islands) threatened by a decline in tourist numbers and revenue due to dramatic pollution by marine debris and especially by plastics that could affect the image and reputation of the local tourism industry.

Plastic debris also engenders navigational hazards for vessels by fouling their propellers, and additional costs associated to damaged engines, litter removal and waste management in marinas and harbors. According to KIMO (2010), marine litter costs harbors in England a total of €2.4 million each year and almost 7 times more in Spain. The majority of the harbors and marinas are reporting incidents involving marine litter, especially fouled propellers frequently caused by derelict fishing gear. Discarded or lost fishing nets (Fig. 1.8) have an impact on the commercial and aquaculture fishing industry, resulting in the loss of catch and increased costs for repairing vessels, damaged nets and fouled propellers. Marine debris and der-

Figure 1.8: From left to right and top to bottom: Large floating debris found off the coast of Hawaii (Source: Algalita Marine Research Foundation (AMRF)). Kamilo Beach (Hawaii) known as "Plastic Beach" for the tons of plastic debris that accumulates on its shores (Source: AMRF). Entangled seal by derelict net, Hawaii (Source: NOAA). Open waste dumping in the Maldives at the artificial Thilafushi Island which serves as a dumping ground for huge quantities of solid wastes and toxic materials that are unloaded every day by the tourism industry (Source: Hani Amir).

elict traps have therefore direct economic impacts such as the ghost fishing that reduces the fishery stocks otherwise available for commercial and recreational fishers (Anderson and Alford, 2013) as well as indirect consequences such as the loss of fishing opportunities due to the time spent for cleaning litter from fishing nets and propellers (Fig. 1.7). Independently of this economic impact, the lost fishing nets and monofilament fishing lines are generally made from synthetic materials that take a long time to degrade in the environment, while they have been found to drift thousands of kilometers trapping and killing fish and seabirds, as well as protected marine species such as turtles, dolphins or seals, through ingestion and entanglement. The accumulation of plastic debris also involves significant economic loss to coastal fish farming and coastal agriculture, and more generally to the habitats and ecosystems that provide human-services. On the other hand, aquaculture is using a lot of plastic fish tanks and fish ponds (Fig. 1.9) made from heavy-duty plastics that are chemical resistant (e.g. polyethylene) and can be potentially emitted to the ocean, for instance subsequent to storm or flood events. The accumulation of large plastic debris is especially visible in coastal areas (beaches and shorelines) and costs millions of dollars in cleanup costs and loss of tourism**.** As debris accumulates, habitats are modified while light penetration and oxygen concentration are decreasing in the underlying waters, in turn affecting the plankton and therefore the entire food web, with possible effects on biodiversity and fish resources. Macroplastics accumulation on the seafloor may also degrade benthic habitats and impact organisms living on the seafloor such as coral reefs and seagrass. In addition to direct substantial economic impacts, marine plastics represent a threat to marine wildlife, ecosystems services and quality (tourism, fisheries and food security).

Figure 1.9: Shrimps aquaculture in India (Source: Florian Thevenon).

CONCLUSION

The increasing utilization of short-lived plastic products in combination with problems related to inadequate waste management have led to a strong pollution of our oceans with small plastic debris that will persist for decades to centuries in the ocean. There is an urgent need for better assessment of plastic sources, transport and sinks (burial in sediment) in the different parts of the ocean, in order to efficiently reduce plastic debris concentration in the pelagic and coastal areas at a global and long-term level. In addition to high economic costs of plastic pollution for cleaning marine debris from harbors and beaches to maintain tourism revenues, floating plastics and lost fishing gears decrease fish stocks and damage the propellers of fishing and recreational vessels. Marine plastics have become an emerging issue because it is well documented that the ingestion of plastic fragments results in the entanglement and suffocation of hundreds of marine species. There are also major concerns about the accumulation in the food chain of the toxic chemicals (the hydrophobic pollutants which float on the water surface) that accumulate on the surface of the plastics during their long residence time in polluted seawaters. There is finally a lack of sufficient knowledge about the impact of the contaminants that are held in the structure of the plastics (plastic additives) and that are released during the slow degradation of the plastic in seawater or sediment by natural degradation processes. The research about the environmental and ecological impacts of marine plastics is recent and the standardized methods that should be widely used to quantify the plastics in the different marine compartments have to include the microscopic particles which are not visible to the human eye but that have nonetheless adverse effects on marine ecosystems and biodiversity, as well as on human health and economy.

2. Sampling and analyzing microplastics in the marine environment

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INTRODUCTION

The general agreement about the definition of microplastics as particles that are smaller than 1 or 5 mm is a significant step towards the development of standardized guidelines for sampling and analyzing marine plastics. However, despite the widespread presence of plastic litter in the world's oceans, there is still an absence of standardized sampling and quantification methods, which impedes a precise evaluation of the fate and the impacts of microplastics in the marine compartments (surface waters, water column and sediments). One of the main issues to improve the characterization of marine plastics is to recommend different reproducible analytical methods, ranging from cost-effective and low-technology methods to state-of-the art analytical techniques, in order to quantify and identify the heterogeneous assemblages of plastic fragments with contrasting physical (density, color and shape) and chemical (chemistry of polymers and additives) properties.

2.1. Sampling in the marine compartments

The sampling of microplastics (i.e. plastic fragments smaller than 1 or 5 mm) in surface waters is based on the techniques developed some decades ago by the biologists for sampling aquatic plankton. Plankton net (~ 300 μm neuston or manta net) is usually strained from the water using boats or pulled along the shores for a defined distance (Fig. 2.1). The net is then thoroughly rinsed with sea water to flush the content (drained plastic but also biological components such as plankton and other non-plastic anthropogenic materials) into a Petri dish or sample jar which is brought to the laboratories for analysis. The quantity of plastic (number of pieces or weight) found in the net is then divided by its towed area (or volume of sampled water), which is calculated by multiplying net mouth width by tow length and using GPS (Global Positioning System) data.

The plastic fragments can be subsequently rinsed with tap water to remove seawater and excess of plankton, and sieved in order to distinguish macro- and microplastics (Fig. 2.1) which are then dried at room temperature or in an oven at around 50°C. Alternatively, the plastic particles can be separated from plankton by using conventional gravity separation techniques (Collignon *et al.*, 2014). An additional treatment step is recommended if a large quantity of biogenic organic material is present on the surface of the plastic fragments (biofilm and macrofouling organisms) using hydrogen peroxide (H_2O_2) in order to facilitate the visual sorting of the plastic debris and to estimate the amount of organic matter by weight loss.

Figure 2.1: From left to right: Sampling of microplastics in surface oceanic waters using a manta trawl (Source: 5gyres.org). Sieving of plastics particles collected from the ocean surface of the North Pacific Gyre (Source: ProjectKaisei.org). Plastics extracted from the stomach of a sea turtle (Source: Seaturtle.org).


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The microplastics present in the water column can be gathered at different water depths using water sampling bottles, rotating drum sampler or sediment traps where natural and anthropogenic sinking particulate matter accumulates. In order to collect relatively large amounts (several kilograms) of surface sediments and to analyze the plastic particles that sank entirely through the water column due to their high density or to the effect of some colonizing (fouling) organisms, different grab samplers can be used depending on the sediment types and the volume of the sample (from about 0.5 to 100 liters). The sediments are disturbed during such a sampling procedure, so that grab samples do not yield information about the sediment structure and about the historical deposition of microplastics. Alternatively, vertical profiles of sediments can be retrieved using sediment corers (e.g. gravity-core sampler) that preserve the layering of the sediment deposits, in order to i) reconstruct the temporal changes in the abundance of microplastics deposition and properties or ii) to investigate the effect of the microbial degradation of the polymers according to their time buried in the sediment compartment. Sedimentary sequences can be dated using chronological markers (e.g. anthropogenic cesium-137 derived from the atmospheric testing of fission bombs in the 1960s) in order to build up time series. However, the initial sample volume is relatively small when working with sedimentary cores, whereas the accumulation of microplastics in sediments can be relatively low and heterogeneous. A relatively low volume of sediment sample potentially limits the abundance of microplastics detected and therefore the reproducibility and reliability of the measurement, but analyzing different cores can improve the spatial and temporal changes in the regional distribution of anthropogenic pollutants (Thevenon *et al.*, 2011).

Sampling microplastics can also be done manually by collecting sand samples from beaches (Dekiff *et al.*, 2014) or sediment and soil from tidal marches or mangroves. The quantity of microplastics identified (number, weight or surface) is then reported to the sediment mass, for which the water content has to be measured by the weight difference between wet and dried initial sample weight. The flux of microplastic particles can be eventually calculated when the sample volume is representative of a given time period, as it is the case for instance for the sedimentary records (mass or surface of microplastics per m^2 and per year).

The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program (MDP) recently recommended standardized sampling methods and monitoring guidelines to estimate the accumulation rate of visible debris items (or flux, when debris is regularly removed from the site) and the accumulation or standing-stock of marine debris on shorelines (Lippiatt *et al.*, 2013). Hence, apart from the large range of methods applied for assessing marine debris abundance on beaches, the lack of standardized approaches for accumulation studies makes it difficult to assess comparative debris loads at different sites, and the quantity of available debris is significantly underestimated when the sampling is too infrequent (Smith and Markic, 2013). In addition to natural loss mechanisms (burial, mechanical and photodegradation degradation mechanisms) there are other natural (e.g. occurrence of storms which can introduce debris from adjacent subtidal habitats) and human (e.g. removal of plastic debris by visitors at popular beaches) factors that should be considered when sampling plastic on beaches; especially the distance to potential sources of marine debris (e.g. sewage outfalls, land use, urban runoff and rivers) as well as local current patterns (strength and direction of wind) but also the survey frequency. Concerning the open ocean, the total oceanic plastics concentrations may be significantly underestimated by traditional surface measurements, because the plastic pieces are vertically distributed within the upper water column due to wind-driven mixing; so that accurate estimates of total plastic content in the upper ocean should take the effect of wind-induced mixing into account (Kukulka *et al.*, 2012; Collignon *et al.*, 2012).

2.2. Extraction from marine samples

Laboratory processes used to separate microplastics from water or sediment matrices are generally based on four main steps: Density separation, filtration, sieving, and visual sorting. One of the main prerequisites before analyzing marine microplastics is to avoid background contamination during the sampling and extraction procedures (e.g. by clothing fibers; Fries *et al.*, 2013) and to ensure the removal of non-plastic materials. The elimination of the organic compounds (planktonic organic material and plant or animal parts) and the extraction of the plastic fragments are particularly tedious and suffer from a lack of standardization; although these steps can potentially modify the efficiency and the reproducibility of the quantification of the plastic particles. Although some biogenic organic matter present in the matrices or adsorbed on the surface of the plastic fragments can be at least partially removed by water rinsing and an oxidation process (H_2O_2 treatment), marine environments contain varying amounts of refractory organic materials from bacterial and terrestrial origin that are strongly resistant to thermal and chemical treatments (Thevenon *et al.*, 2004). Moreover, thermal treatments cannot be applied to plastic extraction to remove biogenic organic material due to the low resistance of most of the common polymers to high temperature. Conversely, a moderate chemical treatment using diluted solvents (e.g., H_2O_2, sodium hydroxide (NaOH) or hydrochloric acid (HCl)) is recommended for eliminating some of the organic and mineral matter coating or embedding the plastic particles (Liebezeit and Dubaish, 2012). However, some polymers can be altered by such chemical oxidative treatment because optical changes (discoloration and partial dissolution) occur at a relatively low solvent concentration (Nuelle *et al.*, 2014). The extraction of microplastics from sediment can be also facilitated using a dispersant or a deflocculant (e.g. a detergent such as sodium hexametaphosphate) and applying ultrasound in a deionised water bath that facilitates the deagglomeration of the clays and thus the sorting of microplastics in fine grained sedimentary material.

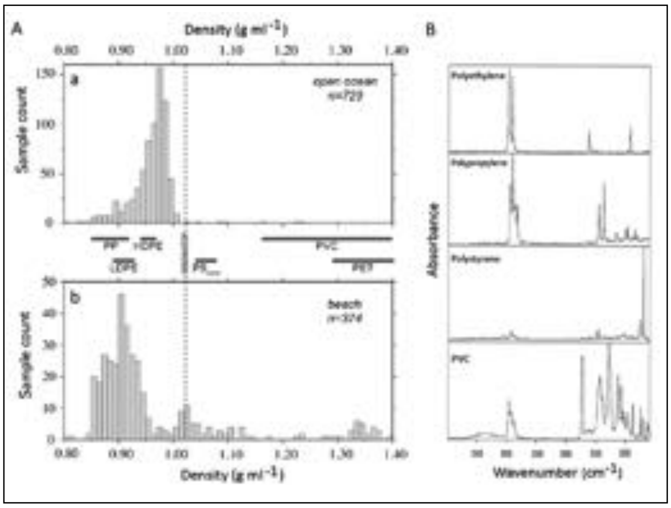

Figure 2.2: (A) Frequency of microplastics of different specific densities found (a) at the sea surface and (b) in beach sediments. Broken vertical line indicates the specific density of seawater and bold horizontal lines show the specific densities of particular polymers; PP: Polypropylene, HDPE: High density polyethylene, LDPE: Low density polyethylene, PS: Polystyrene, PVC: Polyvinyl chloride, PET: Polyethylene terephthalate. (B) Fourier transform infrared spectroscopy (FT-IR) spectra of some common plastic polymers (Source: Hidalgo-Ruz *et al.*, 2012).

The density of the plastic particles ranges from 0.8 to 1.4 g cm^{-3} (Fig. 2.2.A) depending on i) the type of polymer but also of ii) the various additives that can be added during the plastic manufacturing, and of iii) the effects of weathering and biofouling during their long residence time in seawater (Morét-Ferguson *et al.*, 2010). On the other hand, the density of the surface seawater ranges from about 1.02 to 1.03 g cm^{-3} (Fig. 2.2.A) while the density for sand or other mineral sediments is conventionally taken as 2.65 g cm^{-3}. As a consequence:

i) High density plastics such as polyvinyl chloride (PVC), polyethylene terephthalate (PET) and nylon rapidly sink in coastal areas.

ii) Plastics that float in fresh and seawater are polypropylene (PP) and polyethylene (PE) and polystyrene (PS) in foamed form (Fig. 2.2.A).

iii) Density separation can be applied using a concentrated saline solution of sodium chloride (NaCl), a low-cost and environmentally friendly table salt with a density of 1.2 g cm^{-3}, in order to extract the plastics of low density that are transported to the open ocean (Fig. 2.2.A).

In the first step of the sample processing, sediment sample can be sieved (e.g. at 150 or 500 μm depending of the size range of the insoluble material) with tap water to remove macrolitter (Fig. 2.1), then mixed with a saturated NaCl solution and shaken for a varying amount of time depending on the size of the sediment sample (Hidalgo-Ruz *et al.*, 2012). The sediment sample and the saline solution can be alternatively placed in a separation funnel to separate microplastics from sediment. The supernatant containing the microplastic particles is subsequently filtered using a filtration unit and a vacuum pump.

The filter (e.g. nitrocellulose 0.45 micrometer pore width) is eventually dried and sealed in a Petri dish for further analysis.

The use of NaCl is recommended to separate microplastics from sediments by flotation because it is a relatively inexpensive salt, an eco-friendly product, and floating plastic particles that are transported through the mesopelagic portion of ocean necessarily float on seawater. However, using NaCl can lead to an underestimation of the concentration of higher density polymers present in beach sediments (e.g. PET and PVC; Fig. 2.2.A). If necessary, higher density salts (e.g. sodium iodide (NaI) with a density of approximately 1.6 g cm^{-3}) can be used to extract polymers of a higher density range in a second extraction step (i.e. following the NaCl separation procedure). Such a two-step method has the advantage to significantly reduce the analytical cost of using a large amount of expensive salt for treating the initial high sample mass (Nuelle *et al.*, 2014). It is however meaningful to note that higher density salts should not be recommended to standardize the extraction of microplastics from marine sediments, because i) these salts are generally expensive and hazardous to waters, ii) of the relatively high volume of initial sample, and because iii) of the low abundance of high-density plastics in subtidal sediments (Fig. 2.2.B) while plastics are relatively easy to sort manually from coarse-grained sediments such as beach sand.

In the second step of the procedure, the extracted microplastic particles can be separated in different size-classes by manual sieving. The different studies employing either one sieve or several sieves of different mesh sizes in cascade put forward the need for a classification of the plastic particles size in standardized size-classes; similarly for instance to those arbitrary chosen to document the grain-size distribution in sediments, for which laser diffraction is commonly used to automatically measure particle size distribution in number and volume of particles ranging from hundreds of nanometers up to several millimeters in size. Such standard reporting is necessary to enable reliable comparisons of marine debris abundance, distribution and movement across regional and global scales.

2.3. Sorting, counting and weighing

Visual sorting of the plastic particles is noteworthy facilitated by placing them on a homogeneous white support in a laboratory environment and by observing the small fragments with a binocular microscope (Fig. 2.3) or a stereomicroscope. The sorting of the sample by eye is necessary to separate the microplastic fragments from other biogenic or anthropogenic residues that would otherwise overestimate the plastic content. Even in case of limited analytical resources, monitoring programs can be very effective by using the simple extraction procedure described in the former paragraph (flotation in a NaCl solution for sediments or manual sieving and visual sorting), which gives access to the mass (weight) of plastic particles as a function of their size-class. Each plastic piece can be eventually picked up with forceps and placed in a graduated dish to be counted, measured (length), photographed and classified into type (e.g. hard, soft, line, expanded polystyrene, pellet) and color (Reisser *et al.*, 2013; Fig. 2.4). It is meaningful to note that a basic digital photography showing the plastic fragments and the scale of the sample could be used to

Figure 2.3: Some marine plastic samples (left) collected in the Atlantic Ocean with plankton nets by the Association OceanEye, in the Central Environmental Laboratory (GR-CEL) at the Federal Institute of Technology (EPFL) in Lausanne (Switzerland). The plastic are sorted by different types (center) using a binocular microscope (right) after an oxidative treatment (H_2O_2) to remove and estimate the organic matter fraction (Source: Florian Thevenon with courtesy of Pascal Hagmann and OceanEye).

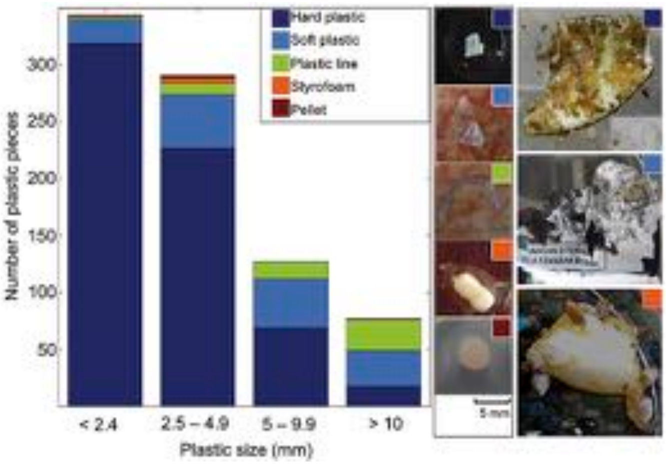

Figure 2.4: Size and types of marine plastics collected around Australia. Bars indicate the number of plastic pieces within each size category (<2.5, 2.5–4.9, 5–10, >10 mm) and colors show the amount of each plastic type within size categories. Examples of the types of plastic collected are shown in the photos (Source: Reisser *et al.*, 2013).

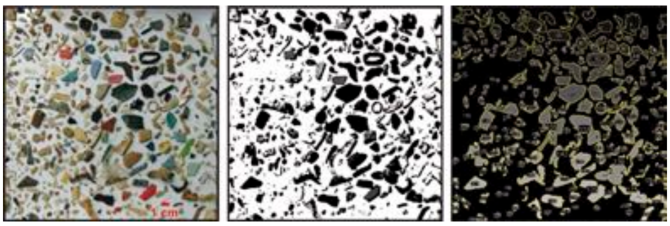

Figure 2.5: An example illustrating the principle of the automated image analysis technique. From left to right: A part of the initial image (Fig. 2.1) showing the plastic particles extracted from the stomach of a sea turtle (Source: Seaturtle.org), the black and white image used for the analysis (after adjusting the grey level threshold), and the result of the analysis showing the particles larger than 0.1 cm^2 detected (Source: Florian Thevenon).

compute automatically the morphological parameters and the surface of a high number of plastic particles, and therefore the total area of plastic; including the smaller pieces that are below current levels of detection (Fig. 2.5). Digital images and image-processing programs such as the free, public-domain software ImageJ (Rasband, WS, Image J, NIH, Bethesda, MD, USA) allow the rapid counting of large numbers of particles. This approach has been used for measuring the surface of the microplastics found in the sea surface of the Northeast Pacific Ocean (Goldstein *et al.*, 2013), in the coastal sediments from the North Sea (Nuelle *et al.*, 2014) and in the stomach or intestine of barnacles from the North Pacific Gyre (Goldstein and Goodwin, 2013). There is nevertheless a lack of recommendations and standardized procedures for this image analysis method. The example shown in Fig. 2.5 fails to separate some particles, suggesting that the transparent and white plastics have to be sorted and photographed independently of the black ones, or that a supplementary image using a black background should be consecutively analyzed in order to detect all the plastic particles.

Photography can be also used to obtain higher resolution images when some optical equipment (e.g. binocular or transmitted light microscope) is equipped with a digital camera. This technique initially developed for the particle size analysis of the opaque particles (larger than 0.1 μm) entrapped in marine sediments and ice cores (Thevenon *et al.*, 2004; Thevenon *et al.*, 2009) demonstrates its advantage and accuracy for measuring the morphological parameters of a high number of microscopic particles, as well as their individual and total surface. This cost effective technique allows quantifying precisely a high number and the total surface of a wide size-range of particles, while the reproducibility of such measurement is much higher than when being done by naked eye, and the level of detection is much lower. The quantification of microplastics can be used to evaluate the regional environmental pollution by looking at the stomachs of some marine organisms (e.g. worms, barnacles, bivalves, fishes and turtles; Camedda *et al.*, 2013). The best known example is the study of the stomach contents of northern fulmars as a standard monitoring tool to measure the marine debris pollution in the North Sea (Fig. 2.6). Results show that although the amount of plastic in the stomachs of fulmars has remained roughly stable over the last decade (Van Franeker *et al.*, 2013), the mass of plastic originating from land-based consumer products has doubled and in some years tripled (Vlietstra and Parga, 2002).

Figure 2.6: The fulmar monitoring program examines the litter abundance in stomachs of dead seabirds found at the coastline from the North Sea region. Over the whole North Sea, 95% of birds examined had ingested plastic, with an average of 40 pieces and 0.33 grams. On this picture, the quantity of all marine debris (including non-plastic and macro debris) found inside a studied fulmar's stomach (right) is compared to the equivalent volume of litter if it were in a human's stomach (left) (Source: Galgani *et al.*, 2010).

2.4. Polymers, additives and pollutants

The image analysis technique previously described can be also used to easily and quickly count large numbers of nanoparticles (smaller than 1 μm in diameter) with images acquired by Transmission Electron Microscopy (TEM) or Scanning Electron Microscopy (SEM). Although not yet clearly quantified, engineered plastic nanoparticles and nanoscale particles produced during the weathering of plastics debris is a serious concern for all marine animals and thus for the entire marine food web, especially for nano- and picoplankton, which are the predominant contributors to primary production in the ocean and of comparable size-scale (Bhattacharya *et al.*, 2010; Andrady, 2011; Brown *et al.*, 2011). At this microscopic scale, fluorescence microscopy and bioimaging techniques enable the visualization of microplastics ingestion by zooplankton, as illustrated on Fig. 2.7 showing the ingestion of polystyrene beads by exposed copepods (Lee *et al.*, 2013; Cole *et al.*, 2013). This technique furthermore reveals that plastic microparticles are egested from zooplankton organisms after few hours (fecal pellet; Fig. 2.7).

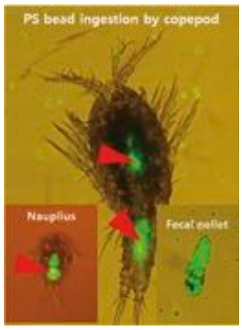

Figure 2.7: Ingestion and egestion (fecal pellet) of polystyrene beads by copepod revealed by fluorescence microscopy (Source: Lee *et al.*, 2013).

SEM images of marine microplastics (Figs. 2.8.A and 2.9.A) can be alternatively used to decipher some morphological details about the surface of the plastic particles, which can testify the effects of weathering by microbial, physical (e.g. fractures and abrasion marks due to wave action and sand-blasting) or chemical (in response to ultraviolet and infrared components from solar radiation) processes (Zetter *et al.*, 2013; Andrady, 2011; Gregory, 1983). The resulting degradation alters the surface texture of microplastics and therefore the amount of toxic chemicals being potentially adsorbed on their surface, as well as the possible leaching of the plastic additives into seawater.

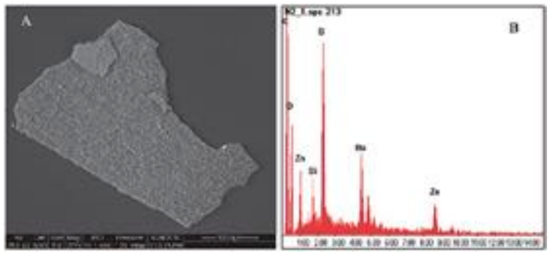

Figure 2.8: (A) SEM image of a particle of microplastic extracted from surface sediments collected on the beach of the island of Norderney, a barrier island located in front of the German North Sea coastline. (B) EDX spectra showing sulphur (S) as well as barium (Ba) and zinc (Zn) content, not specified plastic carbon (C) and oxygen (O) (Source: Fries *et al.*, 2013).

SEM can be furthermore equipped with an energy-dispersive X-ray microanalyzer (EDX) to measure the elementary composition of the microplastics surface (Fig. 2.8). Such EDX spectra demonstrate the presence of carbon in polymer material and some metals like aluminum and zinc that can be adsorbed to marine plastic particles (Holmes *et al.*, 2012), but also nanoparticles of titanium dioxide (TiO_2-NPs) that are inorganic plastic additives added to plastics as white pigments or UV blockers during manufacturing (Fries *et al.*, 2013). These recent observations therefore point out the potential of marine microplastics to act as a source for the sustained release of nanoparticles which may be toxic for marine (micro-) organisms (Handy *et al.*, 2008).

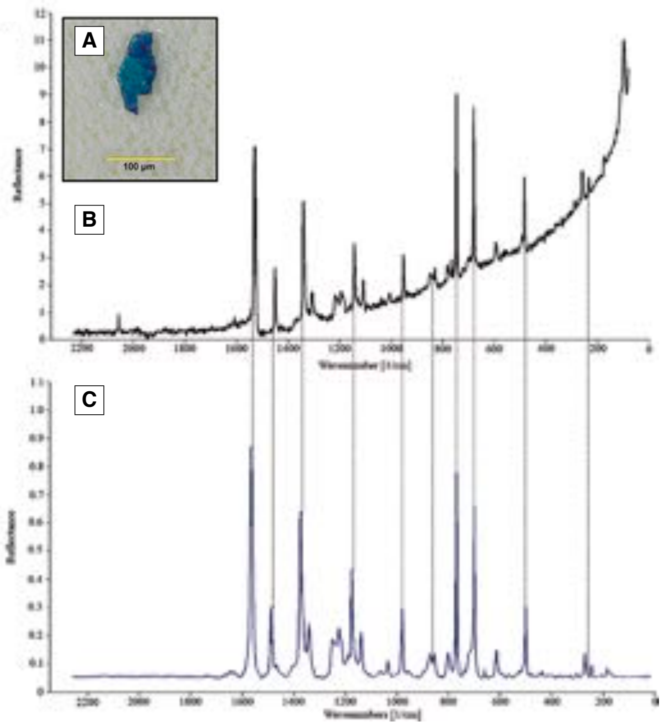

Figure 2.9: Identification of microplastics using micro-Raman spectroscopy. (A) Microplastic particle extracted from sediment originating from the Weddell Sea at 2749 m depth. (B) Raman spectrum for the extracted particle. (C) Raman spectrum for the widely used pigment copper phthalocyanine (blue pigment). The Raman peeks in this spectrum match with those represented in panel B (see dotted lines) (Source: Van Cauwenberghe *et al.*, 2013).

Although visual sorting (optical-based techniques) and weighing are recommended for the routine quantification of microplastic particles in the marine environment, some accurate but more expensive chemical methods allow identifying the plastic polymers and their additives. In particular, the chemical composition of marine plastics can be determined by Fourier transform infrared spectroscopy (FT-IR), or Raman spectroscopy, which both provide additional information about the crystalline structure of the polymer (Claessens *et al.*, 2011; Thompson *et al.*, 2004; Van Cauwenberghe *et al.*, 2013). The principle of these methods is to compare the spectrum obtained from a marine plastic fragment to the spectra of some known plastic polymers (Fig. 2.2.B), or to organic pigments of a non-natural origin that are commonly used in the plastics industry (Fig. 2.9.B). This approach is similar to the one developed using sequential pyrolysis- gas chromatography coupled to mass spectrometry (Pyr-GC/MS) that can simultaneously identify polymer types but also associated organic plastic additives (Fires *et al.*, 2013).

The advantage of the pyrolysis GC-MS method is the possible identification of the signature of known synthetic polymers, which can provide supplementary information on the source and the transport of marine plastics. The main disadvantages of GC-MS techniques are the high cost of analytical instruments and the relatively high quantity of sample needed for one analysis (~ 1 mg or 100 μm; Dekiff *et al.*, 2014), which is moreover not representative of a heterogeneous marine sample composed of many synthetic polymers of different origins. The polymer composition analysis of small plastic particles by FT-IR is easier to implement but requires time- and labour-consuming pre-sorting of particles by hand, while small or less abundant micro-plastics are potentially overlooked. However, this technique is used frequently and provides reliable results and datasets, but also offers possible future analytical development (FT-IR Imaging) for analyzing total micro-plastics in a given sample without prior pre-sorting by hand (Löder and Gerdts, 2013).

There are other chemical methods that can be used to detect a wide range of polymer particles (from nano- to centimeter-scale) but most of them are time consuming, costly (e.g. flow cytometry) and involve a high solvent consumption (e.g. Soxhlet extraction). These methods are consequently recommended for experimental work in laboratory studies to assess the impacts of microplastics and their possible interaction with marine biota, but they do not apply to global monitoring programs that rather need cost-effective methods for an absolute and rapid quantification of heterogeneous plastic fragments. Additionally to the internal plastic additives (e.g. phthalates and bisphenol A) which can leach from the polymer following (chemical, physical or microbial) degradation in the marine environment, microplastics may pose a hazard to marine organisms due to their capacity to adsorb persistent organic pollutants (POPs) present at the sea surface; with concentration up to more than one million times higher than those of the surrounding water (Mato *et al.*, 2001) for plastics that remained during long periods in polluted sea surface water. POPs are synthetic organic (carbon-based) chemicals toxic to living organisms, derived from human activities such as the use of pesticides for pest and disease control, fossil-fuel combustion, agricultural and industrial activities. Although the methods used for the extraction (using the Soxhlet method) and the analysis of polychlorinated biphenyls (PCBs), organochlorine pesticides such as dichloro-diphenyl-trichloroethane (DDT), or polycyclic aromatic hydrocarbons (PAHs) are available, the access to modern capillary gas chromatography equipment coupled with mass spectrometry (GC–MS) for POPs analysis is particularly expensive. With the development of large-scale monitoring programs that aim to evaluate the toxicological effects of plastic ingestion on marine organisms, there is nonetheless an increased need for determining POPs in microplastics but also in marine (micro and macro) organisms. Indeed, although it is clear that harmful substances accumulate on floating plastics when such particles have a long residence time in polluted surface water, there is a lack of knowledge about the transfer of the contaminants in the organisms (bio-accumulation) that ingested contaminated plastics, and in the tissues of the top predators (bio-magnification).

The assessment of the toxicological impact of microplastics also involves the measurement of other pollutants that are sorbed on their surface with organic matter and with fine-grained particles, such as traces (or heavy metals such as lead or mercury) that are toxic, persistent and liable to bioaccumulate. A recent study demonstrates that plastic debris may accumulate greater concentrations of metals the longer they remain in polluted aquatic environments and that a complex mixture of metals can be found on plastic debris composed of various plastic types (Rochman *et al.*, 2014a). These metals can be quantified by inductively coupled plasma mass spectrometry (ICP-MS). Mass spectrometry can be further used to quantify the different isotopes of a specific element and to identify the origin of the metal pollution (e.g. fossil fuel combustion, waste incineration, wastewaters; Thevenon *et al.*, 2011).

In addition to their consistent quantification, the reconstruction of the source of marine plastics is necessary to better understand plastic transport dynamics and for developing mitigation strategies and targeted clean up options that must be efficient on a long-term perspective. In order to assess the sources of marine plastics as well as their rates of deposition on the seafloor and their impact on marine ecosystems, there is an urgent need to establish more standardized methods of integrated assessment that combine:

i) Reproducible-basic techniques and low-cost procedures to ensure the quantification of plastics fragments in the different marine compartments, including the debris smaller than 5 mm.

ii) State-of-the-art chemical methods in order to identify the polymer types and to quantify the external pollutant loads (POPs and metals), fluxes and leaching patterns in seawater (including the internal plastic additives).

iii) Ecotoxicological studies to assess the impacts of contaminated microplastics ingestion on the species at the base of the food chain as well as on top predators and humans.

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CONCLUSION

There is an urgent need to promote improved standardized analytical techniques for sampling and quantifying microplastics in the marine environment, in order to build up international monitoring programs that could provide the required baseline data for understanding the spatial and temporal distribution of microplastics in open and coastal oceans. Low-technology and cost-effective methods based on floatation in NaCl solution and/or sieving and visual sorting of non plastic particles, are relatively easy to implement. There is nonetheless a need of a better standardization for the sampling and reporting of microplastics in marine samples, similarly to the methods that are used for characterizing marine sediments composition. The image analysis technique offers large perspectives for the monitoring of marine plastics that requires the reproducible counting of a high number of particles with contrasting shape and size, including in the micrometric range (i.e. below current levels of detection). Additional state-of-the-art analytical chemical techniques can be further used to characterize the composition and the structure of polymers, but also to identify polymer types and organic plastic additives, which are possibly of concern for evaluating the toxicity of microplastics on marine organisms. Finally, future research is needed to understand the natural microbial degradation process of plastics in the environment by sequencing the genome of bacteria living on plastics, in order to identify gene sequences responsible for plastic degradation in seawater as well as in sediment (plastic life cycle assessment).

3. Impacts of plastics on marine organisms

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INTRODUCTION

Marine plastic debris has major direct and indirect harmful effects on the marine biota and wildlife. Problems associated with absorption and entanglement of plastic debris include ingestion of specific plastic items by animals that mistake plastic waste for prey, and to a lesser extent consumption of pelagic fish and other prey that have plastic particles in their guts. Accumulation of plastic debris in the marine environment can result in habitat degradation whereas floating plastics create new habitats and enable transport of invasive (alien) species over long distances. Finally, plastics contain toxic substances that were added to the polymers during the production process. Marine plastics accumulate toxic pollutants present at the sea surface and serve as a potential transport vector for chemical contaminants of concern. Although pollution by plastics is increasingly recognized worldwide as a major threat to marine biota, the effects of oceanic plastic debris on marine organisms and food webs, community structure, and ecosystems are still poorly understood.

3.1. The physical effects of plastic ingestion

There are two major concerns associated with the ingestion of plastic by marine animals: Entanglement and ingestion of plastics. Potentially leading to suffocation or intestinal blockage, entanglement is largely underestimated as most victims are undiscovered over vast ocean areas when sunk or eaten by predators (Wolfe 1987). The second concern is the increasing exposure of marine organisms to toxic materials through ingestion of plastics and consequently entrance of hazardous pollutants into the food chain, either originating from the material itself (plastic additives) or from the chemical pollutants that adsorb to it from polluted surrounding waters (Rochman *et al.* 2013a). A synthesis report about the impact of plastic debris on marine wildlife indicates that at least 267 different species are known to have suffered from entanglement or ingestion of marine debris including 86% of all sea turtle species and 44% of all sea bird species, while 70 to 100% of the albatrosses are known to ingest plastics (Allsopp *et al.* 2006). The ingestion of plastic debris does not only concern predatory organisms (e.g. birds, turtles, seals, whales or dolphins) but also smaller invertebrate organisms. Experimental studies reveal that microplastics were ingested by i) amphipods, lugworms and barnacles despite their differences in feeding method (detritivore, deposit feeder and filter feeder, respectively; Thompson *et al.*, 2004) but also by ii) mussels (*Mytilus edulis*) which have been shown to ingest and accumulate micrometric polystyrene beads in their gut cavity for over 48 days (with smaller plastics found embedded in circulatory tissue) that may have implications for predators, including birds, crabs, starfish, predatory whelks, and humans (Browne *et al.*, 2008).

Animals can get entangled by plastic floating at the sea surface, and in particular by derelict and lost fishing gear (or fishing nets, ropes, monofilament lines, trawl and gill nets) made of synthetic fibers that are resistant to degradation. These so called ghost nets continue to indiscriminately entangle and trap fishes and non-target organisms while they drift in the ocean. Entanglement by human-made debris and especially by derelict fishing gear has been for example identified as a potential contributing factor in the population declines of the Hawaiian

Monk seal, a rare marine mammal endemic to the Hawaiian Islands (Henderson *et al.*, 2001; Boland and Donohue, 2003); whereas 40,000 seals per year are estimated to be killed by plastic entanglement in the Bering Sea (Derraik 2002). For these reasons, experts on marine debris recommend replacement of traditional fishing gears with eco-friendly designs and establishment of incentive programmes for the fishermen in order to promote eco-friendly gear designs (Kim *et al.*, 2014).

Although the entanglement of marine species due to marine litter has been frequently described as a serious mortality factor, only a small numbers of entanglements are recorded and the impact of suffocation on marine populations specifically due to plastic litter is difficult to estimate. Nevertheless, animal entanglement in marine litter has been reported for 135 species of invertebrates, 32 species of marine mammals (including sea lions, dolphin and whales), 51 species of seabirds and 6 species of sea turtles (Laist, 1997; Allsopp *et al.*, 2006). Plastic, the predominate type of marine litter, can cause death by drowning, suffocation, or strangulation. Even if not immediately lethal, entanglement can produce lacerations and infections from the abrasive or cutting action of attached litter, or impair the ability of animals to swim and therefore to find food or escape from predators (US EPA 1992).

The ingestion of plastic items by marine species has been widely reported, including for sea birds, turtles, fish, mussels, crustaceans and marine mammals. There is evidence that some birds and marine species mistake plastic particles waste for potential prey items, and select specific plastic shapes and colors (Moser and Lee, 1992; Lavers *et al.*, 2013). Accordingly, planktivorous birds are more likely to confuse plastic pellets with their prey than piscivores (Azzarello and Van Vleet, 1987), and albatrosses may mistake red plastic for squid; whereas the ingestion of plastic debris by seabirds (and fish) is directly correlated to foraging strategies. Plastics as part of the animal's diet reduce actual food uptake and cause internal injury and death following blockage of intestinal tract (Derraik, 2002). Sea turtles also often consume plastic debris and semi-inflated floating plastic bags drifting in ocean currents which look similar to their favorite natural prey, jellyfish (Bugoni *et al.*, 2001). The investigation of the scats of fur seals furthermore highlights that predatory organisms also indirectly consume plastic particles in the usual process of their feeding, for example by eating pelagic fish species that have ingested and accumulated plastic debris (Eriksson and Burton 2003). As a consequence, some obstructions caused by ingested plastics can prevent organisms from taking in food and this phenomenon can lead to malnutrition, starvation, suffocation and death with some effects being nonetheless specific to certain species (Gregory, 2009; Thompson *et al.,* 2009).

A study on catfish in an estuary in northeastern Brazil indicates that between 18 and 33 % of individuals have plastic debris in their stomach, depending on the species of catfish (Possatto *et al.*, 2011). Another research on the amount of plastic found in the gut of common planktivorous fish in the North Pacific Central Gyre shows that approximately 35% of the fish studied had ingested plastics, averaging 2.1 pieces per fish (Boerger *et al.*, 2010). Stomach contents of sea turtles washed ashore or incidentally captured dead by fisheries in the Adriatic Sea, on the south of Brazil or in Florida, demonstrate that the majority of the turtles have plastic debris in their digestive tracts (Bugoni *et al.*, 2001; Bjorndal *et al.*, 1994; Tomás *et al.*, 2002). At least 26 species of cetaceans (whales, dolphins and porpoises) have been documented to ingest plastic debris (Baird and Hooker, 2000) with however low plastic ingestion except for some benthic-feeding toothed whale (odontocete) species that mistake plastic debris due to its resemblance to prey (Walker and Coe, 1990). As a consequence of the interaction of plastic debris with marine organisms, some species can be used for evaluating the marine plastic pollution (as bio-indicator of litter pollution), for instance the monitoring of the quantity of litter in the loggerhead sea turtles (in the digestive tracts of dead animals and in fecal pellets of living individuals) in the Western Mediterranean Sea (Sardinia; Camedda *et al.*, 2013). Another example is the monitoring of the marine litter ingested by the northern fulmars which has been used to evaluate the plastic pollution in the North Sea (Fig. 2.4). This investigation estimates that North Sea fulmars could annually reshape and redistribute about six tons of plastic through ingestion of plastic waste (Van Franaker, 2011).

The Figure 3.1 illustrates the result of the 24th annual International Coastal Cleanup organized by Ocean Conservancy in 2009. Cleanup volunteers picked up 3.4 thousand tons of marine debris and also reported entangled wildlife in debris. They found 336 marine birds and animals entangled in debris, of which 120 were alive and released, while 216 were dead, including a seal in California entangled in fishing lines. Birds were the number-one victim, accounting for 41% of dead marine life found. Fishing line and lost or ghost fishing nets were the two most prevalent types of entangling debris (62%). Wildlife didn't just become entangled in debris: Birds, animals, and fish often ingested items they encounter in their ocean homes such as bottle caps, cigarette butts and lighters, fishing lines, and a host of other objects (Ocean Conservancy).

Figure 3.1: Number of marine wildlife found entangled in marine debris during the 24th annual International Coastal Cleanup by volunteers (Source: OceanConservacy.org).

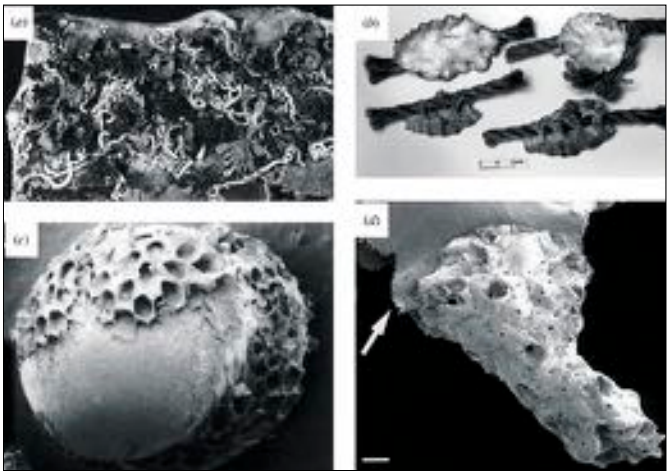

Figure 3.2: Example of colonization and encrustation on plastic debris from the New Zealand coastline: (*a*) heavy and varied colonization of a plastic slab recovered by hard bodied encrustations and soft fleshy epibionts; (*b*) cuttings from a tangled mass of synthetic rope, carrying a cargo of the warm-water Indo-Pacific oyster, *Lopha cristagalli*, a species that is alien to New Zealand waters; (*c*) plastic pellet encrusted by the bryozoan *Membranipora taberculata*; (*d*) small bryozoan colony attached to a frayed plastic flake (arrowed) recovered from a depth of 393 m off the east coast shelf of the South Island; scale bar 200 μm (Source: Gregory, 2009).

Figure 3.3: From top left to bottom right: a tracking buoy mounted on floating debris with marine species attached; a sieve showing a surface oceanic sample containing plastic remains and crabs; the plastic particles from the stomach of a rainbow runner; a plastic bottle colonized by planktonic organisms; and the microbial degradation of two macroplastic items (Source: AMRF).

3.2. The transport of invasive species

It is worth noting that among the environmental problems induced by plastic pollution, the impact of marine plastic debris as a transport vector for invasive (alien) species is one of the less recognized and documented problems. Before the introduction of synthetic and non-biodegradable plastics fifty years ago, the slow trans-oceanic dispersal of marine and terrestrial organisms was limited to the relatively rare floating terrestrial plant matter and other natural flotsam (such as floating tree trunks or logs, pumice or seashells). These materials create hard-substrate habitats that attract a wide range of sessile and mobile marine organisms that include (macro-) algae, invertebrate and fishes (Thiel and Gutow, 2005). The huge amount of plastic debris released to the oceans during the last decades has created an attractive and alternative hard surface substrate for a number of opportunistic colonizers (Fig. 3.2). Floating plastics can persist degradation at the sea surface for long time periods and therefore rapidly become colonized by marine organisms which get carried, as alien species, over long distances, potentially changing the biodiversity and the equilibrium of native ecosystems (Barnes *et al.*, 2009; Gregory, 2009). Surface drift enhances the possibility that animals and plants are transported to areas remote from their source, where they are non-native and were previously absent. The invasion by such unwanted alien species and possibly aggressive invasive species can be detrimental to littoral, intertidal and shoreline ecosystems; especially for the endangered (both marine and terrestrial) flora and fauna of conservation islands or at-risk coastal environments (Gregory, 1999). Hence, the dangers are probably the greatest where endemism is significant, such as in the remote tropical and mid-latitude islands of Oceania, and in the isolated sub-polar islands that could be particularly threatened in the forthcoming years due to global warming and enhanced summer sea ice melting (Gregory, 2009).

Microplastics are also present in remote and deep sea pelagic areas where the concentration of plankton is controlled by the relatively low amount of terrestrial nutrients that limit their development. Sea surface sampling in the North Pacific Subtropical Gyre conducted in 2001 by the Algalita Marine Research foundation (AMRF) indicates that the mass of plastic in the gyre was 6 times that of plankton, even though the plankton outnumbered the plastic particles (Moore *et al.*, 2001). A similar study conducted in summer 2010 in the North Western Mediterranean Sea points out that the mass of neustonic plastic particles was 2 times that of zooplankton (with values similar to those in the North Pacific Gyre), but also that microplastic concentrations in surface water were 5 times higher before mixing by a strong wind event which increased vertical repartition of plastic particles in the upper water column (Collignon *et al.*, 2012). The comparison between the quantity of plastic particles and the abundance of plankton in the surface waters is challenging, because the planktonic primary productivity highly varies during the year (with a maximum of plankton in spring) and through the water column (the major part of the plankton is not present in the uppermost waters). Moreover, unlike microplastics which are passive particles, zooplankton species are relatively little affected by wind stress and mixing in the ocean boundary layer, because they can swim to maintain their distribution in the ocean surface boundary layer (Collignon *et al.*, 2014). Consequently, the quantification of the amount of buoyant plastic distributed in the upper water column should be corrected according to the wind speed measured during the sampling (Kukulka *et al.*, 2012).

The collection of water samples from the surface of oceanic gyres using a Manta trawl (a fine mesh net pictured in Fig. 2.1**)** shows large amounts of plastic debris originating from a wide and diverse range of sources, but also different organisms living amongst or attached to the plastics (Fig. 3.3). Actually, floating pelagic plastic items provide a hard substrate for marine organisms that last much longer than most natural floating substrates (e.g. plant or animal parts), and which are commonly colonized by a diversity of encrusting and fouling marine organisms such as bacteria, algae, barnacles, bryozoans, tube worms, foraminifera, hydroids, tunicates and mollusks (Clark, 1997). A recent study demonstrates that the microplastic concentrations in the North Pacific Subtropical Gyre have increased by two orders of magnitude over the past four decades, and that this increase has released the pelagic insect *Halobates sericeus* from substrate limitation for egg deposition (oviposition), with an overall increase in egg densities (Goldstein *et al.,* 2013). However, despite the facts that invertebrates are a critical link between primary producers and nekton (actively swimming aquatic organisms) and that plastic-induced changes in their population structure could have ecosystem-wide consequences, there is to-date a lack of knowledge about the effects of oceanic plastic debris on pelagic invertebrate communities.

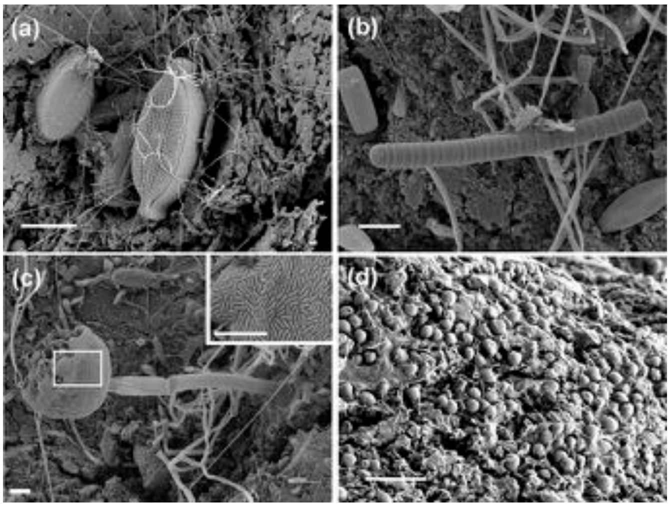

Figure 3.4: SEM images showing examples of the rich microbial community on plastic marine debris: (a) pennate diatom with possible prosthecate filaments produced by Hyphomonas-like bacteria; (b) filamentous cyanobacteria; (c) stalked predatory suctorial ciliate in foreground covered with ectosymbiotic bacteria (inset) along with diatoms, bacteria, and filamentous cells; (d) microbial cells pitting the surface of a sample. All scale bars are 10 µm (Source: Zetter *et al*., 2013).

Plastic marine debris also provides an artificial hard substrate for microbes, as recently demonstrated by Scanning Electron Microscopy (SEM; Fig. 3.4) and gene sequencing analyses of polyethylene (PE) and polypropylene (PP) pelagic plastics collected in the North Subtropical Gyre and Arabian Sea in India; which identify a diverse microbial community referred to as the "plastiphere" (Zettler *et al*., 2013; Harshvardhan and Jha, 2013). These plastisphere communities are distinct from the surrounding surface seawater and indicate that plastics serve as a novel ecological habitat in the open ocean; whereas the identification of several hydrocarbon-degrading bacteria support the possibility that microbes play an important role in degrading plastic marine debris (Zettler *et al.*, 2013). Future research is however needed to better understand the biodegradation of plastics by microorganisms and enzymes in natural environmental conditions (aerobic and anaerobic conditions in seawater and sediment) and for the possible development of innovative biotechnological processes that could facilitate the bioremediation of contaminated (waste) waters by plastics.

3.3. Chemicals associated with plastics debris

Despite the fact that the United Nations Environment Program (UNEP) has declared plastic marine debris and its ability to transport harmful substances one of the main emerging issues in our global environment, little is known about the impact of ingested plastics that potentially contain high amounts of toxic chemicals on their surfaces; as well as regarding the possible bioaccumulation of the associated pollutants and their interaction at organism and ecosystem levels. Moreover, there is a growing concern about the negative health effects of some additives (added to the polymers during the manufacturing process) to which most people are exposed, such as phthalates or bisphenol A **(**BPA) because they are not chemically bound to the plastic matrix and they can easily leach into their surrounding environment; especially when plastics breakdown in smaller pieces and more surface area is exposed to degradation. Experiments furthermore demonstrate that hard plastic trash discarded in the oceans leaches BPA at an accelerated rate when exposed to the salts in seawater (Sajiki and Yonekubo, 2003) and that biodegradation of plastic polymers by bacteria introduces BPA into seawater (Artham and Doble; 2009). Recent studies also show that BPA which was originally developed by the medical industry to be a synthetic estrogen, leaches from the millions of gallons of epoxy plastic paint used to protect the ship hulls from corrosion and fouling with barnacles and other deposits (Saido *et al*., 2010). Although major concern remains about the unknown impacts of the chemicals leached by plastics on marine food chain and concerning potential human health risks, laboratories experiments using aquatic organisms (e.g. molluscs, crustaceans and amphibians) demonstrate that most plasticizers appear to act by interfering with the functioning of various hormone systems (with some phthalates having wider pathways of disruption). There is also a lack of knowledge concerning the long-term exposure to environmentally appropriate concentrations of plastic, and about the ecotoxicity of the complex mixture of plastic materials (Oehlmann *et al*., 2009), while a recent study suggests that ingestion of microplastic by aquatic species does not lead to a relevant exposure to plastic additives (Koelmans *et al*., 2014).

Another major concern for marine organisms is that floating plastics in the ocean can serve as transport vectors for persistent organic pollutants (POPs) that accumulate on their surface (adsorption) during their long residence time in polluted surface water. POPs are persistent synthetic organic compounds with a hydrophobic nature, chemically stable and not easily degraded in the environment. Some of the pollut-

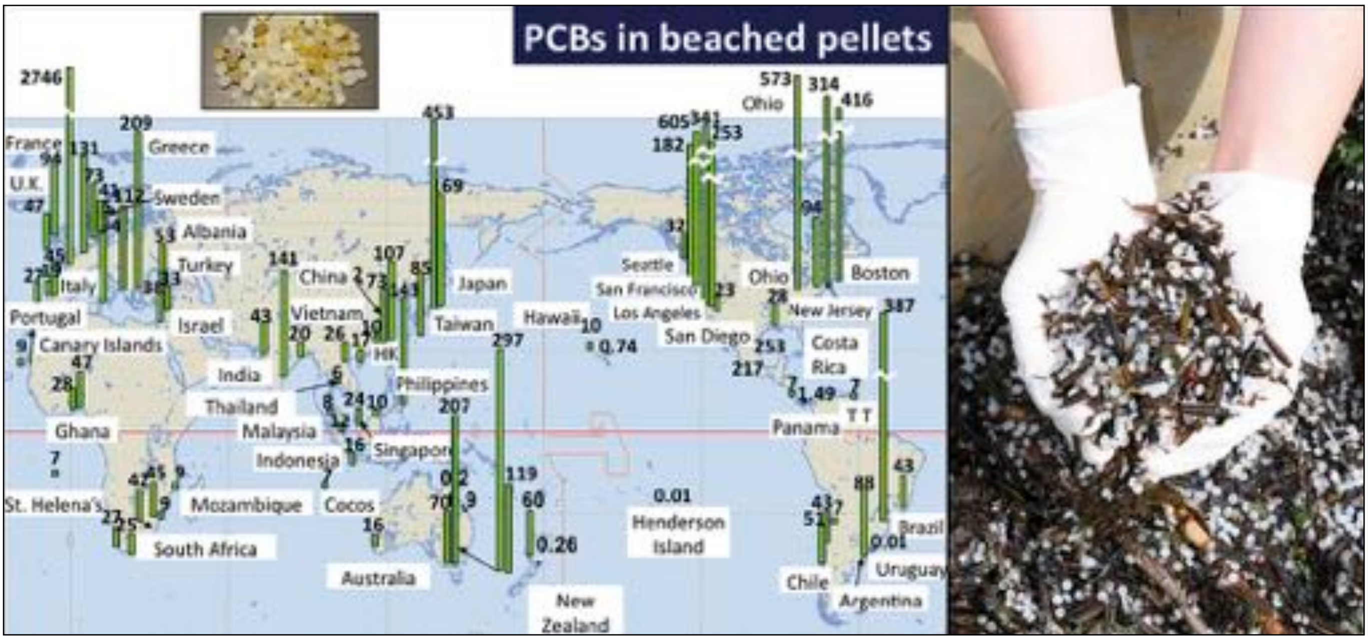

Figure 3.5: The concentrations of toxic Polychlorinated Biphenyls (PCBs) measured in beached plastic resin pellets (in nanograms per gram of pellet) show the highest values in pellets collected at beaches from United States, Western Europe and Japan.
(Source: http://www.pelletwatch.org).

ants released by human activities that are transported to the oceans via atmospheric deposition and stream-river drainage are hydrophobic or lipophilic (i.e. a high affinity for oils and fats) and resistant to natural degradation processes. Thus floating plastics collect and magnify toxic organic contaminants (and inorganic pollutants such as heavy metals; Rochman *et al.*, 2014) if their residence time in polluted waters is long enough. For instance, over 50% of the plastic particles collected in the North Pacific Gyre, which included intact plastic items as well as many pieces smaller than 5 mm in size, contained polychlorinated biphenyls (PCBs), 40% contained pesticides, and nearly 80% contained polycyclic aromatic hydrocarbons (PAHs) (Rios *et al.*, 2010). It is however important to note that the concentration of chemicals associated with plastic debris via environmental sorption is primarily controlled by the pollution of the surrounding waters and therefore by transport pathways, conversely to the concentration of chemicals associated to the manufacturing process (plastic additives). Marine plastics are passive captors that first act as a sink for POPs, but they can also release hazardous pollutants to seawater if they are subsequently transported towards less polluted waters. Experiments in the marine environment additionally reveal that some polymers (especially polystyrene, PS) sorbed greater concentrations of PAHs than others (from 8 to 200 times) and may therefore pose a higher risk of exposure to PAHs upon ingestion (Rochman *et al.*, 2013a).

Plastic pellets are the industrial raw material that is used to manufacture plastic products and that are shipped to factories all over the world to make plastic bottles, caps, bags and packaging. Some plastic pellets have been introduced through accidental releases into the ocean where they accumulate POPs, with PCBs concentration up to million times higher than in the surrounding seawater (Mato *et al.*, 2001). Hence, the consistent size of the plastic resin pellets makes them a useful monitoring tool and they can be used to map the distribution of POPs in the coastal waters around the world after their collection on beaches (Ogata *et al.*, 2009; International Pellet Watch 2011; Fig. 3.5). POPs are highly toxic chemicals which can trigger a wide range of chronic effects, including endocrine disruption and cancer-causing mutations but it is yet unknown how these pollutants that are absorbed into the organisms through the ingestion of microplastics accumulate up in the food chain. Recent experiments carried out on marine zooplankton in laboratories containing relatively high concentration of fluorescent plastic microbeads (Fig. 3.6) nonetheless demonstrate (i) the ingestion (and egestion by fecal pellets) of micrometer polystyrene beads by a variety of zooplankton taxa (mysid shrimps, copepods, cladocerans, rotifers, polychaete larvae and cliliates), and (ii) the transfer of microplastic particles via planktonic organisms from one trophic level (mesozooplankton) to a higher level (macrozooplankton) (Cole *et al.*, 2013; Setälä *et al.*, 2014). Although the residence time in the organism of the ingested plastic marine debris was relatively short (few hours), further research is needed to understand how the contaminated marine plastics sorb and then release pollutants to the tissues of organisms. Recent studies nevertheless demonstrate that the ingestion of contaminated microplastics by different marine organisms (lugworm and fish) can transfer pollutants and additives to their tissues at concentrations sufficient to disrupt ecophysiological functions linked to health and biodiversity (Besseling *et al.*, 2013; Browne *et al.*, 2013; Rochman et al, 2013). These studies also point out that the extent and rate of desorption from plastic are influenced by numerous parameters, such as the chemical composition of the plastic material and the sorbed pollutants that form complex mixtures with colloidal organic matter, but also by environmental conditions (e.g. grain-size and composi-

Figure 3.6: Bioimaging techniques (fluorescence microscopy) showing the ingestion, egestion, and adherence of microplastics (1.7–30.6 µm polystyrene beads) in a range of zooplankton common to the northeast Atlantic (Source: Cole *et al*., 2013).

Figure 3.7: Elephant seal females do not travel to the sea for feeding during the lactation period (~25 days) when they can lose about 180-235 kg (35% of their body mass). The lipids present in the milk come from the blubber mobilization which contributes to the transfer of lipophilic contaminants to the young. © Gerick Bergsma 2009/ Marine Photobank.

tion of the sediment for the transfer of chemicals in the tissues of marine lugworms).

The transfer of plastic-derived chemicals from ingested plastics to the tissues of marine-based organisms has been also suggested by the greater concentrations of PCBs and polybrominated diphenyl ethers (PBDEs, which are applied to plastics and to textiles as flame retardants) found in seabirds with plastic in their stomachs than those who do not have (Yamashita *et al*., 2011; Tanaka *et al*., 2013). Higher brominated congeners of PBDEs measured in lanternfish sampled at stations from the pelagic South Atlantic Ocean containing greater plastic densities, also suggest that PBDEs in fish tissue may be an indicator of plastic contamination in marine habitats (Rochman *et al*., 2014b).

The biomagnification of POPs in trophic chains and food webs has been widely demonstrated from low latitude (e.g. Galapagos sea lion; Alava and Gobas, 2012) to high latitude (Arctic marine food webs; Borgå *et al*., 2004) remote areas, due to the global and long-range atmospheric transport of anthropogenic contaminants that do not easily degrade in seawater. Results of these studies also show that some key species can be used as eco-markers of marine environmental chemical pollution and key indicators of food web contamination (local sentinels or bio-indicator). Moreover, the increase of anthropogenic organic chemicals in end members increases the transfer of lipophilic contaminants to the young marine mammals and therefore the risk of adverse health effects on the developing endocrine or immune system. In cetaceans and pinnipeds, more than 90% of organochlorine contaminants present in neonates are transferred through milk, greatly exceeding gestational transfer before birth (Addison and Stobo, 1993; Borrell *et al*., 1995). Studies on pups of elephant seals (top marine predators) from the North and South Pacific Ocean demonstrate that pups accumulate contaminants through maternal transfer via transplacental and lactational routes and that concentration of organochlorine contaminants generally increase from pups to juveniles to adults (Fig. 3.7) (Debier *et al*., 2006; Miranda Filho *et al*., 2009).

CONCLUSION

Future ecotoxicological studies are needed to assess the harmful effects of plastic material ingestion, especially regarding the transfer of adsorbed pollutants and additives towards high trophic levels in the food web. There are an increasing number of scientific studies focusing on the bioaccumulation of the chemicals associated to plastic debris and about their potential to affect organisms ranging from zooplankton to top predator fish species. Consequently, inadvertent plastic material ingestion represents a threat for marine organisms living in polluted waters, with possible public health concerns for the consumption of fish and seafood living in polluted waters enriched in microplastics. These recent findings strengthen the need for a better assessment of the extent of marine plastic pollution (characteristics, sources, accumulation zones, transport pathways and sedimentation), as well as the necessity to regulate the manufacturing of polymer substances and plastic additives at an international level. In addition to requirements for industry guidelines, there is a general need to improve the plastic waste management and the valorization of plastic wastes (recycling or source of energy through incineration) for protecting marine biodiversity and ecosystems. The present disintegration of large quantities of plastic into small plastic debris (microplastics) as well as the emission of microplastics and microbeads present in consumer products, which will remain for decades to centuries in the marine environments, necessitates a rapid international mobilization to reduce significantly the plastic concentration in the world’s oceans.

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4. Existing legislation and related initiatives

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INTRODUCTION

Ever since the first reports of marine plastic debris impacting on marine species were published in the early 1960's (GEF, 2012) there has been an increase, across the globe, of not only the number of initiatives designed to better understand the issues surrounding marine plastic debris, but also efforts to reduce the overall quantities of plastic input into the world's oceans. Efforts have been both specific to plastic and to the wider problem of marine debris itself, and in many cases the objectives of filling knowledge gaps (e.g. monitoring) and reducing the inputs have been entwined; in that without knowing the distribution, scale and sources of marine debris, it becomes less clear as to the sorts of measures that should be applied and the effect they might have. Because the wider problem of marine debris is fundamentally associated with waste management, efforts to reduce marine plastic debris have also been direct (i.e. those measures designed specifically to prevent the input of plastics into the marine environment) and indirect (i.e. those initiatives that were designed to tackle multiple solid waste streams but which might also reduce the amount of plastics entering the marine environment). Such initiatives have evolved at local, national, sub-regional, regional and global levels and the current situation when assessed at each level includes a mix of voluntary and legally binding exercises.

4.1 Global level initiatives

Since the 1970's a range of initiatives at the global level have been put in place that have been designed to either directly or indirectly address marine plastic debris and the inputs from sea-based and land- based sources. Most of the relevant resolutions concern all marine debris (or otherwise known as marine litter) items and thus can be considered applicable to marine plastic pollution. Below is a summary of some of the key initiatives at the global level:

The United Nations (UN) Convention on the Law of the Sea (UNCLOS) provides the most overarching legal framework that relates to marine plastic pollution. Articles 207 through until 211 refer to the prevention, reduction and control of pollution in the marine environment and here States are called on to adopt laws and regulations, and if relevant through competent international organisations, to prevent, reduce and control pollution of the marine environment from land-based sources, sea-bed sources, by dumping, and from maritime vessels. It also calls on States to take measures as necessary to prevent, reduce and control such pollution and that policies should be harmonized at the regional level.

In 2005 and 2008, the UN General Assembly also delivered important overarching resolutions that relate to both land and sea-based sources of marine plastic pollution including that of "Resolution S/60/L.22":

> "65. Notes the lack of information and data on marine debris, encourages relevant national and international organizations to undertake further studies on the extent and nature of the problem, also encourages States to develop partnerships with industry and civil society to raise awareness of the extent of the impact of marine debris on the health and productivity of the marine environment and consequent economic loss;
>
> 66. Urges States to integrate the issue of marine debris within national strategies dealing with waste management in coastal zones, ports and maritime industries, including recycling, reuse, reduction and disposal, and to encourage the development of appropriate economic incentives

to address this issue, including the development of coastal recovery systems that provide an incentive to use port reception facilities and discourage ships from discharging marine debris at sea, and encourages States to cooperate regionally and subregionally to develop and implement joint prevention and recovery programmes for marine debris;"

And "Resolution A/60/L.3", whereby the General Assembly:

77. Calls upon States, the Food and Agriculture Organization of the United Nations, the International Maritime Organization, the United Nations Environment Programme, in particular its Regional Seas programme, regional and subregional fisheries management organizations and arrangements and other appropriate intergovernmental organizations that have not yet done so, to take action to address the issue of lost or abandoned fishing gear and related marine debris, including through the collection of data on gear loss, economic costs to fisheries and other sectors, and the impact on marine ecosystems;

A more recent development concerns the recognition of plastic marine debris as an emerging global issue (UNEP, 2011) and during the run-up to the 2012 conference of the United Nations Convention on Sustainable Development (Rio + 20), a resolution was adopted in the 'Future we want' outcome document that highlighted plastic as one of the key concerns surrounding marine debris and includes the following commitment:

"163. We note with concern that the health of oceans and marine biodiversity are negatively affected by marine pollution, including marine debris, especially plastic, persistent organic pollutants, heavy metals and nitrogen-based compounds, from a number of marine and land-based sources, including shipping and land run-off. We commit to take action to reduce the incidence and impacts of such pollution on marine ecosystems, including through the effective implementation of relevant conventions adopted in the framework of the International Maritime Organization (IMO), and the follow-up of the relevant initiatives such as the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities, as well as the adoption of coordinated strategies to this end. We further commit to take action to, by 2025, based on collected scientific data, achieve significant reductions in marine debris to prevent harm to the coastal and marine environment."

The above mentioned commitment on marine debris is significant because it obliges parties to the resolution to not only commit to make reductions in marine debris by 2025, but by virtue of doing so, have in place monitoring programmes that enable measurement of the amount of marine debris. The requirements of both achieving significant reductions in marine debris, and monitoring thereof, are two actions that on a global level are seemingly far from operational.

Concerning plastic marine debris that is sourced at sea from either maritime vessels or stationary platforms at sea, the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) is the overarching piece of international legislation that is relevant here. Annex V of the Convention considers the production and management of garbage (including plastics) and it outlines a range of obligations on Member States to the Convention including an outright prohibition on the dumping of plastic at sea. This requirement first came into force in 1988. In addition here, Annex V also considers the role of port waste reception facilities and obliges Member States to provide adequate facilities for the reception of waste.

Annex V of MARPOL also relates to fishing-based sources of marine debris, which will include gear made from plastic, and has specific obligations relating to abandoned, lost, or otherwise discarded fishing gear (ALDFG) - such as an obligation on States to ensure the reporting of ALDFG. Although not a further legally binding agreement, the FAO's Code of Conduct for Responsible Fisheries also outlines recommendations concerning the management of garbage and fishing gear.

Beyond the legally binding agreements adopted at the global level, there have been several other overarching initiatives that address marine debris. This includes the "Honolulu Strategy: A Global framework for the prevention and management of marine debris" (otherwise known as the Honolulu Strategy) that was developed in 2011 through a multi stakeholder process and supported by UNEP and the US National Oceanic and Atmospheric Administration (NOAA). In essence the strategy lays out a relatively detailed approach to tackling marine debris and gives guidance as towards the monitoring of marine debris and the sorts of measures that could be applied.

In 2012, 64 governments and the European Commission adopted the Manila Declaration which concerns the implementation of UNEP's Global Programme of Action for the Protection of the Marine Environment from Land-based Activities. Here, signatories to the declaration made a commitment to developing policies to reduce marine debris, and other land-based forms of pollution that affect the marine environment. The agreement contains a total of 16 provisions focusing on actions to be taken between 2012 and 2016 at international, regional and local levels.

In the Manila Declaration signatories also agreed to establish what is now known as the Global Partnership on Marine Litter (GPML) (launched in June 2012) and whos work would be guided by the previously mentioned Honolulu Strategy. Although the focus of the Manila Declaration is on land-based sources of pollution, the goals of the GPML (and those of the Honolulu strategy) are also to include sea-based sources of marine debris as outlined below:

Goal A: Reduced levels and impacts of land-based litter and solid waste introduced into the aquatic environment;

Goal B: Reduced levels and impact of sea-based sources of marine debris including solid waste, lost cargo, ALDFG, and abandoned vessels introduced into the aquatic environment;

Goal C: Reduced levels and impacts of (accumulated) marine debris on shorelines, aquatic habitats, and biodiversity.

There are also a number of legally binding agreements that concern wider environmental topics than just marine debris, but also give consideration to either marine pollution in a ge-

Type of garbage	Ships outside special areas	Ships within special areas	Offshore platforms and all ships within 500 m of such platforms
Food waste comminuted or ground	**Discharge permitted** ≥3 nm from the nearest land and *en route*	**Discharge permitted** ≥12 nm from the nearest land and *en route*	**Discharge permitted** ≥12 nm from the nearest land
Food waste not comminuted or ground	**Discharge permitted** ≥12 nm from the nearest land and *en route*	**Discharge prohibited**	**Discharge prohibited**
Cargo residues[1] not contained in wash water	**Discharge permitted** ≥12 nm from the nearest land and *en route*	**Discharge prohibited**	**Discharge prohibited**
Cargo residues[1] contained in wash water		**Discharge only permitted in specific circumstances**[2] and ≥12 nm from the nearest land and *en route*	**Discharge prohibited**
Cleaning agents and additives[1] contained in cargo hold wash water	**Discharge permitted**	**Discharge only permitted in specific circumstances**[2] and ≥12 nm from the nearest land and *en route*	**Discharge prohibited**
Cleaning agents and additives[1] contained in deck and external surfaces wash water		**Discharge permitted**	**Discharge prohibited**
Carcasses of animals carried on board as cargo and which died during the voyage	**Discharge permitted** as far from the nearest land as possible and *en route*	**Discharge prohibited**	**Discharge prohibited**
All other garbage including plastics, domestic wastes, cooking oil, incinerator ashes, operational wastes and fishing gear	**Discharge prohibited**	**Discharge prohibited**	**Discharge prohibited**

Figure 4.1: Simplified overview of the discharge provisions of the revised MARPOL Annex V which entered into force on 1 January 2013 (Credit IMO).

neric sense or indeed have taken decisive action on marine debris specifically. There is evident reason here for these potential actions to consider marine plastic pollution and its effect on marine biodiversity. This would include for instance:

COP Decision X/29 of the Convention on Biological Diversity, that states in Article 70 the request of contracting parties to "mitigate the negative impacts and risk of human activities to the marine and coastal biodiversity". In addition, the Annex to this Decision also encourages the use of environmental impact assessments (EIAs) and strategic environmental assessments (SEAs) in relation to activities that may cause marine pollution. It is also interesting to note the recommendations of the CBD's scientific advisory body known as the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA). At the 16th meeting of the SBSTTA, in 2012 parties to the convention were recommended to not only submit information on the impacts of marine debris on marine and coastal biodiversity, but also a request was made to set up regional capacity-building workshops on the issue of marine debris in order to discuss ways to prevent and reduce their impacts on biodiversity and strengthen research on the reduction and management of marine debris.

Resolution 10.4 of the Convention on Migratory Species (CMS) that was adopted in 2011, includes a list of voluntary actions such as encouraging parties to the Convention to: Identify marine debris hotspots and to assess the impacts; develop regional approaches to marine debris; and develop and implement national action plans. The resolution also has instructed its scientific council to: Explore the effect of marine debris on migratory species; to consider best practice concerning waste management on maritime vessels; and to evaluate issues surrounding the public awareness of marine debris. IUCN's Global Marine and Polar Programme is currently involved in a consortium that is exploring these issues at the request of the CMS.

Being that marine plastic pollution is fundamentally linked to waste management, it is also important to consider global initiatives on such a topic. Although there is no overarching legally binding instrument that concerns waste management in its entirety, there have been some developments of relevance here such as:

The UNEP Governing Council decision 25/8 on waste management asks for integrated and holistic efforts on waste management and the need for governments to further develop national policy frameworks to "shift from an end-of-pipe approach in waste management to an integrated waste management approach". Such desires again have a relevance to marine plastic pollution when considering that many plastic items that enter the marine environment are products that have been designed for short life. And hence, in order to tackle marine plastic pollution, it would mean for waste management practices to further instil the internationally recognised approach to Integrated Solid Waste Management (UNEP, 2011), including the waste management hierarchy and the principles of the 3Rs - reduction, reuse and recycling.

Figure 4.2: Waste Hierarchy, according to the Zero Waste International Alliance (Credit: Zero Waste International Alliance).

Being that the Basel Convention concerns hazardous waste and the disposal there-of, its relevance here is perhaps less obvious. Although many marine debris items might be defined as hazardous under the Convention, only solid plastic waste items that exhibit hazardous characteristics (as listed in the Convention) would be applicable here (UNEP, 2005). It is interesting to note that an article in Nature in 2013 (Rochman et al, 2013) by a group of scientists proposed that some plastic waste should in fact be considered as hazardous. Parties to the Basel Convention in 2008 also adopted the Bali Declaration on "Waste Management for Human Health and Livelihoods." Here, the declaration encourages States to take action in order to develop waste management practices that further consider health issues surrounding waste production. Because of the known health risks posed by marine debris items that are plastic, there is clear reasoning for marine plastic pollution to be considered in this context.

Launched in 2010, UNEP's Global Partnership on Waste Management (GPWM) operates as a platform for international agencies, governments, businesses, academia, local authorities, and non-governmental organizations. The GPML (described earlier) in fact is expected to feed into the GPWM, with the latter aiming to enhance international cooperation, identify and fill information gaps, share information and strengthen awareness, political will, and capacity to tackle waste production. Being that marine plastic pollution again is fundamentally linked to waste management, such a platform again has a relevance here when considering how plastic waste can be reduced.

4.2. Regional level initiatives

It is also important to consider the context of relevant initiatives at the regional and national level, and here there are numerous initiatives to consider in this context. Because there are so many initiatives of relevance to marine plastic pollution at the regional and national level, the intention of this section is not to review all existing initiatives but to give an overview of some of the most specific initiatives (to marine plastic pollution) in place across the globe.

UNEP's Global Initiative on Marine Litter, that has been coordinated by UNEP/GPA and UNEP's Regional Seas Programme, has paved the way for a range of initiatives in 12 regional seas. The programme has led to several different actions taking place, including the following:

1) Preparation of a review and assessment of the status of marine litter in each region;

2) Organization of a regional meeting of national authorities and experts on marine litter;

3) Preparation of a regional action plan (or a regional strategy) on the sustainable management of marine litter in each region;

4) Participation in a regional cleanup day within the framework of the International Coastal Cleanup Campaign.

The regional seas that have been involved in the programme are the: Baltic Sea, Black Sea, Caspian, East Asian Seas,Eastern Africa, Mediterranean, Northeast Atlantic, Northwest Pacific, Red Sea and Gulf of Aden, South Asian

Figure 4.3: The 12 Regional Seas participating in UNEP-assisted marine litter activities (UNEP, 2009).

Seas, Southeast Pacific, and Wider Caribbean. According to UNEP's overview of this work that was carried out in 2009, 12 regions have prepared review documents, seven regions prepared regional action plans; nine regions have organized regional meetings of national authorities and experts on marine litter; and all 12 regions have participated in the International Coastal Cleanup Campaign – a global programme involving voluntary beach clean up exercises.

Taken at a wider regional level, the European Union's Marine Strategy Framework Directive (MSFD) is the only legally binding approach to tackle marine debris. The Directive was published in 2008 and aims to tackle several threats including that of marine debris (or otherwise known as marine litter in the MSFD). In essence, the MSFD is a Europe wide legislative initiative that utilises the ecosystem approach to improve the management of human activities that impact on the marine environment. Central to the Directive are the concepts of environmental protection and sustainable use of resources and it also requires a collaborative approach by countries across the European Union and further cooperation within regional seas authorities. The first cycle of the MSFD will result in an assessment of Europe's marine waters by the middle of 2020 and whereby progress towards achieving what is known as Good Environmental Status will be evaluated (the MSFD will undergo consecutive 6-year assessment cycles). Member States of the EU are required to monitor their marine environment and set targets to be achieved by 2020. By 2016 Member States are required to have entered into operation a programme of measures to ensure that their targets are met (IEEP, 2013).

At the time of writing, targets proposed by Member States are now under review by the European Commission, and it has also been proposed in the EU's 7th Environment Action Programme to explore options to set an EU-wide quantitative reduction headline target for marine litter and an associated consultation was run in 2013 on setting of such a target.

4.3 National level initiatives

There are numerous examples of where nations have put in initiatives that address marine debris and many are in essence voluntary initiatives and not legally binding. There is however a distinct lack of specific legislation on marine debris and this lies in the fact that it is considered either directly or indirectly through solid waste management legislation. This comes back to the point made earlier that because waste management is inherently linked with marine debris, efforts to prevent waste production, are also in effect efforts to tackle marine debris and marine plastic pollution. Here, it is the case that almost every urban municipality across the globe will have some form of legislation related to solid waste management. For the purpose of this paper, a review of such initiatives is not considered necessary but it is important to note that because waste management and marine plastic pollution are fundamentally linked, for initiatives to be effective in tackling marine plastic pollution, national solid waste management initiatives should also further consider how to tackle marine plastic pollution. This is perhaps underlined by the fact that municipal solid waste generation is estimated by the World Bank to be at approximately 1.3 billion tons per year, and is expected to increase to around 2.2 billion tons per year by 2025 (World Bank, 2012).

When considering waste management, it is also important to consider measures to treat waste water as sewage outlets are one of the key sources of marine debris. Waste water can include items such as sanitary towels, tampons, plastic cotton and wool bud sticks (all of which might have plastic parts), and microplastic items such as plastic fibres from clothes. At the European level for instance the EU Urban Waste Water Treatment Directive requires that all Member States must ensure that sewerage discharges serving populations over 10,000 in coastal areas and 2,000 in estuarine areas must receive secondary treatment prior to discharge (Interwies et al, 2013). In other less developed regions across the world, the situation regarding measures to tackle waste water treatment are certainly less advanced and it is estimated that 90% of all waste water in developing countries is still discharged directly without treatment into rivers, lakes and oceans (Corcoran *et al*., 2010).

There are however, some notable examples of national and sub-national efforts that are directly associated with marine debris and marine plastic pollution, including but not limited to the following examples:

> In the US there are two key pieces of legislation related to marine debris that are the Marine Plastic Pollution Research and Control Act, and the Marine Debris Research, Prevention and Reduction Act. The former piece of legislation requires further efforts to explore the impacts of marine plastic pollution and measures to reduce plastic pollution, whilst the latter piece of legislation is more concerned with exploration of measures to reduce marine debris and identifications of sources.
>
> In South Korea, between 1999 and 2009, the Practical Integrated System for Marine Debris was in existence and which has in essence utilised an approach to prevent the production of waste, remove debris from the marine environment and where possible treat and recycle the collected debris (CBD, 2012).
>
> A draft 'Scottish marine litter strategy' has been developed by Scotland, and underwent a period of consultation in 2013. The draft strategy includes several objectives including the desire to 'build on the strengths of existing measures, identify proposals that will help overcome weaknesses, and maximise opportunities and minimise threats to addressing the levels of litter present in the coastal and marine environment.'
>
> In 2009 Australia launched what is known as the Threat Abatement Plan (TAP), with the aim of providing a national approach to tackling marine debris. The TAP's objectives include preventing inputs of marine debris, removing existing marine debris and implanting a monitoring programme for the purpose of gauging quantities but also to assess the effectiveness of prevention measures.

Measures targeting specific plastic solid waste items have also been put in place at the national level that might have also had a likely affect on marine plastic pollution. Here, because there are so many different plastic items that can and do end up as marine debris, a review of all relevant initiatives at the national level might uncover numerous relevant efforts. An example of where specific measures have been put in place to tackle a certain item includes that of the short life plastic bag. Over recent years several countries have put in place measures to deter the use of short life plastic bags including bans in different forms in Switzerland, Italy, China, South Africa, Kenya, Rwanda, Congo, Bangladesh, Mexico, Hong Kong, the state of San Francisco in the United States, and several states in Australia and India. Measures that can directly or indirectly affect the price of plastic bags (including the use of levies, charges and taxes) have been applied, for example, in Denmark, Ireland, Romania and South Korea as well as voluntary agreements in Belgium, New Zealand, Japan, and the state of Sao Paolo in Brazil (EC, 2013). Of course, marine plastic items come from numerous different sources other than just discarded plastic bags, and indeed other packaging related items that have been recorded as marine plastic have also been directly or indirectly targeted through national measures to curb waste production.

It is also important to consider the manner in which national efforts have approached the concept of extended producer responsibility (EPR). Here one example of EPR includes the use of container deposit schemes that have been put in place in countries in Europe and Asia, and in the US, Canada and Australia (mostly at a regional level within countries). Being that plastic containers such as bottles are often recorded as marine plastic pollution, the relevance here is clear. One of the longest running schemes has been that of the container deposit legislation in South Australia that was introduced in 1975 and later included within the Environment Protection Act. It has led to a return rate of approximately 80% for containers (Zero Waste SA, No Date) in South Australia. It is important to note that like with other measures earlier mentioned, the basis for implementing most container deposit schemes has not primarily or even partly been because of marine debris and marine plastic pollution.

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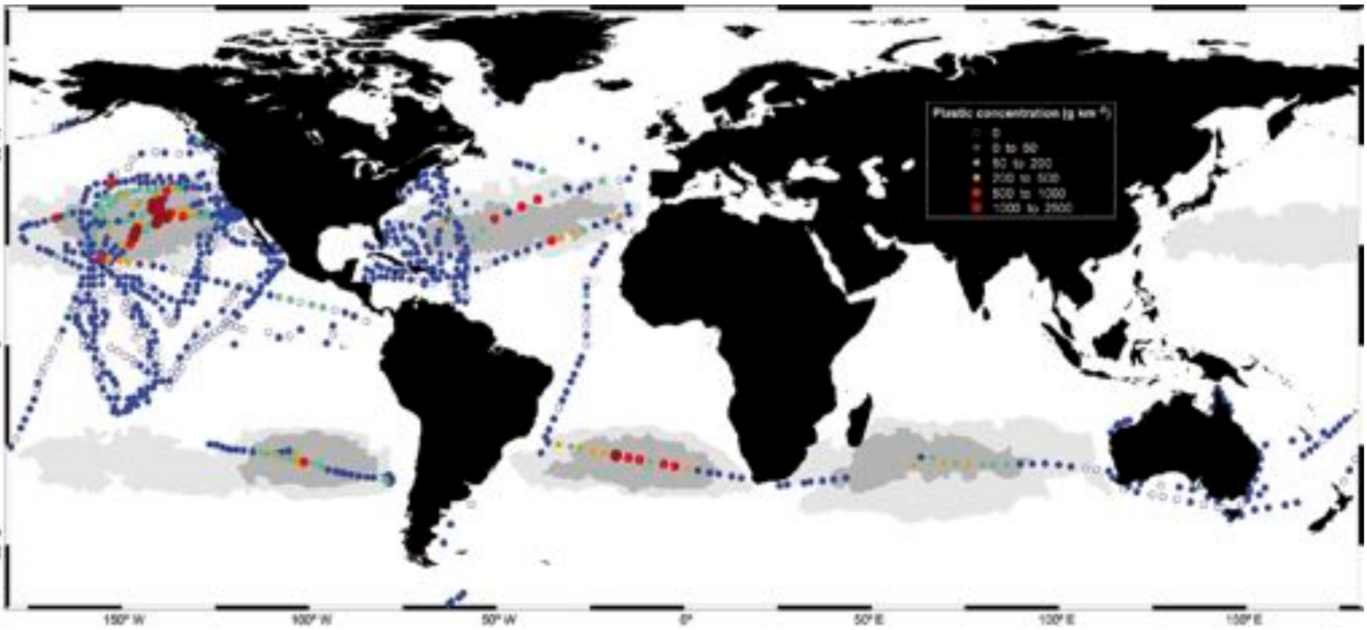
CONCLUSION

Being that the inputs of marine plastic pollution are both from land and sea-based sources, and being that marine plastic pollution does not lie static once present in the marine environment, in order to tackle the problem it is essential that initiatives are in place at the national, sub-regional, regional and international level. As things stand, there are clearly many relevant initiatives here, both indirectly in terms of solid waste management, but also directly in terms of marine debris specific approaches. However, marine debris and the specific problem of marine plastic pollution are, relatively speaking, emerging issues with a scattered array of initiatives in place across the globe. This is perhaps clearest at the regional level where there are only 7 reported regional seas action plans currently in place, and at the national level where there is very little in the way of marine debris specific legislation across the globe. It is also the case that there is a dearth of adequate national and regional marine debris monitoring programmes in existence and thus significant knowledge gaps, as highlighted by the CBD and CMS. When considering the commitment of a significant reduction in marine debris by 2025, as agreed under the Rio+ 20 Convention, it is clear that in order to measure such a decrease it would be essential at the very least to have adequate regional monitoring programmes and action plans in place across the globe, that are dedicated to marine debris and the specific concern highlighted here of marine plastic pollution. Being that marine plastic pollution and waste management practices are closely linked, it is also the case that if estimates for a growth in solid municipal waste by 2025 materialise, then a significant shift towards a truly integrated solid waste management approach is required.



Measurements of plastic concentrations without correction by wind conditions (non-corrected dataset). Color circles indicate mass concentrations (legend on top right). The dataset includes average concentrations in 851 sites (3070 surface net tows). Low estimate of plastic load was derived from this dataset (source: Cózar et al., 2014).

5. Summary and recommendations

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5.1. Plastics in marine environments

Plastic pollution is now recognized by the international community as the main priority issue for the protection of marine environment. There is an urgent need to increase public awareness about the adverse effects of plastic pollution on marine ecosystems and resources, in order to foster a sense of individual responsibility and to encourage public and private initiatives for reducing plastic pollution in the world's oceans.

Plastic pollution affects not only the coastal areas of developing countries that lack appropriate waste management infrastructures, but also the world's oceans because the slowly degrading large plastic items generate microplastics (particles smaller than 1 to 5 mm) which spread over long distances through ocean surface circulation. These plastic fragments will persist for decades to centuries due to their high resistance to natural degradation process in aquatic environment. In addition to high economic costs of plastic pollution for cleaning marine debris from harbors and beaches to maintain tourism revenues, floating plastics and lost fishing gears decrease fish stocks and damage the propellers of fishing and recreational vessels.

The ingestion of plastic fragments results in the entanglement and suffocation of hundreds of marine species. There are also major concerns about the accumulation in the food chain of the toxic chemicals that accumulate on the surface of the plastics during their long residence time in polluted seawaters. There is finally a lack of sufficient knowledge about the impact of the contaminants that are held in the structure of the plastics (plastic additives) and released during the degradation of the plastic in seawater.

To solve plastic pollution, we first need to close the tap, but also to better understand marine plastic sources and transport in order to develop mitigation strategies and targeted clean up options that must be efficient on a long-term perspective. Standardized monitoring data are therefore needed across countries and marine compartments (beaches, water column and sediments) to assess the extent (quantity and type of plastics) and impacts of plastic pollution, including the microscopic particles which are not visible to the human eye but have nonetheless adverse effects on marine organisms and biodiversity, as well as on the ecosystems that provide human services (e.g. fishing and tourism).

5.2. Sources of marine plastics

It is estimated that around 4% of the world's annual petroleum production is converted to plastics (synthetic organic polymers) while a similar amount of petroleum is used to provide the energy for plastic manufacturing. The annual global production of plastics is about 280 million tons per year. Europe is using about 50 million tons of plastic with almost 75% of the demand coming from four major sectors: Packaging, construction, automotive and electrical/electronics. Packaging represents more than a third of European plastic consumption and consists of products which have a very short life span. Less than 10% of the plastic is recycled; the rest is burned or sent to landfills.

Plastic debris now represents the main part of shoreline debris. Their presence was detected from the deep sea to shorelines (including remote islands) of the six continents, from the poles to the equator, with more plastic material near popular tourist destinations and densely populated areas. The majority of marine plastics come from land-based sources including urban and storm runoff, sewer overflows, beach visitors, inadequate waste disposal and management, industrial activities, construction and illegal dumping. Ocean-based sources principally derive from the fishing industry, nautical activities and aquaculture. For example, lost fishing nets and monofilament fishing lines have been found to drift thousands of kilometers, trapping and killing fish and seabirds as well as protected marine species such as turtles, dolphins or seals, through ingestion and entanglement.

Municipal waste stream represents an important source of microplastics, in the form of plastic fibers from washing synthetic clothes and microplastic scrub beads (e.g. polyethylene and polypropylene) used as abrasives in personal care products. These particles that are generally smaller than 1 millimeter

are designed to be washed down the drain and they are usually not captured by treatment screens in wastewater plants. These insoluble particles can be ingested by planktonic and filter feeding organisms at the base of the aquatic food chain.

The abundance of plastics in the marine environment highly varies spatially and temporally as a function of the distance to coastal populated areas and popular tourist destinations, as well as with the occurrence of heavy rain and flood events; but also with the speed and direction of the surface current which control the transport pathway and accumulation of plastic debris in coastal and pelagic areas.

5.3. Effects on marine organisms

The most visible and preoccupant impact of marine plastic pollution is ingestion, suffocation and entanglement of hundreds of marine species, including sea birds, turtles, fish, mussels, crustaceans and marine mammals. However, the effect of entanglement is largely underestimated as most victims are undiscovered over vast ocean areas when sunk or eaten by predators. There is evidence that some birds and marine species mistake plastic particles waste for potential prey items, and select specific plastic shapes and colors. Sea turtles often consume plastic debris and semi-inflated floating plastic bags drifting in ocean currents which look similar to their favorite natural prey, jellyfish. Albatrosses may mistake red plastic for squid, whereas the ingestion of plastic debris by seabirds is directly correlated to foraging strategies.

Even if not immediately lethal, entanglement can produce lacerations and infections from the abrasive or cutting action of attached litter, or impair the ability of animals to swim and therefore to find food or escape from predators; while plastics as part of the animal's diet reduce actual food uptake and cause internal injury and death following blockage of intestinal tract. Animals can get entangled by plastic floating at the sea surface, and in particular by derelict and lost fishing gear (or fishing nets, ropes, monofilament lines, trawl and gill nets) made of synthetic fibers that are resistant to degradation. These so called ghost nets continue to indiscriminately entangle and trap fishes and non-target organisms while they drift in the ocean over long distances.

Floating plastics that are presently the most abundant items of marine litter also indirectly threaten marine biodiversity and food chain. These materials create hard-substrate habitats that attract a wide range of sessile and mobile marine opportunistic colonizers which get carried as alien species over long distances, potentially changing the biodiversity and the equilibrium of native ecosystems.

Floating plastic particles accumulate toxic pollutants on their surface during their long-residence time in polluted seawater and can therefore represent a source of environmental pollution, or serve as a vector for toxic pollutants that accumulate in the food web (bio-accumulation of contaminants). The ingestion of plastic debris also concern small invertebrate organisms (e.g. amphipods, lugworms, barnacles and mussels) with possible implications for human health. Little is known about the impact of ingested plastics that potentially contain high amounts of toxic chemicals on their surfaces, and added to the polymers during the production process, as well as regarding the possible bioaccumulation of the pollutants and their interaction at organism and ecosystem levels.

5.4. Solutions and recommendations

There is today a global concern and an important public awareness regarding the impact of plastic ingested by marine species and concerning the accumulation of plastics in coastal and remote areas of oceans (trash vortex or gyres). Private and public initiatives, such as the volunteer beach cleanups and campaigns for removing beach debris, represent the major source of information concerning the amounts and types of marine litter; whereas regular cleaning by municipalities and public authorities to maintain beaches attractive to tourists and residents engenders major economic costs.

The implementation of action plans to reduce the input of marine plastic around the world needs to involve different stakeholders from the plastic, tourism and fishing industries, the research community, NGOs, local authorities and national governments, in order to effectively address socio-economic and environmental issues related to plastic pollution from a sustainable and global point of view.

There is a particular concern with coastal areas where solid waste stream must be minimized and landfills controlled, in order to prevent the discharge of plastics at sea (including by rivers and following rain and floods). Public awareness should be raised to reduce single plastic use (e.g. plastic bags and plastic bottles) and encourage people to re-use and recycle plastic waste.

Sufficient litter and recycling bins must be placed on beaches and in coastal areas. Commercial, municipal (household waste) and agricultural (packaging and construction materials) wastes must be collected from residential areas, streets, parks and waste dumps. Burning plastics with other wastes in incinerators should be preferred over dumping in landfills or littering, while this process can produce energy; but open-air combustion of plastics release hazardous chemicals to air, surface waters and soils from where they can enter the food-chain and be of concern to living organisms and human health.

Concerning marine areas, shipping, fishing and tourism industries should be informed about the necessity to prohibit throwing plastic wastes into the sea. Traditional fishing gears could be replaced by eco-friendly products. Fishermen and the public should be encouraged to participate to the monitoring and collection of marine litter.

Recycling or valorization of plastic materials are the most important actions available for reducing the environmental impacts of open landfills and open-air burning that are often practiced in developing countries to manage domestic wastes, and especially to stem the spread of ocean plastic pollution.

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Web ressources

Free and up-to-date web resources from the activities of several NGOs and international organizations help to raise public and political awareness of the global scale ot the plastic debris problems, together with the larger issue of marine litter.

The 5 Gyres Institute is a non-profit organization dedicated to researching the issue of plastics in the world's oceans. Utilizing scientific findings, 5 Gyres engages corporate partners, policymakers, and the general public to reduce plastic pollution by improving product design, recovery systems, and individual responsibility for plastic waste.

http://5gyres.org/

The National Oceanic and Atmospheric Administration (NOAA) is a federal agency focused on the condition of the oceans and the atmosphere.

The Marine Debris Program supports national and international efforts to research, prevent, and reduce the impacts of marine debris, and monitor beaches and surface waters for all debris types, including plastics.

http://marinedebris.noaa.gov/

Algalita Marine Research Institute is a California-based non-profit marine research and education organization dedicated to the protection of the marine environment and its watersheds through research, education, and restoration. They focus on the issue of plastic pollution and its effects on the marine ecosystem and potential risks to human health by conducting research on five different garbage patches.

http://www.algalita.org/

Project Kaisei is a non-profit scientific and commercial organization focused on increasing awareness of the scale of marine debris, its impact on our environment, and the solutions for both prevention and clean-up (expeditions and clean-up beaches).

http://projectkaisei.org/

Plastic Free Seas is a Hong Kong based non profit organisation dedicated to advocating change in the way we all view and use plastics in society today, through education and action campaigns. They provide assistance to education programs, beach cleanups and event, and business development.

http://plasticfreeseas.org/

The Ocean Health Index is a comprehensive new measure that scores ocean health from 0-100. It defines a healthy ocean as one that sustainably delivers a range of benefits to people, both now and in the future. The Index calculates an annual global score that reflects the current status, recent trends, and positive and negative influencers of ocean health in 133 countries, indicating sustainable achievement of goals.

http://www.oceanhealthindex.org/

International Pellet Watch is a volunteer-based global monitoring program designed to monitor the pollution status of the oceans. It is based on the fact that persistent organic pollutanta (POPs) accumulated in resin pellets (plastic raw material) from the surrounding seawater by a factor of millions, and it has demonstrated that marine plastics transport POPs in remote marine environments.

http://www.pelletwatch.org/

Plastic Oceans Foundation is a registered United Kingdom Charity dedicated to protecting and improving the environment.

Through a wide range of activities the Foundation will educate, provide a resource base for study and research, campaign for improvements in legislation and policy, raise funds for the development of solutions and develop a worldwide integrated social media network aimed at achieving the mission.

http://www.plasticoceans.net/

Plastic Pollution Coalition was created with the vision of a world free of plastic pollution and of the toxic impacts of plastic on humans, the environment, wildlife and marine life. It aims to create a collaborative space for community, synergy, strategy and support in the battle against plastic pollution. It does not replace the actions of any particular organization, but seeks to enhance them all, to provide opportunities to effectively collaborate with one another, and to amplify the voice of our common cause.

http://plasticpollutioncoalition.org/

Ocean Recovery Alliance is a non-profit organization that aims to bring together new ways of thinking, technologies, creativity and collaborations in order to introduce innovative projects and initiatives that will help improve our ocean environment.

http://www.oceanrecov.org/

Major reports about plastic litter in the ocean

Marine litter and in particular the worldwide accumulation of plastic debris in coastal and open marine environments since the last three deades is becoming a major concern because of adverse environmental, heatlh and economic effects. For about 10 years, the awarness for this growing threat to individual organisms, species and ecosystems has been recognised by the international community as as a priority issue for the protection of marine environment.

Many international organisations, including UN organisations and non governmental organisations, have cooperate to assess the global threat caused by marine litter worlwide.

The following key reports have been dedicated to this problem, with a broad approach and inter-agency partnerships, in order to provide a comprehensive source of knowledge to the global threat caused by marine litter.

Marine Litter: An analytical overview was published in 2005 by United Nations Environment Program (UNEP) Regional Seas and the Global Programme for Action for the protection of the Marine Environment from Land-based Activities (GPA).

This document presents the problems posed by marine litter and examines the efficacity of the instruments, programmes and innitiatives that adress this global threat.

http://www.unep.org/regionalseas/marinelitter/publications/

Plastic Debris in the World's Oceans. This reposrt published by Greenpeace in 2006 draws together scientific research on the distribution of marine debris in the world's oceans and its impacts on wildlife. The information is sourced largely from papers that have been published on this subject between 1990 and 2005.

Finally it addresses workable solutions to help curb this threat to the marine environment.

http://www.unep.org/regionalseas/marinelitter/publications/docs/plastic_ocean_report.pdf

This Scientific and Technical Advisory Panel document published in 2011, Marine Debris as a Global Environmental Problem, aims at contextualizing the latest scientific knowledge about the causes of marine debris, and investigating and suggesting opportunities for catalytic activities to address this challenge within the Global Environment Facility program.

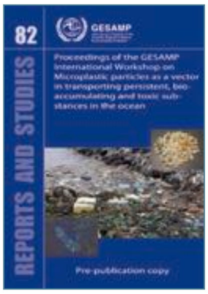
http://www.thegef.org/gef/sites/thegef.org/files/publication/STAP%20MarineDebris%20-%20website.pdf

In 2009, the report Marine Litter: A Global Challenge (2009) prepared under a collaborative partnership between the Ocean Conservancy and UNEP Regional Seas Programme, aims to provide an overview of the status of marine litter in UNEP's assisted Regional Seas, based on the analysis of regional reviews, and regional action plan documents prepared in the regions. This report draws conclusions regarding the state of marine litter at the global and regional levels, and concludes about the need to approach this issue through better enforcement of laws and regulations, expanded outreach and educational campaigns and the employment of strong economic instruments and incentives.

http://www.unep.org/pdf/unep_marine_litter-a_global_challenge.pdf

In 2010, the Marine Strategy Framework Directive - Task Group 10 Report Marine litter requires that the European Commission should lay down criteria and methodological standards to allow consistency in approach in evaluating the extent to which Good Environmental Status (GES) is being achieved. Reports prepared by groups of independent experts provide experience related to four marine regions (the Baltic Sea, the Northeast Atlantic, the Mediterranean Sea and the Black Sea).

http://ec.europa.eu/environment/marine/pdf/9-Task-Group-10.pdf



The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) hold its International Workshop on Microplastic particles as a vector in transporting persistent, bioaccumulating and toxic substances in the oceans in 2010 in Paris (France) on 'new and emerging issues' in relation to the state of the marine environment. The invited participants represented the scientific community, the plastics industry, policy makers and environmental NGOs, as well as regional bodies and developing as well as developed countries.

http://www.gesamp.org/data/gesamp/files/media/Publications/Reports_and_studies_82/gallery_1510/object_1670_large.pdf

In 2011, The Second Research Workshop hold by NOAA on Microplastic Marine Debris was intended to update microplastics science and take steps toward clarifying the risks of microplastics.

Life cycles and impacts are important elements of the larger picture and are critical to an improved understanding of the risk of ecological harm from microplastics. This report adresses to scientists, policymakers, and public citizens.

http://marinedebris.noaa.gov/sites/default/files/Microplastics.pdf

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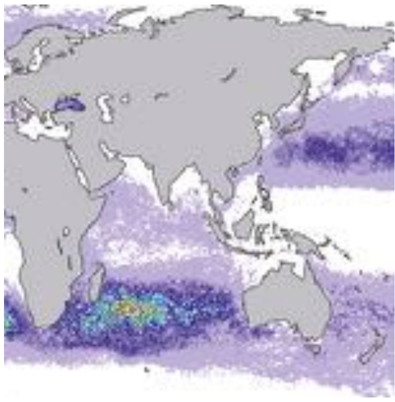

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