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IN-DEPTH REPORT

Plastic Waste:

Ecological and Human Health Impacts

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EXECUTIVE SUMMARY

Plastic waste is a growing concern and the drivers behind it look set to continue. Although recently there has been a slight decrease in plastic production, this is unlikely to be maintained. Plastic is a highly useful material and its applications are expected to increase as more new products and plastics are developed to meet demands. The increased use and production of plastic in developing and emerging countries is a particular concern, as the sophistication of their waste management infrastructure may not be developing at an appropriate rate to deal with their increasing levels of plastic waste.

Management of waste in the EU has been improving in terms of recycling and energy recovery, but there is still much to be done. At the heart of the problem is one of plastic's most valued properties: its durability. Combined with the throwaway culture that has grown up around plastic products, this means that we are using materials that are designed to last, but for short-term purposes.

The state of plastic waste is notoriously hard to measure. It is estimated that in 2008 EU-27, Norway and Switzerland produced about 24.9 megatonnes of plastic waste (Mudgal *et al.*, 2011) but its distribution is difficult to ascertain. This is especially so in the marine environment where the constant movement of the oceans, both horizontally on the surface and vertically within the water column, make it difficult to develop an accurate picture. Since the discovery of the Northern Pacific Garbage Patch, research has explored the gyres as areas of plastic waste accumulation, as well as beaches and river estuaries. There are a number of methods used to survey marine litter and currently there are initiatives to harmonise these. Several standardised surveillance guidelines have been developed, for example, those produced by the Oslo Paris Convention for Protection of the Marine Environment of the North-East Atlantic (OSPAR) and the United Nations Environmental Programme (UNEP).

On land, there are few figures on the level of plastic waste and there is a need for more information on sources and possible pathways into the environment. There has been increasing concern about the presence of microplastics, which are generally defined as plastic fragments less than 5mm in size. These are produced either from the weathering of larger plastics or deposited directly as pre-consumer plastic or from use in abrasives, such as those used in some cosmetics. Microplastics are particularly difficult to monitor and they may also have more influential impacts than larger plastics.

The impacts of plastic waste on our health and the environment are only just becoming apparent. Most of our knowledge is around plastic waste in the marine environment, although there is research that indicates that plastic waste in landfill and in badly managed recycling systems could be having an impact, mainly from the chemicals contained in plastic.

In the marine environment, the most well documented impacts are entanglement and ingestion by wildlife. Other lesser-known effects are the alteration of habitats and the transport of alien species. Perhaps one of the most difficult impacts to fully understand, but also potentially one of the most concerning, is the impact of chemicals associated with plastic waste. There are several chemicals within plastic material itself that have been added to give it certain properties such as Bisphenol A, phthalates and flame retardants. These all have known negative effects on human and animal health, mainly affecting the endocrine system. There are also toxic monomers, which have been linked to cancer and reproductive problems. The actual role of plastic waste in causing these health impacts is uncertain. This is partly because it is not clear what level of exposure is caused by plastic waste, and partly because the mechanisms by which the chemicals from plastic may have an impact on humans and animals are not fully established. The most likely pathway is through ingestion, after which chemicals could bioaccumulate up the food chain, meaning that those at the top could be exposed to greater levels of chemicals.

Plastic waste also has the ability to attract contaminants, such as persistent organic pollutants (POPs). This is particularly so in the marine environment since many of these contaminants are hydrophobic, which means they do not mix or bind with water. Again, the role of plastic waste in the impact of these toxic chemicals is unclear. Plastic could potentially transport these chemicals to otherwise clean environments and, when ingested by wildlife, plastic could cause the transfer of chemicals into the organism's system. However, in some conditions plastic could potentially act as a sink for contaminants, making them less available to wildlife, particularly if they are buried on the seafloor. With their large surface area-to-volume ratio, microplastics may have the capacity to make chemicals more available to wildlife and the environment in comparison to larger sized plastics. However, once ingested, microplastics may pass through the digestive system more quickly than larger plastics, potentially providing less opportunity for chemicals to be absorbed into the circulatory system.

Although plastic waste may not always cause detectable harm or death as an isolated factor, when combined with other impacts, such as uncontrolled fishing or oil spills, it may contribute cumulatively to serious impacts. These sub-lethal effects are difficult to monitor, but are nonetheless important to recognise. Research has indicated that some species or developmental stages are more vulnerable to ingestion of plastic waste and the toxic effects of the chemicals associated with it.

Policy responses to plastic waste come in many forms and

work on many levels, ranging from beach clean-ups to bans on plastic waste disposal at sea, to targets for waste management and recycling. Several market-based instruments have been explored such as deposit schemes to encourage the return and multi-use of plastics, and taxation on single-use plastics that do not fit into deposit return systems. However there has been little widespread application of these instruments and more research is needed to maximise their effectiveness and ensure they do not have secondary effects other than those intended.

Plastic waste has the additional complication of spanning many policy areas, such as marine management, coastal management, waste management and the regulation of chemicals. This range of responses is necessary for such a global problem with such local variation, but to ensure plastic waste does not fall through the holes in the net of responsibility, there is a need to harmonise efforts and co-ordinate between different policy areas. A number of reports have called for better implementation of existing policy. The Marine Strategy Framework Directive has specified 'marine litter' as one of its descriptors of good environmental status and four indicators of this have been identified which can be applied to plastic waste. However, there may also be room for policy that is more specifically related to plastic waste, while still allowing for its connection to different policy areas.

Lastly, there are a number of research gaps that need to be addressed to provide a stronger evidence-base on which to develop policy. Some of these are at the detailed level of impact, such as the actual levels of chemical exposure caused by plastic waste. Others are more action-orientated, for example, identifying potential hotspots where plastic waste is problematic, identifying high-risk products that use plastic or identifying wildlife and human groups that are more vulnerable to the impacts of plastic waste. However, the very nature of plastic waste as a fluctuating and mobile issue means that science is unlikely to be able to answer all the questions. It may be preferable to take policy action before waiting for a completely clear research picture to emerge so as to avoid the risk of impacts worsening and becoming more difficult to manage in the future.

INTRODUCTION

In the last 60 years, plastic has become a useful and versatile material with a wide range of applications. Its uses are likely to increase with ongoing developments in the plastic industry. In the future, plastic could help address some of the world's most pressing problems, such as climate change and food shortages. For example, plastics are used in the manufacture of rotors for wind turbines and tunnels made from polyethylene can help crops grow in otherwise unfavourable conditions.

As demand for materials with certain qualities increases, the plastics industry will aim to supply them. Meanwhile, increasing plastic production and use in emerging economies looks set to continue, and waste management infrastructure will have to develop accordingly.

Unfortunately, the properties of plastic that make it so valuable also make its disposal problematic, such as its durability, light weight and low cost. In many cases plastics are thrown away after one use, especially packaging and sheeting, but because they are durable, they persist in the environment. If plastic reaches the sea, its low density means it tends to remain on the surface.

Increasing attention has been paid to plastic waste by policymakers, scientists and the media and probably one of the most influential factors was the discovery of the Great Pacific Garbage Patch by Charles Moore in the late 1990s. This is a layer of rubbish floating between California and Hawaii that has been estimated to span about 3.43 million km2 (the size of Europe). It is mostly plastic and contains everything from large abandoned fishing nets to plastic bottles to tiny particles of plastic (or 'microplastics'). This type of mass in the seas can be known as 'plastic soup' and there are concerns that Europe hosts similar patches, in areas such as the Mediterranean and the North Sea. As such, marine litter and plastic waste is a priority on the EU policy agenda.

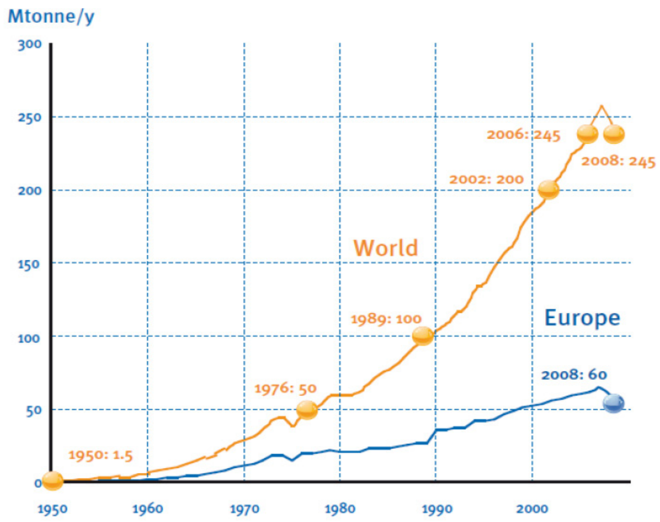
Plastic is still a relatively new material, which means the problem of plastic waste has only recently been realised, as has knowledge about its environmental persistence (Barnes *et al.*, 2009). Even more recent is the discovery of possible health and environmental effects, such as the impacts of the chemicals contained in plastics. The monitoring of plastic waste and research into its impacts are still in their infancy, but so far the implications are worrying.

The complexity of the issue is enhanced by the global nature of plastic waste and its constant movement, particularly at sea. This makes it difficult to confidently identify sources and scale up impacts from a specific location to create a global picture. The content of plastic waste can differ according to the location and time of year, while its impacts can vary between species and human life stages. So far, research has been somewhat piecemeal in documenting plastic waste's distribution and impacts. To effectively inform policy, there needs to be more collation of existing data and greater harmonisation of research methods. This is also necessary to implement and monitor policy.

This Science for Environment Policy In-depth Report on the human health and ecological impacts of plastic waste summarises and collates current research in this area. Using the Drivers Pressures State Impact Response (DPSIR) framework, it highlights major issues and concerns, as well as outlining questions around existing responses and possible strategies for the future.

With the global nature of plastic waste, it is difficult to be precise about the Drivers and Pressures that bear influence and Section 1 combines the two and concentrates on measurement and monitoring. The sections covering State and Impacts concentrate on human health and ecological impacts. Finally, Section 4 deals with Responses to Plastic Waste and highlights current and future issues that need to be addressed, as well as knowledge gaps where more research is required to inform policy responses.

1.0 PLASTIC WASTE: DRIVERS AND PRESSURES



Includes Thermoplastics, Polyurethanes, Thermosets, Elastomers, Adhesives, Coatings and Sealants and PP-Fibers. Not included PET-, PA- and Polyacryl-Fibers

Figure 1. World Plastics Production 1950-2008. From *The Compelling Facts about Plastic*, PlasticsEurope (2009), p33.

In 2009, around 230 million tonnes of plastic were produced and around 25 per cent of these plastics were used in the EU (Mudgal *et al.*, 2011). This global figure has been increasing by an average rate of 9 per cent since 1950 to a peak of 245 million tonnes in 2008, after which there was a slight drop in production. The financial recession may be responsible for this slight decline in plastic production, (PlasticsEurope, 2010 see Figure 1).

About 50 per cent of plastic is used for single-use disposable applications, such as packaging, agricultural films and disposable consumer items (Hopewell *et al.*, 2009). The drivers for plastic use are its improved physical and chemical properties compared to alternatives, its low cost and the possibility of mass production. Drivers for its reduction lie in a desire to minimise the use of resources (Kershaw *et al.*, 2011). A life cycle analysis study has indicated that the use of plastics leads to significantly less energy consumption and emissions of greenhouse gases than the use of alternative materials (Pilz *et al.*, 2010). In other words, plastic has surpassed other materials for certain functions and its comparative advantages may be increasing as technology improves.

In addition, the increasingly short lifetime of products that use plastic, especially electronic goods, means that more plastic waste is being produced in today's upgrade-and-dispose culture. A key example of this is the mobile phone: its plastic components contain several toxic substances (Nnorom & Osibanjo, 2009). Although these substances are not at levels to cause immediate risk, if quantities increase and end-of-life management is inadequate, such as the open burning often practised in developing countries, there is potential for environmental pollution and human health impacts.

Production of plastic has levelled off in recent years, however, it is not declining and may well increase in the future as applications for plastic increase and its use continues to grow in developing and emerging economies (Global Industry Analysts, 2011). Without appropriate waste management, this will lead to increased plastic waste, which will add to the 'back log' of plastic waste already in existence. There is no agreed figure on the time that plastic takes to degrade, but it could be hundreds or thousands of years (Kershaw *et al.*, 2011).

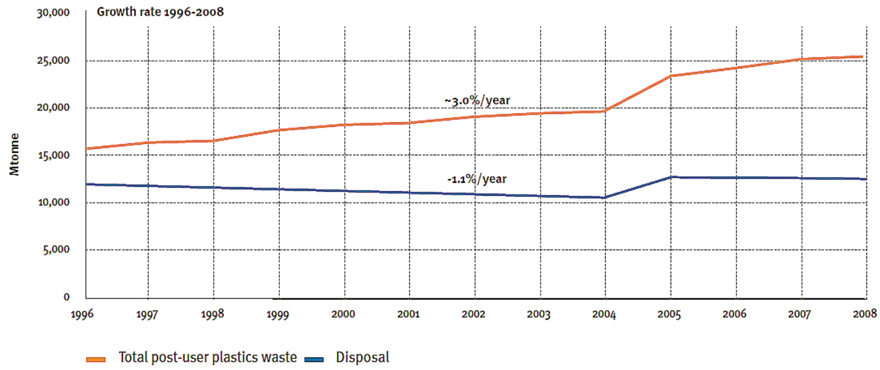
Most types of plastic are not biodegradable. Some plastics are designed to be biodegradable and can be broken down in a controlled environment, such as landfill, but it is uncertain if this will occur under other conditions, especially in oceans where the temperature is colder (Song *et al.*, 2009; O'Brine & Thompson, 2010). Even if plastic does eventually biodegrade, it will temporarily break into smaller fragments, which then produce so-called 'microplastics'. These have a specific and significant set of impacts (see sections 3.4, 3.7 and 3.9).

Box 1 Examples of the distribution of plastic waste

- In 1992, a container ship lost 30,000 rubber ducks off the coast of China. Fifteen years later, some of these turned up on the shores of the UK (Maggs *et al.*, 2010).
- In 2005 a piece of plastic found in an albatross stomach bore a serial number traced to a World War II seaplane shot down in 1944. Computer models re-creating the object's journey showed it spent a decade the Western Garbage Patch, just south of Japan, and then drifted 6,000 miles to the Eastern Garbage Patch off the West Coast of the U.S., where it spun in circles for the next 50 years (Weiss *et al.*, 2006)
- Van Franeker (2011) estimated that North Sea fulmars annually reshape and redistribute about six tons of plastic through ingestion of plastic waste.

1.1 Sources of plastic waste

Plastic waste is a global problem, but with regional variability. This is particularly true of plastic waste in the marine environment, which can travel long distances, carried by currents or transported by wildlife, which ingest or become entangled in plastic.



The figure shows the history for EU15+NO/CH until 2004 and for EU27+NO/CH from 2005 onwards.

Figure 2. Continued decoupling of plastic waste and landfill. From *The Compelling Facts about Plastic*, PlasticsEurope (2009) p11.

The EU's Waste Framework Directive prioritises prevention in waste management. To develop effective prevention strategies, it is useful for policymakers to know the major sources of plastic waste and, if possible, which of these represent the greatest risk. Furthermore, to implement prevention-orientated policy effectively, meaningful monitoring of plastic waste is needed to assess the impact of policy. An example of this is the EU's Marine Strategy Framework Directive (MFSD), which has established that Member States should take necessary measures to achieve or maintain good environmental status of marine waters by the year 2020. This requires monitoring and therefore the development of indicators of good environmental status. The MFSD has outlined 11 descriptors of environmental status, one of which is marine litter and identified four indicators for marine litter which, by default, also apply to plastic waste in the marine environment (see Box 2).

A significant issue is that, while there is an abundance of data on debris in the marine environment, there is a comparative shortage of data on plastic waste on land. This is despite the estimate that 80 per cent of plastic waste in the sea is from land-based sources (Sheavly, 2005). The main land-based sources of marine plastic waste include storm water discharge, combined sewer overflows, tourism related litter, illegal dumping, industrial activities e.g. plastic resin pellets, losses from accidents and transport, and blowing from landfill sites (Allsopp *et al.*, 2006). The ocean-based sources tend to be commercial fishing, recreational boaters, merchant/military/research vessels, losses from transport, offshore oil and gas platforms (Sheavly, 2005). A disproportionate amount of waste in the marine environment is plastic. Plastics make up an estimated 10 per cent of household waste, most of which is disposed in landfill (Barnes, 2009; Hopewell *et al.*, 2009). However, 60- 80 per cent of the waste found on beaches, floating on the ocean or on the seabed is plastic (Derraik, 2002; Barnes, 2005).

Waste management varies from country to country. One of the most instrumental EU waste management regulations is the Landfill Directive (1999), which sets targets for the diversion of biodegradable municipal waste from landfill, allowing Member States to choose their own strategies for meeting these targets. However, there are no specific targets for diversion of plastic waste. An EEA review (Herczeg *et al.*, 2009) of the Directive in five EU countries and one sub-national area (Estonia, Finland, the Flemish Region of Belgium, Germany, Hungary and Italy), indicates that there has generally been a drop in the amount of waste going to landfill from 1999-2006. Separate data from a PlasticsEurope report (PlasticsEurope, 2009) indicate that, despite a 3 per cent annual growth in the past decade for post-consumer plastic waste in EU15, landfill amounts have increased by only 1.1 per cent per year (see Figure 2), thanks to increases in recycling and energy recovery.

Sources of plastic waste vary by region, for example, shipping and fisheries are significant contributors in the East Asian Seas region and the southern North Sea (Kershaw *et al.*, 2011), whereas tourism is a major source in the Mediterranean.

Plastic waste accumulates in certain areas of the sea, such as gyres, which are large rotating currents, which have lower sea levels near their centres. There are five major gyres in the world: the North Pacific, the South Pacific, the Indian Ocean, the North Atlantic and the South Atlantic. These act as accumulation zones for marine debris, which is forced into the centre where winds and currents are weaker (Moore *et al.*, 2001).

Currents, wave action, and the nature of the continental shelf and seafloor also affect the distribution of plastic waste. Harbours and estuaries near urban areas tend to attract large amounts of plastic waste from recreation and land-based sources, while more remote beaches tend to be littered with fishing debris (Derraik, 2002). This is supported by findings from a study in a conservation area in north-eastern Brazil (Ivar

Box 2 MSFD indicators of marine debris to measure good environmental status:

1. Trends in the amount, distribution and composition of marine debris on coastlines.
2. Trends in marine debris in the column and deposited on seafloor.
3. Trends in the amount, distribution and composition of micro particles (mainly microplastics)
4. Trends in the amount and composition of marine debris ingested by wildlife.

do Sul *et al.*, 2011) which indicated that 70 per cent of debris on populated beaches comes from local sources, mainly tourism activities, while on unpopulated beaches, non-local sources account for 70 per cent of plastic waste, mainly from fishing and domestic activities, such as household waste from rivers and onshore, as well as waste from transiting ships.

Although it is important to try and determine sources of plastic waste for developing and monitoring policy, it should be remembered that the distinction between land-based and sea-based sources is irrelevant for prevention, as all plastic is produced on land. If we are to reduce overall amounts of plastic waste, the land is where the greatest efforts need to be made.

1.2 Categories of plastic waste

Categorisation can help us understand plastic waste and identify sources. However, most classifications have a purpose and waste is often categorised with a specific goal in mind. For example, a waste classification designed to support a recycling programme would identify commonly recycled plastics (Barnes *et al.*, 2009). Classification can also depend on policy, for example, Moore *et al.* (2011) conducted a study on plastic debris in two Californian rivers that categorised pieces as below or above 4.5mm, because Californian law defines rubbish as being 5mm or greater.

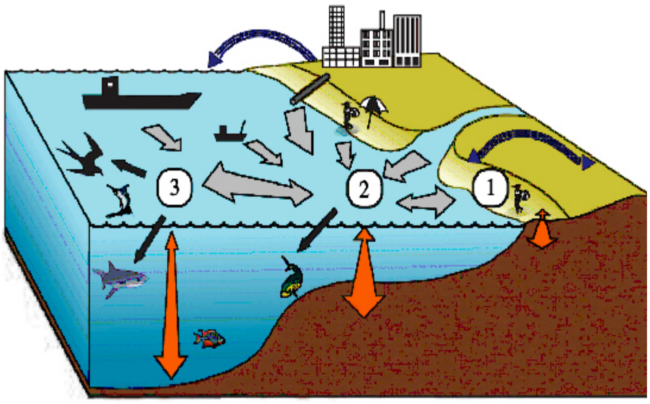


Figure 3. Main sources and movement pathways for plastic in the marine environment. (from UNEP Year Book, Kershaw *et al.*, 2011)

One of the most fundamental categorisations is into pre- and post-consumer plastic waste. Pre-consumer plastic waste is produced during manufacturing or converting processes, while post-consumer plastic waste is produced after a product is consumed or used. Pre-consumer plastic waste often consists of small pellets that are used to make larger plastic objects. Many statistics are concerned with post-consumer plastic waste. In 2008, the EU-27, Norway and Switzerland were estimated to generate a total of 24.9 megatonnes of post-consumer plastic waste (PlasticsEurope, 2009). This was further categorised according to function. (See fig. 4)

At sea, plastic waste is often categorised into macro- (over 20mm diameter), meso- (5-20mm diameter) and micro- (under 5mm diameter) plastics. Very small microplastics are barely detectable, and for practical purposes, microplastics are usually defined as those that range from 5mm to 333 micrometres (µm). Practically, this is the lower limit because 333µm mesh nets ('Neuston nets') are commonly used for sampling (Arthur *et al.*, 2009). However, methods, such as 'Fourier Transform infrared spectroscopy', can detect particles less than 1.6µm. Macroplastics can be further categorised according to type of object, for example, bottle, bag or lid.

1.3 Microplastics: sources and categories

Microplastics are a significant issue in plastic waste, partly because they are more difficult to monitor, and partly because they may have greater impacts at a chemical and physical level on ecosystems and human health, owing to their size and large volume-to-surface area ratio.

In the ocean as well as on land, plastics tend to fragment into smaller particles. This can be aided by the action of ultraviolet (UV) radiation, waves and wind. In landfills, leachate acidity and chemicals can break down plastics. In the sea, water absorbs and scatters UV so plastics floating near the surface will break down more rapidly than those at depth. For those on the seabed, breakdown is significantly slower since there is no UV radiation and temperatures are colder.

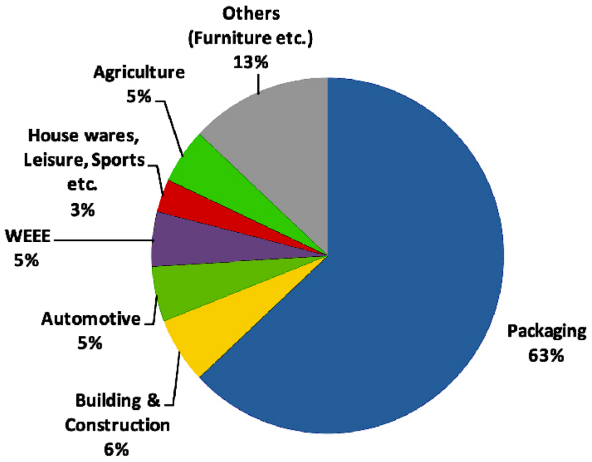


Figure 4. Proportion of post-consumer waste in EU-27, Norway and Switzerland according to function, 2008. From *Plastic Waste in the Environment*, Mudgal *et al.*(2011)

Plastic fragments can also come from the use of plastic particles as abrasives in 'sandblasting' and exfoliants in cosmetics (Barnes *et al.*, 2009; Andrady, 2011), from spillage of pre-production plastic pellets and powders used for moulding plastic objects, as well as from plastic items deliberately shredded on board ships to conceal plastic waste in food waste (Barnes *et al.*, 2009). These sources are known as primary microplastic sources, whereas secondary microplastics are those formed from breakdown of larger plastic material (Arthur *et al.*, 2009). The relative importance of primary and secondary sources of microplastics to the environment is unknown and addressing this gap could help inform measures to mitigate and prevent microplastic pollution (Arthur *et al.*, 2009).

Andrady (2011) provides a comprehensive review of the degradation processes of plastics under marine conditions and the origin of microplastics. The review raises the concept of nanoplastics. These are engineered plastic nanoparticles derived from post-consumer waste via degradation. Although they have not been quantified yet the review suggests there is little doubt that weathering of plastic can produce nanoscale particles, which could potentially be easily absorbed by phytoplankton and zooplankton (Andrady, 2011).

Another potential secondary source of degradation into microplastic is through digestion by wildlife, which also transport plastic waste. Van Franeker (2011) suggest that fulmars (a type of seabird) reduce the size of plastic particles in their muscular stomach and excrete them back into the environment in the form of microplastics. They estimate that fulmars reshape and redistribute about 630 million plastic particles every year, representing about six tons in plastic mass.

2.0 STATE OF PLASTIC WASTE IN THE ENVIRONMENT

As production and use of plastic has increased over the years, a large amount of plastic waste has accumulated in the environment. As a durable material, it is also persistent. Recycling and recovery rates may be improving, but the actual amount of plastic waste produced remains roughly the same and adds to existing waste.

There is little information on the amounts, rates, fate or impacts of plastic waste on land, whereas there has been a major effort to quantify impacts on shorelines and sea (Barnes *et al.*, 2009). If it is not recycled or recovered, most plastic waste is disposed of in landfill sites where, although not visible, it may still come to the surface as 'debris'. In addition, the conditions within landfill may cause the chemicals contained within plastic to become more readily available to the environment (see section 3.6). This is a particular concern in developing countries where landfill management is not as closely monitored as in the EU.

2.1 Between land and sea - Monitoring plastic waste on coastlines

Although it is difficult to determine source and type of plastic at sea, particularly if it is weathered or partially degraded by sunlight, there are several methods to monitor plastic waste in the marine environment, including beach surveys, surveys at sea and monitoring species affected by plastic waste.

Beach surveys vary in their sampling protocols. For example, they can record the number of items and/or the mass of waste, and can differ in the areas covered and whether they include buried litter. There is debate on whether standing 'stocks' of plastic waste should be recorded, i.e. snapshots of plastic waste at points in time, or rates of accumulation, i.e. how much plastic waste accumulates per unit of time. The latter requires an initial clean-up of the area, which is difficult, particularly for microplastics.

Plastic waste monitoring is usually embedded in the monitoring of general marine litter. The OSPAR (Oslo Paris Convention for Protection of the Marine Environment of the North-East Atlantic) Pilot Project on Monitoring Marine Beach Litter in the North Sea was one of the first region-wide projects in Europe to develop a standard method to monitor marine litter found on beaches. It identified the sources and quantitative trends in marine litter on the beaches of nine countries within the OSPAR network. This confirmed that the predominant type of marine litter is plastic. On the Greater North Sea coast, plastic dominated with the highest levels in the north where it made up 80 per cent of beach litter; on average there were 900 items of litter per 100m of beach. Lower percentages of plastic were found further south, where it made up 75 per cent of items on the Southern North Sea coast (out of 400 items per 100m), 70 per cent on the Celtic Sea Coast (out of 650 items per 100m) and 62 per cent on the Iberian Coast and Bay of Biscay (out of 200 items per 100m) (OSPAR, 2007). These plastic items were classified according to type (see Figure 5), with plastic/polystyrene pieces smaller than 50cm dominating.

Overall quantities of plastic waste on OSPAR beaches fluctuated between 2001 and 2006 with no discernible pattern. The composition of the plastic waste also changed, particularly for plastic/polystyrene (see Figure 6). It is difficult to find a consistent trend over time for plastic waste both on beaches and at sea. This lack of pattern is likely to be partly because plastic debris in the marine environment is always moving. Barnes and Milner (2005) found no consistent trend in general debris in northern hemisphere shores, but there were increasing densities throughout the 1980s, 1990s and early 2000s in the southern hemisphere with the highest increases at high southern latitudes. More recent data (Barnes *et al.*, 2009) suggests that patterns of debris accumulation may be stabilising on islands (those considered were South Orkney, South Georgia and NW Hawaii).

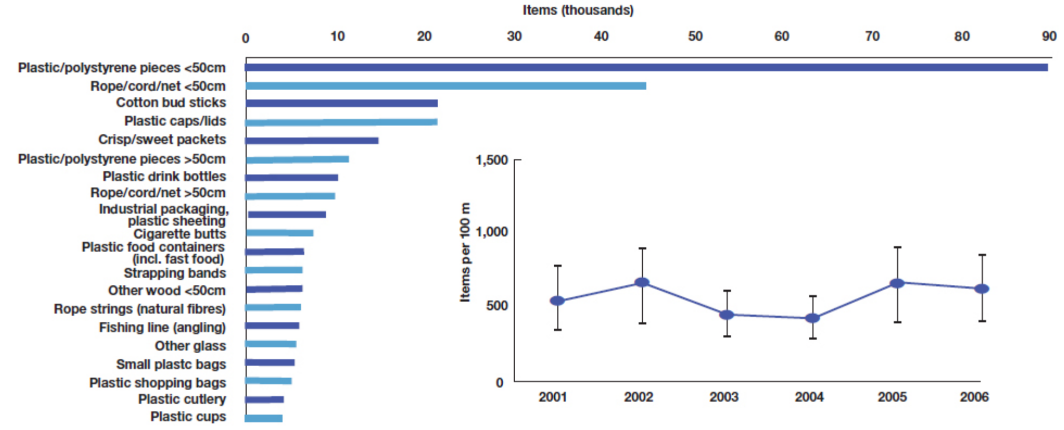


Figure 5. Composition and numbers of marine litter items found on beaches within OSPAR network. From Marine litter Preventing a Sea of Plastic (2009), OSPAR Convention

A relatively new survey method combines the use of aerial photography and in situ measurements. This calculates the mass of litter per unit area using a sample and then combines it with balloon-assisted photography to define the area covered by litter. On an island beach surveyed in Japan, the mass of litter was calculated to be 716 kg, 74 per cent of which was plastic (Nakashima *et al.*, 2011). Despite being measured by weight, 55 per cent of the plastic waste was light plastic. Polyethylene was the most common type found and the study suggested further research is needed to determine if lighter plastics, such as polyethylene, are more readily transported by winds and currents than heavier plastics, such as PVC which tends to sink and so is subject to different patterns of transportation than plastic on the surface. From -their pilot project, OSPAR have developed a set of guidelines for monitoring marine litter on beaches (OSPAR, 2010a) that sets out recommendations on selecting reference beaches, sampling, timing and identification of litter. As part of Cheshire *et al.*'s (2009) UNEP/IOC Guidelines on Survey and Monitoring marine litter, there is also a set of operational guidelines for comprehensive beach litter assessment. More informally Ryan *et al.* (2009) have set out best practices for beach surveys (see Box 4).

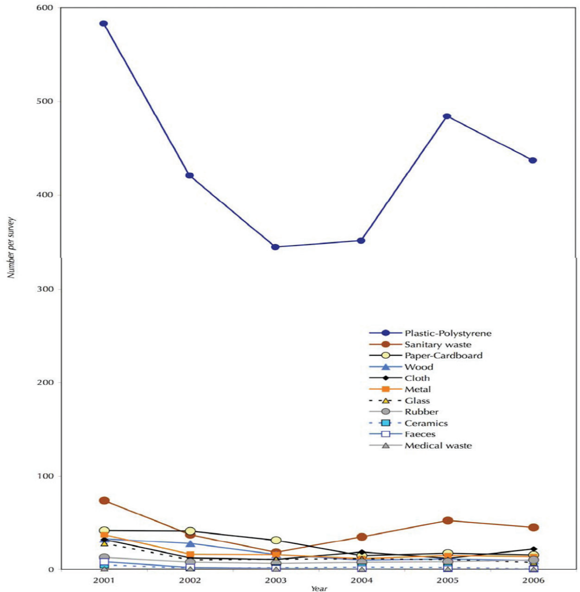


Figure 6. Changes in composition of marine items found on beaches within OSPAR network. Diagram from Marine Litter Preventing a Sea of Plastic (2009) OSPAR Commission

Box 3 **Local variability in plastic waste**

A study in Portugal (Frias *et al.*, 2011) researched plastic debris on mainland coasts. This found that out of 9655 plastic items identified from 10 beaches, about 85 per cent were plastic fragments, plastic pellets and styrofoam. There was a decrease in volume of plastics from north to south, probably because north-south main currents carry and deposit plastic debris from both land-based and sea-based sources.

Box 4 **Best practices for beach surveys of plastic waste, Ryan *et al* (2009)**

- Record litter from the sea-edge to the highest area at the top of the beach where debris is deposited (strandline)
- Record both the mass and the number of items of plastic waste
- Categorise according to composition and function
- Ideally sample across a network of sites
- Sampling of meso-debris should be done with a combination of methods

2.2 The marine surface - monitoring plastic waste floating at sea

Surveys at sea are more costly and challenging than beach surveys and can only assess standing (or floating) stocks rather than accumulation rates, because it is impossible to perform a complete clean-up. Amounts of floating debris can be estimated either by direct observation or by net trawls.

Most observation surveys are conducted from ships or small boats. Aerial surveys have also been used which have the advantage of covering large areas but the disadvantage of only detecting large items of waste (Ryan *et al.*, 2009). In 2008, an assessment prepared by MED POL (the marine pollution assessment and control component of the Mediterranean Action Plan) reported finding 2.1 items of general debris per km^2 floating in the Mediterranean Sea (observation with binoculars) and 83 per cent of this waste was plastic (UNEP, 2009). All observation surveys suffer discrepancies between individual observers (inter-observer variability), but variability can also occur for other reasons, such as meteorological conditions, ocean currents and the constant movement of plastic waste. For example, in a visual survey of general debris conducted in the northwestern Mediterranean 15-25 items per km^2 were reported in 1997, and just 1.5-3 items per km^2 were reported in 2000 (Aliani *et al.*, 2003).

In general, net-based surveys tend to be less subjective. Most research has been done using Neuston or Manta trawl nets, which have a small mesh (usually 0.3mm, and small net opening and thus focus on microplastics). Manta trawls have been used to sample and characterise the large gyre systems in the oceans with elevated amounts of clustered marine litter (Pichel *et al.*, 2007). One of the most well known research programmes that use this method is the Algalita Centre, which regularly monitors the North Pacific Subtropical Gyre (see Figure 7). In 1999, they reported just under 335,000 items of plastic per km^2, weighing 5.1 kg per km^2 (Moore *et al.*, 2001).

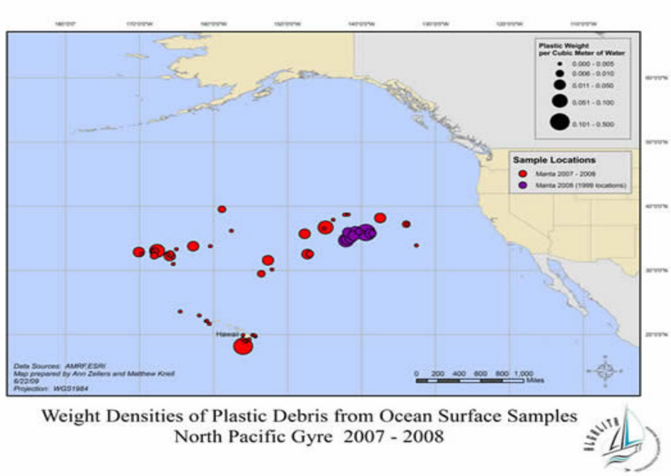


Figure 7. Algalita Research Centre monitoring. Weight density refers to the total weight of plastic particles found per cubic metre of water. The larger the circle on the map, the greater the weight of plastic particles found at that particular site.

particles on coastlines was similar to that of virgin plastics i.e. the plastic had changed little from its original form, whereas at sea the density of plastic particles were greater, indicating a change from its time at sea. This was thought to be due to biomass accumulation on the plastic or biofouling, which is likely to increase the density of the plastic. The researchers suggest that data on particle density could help us understand what types of plastics are sinking or floating and the potential impact of plastics on wildlife.

Methods to ascertain composition of plastics tend to rely on 'Fourier transform infrared spectroscopy'. However, Moret-Fergusson *et al.* (2010) suggest that this technology is scarce and expensive, and propose a simpler alternative for establishing composition, which analyses the amount of carbon, hydrogen and nitrogen in plastic. This method may be cheaper, but it is not as accurate and requires combusting samples of plastic. Infrared spectroscopy methods are under further development and may become cheaper in the future.

2.3 Monitoring plastic debris in rivers and estuaries

Studying plastic waste in rivers and estuaries could prove useful in trying to identify sources. Browne *et al.* (2010) investigated the composition of plastic debris on the banks of a UK estuary from both the surface and the underlying 3cm of sediment. Out of the 952 items found, microplastic (less than 1mm) accounted for 65 per cent of debris and mainly (80 per cent) consisted of the denser plastics such as PVC, polyester and polyamide. Macroplastics tended to be less dense. There are a number of possible explanations for this. For example, it could be that denser plastics are more likely to suffer weathering as they are in contact with abrasive particles in sediment, or it could be that denser microplastics are easier to distinguish from the sediment so appear to be more abundant. The research found a larger amount of microplastics at the more exposed sites towards the mouth of the estuary where debris is likely to experience strong wave-action and abrasion. Another possible source is the discharge from sewage treatment, as domestic laundry may act a source of fibres or microplastics.

Galgani *et al.* (2000) suggest that strong currents in large rivers may transport litter offshore while in the smaller rivers, where currents are weaker, the litter tends to become beached in the estuaries. As existing research indicates, there is much speculation about the reasons for the composition and distribution of plastic debris and much still needs to be done on the major influences to identify where policy can be effective. Moore *et al.* (2011) studied quantity and type of plastic debris from two urban rivers to coastal waters and beaches in Southern California. Using nets in the rivers they found 2.3 billion pieces over 72 hours, which weighed 30,500 kg. The majority were foams, such as polystyrene (71 per cent), followed by 'miscellaneous fragments' (14 per cent), pre-production pellets (10 per cent) and whole items (1 per cent). 81 per cent of all plastics were between 1 and 4.75 mm (the size above which California officially classifies them as rubbish). The study suggests more systemic monitoring could provide a picture of how much debris is being transported by rivers, which in turn could provide a baseline to support decisions by policymakers on how to prevent plastic entering rivers.

2.4 Monitoring plastic waste in the water column and on the seafloor

Most studies tend to sample floating plastic debris, but it is also important to monitor suspended plastic and plastic on the sea bottom. Bongo nets can be used to sample suspended debris, while trawl surveys, scuba diver surveys, and submarine vehicles can be used to sample plastic waste on the sea bottom. Data from the KIMO (Kommunenes Internasjonale Miljøorganisasjon) 'Fishing for Litter' activities organised by national governments in the Netherlands, Scotland and the United Kingdom found that plastic made up a large percentage of marine litter on the seabed.

For example, in Scotland 55 per cent of the 3464 items of marine litter recovered (which made up 117 tonnes in weight) were plastic (KIMO, 2008). In their study of benthic marine litter, Galgani *et al.* (2000) found relatively lower percentages of plastic in the Celtic Sea, the Baltic Sea and the North Sea (30 per cent, 36 per cent and 49 per cent, respectively) while

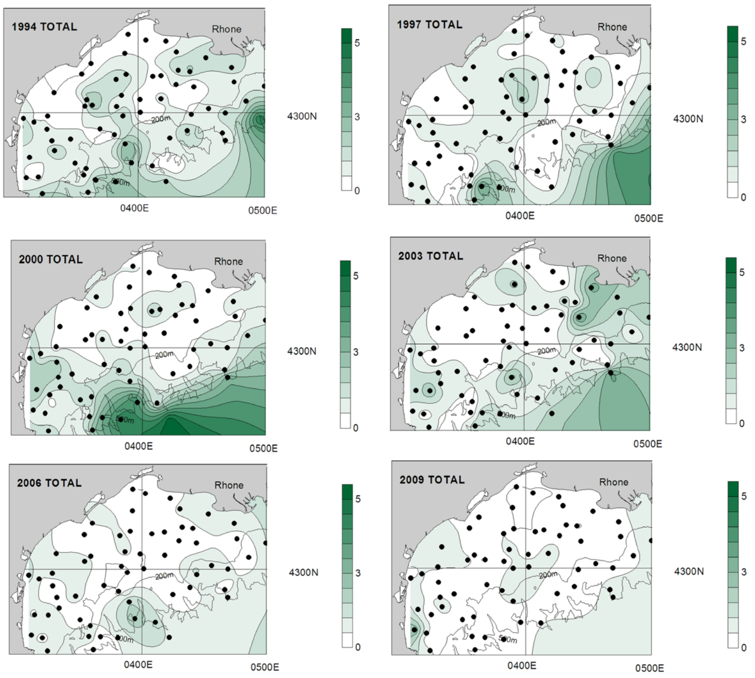


Figure 8. Litter (items/ hectare) on the sea bed in the channel (x) and the gulf of Lion (y) 1998 -2010. Data collected from International Bottom Trawl Surveys from the IBTS and MEDITS programs in France (Source: Galgani, F. IFREMER).

in the north-western Mediterranean, the East English Channel and Bay of Seine, the percentages were higher (77 per cent, 85 per cent and 89 per cent, respectively).

The figures are most concerning for the north-western Mediterranean where the level of litter is much higher than other regions at just under 20 items per hectare (ranging between 0 and 78 items), which means there are, on average, 15 items of plastic waste per hectare, most of which are plastic bags. Other regions had between 1 and 6 items of marine litter per hectare. As well as regional variability, there was also seasonal variability, for example, in the Bay of Biscay there are approximately two items of marine litter per hectare during the summer and 14 items per hectare in winter. Most of the items were plastic (92 per cent) and out of those, the majority (94 per cent) were plastic bags.

The densely populated coastline, shipping and limited tidal flow or water circulation which traps the bottom debris may be responsible for the large amounts of plastic waste in Mediterranean sites. High sediment accumulation also tends to trap plastic. Large rivers are responsible for inputs of plastic debris to the seabed and collections are often found around the river mouth. At a smaller scale, there is a high concentration of plastic around rocks and in channels or canyons, particularly on the continental shelf (Galgani *et al.*, 1996). As most polymers degrade through exposure to UV radiation, it is likely that plastic on the sea floor will be even more persistent than that on the surface or on the beach.

Just as plastic waste moves on the surface of the sea and from the sea to the coast, it can also move vertically. So-called 'biofouling' or accumulation of micro-organisms, plants or algae onto plastic debris causes it to become heavier and eventually sink. In their sample of plastic debris in the western North Atlantic Ocean, Morét-Ferguson *et al.* (2010) found that the range in specific gravities (specific gravity is the ratio of the plastic density to the density of water) was 0.808 to 1.24 grams per milliliter. This range was greater than most virgin plastics and indicated that the plastics had been subject to fouling. They also found that the plastic in the sea had a different specific gravity to plastic debris found at the beach, suggesting that plastic undergoes changes when it is at sea.

Lobelle and Cunliffe (2011) investigated the formation of films of micro-organisms (biofilms) on plastic waste in the sea and found that films developed rapidly and were visibly apparent after one week. By three weeks, the plastic started to sink below the surface. These data could help identify what types of plastic are floating or sinking, and which are therefore potential hazards for either surface-feeding or seafloor-feeding wildlife. Establishing the size, mass and composition of plastics that persist in the ocean is important for understanding the impacts of plastics (Morét-Ferguson *et al.*, 2010)

2.5 Trends in plastic waste over time

It is difficult to find any clear patterns in the quantities of plastic waste over time. In some regions, and over some timescales, there appears to be an increase, whereas in others there may be a short-term decline and then stabilisation. This is evidenced by the findings from the OSPAR survey (see Figure 9). As yet, no studies have found evidence of a continuing decline in the quantity of plastic debris in the oceans over time and the majority of studies show considerable variability between sampling dates and therefore give little evidence of temporal trends. The monitoring data we have is mostly from beaches or surface waters. There is evidence that plastics are sinking from the sea surface to the seabed with substantial quantities observed by submersibles, there are also reports of plastic debris accumulating beneath the surface in beach sediments. Hence movement of debris away from the compartments that have traditionally been monitored will also influence our ability to detect underlying trends in the accumulation of debris (Thompson, 2011, in correspondence). As plastic is continually being manufactured and notoriously difficult

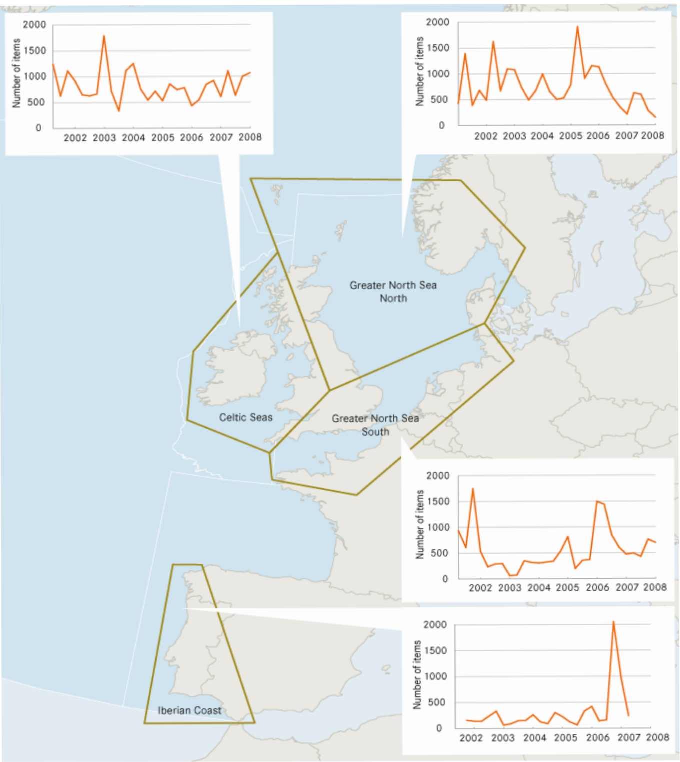


Figure 9. Trends in the average number of marine litter items collected on reference beaches over three time periods. OSPAR Quality Status Report, chap 9: other human uses and impacts, 2010b.

to degrade, plastic waste could be moving to areas where it cannot be monitored, either in an inaccessible location (buried or in the deep sea), or because it has been ingested by wildlife. It could also have changed into microplastic that is more difficult to monitor.

2.8 Microplastics: monitoring trends

The MSFD specifies that trends in micro-particles, especially microplastics, should be an indicator of marine debris to determine good environmental status. However, the sampling of microplastics is still in its infancy. With beach surveys it is not possible to conduct accumulation studies as they require an initial clean-up, and, when sampling is performed, it needs to be done by sieving, typically to a depth of 50 mm and then sorting by floating in seawater (Ryan *et al.*, 2009). Various studies at sea have indicated that microscopic plastic fragments and fibres are widespread. Browne *et al.* (2007) reported that microplastics account for 80 per cent of the number of stranded plastics in the Tamar Estuary, UK (see Figure 10), and Moore *et al.* (2011) reported that microplastics contribute about 80 per cent by count of total plastic debris in Los Angeles watershed. Browne *et al.* (2010) indicated that microplastics tend to be composed of denser plastics and are more abundant at the mouth of the river. Microplastics often become part of the sediment, both on the beach and on the sea bottom. Currently it is unclear whether this sedimentation could actually act as a sink for microplastics and alter their exposure to the environment and wildlife (Zarfl *et al.*, 2011).

KIMO Sweden has assessed the abundance of microscopic plastic particles that are less than 4.5mm in Swedish west coast waters (Norén, 2007). A considerably higher amount of microplastic particles was found using an 80µm mesh, compared to using a 450µm mesh, to concentrate the water samples. Up to 100,000 times higher concentrations, (150-2400 per m^3), of small plastic fibres were retained on an 80µm mesh with the highest concentration (102,000 per m^3) found locally in the harbour outside a polyethylene production plant. This illustrates the impact of different methodologies on findings and local influences.

A study in the Hawaiian island of Kauai investigated the degradation processes involved in production of microplastic by analysing the relationships between particle composition and surface texture on plastics collected from beaches (Cooper & Corcoran, 2010; Corcoran *et al.*, 2009). Over ten days of sampling, the research found that, on average, 484 pieces of plastic were deposited on the beach daily. Results indicated that both chemical breakdown (usually caused by sunlight exposure) and mechanical breakdown (usually from the motion of currents and abrasion against rock and sand) are occurring. Examination of texture indicated that mechanical erosion had occurred on most samples, for example impacts caused fractures, sand abrasion caused grooves, and the effects of salt caused notches. Pits were identified on almost half of the plastic samples, indicating the occurrence of chemical

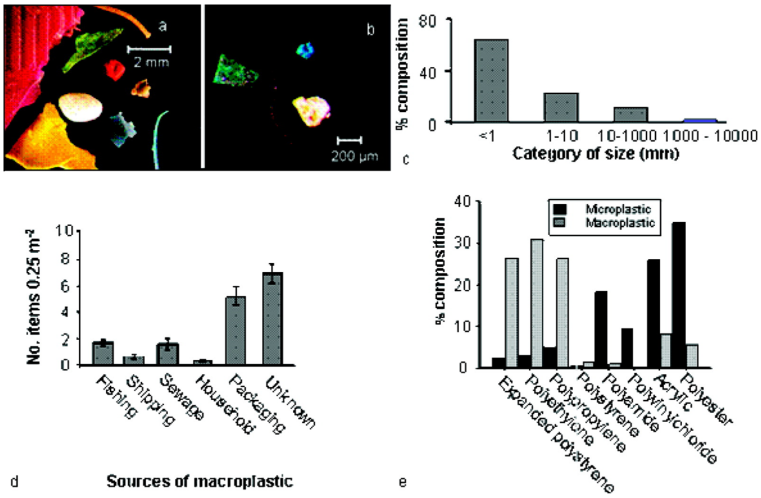


Figure 10. Identity and composition of plastic debris collected from the strandline of the Tamar Estuary (UK) From Browne *et al.* (2010)

Box 5 Ryan *et al.* (2009) – Best practices for at-sea surveys of plastic waste

- Effective monitoring of floating plastics requires huge sample sizes to overcome large variation in spatial distribution.
- Stratified sampling could be helpful which places similar water masses in the same category before sampling occurs.
- Probably the best sampling tool is the Neuston net with a 0.33mm mesh
- The continuous plankton recorder (CPR) is a valuable subsurface tool to track changes in microplastic particles
- For shallow waters, monitoring plastic litter on the seafloor can use the same protocols as beach sampling. For deeper waters, sampling issues have to be considered because variation in the efficiency of trawling means trawling nets may become clogged. Remote cameras may provide a more accurate sampling strategy.

weathering. There was also a tendency for fractures and edges in particles to contain oxidation products, which suggested that fractures created by mechanical weathering were then favourable locations for chemical weathering, which further weakens the surface and causes the plastic to become brittle and break. The results also suggest that polyethylene has the potential to degrade more readily than polypropylene, as it is more conducive to the oxidation process. There is a possibility that additives may provide preferential sites for continued degradation, as indicated by the small patches of heavily oxidized areas in otherwise intact plastic pellets.

O'Brine & Thompson (2010) have investigated the degradation of plastic carrier bags. They studied compostable and oxo-biodegradable plastics (which contain metal salts to speed up the degradation process) and found compostable plastics were completely lost from the wooden platforms to which they were stapled within 16 to 24 weeks, whereas 98 per cent of the oxo-biodegradable plastic remained after 40 weeks. Increasing the degradation rates of plastic could have unintended negative impacts in some cases due to the possibility that plastic does not fully degrade in the marine environment and could therefore speed up the creation of microplastics.

Better methods to isolate microplastics from surface waters, sediments and organisms are needed, as well as research methods that produce comparable data across different studies. Where possible, microplastic measurements could be added to existing and ongoing plankton surveys, especially in coastal areas (Arthur *et al.*, 2009). At the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) workshop on this subject there was a call for a taxonomy of plastic particles in terms of size, shape, density, chemical composition and properties as well as the age of particles (Bowmer & Kershaw, 2010). This could be incorporated into more specific standards that define Good Environmental Status in the EU MFSD and help develop guidelines of sampling and reporting.

2.7 Monitoring the impact of plastic waste on wildlife

One of the major concerns about plastic waste is the impact on wildlife. The actual impacts and their implications for biodiversity and environmental health will be discussed in more detail in section 3.1. Here, impact is considered in terms of its role in monitoring the state of plastic waste in the environment. Once again, there is very little research on land-based wildlife.

Monitoring entangled wildlife can be used to evaluate the effectiveness of policy. However, it must be remembered that this type of monitoring indicates changes in abundance of debris that are responsible for entanglement, which can vary according to species and location. For example, after the MARPOL Annex V banned the disposal of plastics at sea, there was no decrease in entanglement rates of Hawaiian Monk Seals (Henderson, 2001). This is probably because most entanglements are due to lost fishing gear rather than plastics disposed by ships at sea. If the monitoring had considered a species that tended to be entangled by the type of plastic waste disposed by ships, then the impact may have been noticeable. With this variability and the relatively small numbers of entanglements that are recorded, caution has to be taken when scaling up figures. For example, UNEP's general figure of 100,000 mammals dying each year has been called into question. (National Oceanic and Atmospheric Administration, 2010).

Ingestion of plastic occurs more frequently than entanglement. The MFSD has identified ingestion of waste as an indicator for monitoring environmental status. Ingestion of plastic waste has been documented in a number of species. For some species, almost all individuals contain ingested plastic (Ryan *et al.*, 2009), including sea birds, fish, turtles, mussels and mammals. Clearly different species ingest different types and sizes of plastic debris. Many animals mistake plastic waste for prey, for example, fish can confuse plastic pellets for plankton, birds may mistake pieces of plastic for cuttlefish or other prey and sea turtles can confuse plastic bags for jellyfish (Derraik, 2002; Gregory, 2009). Young birds typically contain more plastic than adults, probably because they cannot discriminate between suitable food items, and sometimes parents will accidently feed plastic to offspring (Ryan, 1988). Other animals may ingest plastic that is present in their prey, for example, pelagic fish (those that live between the sea bottom and the surface) are thought to consume plastic particles and these fish are then eaten by fur seals.

Recent research on plankton-eating (and pelagic) fish in the North Pacific Gyre (Boerger *et al.*, 2010) has indicated that 35 per cent had ingested plastic, averaging 2.1 pieces per fish. However, Davison & Asch (2011) found only 9.2 per cent of sampled mesopelagic fish (those that inhabit water at depths from about 200m to 1000m) contained plastic in the North Pacific Gyre. This study was the first to account for the potential bias of 'net feeding', which is when fish are more likely to ingest plastic because the nets that capture them also catch and concentrate plastic waste. Davison & Asch (2011) suggest that the higher levels of plastic waste in Boerger *et al.*'s study could be the result of net feeding as they used Manta nets, which have very long tow duration.

To give some idea of the overall level of plastic in fish stomachs, Davison & Asch (2011) scaled up their findings to estimate that mesopelagic fish in total ingest 12,000 to 24,000 tons of plastic in the North Pacific. However, similar to entanglement, there is a great deal of variability and caution must be taken when scaling up or extrapolating figures to cover numbers or regions larger than the sample.

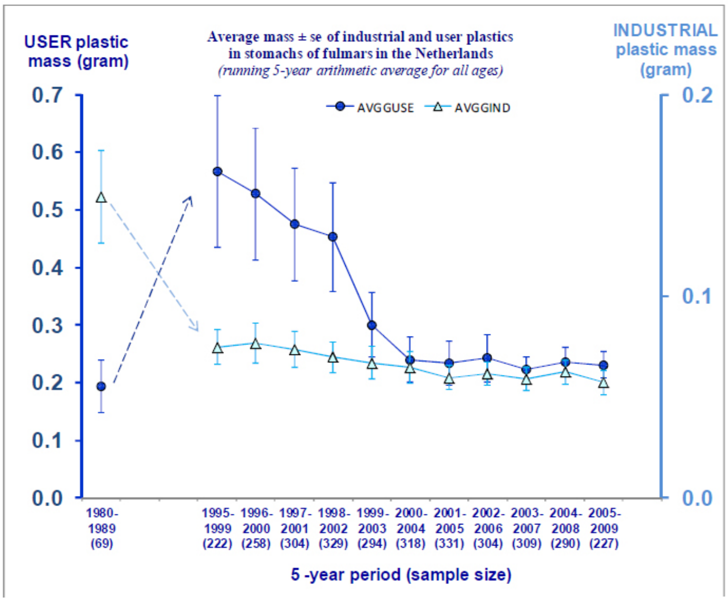


Figure 11. Amount of user and industrial plastic in Fulmar stomachs in Netherlands over time. Van Franeker, J.A.; & the SNS Fulmar Study Group (2011a).

A study on catfish in an estuary in northeastern Brazil indicated that between 18 and 33 per cent of individuals had plastic debris in their stomach, depending on the species of catfish (Possatto *et al.*, 2011). This illustrates the variability between different species of the same type of fish. Despite the variability between species, catfish could be a good species for monitoring plastic ingestion in rivers, as they are both predators and prey to larger fish.

Seabirds are commonly used to monitor ingested plastics and the best-known example is the northern fulmar that has been used by the OSPAR Commission to develop ecological quality objectives (EcoQOs). It is a convenient species to measure plastic pollution because it frequently ingests plastic litter, is abundant in the North Sea, forages exclusively at sea and retains slowly digesting materials in the stomach. Patterns have been found over time with types of plastic (Van Franeker *et al.*, 2011). Figure 11 indicates that the amount of consumer plastic in fulmar stomachs in the Netherlands increased almost threefold from the 1980s to 1990s, then decreased, but is currently stable at a level still above that in the 1980s. Industrial plastic granules followed a different pattern and almost halved in quantity between the 1980s and 1990s; since then that trend has slowed to an insignificant level of change. Overall, the amount of plastic in fulmar stomachs is currently similar to that in the 1980s, but has a different composition with less industrial and more consumer plastic debris.

From a long-term study, OSPAR have put forward the following EcoQO that spells out the target and temporal and spatial frame in which it must be reached:

> *'There should be less than 10 per cent of northern fulmars having more than 0.1g of plastic particles in their stomach in samples of 50 to 100 beach-washed fulmars found from each of 4 to 5 areas of the North Sea over a period of at least five years.'*

The initial suggestion for a target was more strict (less than 10 per cent of northern fulmars having more than 10 pieces of plastic particles in their stomach, equal to about 0.01g) but it such a target was thought not be achievable. The 0.1g limit for ten per cent is ambitious but achievable and currently only occurs in more pristine conditions (Van Franeker *et al.*, 2011). So far the EcoQO has not been met in any of the study areas and is probably only achieved in Arctic populations. From 2005 to 2009, the stomachs of 916 beached fulmars from the North Sea were analysed and the percentage with more than 0.1g of plastic in their stomach ranged from 53 per cent to 86 per cent. The English Channel area is the most heavily polluted with plastics in the North Sea, while seas around the Scottish Islands are the cleanest (Figure 12).

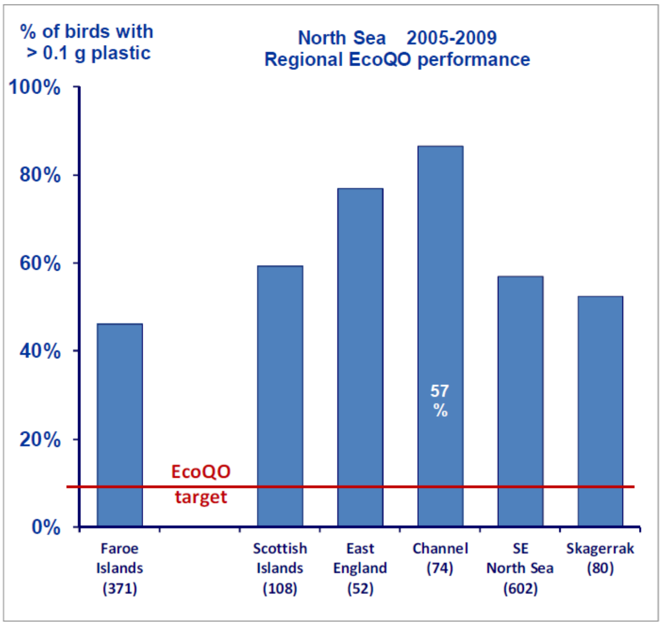


Figure 12. EcoQO performance in North Sea regions 2005-2009 and preliminary trends. Trend shown by connecting running average 5 year data . From Van Franeker, J.A.; & the SNS Fulmar Study Group (2011a).

In terms of trends over time in plastic waste found in the stomachs of fulmars in different regions of the North Sea, the most recent data suggest stability or slow decline in the southern North Sea, and slow increases in most other areas, but none of these are significant (Van Franeker & the SNS Fulmar Study Group 2011a, see Figure 13). The lack of a clear trend in marine litter in the North Sea is not dissimilar to the findings from beach surveys by OSPAR.

It should be noted that the 10 per cent target established by OSPAR is not directly related to the current health status of fulmars, but is more a political choice. It is difficult to establish a biologically meaningful level because a 'no effect' level for fulmars could still be harmful to other ecosystem components, and the EcoQO is an indication of the level of litter and only indirectly of harm to marine organisms from that litter. It is a 'thermometer' of the environment and other species could be affected more or less (Galgani *et al.*, 2010). In order to harmonise the monitoring of fulmars, a manual has been produced describing methods, standard forms and codes (Van Franeker, 2004). The cost of implementing such a monitoring initiative in the OSPAR region has been estimated at €10,000 per contracting partner (Barnay *et al.*, 2010) when added to the Dutch basic monitoring program and made into a larger project. In addition to being a valuable policy instrument, studying ingestion of plastic waste by wildlife is a useful communication tool to attract public attention. The image of a bird with plastic in its stomach makes the ecological impact of plastic waste very real. However, the fulmar is not present globally and parallel species for monitoring may need to be identified in other parts of the world. For areas where fulmars are not so abundant, the project has initiated pilot studies into the suitability of another seabird species (Cory's Shearwater) for monitoring. In time, it may be useful to monitor other species, such as mammals, turtles and fish, with standardised measures. For example, the turtle may be the most appropriate monitoring species in the Mediterranean. The identification of marine species or life stages that are most vulnerable to plastic exposure could be useful to perform exposure studies in locations likely to be 'plastic or microplastic hotspots' as well as habitats to these vulnerable species (Arthur *et al.*, 2009).

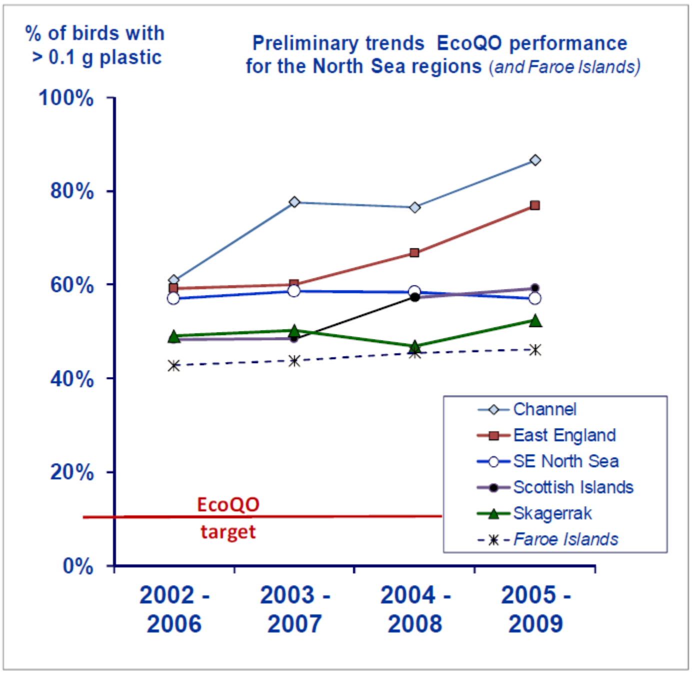


Figure 13. Trends in EcoQO performance in different regions of the North Sea since 2002 (by running 5-year average data). Van Franeker, J.A.; & the SNS Fulmar Study Group (2011a).

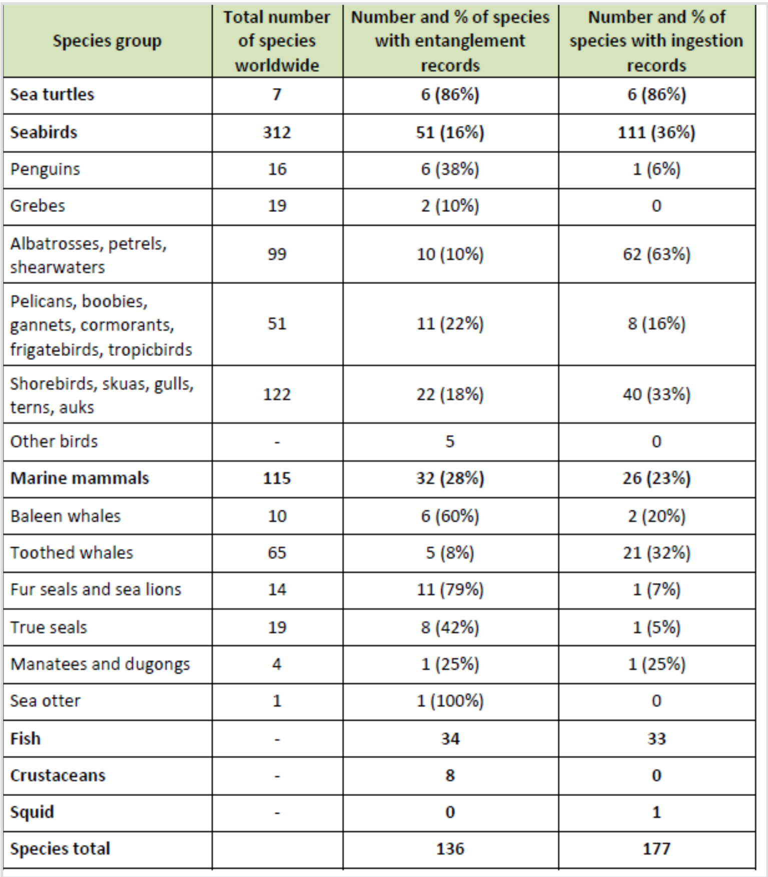
3.0 IMPACTS OF PLASTIC WASTE ON THE HEALTH OF ECOSYSTEMS AND HUMANS

Plastic waste has several impacts on the health of ecosystems and humans. Some of these are more obvious and clearly proven, for example, the entanglement of marine wildlife. Others are subtler and not well understood, such as the transport and possible concentration of contaminants by plastic waste. Again, there appears to be more monitoring of ecological and human health impacts in the marine environment than on land.

3.1 Harm to wildlife

Although there is little research on the specific impacts of plastic waste on land-based wildlife, there is concern that incorrectly managed landfills could lead to either the escape of plastic waste or the escape of landfill leachate containing the chemicals associated with plastic. In addition, unofficial recycling methods, particularly in developing countries, can cause the release of chemicals into the environment, for example, the burning of plastic coated wires to extract metal. The possible impacts of the release of these chemicals are examined in section 3.62 on plastic additives.

UNEP (2006) claims that plastic waste causes the death of up to a million seabirds, 100,000 marine mammals and countless fish through various impacts. Although this figure is useful in raising awareness, it is important to remember that it has been derived from the scaling up of smaller samples from a study in Canada (NOAA, 2010). Probably a more accurate representation is that compiled by Laist (1997), which reported that at least 267 different species are known to have suffered from impacts of plastic waste. This includes 86 per cent of all sea turtle species, 44 per cent of all seabird species and 43 per cent of all marine mammal species (Laist, 1997). This is likely to be an underestimate as the list was compiled over ten years ago and, even with updating, there are probably a large number of species that have not been studied and therefore impacts are not included. There is a huge amount of literature on ingestion and entanglement (Gregory, 2009) and Figure 14 lists examples of known impacts on wildlife in terms of entanglement and ingestion. This list is far from complete, but gives a good indication of impacts.



Species group	Total number of species worldwide	Number and % of species with entanglement records	Number and % of species with ingestion records
Sea turtles	7	6 (86%)	6 (86%)
Seabirds	312	51 (16%)	111 (36%)
Penguins	16	6 (38%)	1 (6%)
Grebes	19	2 (10%)	0
Albatrosses, petrels, shearwaters	99	10 (10%)	62 (63%)
Pelicans, boobies, gannets, cormorants, frigatebirds, tropicbirds	51	11 (22%)	8 (16%)
Shorebirds, skuas, gulls, terns, auks	122	22 (18%)	40 (33%)
Other birds	-	5	0
Marine mammals	115	32 (28%)	26 (23%)
Baleen whales	10	6 (60%)	2 (20%)
Toothed whales	65	5 (8%)	21 (32%)
Fur seals and sea lions	14	11 (79%)	1 (7%)
True seals	19	8 (42%)	1 (5%)
Manatees and dugongs	4	1 (25%)	1 (25%)
Sea otter	1	1 (100%)	0
Fish	-	34	33
Crustaceans	-	8	0
Squid	-	0	1
Species total		136	177

Figure 14. Number and percentage of marine species with documented entanglement and ingestion records from Mudgal *et al*. (2011) Plastic Waste in the Environment p114 (adapted from Laist, 1997)

3.2 Entanglement of wildlife in plastic waste

Wildlife entanglement in plastic can happen in a number of ways and the results can be devastating. The research in this area tends to be limited to certain species and certain locations and it is difficult to understand changing rates of entanglement (Gregory, 2009). Once an animal is entangled it can drown, incur wounds or be less able to catch food or avoid predators. Young fur seals have been documented as being badly affected (Mattlin & Cawthorn, 1986) and it appears the decline in the Hawaiian monk seal and the northern fur seal has been aggravated by entanglement of young animals. In 1976 it was estimated that up to 40,000 fur seals were being killed a year by plastic entanglement (Weisskopf, 1988). There have also been sightings of whales towing masses of tangled rope and other debris, including crayfish pots and buoys. (Gregory, 2009).

Major sources of the plastic responsible for entanglement are abandoned or lost fishing nets and pots (also known as 'ghost fishing'), plastic packing loops, six-pack carriers and plastic rope (Derraik, 2002; Gregory, 2009). Ghost fishing can trap and kill fish, which can reduce catches for fisheries. It is not restricted to surface waters as trawl gear can also be caught during passage across the seabed and, because it is durable, it is likely to remain there almost indefinitely. For example, a 1500 metre long section of net was found south of the Aleutian Islands containing 99 seabirds, 2 sharks and 75 salmon and the net was estimated to be adrift for about a month and to have travelled over 60 miles (US EPA, 1992). Local environmental conditions influence the lifetime of a ghost net, for example, in calm waters the net can continue to 'fish' for decades, while nets in areas of large swell and storm activity are more likely to be torn apart and destroyed (Allsopp *et al.*, 2006). Derelict fishing gear can also be destructive to coral reefs by becoming snagged on coral and causing coral heads to break-off. These can then become caught in the nets and cause more damage (NOAA, 2005).

3.3 Ingestion of plastic waste

Harm to wildlife caused by ingested plastic will vary, depending on their digestive system, the amount and type of plastic ingested and the developmental stage of the animal. For example, certain birds (*procellariiformes* – a group of birds that includes albatrosses) are more vulnerable because they generally do not regurgitate plastics. When feeding their chicks, they can regurgitate the contents (including plastics) of their larger stomachs, but they retain the plastics in their second muscular stomach. Fry *et al.* (1987) found that 90 per cent of Laysan albatross chicks had plastic debris in their upper tract, most likely the result of feeding by parents. Further evidence of plastic ingestion by Laysan albatross chicks comes from studies by Auman *et al.* (1998) and Young *et al.* (2009).

One major effect of ingestion is reduced appetite, as it causes the stomach to feel full. This can lead to starvation. Ryan (1988) investigated this experimentally by feeding polyethylene pellets to domestic chickens. Results indicated that ingested plastics reduced the volume of the stomach and therefore the meal size. Spear *et al.* (1995) provided evidence that the higher the number of plastic particles ingested, the worse the physical condition (body weight) is in seabirds from the tropical Pacific.

Ingestion of plastic can cause more serious blockage of the digestive tract and internal injuries. Sea turtles have been particularly prone to this, but studies differ in their findings according to the geographical area. Tomás *et al.* (2002) found that plastic debris had been ingested by over three quarters of a sample of loggerhead turtles caught by fishermen in the western Mediterranean, while Casale *et al.* (2008) found about half of their sample in the central Mediterranean had ingested plastic. Lazar and Gracan (2011) found just over a third of sea turtles had ingested plastic debris. This indicates geographical and possibly temporal variation in recordings of plastic waste ingestion, despite research involving the same species.

Among cetaceans (mammals best adapted to aquatic life), at least 26 species have been documented with plastic debris in their stomach (Denuncio *et al.*, 2011). A recent study on Franciscana dolphins accidently captured by fisheries in Argentina found that 28 per cent of the sample had plastic debris in their stomachs (Denuncio *et al.*, 2011). Packaging debris (cellophane, bags and bands) was found in just under two thirds of these dolphins, while just over a third had ingested fishery gear fragments (monofilament lines, ropes and nets). Ingestion of plastic was high in recently weaned dolphins, possibly because young dolphins are still learning how to catch prey and misidentified plastic as food. It is also at this life stage when heavy metals, such as mercury and cadmium, start to bioaccumulate (Gerpe *et al.*, 2002). It could be that, although ingestion of plastic debris on its own is not lethal, when it combines with other impacts, it could cause a lethal cumulative effect. In turn, this interaction could be more likely at certain points in an animal's life, such as just after weaning in the Franciscana dolphin. This type of information could be useful for conservation management.

Murray and Cowie (2011) investigated plastic ingestion by Nephrops norvegicus (langoustines). They found 81 per cent of their sample contained plastics, mainly in the form of filaments, but also in tightly tangled balls of plastic strands. In a parallel experimental study, they also found that N. norvegicus that were fed with fish containing plastic did ingest the strands, but did not excrete them. Although the ecological impacts are uncertain, this is a commercial species fished on a large-scale and the presence of plastics in their stomach may have implications for human health, particularly in terms of chemicals moving from the plastic into the flesh (see section 3.6).

3.4 Ingestion of microplastics

The specific impacts of microplastics is a growing concern and also an area that is not well understood (Browne *et al.*, 2008), as it is difficult to quantify microplastics in animal tissues. Experimental studies have revealed that amphipods, barnacles and lugworms ingest microplastics (Thompson *et al.*, 2004). Studies on mussels (Browne *et al.*, 2008) indicate that microplastics are translocated from the gut to the circulatory system within 3 days and then persist in circulation for over 48 days. The research also found a higher number of smaller particles (3.0 μm microspheres) in the circulatory fluid than larger particles (9.6 μm microspheres), which indicates that these smaller particles have greater potential for accumulation in tissues of organisms. The study did not find any significant toxicological effects, but these may occur over a longer period of exposure (as might occur in a natural environment). Research on the final fate of microplastics after ingestion is still sparse and more knowledge is needed on the processes by which they move into the circulatory system.

3.5 Sub-lethal effects of ingesting plastic waste

On a few occasions it can be confidently inferred that ingestion of plastic waste has caused death, for example, one juvenile turtle in Lazar and Gracan's study (2011) had ingested enough plastic to occupy a major part of the stomach and was very likely the cause of death. Such observations are rare. Nevertheless, there are numerous sub-lethal effects of ingesting plastic waste and more research is needed to understand these and to determine if animals can pass plastic through the gut or if some plastic remains throughout the life span (Boerger *et al.*, 2010). This could inform mitigation of negative impacts before populations become threatened, rather than waiting for population decline (Williams *et al.*, 2011). Effects associated with chemicals that are part of plastic or transported by plastic may also be sub-lethal (see section 3.6). There could also be other impacts not necessarily linked to digestion, for example, plastic ingestion could increase the buoyancy of fish making it difficult for mesopelagic fish to return to deeper waters (Boerger *et al.*, 2010).

It has been suggested that research on ingestion may be skewed, in that animals studied are those that have been stranded and might have had 'abnormal' foraging patterns before their death. However, in their study of northern fulmar monitoring, van Franeker & Meijboom (2002) compared birds that were found stranded and died of starvation to those that died accidentally, such as from collision, and found the same amount of plastic within the stomachs of the two groups. This indicates that those birds found stranded can be considered representative of the 'healthy' population. Similar assessments will be needed when initiating monitoring work that uses other species.

Research in British Columbia, Canada, (Williams *et al.*, 2011) has attempted to identify where marine animals and marine debris overlap by mapping and super-imposing the distribution of both. They combined survey results and modelling on both the distribution of marine debris and the distribution of 11 marine animals. Areas of overlap were identified and the researchers suggest that high-overlap areas should be prioritised for future research. They also highlight the fact that many of the species most likely to ingest plastic are not protected species and there is little incorporation of vulnerability to plastic debris ingestion or entanglement into conservation policy.

Although this study has used modelling to estimate the larger scale impacts its dataset was limited and it is still very difficult to quantify population level deaths or effects. There is a need for more co-ordination between data and regions. Any scaling up must be done to an optimum level, i.e. at an appropriate regional scale, as there is high geographical variability in the level of plastic waste.

3.6 Possible impact of chemicals on human health and ecosystems

A lesser-known impact that could result from ingestion, entanglement and inadequate waste management is the impact of chemicals on humans and ecosystems, either contained in plastic or transported by plastic waste. Plastic is not inert, but contains several chemicals with toxic potential. It also has the potential to transport contaminants. Although much is known about the impact of actual chemicals themselves, there still remain many questions about the role of plastic and plastic waste in exposing humans and wildlife to these chemicals.

3.6.1 Toxic monomers

Polymers are composed of repeating subunits, or 'monomers', and some of the major plastics (for example, PVC and polystyrene) have been found to release toxic monomers linked to cancer and reproductive problems (Marcilla *et al.*, 2004; Garrigos *et al.*, 2004). Often, during plastic production, polymerisation reactions are not complete and the unreacted monomers can be found in the final material. Polymers can also be broken up into monomers by heat, UV radiation, mechanical action and other chemicals. Lithner *et al.* (2011) compiled an environmental and health hazard ranking of 55 polymers based on the hazard classifications of their component monomers from the EU classification, labelling and packaging regulation. Thirty-one of these were made from monomers that belong to the two worst hazard levels and many have high global annual production. The study indicated that PVC should receive extra attention because it contains a carcinogenic monomer and is produced globally in large quantities. The study did not include risks from additives and this could increase the hazard ranking of many polymers.

3.6.2 Plastic Additives

Plastic contains chemicals or additives to give it certain properties. There is a wide range of additives, but probably the most relevant to ecology and human health are the following:

1. Bisphenol A is a monomer that is used to make the hard, clear plastic in polycarbonate food and beverage containers, CD cases and many other consumer products. It is an endocrine disruptor and acts like the female hormone oestrogen. It leaches in variable amounts and for different lengths of time, depending on the product and conditions, i.e. it is released more easily at higher temperatures and with changes in acidity. Early development appears to be particularly sensitive to its effects, with a growing body of evidence for associations with chronic disease, including cardiovascular disease and type 2 diabetes and with hormonal changes in adults (Lang *et al.*, 2008, Galloway *et al.*, 2010, Melzer *et al.*, 2011). Experiments on animals have revealed that Bisphenol A (BPA) causes various impacts on their reproductive systems, as well as increases in body weight and insulin resistance (Ben-Jonathan *et al.*, 2009). A major concern is that these adverse effects relate to current disease trends in human populations, such as increases in prostrate cancer, breast cancer, sperm count decreases, miscarriage, obesity and type 2 diabetes (Oehlmann *et al.*, 2009).

2. Phthalates (diesters of 1,2 – benzenedicarboxylic acid) are a group of industrial chemicals used as plasticisers, which make plastics, such as PVC, more flexible or resilient. They are extremely widespread and are found in items including toys, food packaging, hoses, raincoats, shower curtains and vinyl flooring. High-molecular weight phthalates (e.g. di(2-ethylhexyl) phthalate, DEHP) are primarily used as plasticisers, but the low-molecular weight phthalates (e.g. diethyl phthalate, DEP) are used as solvents in personal-care products. This means the sources of phthalates in the environment are numerous. Certain phthalates have been shown to function as endocrine disruptors, and to have anti-androgenic activity. They are not chemically bound to the plastic matrix, which means they can easily leach out of products to contaminate the environment (Talness *et al.*, 2009; Meeker *et al.*, 2009). There is experimental evidence of negative impacts on reproductive systems of animals and these resemble human reproductive disorders, especially testicular dysgenesis syndrome, indicating a possible link between phthalate exposure and human disease. However, the dosages in animal studies are likely to be much higher than exposure levels to humans. Links have also been made between phthalate exposure and obesity and allergies.

3. Brominated Flame Retardants are deemed necessary in plastics for safety reasons. Common examples of these are polybrominated diphenyl esters (PBDEs) and tetrabromobisphenol A (TBBPA). They are added to a variety of consumer products, including textiles and thermoplastics used in electronics, e.g. televisions and computers. Studies indicate that PBDEs and TBBPA have hormone-disrupting effects, in particular on oestrogen and thyroid hormones, and that exposure to PBDEs impairs development of the reproductive and nervous system.

The potential harmful effects of these chemicals have been documented (for reviews see Talsness *et al.*, 2009; Meeker *et al.*, 2009; Oehlmann *et al.*, 2009; Hengstler *et al.*, 2011), as has their presence in the environment and within the biological systems of wildlife and humans (Koch & Calafat, 2009). There is some variation across different demographic groups and, of particular concern, is the higher concentrations of Bisphenol A and phthalates in young children (Koch & Calafat, 2009).

Bisphenol A and phthalates are rapidly metabolised once ingested but their concentration within the tissues varies between species for the same exposure. The bioconcentration factor is the concentration of a chemical within the tissue of the species compared with its concentration in the surrounding environment. For example bioconcentration factors of the phthalate DEHP (bis(2-ethylhexyl)phthalate) are between 42 and 842 in fish, but they are 3600 for an amphipod and 2500 for a type of mussel (Oehlmann *et al.*, 2009).

A review by Talsness *et al.* (2009) has identified several studies that demonstrate BPA is leaching from products that have been thrown into landfills and entering groundwater, contaminating rivers, streams and drinking water. Because BPA breaks down slowly, the compound could build up in waters and harm fish and other aquatic life. Research on 10 landfill sites in Japan (Yamamoto *et al.*, 2001) found concentrations of BPA ranging from 1.3 to 17,200 µg per litre with a median concentration of 269 µg per litre. In some cases, the concentrations exceeded the level above which it is considered toxic to aquatic biota. Plastic waste was the major type of waste in landfills with the highest levels of BPA, indicating that plastic waste was an important source of the BPA.

Teuten *et al.*, (2009) suggested that the migration of additives from plastic to the landfill leachate depends on several factors, including the pore size of the plastic, the molecular size of the additive and the nature of the leachate, in terms of its acidityand organic content. By comparing

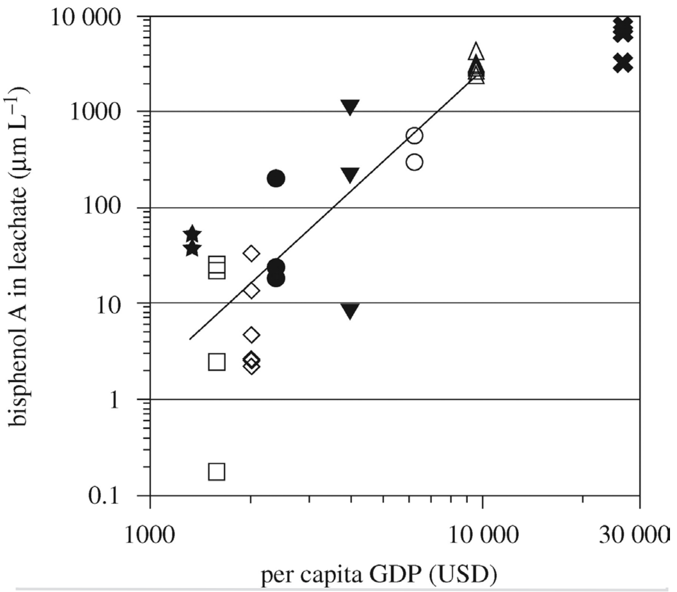


Figure 15. Relationship between BPA concentrations in leachate and per capita GDP of Asian countries. From Teuten et al (2009)

studies on endocrine disrupting chemicals in tropical Asian countries, Teuten *et al.* (2009) found evidence that the more industrialised countries (Malaysia and Thailand) had higher BPA concentrations in landfill leachate than less industrialised countries (e.g. Laos and Cambodia). They suggested that the most probable reason for this is the greater use of plastics in the industrialised countries, which thus generates more plastic waste. (See Figure 15).

If badly managed, recycling processes can cause the release of chemicals from plastics into the environment and subsequent impacts on human health. This can be the case of electronic waste, which is exported outside Europe where it is recycled in small workshops, sometimes without proper ventilation, often by burning to extract the valuable metals. Chipping and melting of plastics releases toxic chemicals, for example, copper wires are often recovered by burning the PVC, and PBDE (flame retardant) protected cables and can release toxic chlorinated and brominates dioxins (PCDD/PBDD) and furans (PCDF/PBDF). Kyung-Seop *et al.* (2007, 2009) demonstrated that combustion of PVC with other plastics in the laboratory produced substantial levels of PAHs (polycyclic aromatic hydrocarbons) and these were strongly associated with plasticiser content. Wong *et al.* (2007) studied the concentrations of POPs (persistent organic pollutants) in a province in China, which had become an intensive electronic waste recycling site. In comparison to levels of chemicals in other sites and to guidelines adopted by other countries, the air, soil and sediment was highly contaminated, in some cases, 100 times higher than published data (for PBDE). In general, it appeared the incomplete combustion of plastic wastes (plastic chips, wire insulations, PVC materials) was the main source of POPs. Such high concentrations of toxic chemicals would affect workers and residents through inhalation, dermal exposure and ingestion of contaminated drinking water and food, especially as the province was also a rice-growing region. Since Wong *et al.*'s (2007) study was conducted, the Chinese government has tightened regulations on the import of electronic waste, but it is likely that it may make its way to other countries and be processed in a similar way.

3.6.3 Metals

There has been some concern about heavy metals, such as cadmium, in plastic especially in children's toys and in plastic crates and pellets. Although there is little evidence that these traces of heavy metals present a health risk to humans, there is also a lack of research on the presence of heavy metals in children's toys, which could potentially leach out when thrown away (Mudgal *et al.*, 2011). Waste plastic components of mobile phones have also been found to contain lead, cadmium, nickel and silver (Nnorom & Osibanjo, 2009).

Ashton *et al.* (2010) analysed pre-production plastic pellets from four UK beaches for traces of major metals such as aluminium and iron, and for trace metals such as copper, zinc, lead etc. Results showed that production pellets are able to accumulate metals to concentrations that, in some cases, approach those on other marine solids such as sediment and algal fragments.

Plastics may represent only a small reservoir of metals on beaches and there are other more important sources, but when the plastics move into the open sea their importance in the transportation of metals is greater. In addition since metals are adsorbed to the surface of plastic, they are likely to be accessible to fauna that inadvertently ingest them.

3.6.4 Status of knowledge and research

A large number of questions remain about the toxicity of plastic. Currently little is known about the possible exposure levels of chemicals from plastic waste and the specific impact caused by plastic waste. Plastic waste is not the only source of these chemicals. For example, BPA also comes from thermal paper and printer ink, while phthalates are also used in solvents, personal-care products, textiles and pesticides, and flame retardants have a number of applications other than protecting plastic objects from fire. In addition, it may not be plastic waste but the product during its lifetime that is a source of contamination, for example, exposure to BPA

Box 6 Major challenges facing research into impact of chemicals within plastic (Meeker *et al*., 2009; Oehlmann *et al*.2009)

- Shifts in exposure levels among populations over time, causing ever-changing patterns of production.
- The impact of mixtures of different chemicals and their cumulative effect on ecosystems and human health, also known as the 'cocktail effect'.
- The possibility of multiple interaction sites within the body affecting a wide range of biological processes
- Potential latent and transgenerational effects (e.g. epigenetic modification) of exposure to chemicals

Innovations that can help meet these challenges:

- Improved biomarkers (substances used as indicators) of the level of exposure to chemicals
- Better statistical methods to deal with multiple exposures
- New measures to assess the routes of exposure and links between exposure and impacts on human health and ecosystems

and high molecular-weight phthalates result primarily from ingesting food that has been in contact with plastic (Koch & Calafat, 2009). More research is needed to try to establish the pathways by which these chemicals reach the environment and how much plastic waste contributes to the levels of these chemicals within wildlife and humans. The sources and routes to exposure need to be identified and their relative contributions assessed to inform measures to reduce exposure.

3.7 Microplastics: potential toxic impacts

Microplastics have a larger surface to volume ratio than macroplastics, which potentially could encourage the exchange of contaminants (Bowmer & Kershaw, 2010). Very little is known about the rates of leaching of integral plastic components, such as additives and toxic monomers, to seawater. The proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Micro plastic Marine Debris (Bowmer & Kershaw, 2010) suggested realistic exposure experiments of microplastics are needed to determine their toxicity levels in the laboratory and better knowledge on the dose-response relationships between specific types of microplastics and vulnerable marine species or life stages. The toxicity studies could then be scaled up to levels of microplastics observed in hotspots to provide an idea of the possible real-life impact (Arthur *et al.*, 2009). Similarly, little is known about the bioavailability of chemicals through ingestion of microplastics, but the evidence from filter feeders, deposit feeders and detritivores (Thompson *et al.*, 2004; Browne *et al.*, 2008) indicates that these animals can absorb microplastics from the gut into the bloodstream. Further study is needed on possible bioaccumulation, especially with phthalates, and whether it occurs selectively in different species and at different life stages within species.

3.8 Collection and transport of other contaminants by plastic waste

Other chemicals may also contaminate plastic debris. This can happen in a number of ways. Plastic particles from hand cleaners, cosmetic preparations and air blast cleaning may all have collected chemicals. In air blasting technology, polyethylene particles are used to strip paint from metallic surfaces and clean engine parts. These can be used up to ten times before they are discarded, which means they can become significantly contaminated by heavy metals (Derraik, 2002). Many will find their way into marine waters where they could be transferred to filter-feeding organisms and other invertebrates, eventually reaching species higher up in the food chain.

Plastic can also pick up contaminants that are present in water, particularly those that are hydrophobic (repel or unable to mix with water). This includes many POPs, such as PCBs (polychlorinated biphenyls) and PAHs (polyaromatic hydrocarbons), as well as organo-chlorine pesticides, such as DDT (dichlorodiphenyltrichloroethane). Some are highly toxic and have a wide range of chronic effects, including endocrine disruption, mutation and cancer (Rios *et al.*, 2007). At least half the PCBs ever produced are still in use, especially in older electrical equipment, so there remains a large reservoir of PCBs with the potential to be released into the environment through spills or leakages from transformers and other devices (Rios *et al.*, 2007). PAHs are formed during the incomplete combustion of coal, oil, gas, garbage and other organic substances. In laboratory studies where animals are exposed to some PAHs over long periods, they have developed lung cancer from inhalation, stomach cancer from ingesting PAHs in food, and skin cancer from skin contact. Human health effects from chronic or long-term exposure to PAHs may include decreased immune function, cataracts, kidney and liver damage, breathing problems, asthma-like symptoms, and lung function abnormalities, and repeated contact with skin may induce skin inflammation. Evidence primarily from occupational studies of workers exposed to mixtures containing PAHs shows an increased risk of predominantly skin and lung cancers but also bladder and gastrointestinal cancers (Toxipedia, 2011). Pesticides such as DDT are toxic to a wide range of animals, particularly birds. DDT and DDE have been linked to diabetes, developmental and reproductive toxicity and cancer in humans. Although some of the more toxic pesticides, such as DDT, have been banned, they are still persistent in the environment.

Many of the hydrophobic contaminants are concentrated at the sea surface and their levels are up to 500 times greater than in the underlying water column (Teuten *et al.*, 2007). As most plastics float, they have the potential to adsorb these contaminants that are concentrated at the sea surface leading to several possible outcomes. The plastics can either transport the contaminants to other areas and, if washed up, the contaminants could be transferred to shoreline sediment or plastic could be eaten by wildlife and potentially transferred to their tissues and further up the food chain. Plastic could be subject to fouling and then sink to the bottom where it becomes part of the sediment or is eaten by benthic organisms that live on the sea bottom. If plastic does become part of the sediment, whether on the shore or sea bottom, then it is no longer as available for degradation by micro-organisms as it was in the water, especially if it is buried (Teuten *et al.*, 2007). According to the Stockholm Convention on POPs, persistence, long-range transport potential and bioaccumulation potential are fundamental criteria in assessing the risk of POPs. A compound's persistence tends to be based on environmental half-lives while transport potential is based on monitoring data in remote regions. Bioaccumulation potential is derived from bioconcentration factor (BCF), which is the concentration of a chemical in a tissue compared to its concentration in the surrounding water.

Rios *et al.* (2010) investigated the amount of POPs on samples of plastic debris from the Northern Pacific Gyre and found that over 50 per cent contained PCBs, 40 per cent contained pesticides and nearly 80 per cent contained PAHs. The concentrations of pollutants ranged from a few parts per billion (ppb) to thousands of ppb, with the types of contaminants similar to those found in marine sediments. The researchers suggested that plastic debris behaves similarly to sediments in the way it accumulates pollutants but, unlike sediments, micro-plastics tend to remain at the surface where they are potentially more available to wildlife. Research on plastic found on beaches and in stranded albatrosses in California, Hawaii and Mexico, found a ratio of different PAHs that indicated the principle source of the PAHs on the plastic was incomplete combustion of fossil fuels, most probably from urban and industrial areas (Rios *et al.*, 2007). The main types of polymer were polyethylene and polypropylene, which are very common thermoplastic resins used mostly in packaging. Teuten *et al.* (2009) suggested that polyethylene might accumulate more organic contaminants than other plastics.

More recently Hirai *et al.* (2011) analysed the concentrations and composition of organic pollutants on plastic fragments (about 10 mm in size) at eight locations including gyres, remote beaches and urban beaches. PCBs, PAHs, DDT, PBDEs, alkylphenols and Bisphenol A were detected in concentrations ranging from one to 10,000 nanogrammes per gram of plastic. There was variability in how the pollutants had become associated with the plastic. Hydrophobic compounds such as PCBs and PAHs appeared to have

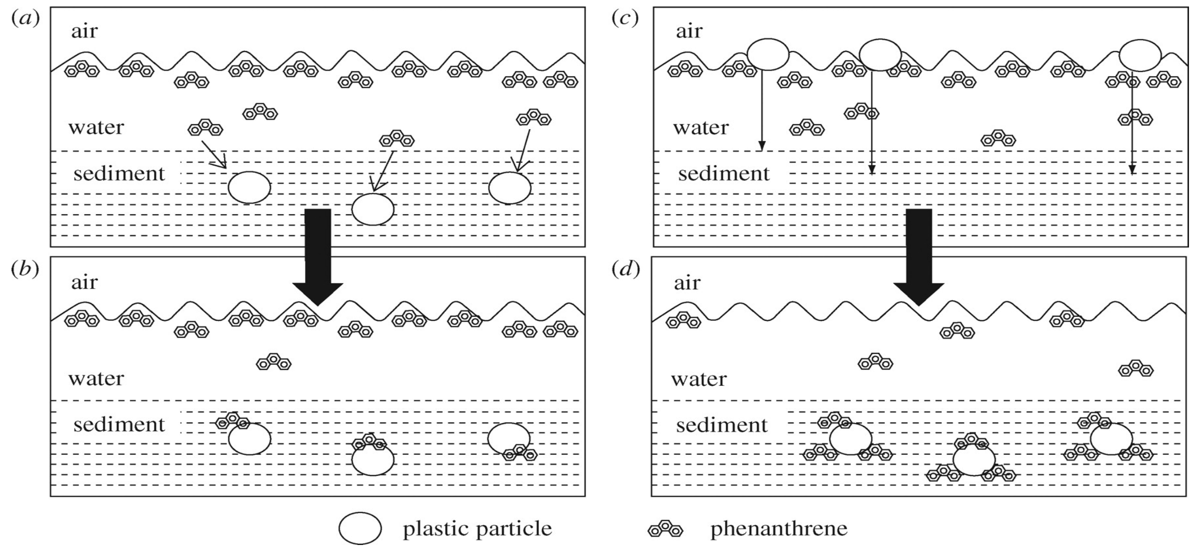


Figure 16. Illustration of additional effects of plastics in transport of phenanthrene. From Teuten *et al.* (2009).

been absorbed to the plastic from the seawater. They tended to be in higher concentrations at urban beaches, although there were occasionally in very high concentrations at sea. In comparison PCBs were derived mainly from legacy pollution i.e. pollution still remaining from before the time when they were banned. The source of PAHs seemed to be on the whole from oil slicks while Bisphenol A and PBDEs came from additives in the plastic.

Monitoring in remote regions is one means of assessing long-range transport. Zarfl & Matthies (2010) estimated the fluxes of PCBs, PBDEs and perfluorooctanaic acid (PFOA) to the Arctic via plastic debris on the main ocean currents. They estimated that fluxes in pollutants caused by plastic was in the order of four to six times smaller than fluxes caused by atmospheric or seawater currents, which accounted for several tons of pollutants per year. However, the researchers did highlight that the significance of pollutant transport routes does not only depend on the absolute amount of pollutants, but also on their impact from direct plastic ingestion and bioaccumulation in food chains.

Teuten *et al.* (2009) investigated in more detail the uptake and subsequent release of one POP – phenanthrene – on three major plastics: polyethylene, polypropylene and polyvinylchloride. In all cases they found that pollutants adsorbed onto the plastics at a much higher rate than onto natural sediments. However, desorption (or release) of the phenanthrene occurred more rapidly from sediments than from plastic. This has several possible consequences as it could mean the plastic acts like a sink for the pollutants by lessening their availability to the environment, or it could mean that it increases their lifetime in the environment by hindering their disposal by natural means, such as microbial degradation. There is therefore a debate as to whether plastic debris acts as a sink for pollutants or as a storage and transport vessel whose impact ultimately depends on the fate of the plastic.

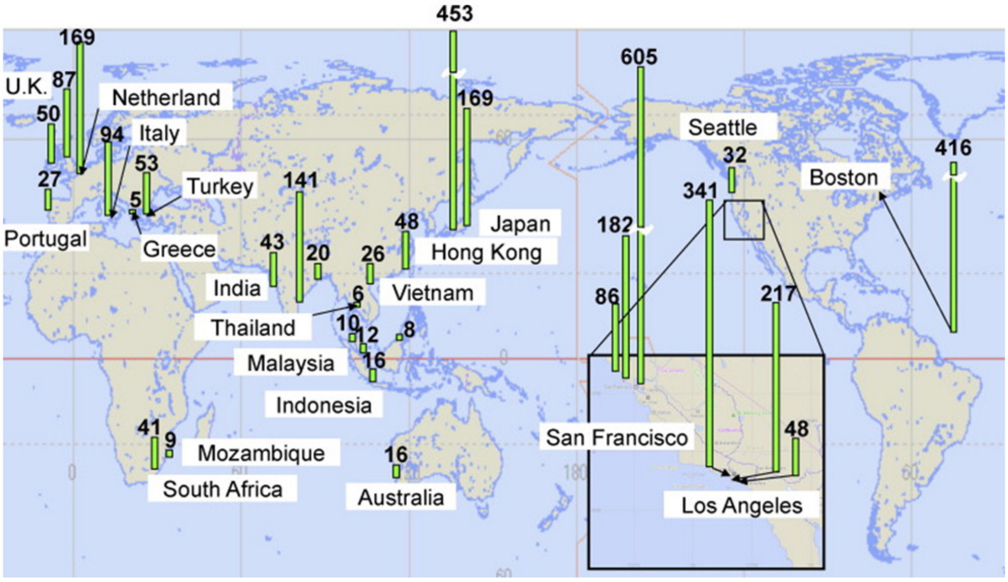


Figure 17. Concentrations of PCBS in beached plastic pellets. From Teuten *et al.* (2009) paper in PNAS but also from International Pellet Watch paper (Ogata *et al*, 2011)

Another factor to consider is what happens to plastic loaded with pollutants when it is ingested by wildlife. Research demonstrates the potential for plastic to gather toxic contaminants, but little is known about the potential for plastics to release contaminants or additives to marine wildlife. Once inside an organism, the presence of digestive surfactants (which prevent particles sticking together) is known to increase the desorption rate of PAHs from plastics by up to 20 times compared with seawater (Murray & Cowie, 2011). Teuten *et al.* (2007) investigated this by modelling the possible effects on the lugworm, which is a common benthic deposit feeder. They estimated that the addition of as little as 1 µg of contaminated polyethylene to a gram of sediment would produce a significant increase (80 per cent) in phenanthrene accumulation by the lugworm. As this plastic concentration is lower than that found in the environment, it suggests plastic debris may play an important role in transporting contaminants to sediment-dwelling organisms.

Ryan *et al.* (1988) found a positive correlation between the mass of ingested plastic and PCB concentrations in fat tissue of Great Shearwater birds, providing the first indication that marine organisms can absorb toxic chemicals into their flesh. Further study with shearwater chicks that were fed with polyethylene pellets containing PCBs (Teuten *et al.*, 2009) indicated that plastics could transport environmental contaminants to organisms at various levels of the food chain. This study analysed levels of PCBs in preen gland oil (produced by birds for preening) and found higher levels in chicks that had been fed on PCB plastic. More research is needed on other organisms, considering a range of contaminants and plastic types, as well as the effects of environmental exposure in terms of weathering and aging of polymers.

3.9 Microplastic accumulation and transport of chemicals

A number of studies have focused specifically on the role of microplastics in the transport of pollutants, partly because they are more likely to be ingested, but also they have an increased surface-to-volume ratio. Rios *et al.* (2007) analysed pre-production plastic pellets and post-consumer fragments from beaches and regurgitated albatross stomach contents in California, Hawaii and Mexico. They found PAHs in all samples and PCBs only in the debris collected on beaches. The only pesticide detected was DDT. Observations suggested that the concentration of POPs on plastic debris could be a function of the age of the plastic. Teuten *et al.* (2009) indicated that time-scales of adsorption and desorption are a function of the type of plastic, its size and the compound.

One study (Ogata *et al.*, 2011) actually used plastic pellets as a means to monitor the amount of POPs in coastal waters. International Pellet Watch has been in operation since 2006, sampling pre-production polyethylene pellets from countries around the world by asking local communities to collect plastic pellets and send them to the laboratory where they are analysed for PCBs, DDTs and HCHs (hexachlorocyclohexanes). Initial findings have indicated that PCB concentrations are highest in US coasts, followed by Western Europe and Japan, whereas concentrations are lower in tropical Asia, southern Africa and Australia. However, in India, especially in Chennai, there were high PCB concentrations, probably from recycling of electronic waste and poor management of ship-breaking activities.

These high concentrations could expose wildlife, which ingest plastics in that area to significant amounts of pollutants (Bowmer & Kershaw, 2010). High concentrations of DDTs are found on the US west coast and in Vietnam, probably the result of high pesticide use in the past. Although this research was primarily to monitor POPs, it has the dual purpose of clarifying the role of plastic waste in transporting these chemicals and identifying patterns of prevalence of POPs in the marine environment.

Interestingly, a study on POPs and microplastics on a Portuguese beach very close to one of the beaches sampled in the International Pellet Watch study indicated much higher levels of PCBs and PAHS, which suggests either a large variation within close proximity or variation in the results produced by different sampling methods (Frias *et al.*, 2010). This research in Portugal also indicated that older particles have higher levels of POPs, suggesting that microplastics continue to accumulate contaminants throughout their lifetime.

Although we are knowledgeable about the harmful effects of most chemicals, it remains unclear as to the degree of their bioavailability once they are adsorbed to plastics. The challenge is how to identify the added or reduced chemical impact of plastics and microplastics relative to the ‘natural’ bioaccumulation of pollutants from water and through the food chain (Bowmer & Kershaw, 2010).

Research has indicated that animals at lower trophic levels do ingest microplastics and they are absorbed into their system. There is a possibility that microplastics could act as a sink for POPs (as described in scenario 3 in Box 7), but it is likely that this will depend on the surrounding environment in terms of concentration of POPs in the water column, level of fouling, ocean and air currents, level and type of sediment, age and type of plastic (Teuten *et al.*, 2009).

In turn, any impact on wildlife, whether from transported contaminants or those contained within the plastic, will depend on species, its distribution in that area, its stage of development, surrounding environmental conditions, food availability, and perhaps its position in the food web. Very little

Box 7 Possible scenarios of the fate of transported chemicals in microplastics (Bowmer & Kershaw, 2010)

1. Microplastics will take up and release pollutants from the water column. This could mean they adsorb pollutants where concentrations are high and then release them in cleaner, remote regions. The speed of this could depend on the type of microplastic.

2. For most pollutants, atmospheric transport by wind and ocean currents will be the most dominant form of transportation, as suggested by Zarfl & Matthies (2010). The influence of microplastics will be relatively low, apart from in locations where atmospheric transport is small.

3. Microplastics will serve as a stable phase in the water column in addition to organic matter and sediments and act as a sink for pollutants. To assess this modelling is needed to evaluate the tendency of chemicals to partition between air, water, plastics and organic carbon in the sediments.

Box 8 Observations in mass mortality of the northern fulmar (Van Franeker, 2011c)

- As part of the North Sea monitoring of fulmars, surveyors encountered an exceptionally large number of dead fulmars in March to June 2004 in the southern North Sea. Patterns of delayed moult (renewal of feathers) indicated that most of the birds had suffered continuous food shortages since the previous autumn. The poor plumage may have affected waterproofing, flying and insulation. The large majority of the birds were adult females, which is unusual. Some of these were egg-carrying females, which again is unusual as the normal strategy for fulmars under poor food conditions is to cease reproduction.
- Both moulting and reproductive decisions tend to be hormonally regulated, which suggests the possibility of a disturbed endocrine hormonal system in these fulmars. As fulmars grind down plastic in their digestive tract, this is likely to maximise uptake of plastic-related chemicals but, even if absorbed, the effects of pollutants can only become apparent when the birds use their fat reserves and contaminants start circulating in the blood.
- Under prolonged periods of reduced food and therefore body condition, it is likely that endocrine hormone disruptors take full effect. If this is the case, it would mean that chemicals related to plastic ingestion could be latent and then, under unfavourable conditions, their release is triggered. This explanation could not be proven as no funds were available to test levels of pollutants and hormones in the birds; it is however an argued example of how sub-lethal effects of plastic waste can combine with other effects and contribute to lethal impacts.

is known about bioaccumulation of these chemicals and since humans could be one of the creatures most affected by this, there is a need for greater understanding. Already, concern has been raised about the presence of microplastics in crustaceans and mussels and the possible impact on human health further up the food chain (Murray & Cowie, 2011; Browne *et al.*, 2008).

3.10 Plastic waste: impact on habitats

As well as a direct physical impact on marine wildlife and humans, plastic waste also affects habitats, both on land and sea. Visually, plastic waste is a problem for human habitats, but it also has substantial impacts on wildlife habitat. Most documented effects are on the marine environment and, once again, there is a lack of evidence on possible land-based impacts. Although plastic is often buoyant, it can sink to the bottom of the sea, pulled down by certain 'bottom-hugging' currents, oceanic fronts or rapid and heavy fouling. Sediment may also help keep plastic on the seafloor.

It is likely that once on the seafloor, plastic waste will change the workings of the ecosystem. Goldberg (1997) has suggested the plastic sheets could act like a blanket, inhibiting gas exchange and leading to anoxia or hypoxia (low oxygen levels). Plastic waste could also create artificial hard grounds (Gregory, 2009) and cause problems, especially for burying creatures. Katsenevakis *et al.* (2006) investigated the effect of marine litter on benthic (seafloor dwelling) animals by purposefully placing litter on the seafloor of Greek coves, most of which was plastic bottles. In areas of litter, there was an increase in abundance and number of species, either because the waste provided refuge or reproduction sites for mobile species, such as Alica mirabilis (a sea anemone) or because species which prefer hard surfaces had the opportunity to settle, such as barnacles and sponge. However, it would be naïve to interpret the results as indicating that litter can be beneficial, as this would ignore the long-term effects of ecological change on benthic communities. Plastic waste could encourage the invasion of species who prefer hard surfaces and, as a result, indigenous species may be displaced, particularly those who prefer sandy and muddy bottoms. The researchers called for further research into the impact of plastic waste on other habitat types, such as coral reefs, seagrass beds and deep bottoms.

Plastic waste also affects beaches. So-called 'wrack' environments consist of natural flotsam and jetsam such as seaweed, driftwood etc. that is washed up on the shore, and often contains plastic waste. These habitats can support diverse, marginal invertebrate species and are also visited by many vertebrates, mostly birds who can use plastic waste as nesting material. However, they can also displace species that live in unspoiled beach conditions and affect the ability of wildlife to find food. For example research by Aloy *et al.* (2011) in the Philippines showed that the efficiency of the gastropod Nassarius pullus to locate and move towards a food item decreased as the level of plastic debris increased on the beach. Beach clean-ups are a way to remove plastic waste, but it is often assumed that the beach will return to its previous state once the clean-up is done. However, it can take time for certain displaced species to recolonise. Another problem with clean-ups is that they can miss buried plastic waste and microplastics that are often mixed up with the sediment itself.

Carson *et al*. (2011) assessed the impact of plastic fragments on beaches in terms of how they alter the physical properties when they are part of the sediment. They compared sand from a beach in Hawaii that contained up to 30.2 per cent of plastic by weight (mainly in the top 15 cm) to sand from a beach with a negligible amount of plastic. Their results indicated that the presence of plastic fragments changed the water movement and heat transfer of the beach. Plastic fragments appeared to increase the permeability of the beach so that greater volumes of water could pass through it, which could enrich the beach water with nutrients and potentially alter ecosystems. They also found that the beach containing plastic fragments warmed at a slower rate and reached a lower maximum temperature. This could have implications for beach wildlife, including those who bury eggs in the sediments and whose sex of offspring depends on the temperature of the sand, such as sea turtles.

3.11 The role of plastic waste in invasions of alien species

As well as transporting pollutants, plastic waste can also be a mode of transport for species, potentially increasing the range of certain marine organisms or introducing species into an environment where they were previously absent (Derraik, 2002). This in turn can cause subsequent changes in the ecosystem. Although large-scale and long-term documentation of this is difficult to establish, there are a number of examples that provide insight into this problem. Plastic debris is most commonly colonised by encrusting and fouling organisms that tend to live on the surface of other creatures, including: barnacles, tube worms, foraminifera, coralline algae, hydroids and bivalve molluscs. Recorded plastics that have transported alien species are virgin plastic pellets, synthetic rope, crates and netting, but many other forms of plastic could serve as vessels or vehicles for transport. Often plastic debris can provide habitat for the larval and juvenile stages of marine animals that can then be transported and develop in the new environment. However, not all the species that are transported will necessarily prove harmful to their new host environment (Gregory, 2009). Little is known about the current and future implications of the transport of invasive species via plastic waste, especially the role of microplastics in transporting microorganisms that are very difficult to observe or study.

Invasive species and their impacts on ecosystems are becoming an increasing concern, especially with the potential of climate change to alter population distributions. Despite the lack of knowledge of the impact of plastic waste on the transportation of alien species it should not be underestimated as it may have larger effects in the future, especially if combined with other impacts such as climate change.

3.12 Social and economic impacts as result of ecological and health impacts

Mouat *et al.* (2009) investigated the North Atlantic region and estimated substantial economic losses caused by marine litter. For example, costs associated with removing beach litter each year for local municipalities is approximately €18 million in the UK, and €10.4 million in the Netherlands and Belgium. In terms of fishing, Mouat *et al.* (2009) estimated the cost of marine litter to the Scottish fishing fleet was between €11.7 - 13 million on average per year, which is the equivalent of 5 per cent of the total revenue of affected fisheries. This is mainly because marine litter restricts and contaminates catch, and nets become caught on debris. Given that plastic waste often makes up the majority of marine litter, then the cost of plastic waste in the environment is substantial. However, the cost attributable only to ecological harm caused by plastic waste is difficult to extract from existing figures.

The study by Mouat *et al.* (2009) also examined costs to several other areas, such as tourism, rescue services and voluntary organisations. Galgani *et al.* (2010) highlight that these figures are based on voluntary responses to surveys and may be lacking in spatial coverage. In terms of tourism, Balance *et al.* (2000) considered beaches in South Africa and estimated that an increase in litter of 10 pieces per m2 would deter 40 per cent of foreign tourists and 60 per cent of domestic tourists from returning to the beaches. Little research has been carried out on the specific social and economic impacts of plastic waste, although the type of impacts are likely to be similar to those identified for general debris. There has been no specific research on the social and economic repercussions of the ecological and health impacts of plastic waste, but some studies have incorporated cost implications into their analysis, for example, Sancho *et al.*, (2003) calculated that the amount of monkfish trapped by ghost nets in Cantabrian Sea may be around 1.5 per cent of commercial landings.

Mouat *et al.* (2009) have suggested that economic impact could provide a more powerful incentive for removing and preventing beach litter than current legislation. Whether a specific cost analysis of the impacts of plastic waste will add anything further to this is difficult to know. Analysing economic costs may be easier for the more direct impacts, such as ingestion and entanglement, but difficult for the toxic impacts of additives in plastic waste or contaminants transported by plastic waste, especially as little is known about the specific effects of these. Contaminated marine species could create costs for fishing, aquaculture and coastal agriculture, and chemicals within or transported by plastic waste could potentially create costs human health costs. Furthermore, costs may be incurred by damage to ecosystem services (Galgani *et al.*, 2010), such as the oceans' ability to store CO2 and water quality regulation provided by soil. To accurately calculate these costs more detailed assessments are needed on the ecological impact of plastic waste. As the impacts of plastic waste could be greater when considered as part of a system that includes several anthropogenic impacts rather than on its own, it may be more valuable to consider the total cost of impacts or create 'scenarios' where plastic waste plays a part to demonstrate its effects.

Plastic fragments inland, on beaches and on the sea are potentially dangerous to small children as they may be ingested. Depending on the seriousness of the toxic impacts of chemicals involved in plastic waste, there could also be social impacts in terms of human health, particularly if it occurs at an important developmental stage. If these impacts occur there would also be subsequent pressures on health and care systems. Since plastics are relatively new, it may be that the human health impacts and wider social implications of plastic waste may become more serious and widespread in the future as we learn more.

4.0 RESPONSES

There is a wide range of policy responses to marine litter, but there are also some more specifically aimed at plastic waste. Responses can be at the international level, such as Annex V to International Convention for Prevention of Pollution from Ships (MARPOL), the UNEP Global Programme of Action for Protection of the Marine Environment from Land-based activities and the EU Marine Strategy Framework Directive (MSFD). The Basel Convention on the control of transboundary movements of hazardous wastes and their disposal was adopted in 1989. This year, the meeting of those party to the Basel Convention (COP10) chose as its theme the prevention, minimisation and recovery of wastes. It links waste management to the achievement of the Millennium Development Goals and could create opportunities to draw attention to plastic waste in the future. The UNEP (DTIE IETC) Global Partnership on Waste Management was created in 2009 and earlier this year it drafted its framework document. It aims to coordinate different waste sectors and related activities/initiatives and has eleven thematic focal areas, one of which is plastic waste while another is marine litter. Each focal group will have a working group that will develop a work plan for their activities, including timeline, identification of resources, and a fund-raising strategy.

Other responses are regional, such as the Barcelona Convention for the protection of the Mediterranean Sea against pollution, or the OSPAR EcoQO initiatives or HELCOM convention's Strategy on Port Reception Facilities for Ship-Generated Waste in the Baltic (Galgani *et al*., 2010). There are also national and local policy responses, sometimes to implement international policy, but also as initiatives in their own right. Many of the clean-up and monitoring programmes are conducted at this level.

As well as crossing many levels of policy, plastic debris is an issue that crosses many policy areas, including waste management, enterprise and ecodesign, chemical regulation, marine policy, integrated coastal zone management and fishing policy. Some of the themes that are important to consider in policy responses are discussed below.

4.1 Who is responsible for plastic waste?

One of the difficulties with responding to the problem of plastic waste lies in locating responsibility for its impacts. Identifying sources is particularly difficult, exacerbated by the transport of plastic waste on the world's oceans. It is very much a global problem and comes with all the issues of responsibility that surround governing the commons. It is further complicated by the lack of research into the impacts of plastic waste on land, where all plastic originates. More research is needed to identify sources and locate areas where policy can have an effect. The research must be clearly policy-relevant, for example, establishing if plastic waste comes from landfill, fishing equipment or littering could inform policy, whereas establishing the details of whether microplastics are formed by physical weathering or photo-oxidation may not be so directly useful to policymakers.

> *'The seas are shared and major research infrastructure and programmes require funding beyond the capacity of single member states, demanding an improved synergy within an inter-disciplinary, multi-sector scientific and industrial community which in turn calls for new governance mechanisms. This is broadly speaking the aims of the EU marine/maritime research strategy.' (Bowmer & Kershaw, 2010)*

What must be remembered is that, although little is known about the specific sources of plastic waste, we do know that plastic waste is driven by the production of plastic and this, in turn, is driven by human demand and consumption. Regardless of which pathway the plastic takes to becoming waste and its eventual fate in the environment, and regardless of whether it comes from the land or sea, human production and consumption of plastic is the primary source.

At the heart of recognising this responsibility is the 'prevention' level of the European Waste Framework Directive hierarchy. Prevention can be approached in two ways: prevention of plastic production and prevention of plastic becoming waste. These two sub-levels feed into each other: if less plastic is produced then less plastic becomes waste. If less plastic is thrown away through reuse or recycling, then potentially there is less demand for virgin plastic and production decreases. This is just one illustration of how the different levels of the waste management hierarchy interact.

4.2 Preventing plastic production

In very basic terms there are two parts to the prevention equation: the consumer and the producer, or supply and demand. Both need incentives to produce and use less plastic and, ideally, the incentives would come from each other. However, the supply chain is more complex than this and involves many players who are both consumers and producers. Incentives do not happen naturally and may need a third party to introduce them.

Incentives can take many shapes and forms, working at

Box 9 Findings from the UNEP/DTIE CIP Report on information on chemicals in products

1. Information is available about chemicals, but does not flow easily through supply chains and is often lost mid-chain between chemical production and manufacture of the final product. Engagement of mid-chain actors, such as distributors and brand name companies, is therefore crucial.
2. A harmonised industry-wide effort by the plastic sector to improve information flow would be more efficient and effective than individual company actions.
3. Such a project would require commitment from a few leading companies in selected sectors, e.g. textiles, toys, construction or electronic equipment.
4. Systems that indicate the harmful chemicals that are not contained in a given product could be used as a simplified approach.
5. Improving information flow should take a two-tier approach: to address the challenges of knowing which substances are present in the product, and possibly which ones can migrate from it, and to address the challenge of interpreting and evaluating information to serve stakeholder needs.

several levels and scales and sometimes working alongside disincentives. There can be incentives for manufacturers to increase the lifetime of products through redesign, replaceable parts, recycling and producing upgrades. Already the EU Ecolabel initiative is awarded to products designed for greater durability and recyclability (for example, televisions) or whose durability is increased through upgrades (for example, computers). However, it may be possible to make the Ecolabel more specific to plastic or create a plastic Ecolabel.

Alongside incentives for manufacturers, there will need to be incentives for consumers to reuse and recycle. Ecolabels, deposit schemes and reverse vending schemes that incentivise the reuse of plastic bottles can help encourage this (Mouat *et al*., 2009). These have been proven to be effective for refillable bottles, with return rates of up to 90 per cent in Germany, Denmark and Malta (Ten Brink *et al*., 2009). For higher value items, extended producer responsibility could be adopted, for example, fishing nets that are rented by producers (fisheries) rather than sold outright (Macfadyen *et al*., 2009). This aims to encourage the producer to reuse the net, eventually returning it at the end of its life, thus reducing the temptation to dispose of it at sea. Disincentives for consumers can also be applied to encourage reuse, for example, taxes on plastic bags.

Another alternative is to charge extra for certain problematic products, such as fishing line, fishing floats and plastic food containers (Ten Brink *et al*., 2009). In terms of targeting specific products, labels could be instrumental in informing consumers of the plastic content of the product or indeed a breakdown of the plastic and its potentially harmful additives. However, this must go alongside education so that consumers fully understand the implications of the labels and impacts of plastic waste. The Chemical Branch of the UNEP Division of Technology, Industry and Economics CIP has investigated the information flow about chemicals in products and made several recommendations on how this could be improved at an industry level (see Box 9)

A more stringent response could be the banning of problematic types of plastic (particularly packaging), but it should be noted that bans can have unintended impacts caused by replacement products and should be thoroughly reviewed before implementation (Ten Brink *et al*., 2009).

In terms of targeting specific consumers of plastic, fishing and marine-based litter is more abundant in the North Sea than in other European seas, so interventions here should perhaps target the fishing community. For the Mediterranean, much of the litter is caused by tourism, so policy should be directed at this sector.

4.3 Preventing plastic becoming waste

Preventing plastic becoming waste could depend on how it is viewed. Mouat *et al*. (2009) suggest that, as a starting point, marine litter needs to be regarded as a pollutant on the same level as heavy metals, chemicals and oil, which would then give it the same political credibility. They explain that, in most countries, NGOs and volunteers undertake monitoring of marine litter and there are no national monitoring programmes as there are for other pollutants.

The prevention of plastic becoming waste can be addressed by some activities including reuse and recycling, but it also needs to address the activities that lead to its disposal. The high movement of communities linked to plastic waste, such as tourists and fishing fleets, causes another responsibility issue, as they may not have any long-standing relationship with the region that they are potentially affecting. As such, some preventative measures can be directly targeted at these communities, as well as at more permanent groups. Ten Brink *et al*. (2009) have reviewed several of these measures in their guidelines on the use of market-based instruments to address the problem of marine litter. These include:

- Applying the polluter pays principle, in terms of fines for littering, dumping waste and illegal disposal.
- Applying the user pays principle, in terms of tourist taxes, car park fees, port reception and ship berthing fees. These can then contribute to beach cleaning and improving waste infrastructure.
- Incentives for portside disposal of ship-generated waste can curb waste discharges at sea. In addition, economic incentives can be provided to encourage disposal of waste onshore, such as the no-special-fee system for oils and waste discharged to port reception facilities in the Baltic Sea Area implemented by HELCOM.
- Landfill taxes. These are present in many EU Member States and vary from country to country, and have different effects on different actors with industry tending to feel a greater impact. Sometimes, high landfill taxes can lead to an increase in illegal dumping so they should be set at an affordable level.
- Tradable permits. In theory these would allow actors to produce plastic waste in exchange for buying permits to fund organisations or initiatives that were reducing plastic waste elsewhere. In general, it is thought that tradable permits are not appropriate for littering.
- Incentives to fishermen for reporting on and removing debris, for example the 'Fishing for Plastic' project in the Save our North Sea programme, which pays fishermen to remove plastic.
- Financial and technical support for installing waste management systems on board fishing vessels, leisure crafts and larger ships with inadequate facilities.
- Award based incentives for coastal villages with Integrated Waste Management systems, which incorporate all the policies, programmes and technologies that are necessary to manage the entire waste stream.

4.4 Waste management

Waste management has a large part to play in preventing plastic waste becoming harmful. Incorrectly managed landfills may cause waste to reach the environment, as well as the additional issue of chemicals from plastic waste escaping in the leachate. Wastewater is another potential source, both in terms of microplastic that has not been effectively filtered or the presence of chemicals released from the plastic within wastewater. The endpoint of treated wastewater is generally into rivers or the sea. Prevention in this area can take the form of bans, such as Annex V to the MARPOL agreement, which prevents the disposal of plastic waste in the sea. However, many are sceptical about the impact of Annex V and call for better implementation and monitoring (Mouat *et al*., 2010; Kershaw *et al*., 2011). The EU Landfill Directive has restricted some specific waste streams, such as tyres, liquids and explosives, going to landfill, but there is no specific mention of plastic.

The most noticeable shift is in newer Member States who have greater room for improvement. Recycling of plastic has increased from 20.4 per cent in 2007 to 21.3 per cent in 2008 across Europe, while energy recovery increased from 29.2 per cent in 2007 to 30 per cent in 2008 (PlasticsEurope, 2009). Since plastic lends itself well to alternative means of disposal, such as recycling and energy recovery, it has been suggested that landfill bans could reduce the amount of plastic waste in landfill. Nine of the EU 27+2 Member States have achieved plastic recovery of 80 per cent, and all these nine countries have legislation on restricting the 'Total Organic Carbon' content of waste sent to landfill. This indirectly affects the recycling of plastic waste as it has a high organic carbon content, but there may be potential for landfill legislation to address plastic waste more directly.

There are concerns that waste management is inadequate. This is particularly the case for some developing countries, which can also be the recipients of illegally exported waste. This raises the issue of responsibility again, as waste may have originated in developed countries, yet its poor management elsewhere is contributing to the harmful effects of plastic waste on the environment and human health.

The use of targets could be instrumental in this area. While there are currently targets for the amount and type of waste going to landfill, targets could be set more specifically for plastic waste. For example:

- Specific recycling targets for plastic waste
- 100 per cent collection and separation of plastic waste from households and businesses
- Full recyclability of plastic products
- Specific targets for plastic waste within the MSFD descriptor for marine litter
- Targets on the percentage of plastic produced that must be fully biodegradable

This raises the issue of whether plastic waste requires its own monitoring and legislation, or if it can be embedded in more general legislation of waste or marine litter. Again, this touches on the issue of responsibility. Plastic waste does require responses from several policy areas, but by distributing the responsibility it may mean that less direct action is taken. The EU has a directive specifically on packaging and perhaps it may be worth considering a specific directive on plastic waste.

4.5 Plastic waste: a cross-boundary issue

Plastic waste crosses and straddles many boundaries, one of the most important being the boundary between land and sea. The frameworks to address these transboundary issues are in place, such as the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities and the EU's recommendation on Integrated Coastal Zone Management. However, both of these could be more specifically instrumental in the area of marine debris and plastic waste. Plastic waste does not recognise boundaries in the environment and, although it is important to identify sources, it may be more useful to identify the routes that plastic takes to reach the environment, which would highlight appropriate locations for intervention.

Geographical boundaries are not respected by plastic waste, but are necessary to propose locally tuned responses, for example, through regional initiatives such as the UNEP Regional Seas Programme and the various conventions targeted at specific seas, such as the Barcelona (Mediterranean), OSPAR (North Atlantic) and HELCOM (Baltic Sea) conventions. There are disparities between regions, for example, in the Black Sea all affected states are in the process of developing and updating their national instruments aimed at combating marine pollution. One of the main problems affecting Black Sea countries in this process is that they do not fully implement and apply existing laws and regulations (Galgani *et al*., 2010).

The issues of plastic waste are covered and implemented by several authorities, including maritime authorities, environmental authorities and waste authorities. They also involve many sectors, such as politicians, the plastics and retail industry, science, education and the general public. Co-ordination of enforcement is essential as each authority and sector may consider plastic waste to be another's responsibility. As several reports suggest, (Mouat *et al*., 2010; Kershaw *et al*., 2011) the legislation is often in place, but there are difficulties with enforcement.

> *'Coordination of enforcement is therefore essential. Many countries reported the general legislations to be insufficient and some of the present regulations to be too vague or difficult to understand for the people working with marine litter in practice. To have marine litter policy, in most of the countries, it is necessary to compile all the texts relative to the water pollution, to the waste and to the protection of habitats and species. The difficulty lies in the fact that public policies relative to waste are often separated from that relative to water pollution. The marine litter is situated at the cross of these two sectoral policies.'* (Galgani *et al*., 2010)

Another boundary issue is that of establishing the level of impact above which plastic waste is considered harmful. The presence of plastic waste is clearly a concern and some of its impacts are visible. However, many of its more potentially concerning impacts are not so observable or provable. Ingestion of plastic can be studied, but the level at which ingested plastic starts to cause harm is not well established. Similarly, the potential effects of chemicals within plastic and transported by plastic are not known in terms of the level at which they become toxic. It could be that plastic waste acts a sink for some of these chemicals. Many of the impacts of plastic waste are sub-lethal, but in conjunction with other impacts from plastic waste or environmental effects, such as oil spills or harsh weather conditions, they could become lethal. As such, it may prove useful to not only study the immediate impacts of plastic waste but also the cumulative impacts. This could have the possible objective of establishing risk factors or situations that exacerbate the effects of plastic waste, or indeed identifying other impacts that are exacerbated by the presence of plastic waste.

4.6 An appropriate evidence-base for plastic waste policy

There is no question that environmental policy needs to be evidence-based. However, where questions do arise is how hard the evidence base needs to be before policy action is taken. There is currently a wide range of evidence for various ecological impacts of plastic waste and some serious implications for impacts on human health. However, there are also many research gaps, which means that the overall picture is not entirely clear. The question is whether to wait until the picture becomes clearer but, by which time, impacts could have worsened and be more difficult to manage. A good example of when policy action was taken before a firm evidence base was established is the OSPAR Ecological Quality Objective (EcoQO), which has set a target for the number of fulmars found with a certain percentage of plastic waste in their stomachs. When this objective was set it was not based

Box 10 Restrictions on use of plastic additives

Bisphenol A - There has been ongoing debate about the use of Bisphenol A in Europe, and the EU has now banned the placing on the market and importing of polycarbonate baby bottles containing Bisphenol A. Although this ban will affect the type of new plastic waste entering the environment it will not affect debris already in the environment.

Phthalates - The use of some phthalates has been restricted in the EU for use in children's toys since 1999. DEHP, BBP, and DBP are restricted for all toys; DINP, DIDP, and DNOP are restricted only in toys that can be taken into the mouth. The restriction states that the amount of phthalates may not be greater than 0.1 per cent mass per cent of the plasticised part of the toy. There are no other specific restrictions in the EU, although draft proposals have been tabled for the inclusion of BBP, DEHP, and DBP on the Candidate list of Substances for Authorisation under REACH

Flame-retardants - In 2008 the EU banned several types of PBDEs when it was discovered that they were accumulating in breast milk. This is of particular concern as is their release through the burning of electronic and electric waste when it is dismantled/recycled in uncontrolled environments.

on hard scientific fact, but was an estimate of the amount of fulmars with this level of plastic in relatively untouched areas, such as the Arctic. The estimate did fit well with later monitoring findings, suggesting that sometimes targets need to be set before the full scientific picture is clear.

The four indicators outlined in the Marine Framework Strategy Directive are a good starting point (see Box 2). Already based on scientific findings, they call for further research to explore the acceptable levels of plastic waste with the aim of monitoring and managing them. However, there is still a knowledge gap concerning the impact of plastic waste on land and eventual impact of land-based plastic waste at sea. The scientific world needs to be clear about how realistic it is to answer some of the research questions that policymakers would like to pose in order to inform policy and, if these cannot be answered, then scientists and policymakers need to reach a middle ground. This is particularly relevant to sources of plastic waste and whether there is any possible way of tracing or identifying major sources that could then be addressed. For macro debris, there is evidence that certain objects, such as plastic bottles and plastic bags, are more widespread than others, and highlighting these in education and public awareness around littering and the types of plastic objects that are particularly problematic could be useful.

There is also evidence that certain types of polymer are present in far greater quantities than others, for example, polyethylene. What is not known is whether amounts of certain polymers are excessive, considering the ratio of different polymers produced. What has been noted is the amount of plastic waste direct from industry (pre-consumer) has declined, while post-consumer plastic waste has increased (van Franeker & SNS Fulmar Study Group, 2011a; Ryan, 2008).

Policy based on findings about chemicals within plastics has already been made, such as the ban on Bisphenol A (see box 10 below), but for chemicals with less clear impacts (especially if their effects are sub-lethal or sub-toxic but could still accumulate) other initiatives may need to be developed.

4.7 Marine Strategy Framework Directive response to plastic waste

There are already methods in use to investigate the four indicators for the marine litter outlined in the MSFD (see Box 2) and their definition has been established (Galgani *et al*., 2010). Plastic waste is not only influential in marine litter, but also in several other elements of the MSFD, such as non-indigenous species introduced by human activities, marine food webs and concentrations of contaminants.

The MFSD task force dedicated to marine litter suggested in their report (Galgani *et al*., 2010) that monitoring of marine litter should occur at appropriate spatial and temporal scales. For all four indicators it recommended the harmonisation of monitoring protocols and methods in the European region and recording the composition of litter in categories indicative of sources. This is likely to include plastic but could possibly be sub-divided into other categories to help identify types and sources of plastic.

One of the main goals of identifying the indicators is to establish targets to work towards to establish good environmental status. Setting targets is not easy and, as discussed in section 4.6, scientific evidence on which to base targets is sometimes lacking. Possible targets can be based on levels found in

Box 11 **Future issues that may influence the impacts of plastic waste**

- Increases in plastic production, use, waste and recycling in developing and emerging countries, taking into account projected population growth
- Continuing production of plastic waste on top of existing plastic waste – how big is the problem and how much bigger will it get in the future?
- Impacts of climate change, such as flooding and emergency events, may increase plastic waste. For example, the floods in China in 2010 carried tonnes of plastic to the Three Gorges dam, threatening the functioning of water overflow valves. Increases in temperature and environmental conditions may affect the degradation of plastic into microplastics or the release of chemicals contained or transported on plastic waste.
- Synergic or interactive effects of plastic debris with other impacts, such as bioaccumulation of mercury and cadmium in Franciscana dolphins, alongside ingested plastic waste and entanglement in fishing nets (Denuncio et al, 2011).
- Potential positive or negative impacts of biodegradable plastics in terms of biodegradation of plastic so that it is no longer waste but, depending on the time scale of degradation, could risk accelerating the formation of microplastics.

relatively untouched regions, such as the Arctic, but, in some cases, they may have to be more arbitrary (Galgani *et al*., 2010). The EcoQO target set by OSPAR provides a good example from which to follow and has already been adopted by the Netherlands to monitor the effects of implementing the EU Directive on port reception facilities for ship-generated waste and cargo residues (Van Franeker, J.A. & the SNS Fulmar Study Group, 2011a).

As well as the complexity of the current situation of plastic waste there are also numerous future impacts and possible trends that could further complicate matters (see Box 11).

4.8 Identifying and filling knowledge gaps

By its nature, plastic waste is a difficult area to research and is also a relatively recent phenomenon so that research is still in its infancy. As such there are various knowledge gaps about the ecological and human health impacts of plastic waste and it is important to identify and prioritise the most pressing gaps that need to be filled for effective policymaking.

4.8.1 Knowledge gaps: monitoring data

> *'There is a dearth of information on the actual inputs of plastics to the oceans; this needs to be urgently addressed by Governments, municipalities, the plastic industry and multi-national retailers because land-based sources are expected to have a far greater contribution than maritime activities.' (Bowmer & Kershaw, 2010).*

A great deal is unknown about the state of plastic waste in the environment, but there is also a great deal that it is not possible to know. Effective responses need better information on geographic origins of plastic waste, which require regular surveys and analysis on the relationship between local weather conditions and geography, such as the washing out of litter from land into sea after torrential rain on Mediterranean coasts (Galgani *et al*., 2010). Surveys should cover different seasons and variability in human activities, such as tourism and be done at a local, regional, river basin and European level.

It is clear that there is a need for better harmonisation and initiatives like the MSFD and established guidelines by OSPAR and UNEP are moving towards this. The role of citizen science has great potential in this area and research has shown that the use of volunteers to conduct litter surveys is a reliable method with no statistical difference between results of data gathered by inexperienced and experienced surveyors (Tudor & Williams, 2001). High-resolution geo-referenced images used for wildlife monitoring could provide a platform for litter monitoring alongside better satellite images. Other possibilities include ship-based camera monitoring and cameras on stationary platforms (Galgani *et al*., 2010). However, it is also important to prioritise what needs to be known to inform policy and to ensure that this can be done realistically.

The GESAMP report (Bowmer & Kershaw, 2010) has questioned the necessity of a global assessment of microplastics, bearing in mind the length of completion and costs. The report suggests it should be firmly embedded in the wider scientific context of marine debris and that microplastic monitoring in the water column could be introduced into routine programmes of plankton sampling. It has also been suggested that aerial surveys conducted for oil spill detection could be used to evaluate litter (Galgani *et al*., 2010). The GESAMP report (Bowmer & Kershaw, 2010) also suggests that classical monitoring may not be the best use of scarce resources when considered globally. A clearer focus on specific areas, such as

Box 12 Recommendations for monitoring the four different indicators of marine debris in the MFSD (Galgani *et al.*, 2010)

1. **Coastlines** – Four counts of marine litter each year for each season to monitor the number of items, volume or weight. A unified system of classifying litter at least on the regional scale.
2. **Water column, surface and seabed** – Frequency of surveys can vary from a count every year (shallow waters) to one every five years or decade (deep seafloor). It should be reported in appropriate units, such as items per m^2 of seabed or per m^3 of water. A classification system of a minimum of six categories is suggested.
3. **Biomonitoring in marine wildlife** – The use of the fulmar in regions where it occurs and other suitable species in non-fulmar regions, for example, shearwaters, in warmer parts of the Atlantic and Mediterranean. Other representative species should be investigated.
4. **Microplastics** – The monitoring of both sediments and seawater, including intertidal and subtidal zones. Possible target areas could be industrial areas where plastic powders are used, sewage outfalls and locations where plastics are used for shot blasting. Results should be recorded in density units.

hotspots, might translate more quickly and effectively into policy decisions. The question is then how to define these hotspots, bearing in mind not only concern in terms of human health and the environment, but also what can realistically be determined. An example is provided by Galgani *et al.* (2010) who suggested targeting research on microplasatics in sewage outfalls and locations where microplastics are used for shot blasting. Once appropriate measures for the four EU MSFD indicators related to marine litter have been developed, then they could also be used to identify hotspots for policy action at a regional and national level. Galgani *et al*. (2010) have identified a lack of data on waste on the seabed and generally, more research needs to be conducted into microplastics (see Box 12).

There is a need to harmonise research methods to assess impacts, but at the same time, the regional or local context must be taken into account. For example, difficulties arise in selecting the wildlife in which to measure the amount of ingested plastic waste. Modelling is another option for estimating the state of plastic waste and identifying hotspots, particularly as policy decisions need to consider future distribution of plastic waste. However, an accurate model would need to consider a huge amount of meteorological, oceanic and wildlife variables. Some research has modelled the overlap of plastic waste distribution with the distribution of marine species (Williams *et al*., 2011), which could provide useful information for identifying problematic areas. However, Galgani *et al*. (2010) have urged caution in this approach, as the two parameters (distribution of species and distribution of plastic waste) are influenced by a wide range of natural and human circumstances. They do, however, highlight the potential in using existing datasets and models of drift times, regional connectivity and weather and currents.

A better understanding of the degradation process of plastic waste would be useful to inform policy, particularly relating to biodegradable materials, as there is concern that these could exacerbate issues surrounding microplastics if materials do not biodegrade completely and/or within an adequate time frame. Finally, monitoring of plastic waste on land is a large research gap. Although there is plenty of monitoring on beaches and coastlines, inland monitoring is not well reported and better data are needed on the level and type of plastic waste within landfills.

4.8.2 Knowledge gaps: impacts of chemicals in plastic

There is currently an absence of knowledge on exposure levels and toxicity of chemicals associated with plastic in the environment.

As awareness of the harmful impacts of chemicals associated with plastic is recent, there is a need for more longitudinal studies to explore the long-term impacts and the temporal relationship between exposure to additives and adverse reproductive and developmental outcomes to ascertain causality, i.e. how long they take to have a harmful impact (Meeker *et al*., 2009).

Longitudinal research would also allow analysis of shifts in exposure among populations, while larger scale epidemiological studies could help quantify human health impacts and allow meaningful samples of particularly vulnerable groups, e.g. children and women of reproductive age (Koch & Calafat, 2009; Meeker *et al*., 2009).

Studies are also needed to identify which phthalate metabolites and BPA species should be monitored, i.e. which are relevant to human health (Koch & Calafat, 2009). Research on wildlife has indicated that the concentrations of plasticisers at which there is a biological effect in the laboratory are similar to the concentrations found in real environments. This suggests that some wildlife populations are being affected (Oehlmann *et* *al*., 2009), but there are as yet no studies on the population effects of additives. The impacts of long-term exposures on species that are most sensitive to additives should be a research priority, amongst these are molluscs, crustaceans and amphibians (Oehlmann *et al*., 2009). There is growing concern about the impact of chemical mixtures and the possibility that the harmful impacts of some chemicals could be greater when they are combined with other chemicals. It is possible that plastic waste could act as a platform for the mixing of chemicals. Similarly, looking at the impacts of chemicals it could be mixtures of impacts that are harmful to the environment or human health. For example, Meeker *et al*. (2009) suggested that evaluations of impact should not be just at the level of individual hormones, but on the ratios between hormones as well.

Modelling may have a role to play in filling some research gaps. Teuten *et al*. (2009) have modelled the desorption of persistant organic pollutants (POPs) from plastic waste and this could prove useful in predicting impacts of real levels of plastic waste. There is also potential to model the tendency of chemicals to partition between air, water, plastics and organic carbon in the sediments, in order to understand more about whether plastic waste could be a sink for POPs or a dangerous transport vessel.

4.8.3 Knowledge gaps –exposure levels to chemicals associated with plastic waste

Better knowledge is needed on the actual impact of chemicals associated with plastic waste on the environment and human health. This would include the differential impacts of chemicals on different forms of wildlife. Better understanding is needed of the biological mechanisms involved in the exposure of humans and animals to chemicals associated with plastic waste and the transfer of chemicals into biological systems.

Box 13 Targeting current bad practices

- Landfill management and waste management in new Member States and developing countries.
- Littering on land, the coastal zone and at sea.
- The use of microplastics for abrasion in products including cosmetics.
- Shredding plastic waste (particularly on boats) to put in food waste.
- Excessive use of plastic bags and packaging.
- Use of additives that are a risk to health, especially Bisphenol A and some phthalates.
- Use of plastics that will degrade quickly but not completely, leading to increase in microplastics i.e. oxo-degradable plastics.

In terms of management, it would be useful to identify the sources and routes by which wildlife and humans are exposed to chemicals in plastic waste. If possible, some kind of identification of which plastics transfer contaminants and which contaminants are most likely to be adsorbed and transferred. This would include more land-based research on plastic waste and research on chemicals in landfills, particularly measuring level of additives leached into environment (Oehlmann *et al*., 2009).

4.9 Possible interventions

> *'There is a need for scientists to express 'damage' in terms that can be easily understood by the general public. Where resources are limited it will be important to focus on policies that deliver benefits to the largest proportion of the population on the most important sociological/health issues and micro-plastics might fare better in this regard when considered as a subset of marine litter problem.' (Bowmer & Kershaw, 2010).*

Plastic waste prevention is preferable to clean-up, which is very difficult to implement. Prevention can work at the level of production of plastic in terms of redesigning products to use less plastic, design for reuse and recycling and reduced packaging material. For these to be successful interventions, there may need to be a value placed on disposable products to encourage their reuse and encourage manufacturers to design them for reuse and recycling. Prevention can also work at the level of plastic becoming waste with the use of targets, taxes and bans but these must be carefully implemented.

Although prevention is a priority, due to the amount of plastic waste already in the environment, clean-up initiatives must also continue. These can be combined with monitoring exercises and involve local communities and fishing communities, such as KIMO's Fishing for Litter. Some, such as International Pellet Watch, can assess levels of POPs. With such a huge issue as plastic waste, citizen science is a good approach to cleaning-up and monitoring, while also increasing awareness.

Effective policy requires effective monitoring and the current state of plastic waste monitoring needs harmonisation, which is being put into place by various guidelines on marine debris in general. Although it is good to take into account regional differences, production of an excessive number of guidelines should be avoided as these would later require harmonisation. Monitoring can be embedded in more general marine debris initiatives as long as there are figures specifically related to plastic. Similarly, microplastic monitoring can be performed alongside plankton sampling.

There is also a need for better education and awareness around plastic waste. Plastic footprints and labelling on products are possible but need the appropriate education to make them meaningful. Alongside this there could be labelling of products that contain known harmful additives. Banning of some harmful chemicals contained in plastic, such as Bisphenol A and some phthalates, has already occurred, but for others restriction may have to be voluntary. A harmonised industry-wide effort is needed to communicate information about chemicals used in plastic, alongside public education about the chemicals.

Waste management is highly important in addressing the issues of plastic waste. The systems differ from country to country and region to region. Although international and European legislation exists, it requires better monitoring to ensure complete implementation. More specific legislation or clauses within existing legislation relating to plastic waste could be considered.

In terms of addressing existing problems with plastic waste the identification of plastic waste 'hotspots' may prove useful. This can be done by monitoring or by some forms of modelling, for example, models of ocean currents such as gyres and the Gulf Stream that casts floating objects to Caribbean and eastern North Atlantic shores (Bowmer and Kershaw, 2010). Another approach is the identification and protection of species, habitats and human groups that are vulnerable to plastic waste and the chemicals associated with it.

In general, there needs to be better integration of marine planning with terrestrial planning. The frameworks are in place for this in terms of the EU Recommendation for Integrated Coastal Management and the Integration of Marine and Maritime Research, but more needs to be done to ensure better implementation and this may need to be more focused on plastic waste (Mouat *et al.*, 2010; Kershaw *et al.*, 2011).

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