Plastics Do Not Belong In The Ocean

Towards a roadmap for a clean North Sea

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Cover Picture: Assorted diatoms living between crystals of annual sea ice in McMurdo Sound, Antarctica.
Source: NOAA. Photo credit: G.T. Taylor

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Preface

The Plastic Marine Litter programme aims to address the problem of plastic waste in oceans and seas worldwide and in the North Sea in specific by initiating, stimulating and preparing:

- research that increases our understanding of the causes and consequences of plastic marine litter
- the development of long-term solutions that will lead to a significant reduction of the amount of plastic litter in marine environments
- the development of quick win solutions (“low hanging fruit”) in the mean time.

The Plastic Marine Litter programme (PML) was initiated by IMSA Amsterdam after Charles Moore’s impressive speech at the 2009 Club of Rome Global Assembly in Amsterdam. Since then a growing group of organizations became involved in the programme, including:
The Association of the Dutch Chemical Industry (VNCI), Crystal Sea Foundation (CSF), Desso Group, Dutch Polymer Institute (DPI) and DPI Value Centre, Dutch Rubber & Plastics Federation (NRK), IMARES, IMSA Amsterdam, KIMO (NL & BE), Ministry of Infrastructure & Environment, PlasticsEurope (NL), The North Sea Foundation, Waddenvereniging, Waste Free Oceans and Wetsus. These organizations all agree that plastics do not belong in the ocean and cooperate closely in order to create opportunities to work on solutions that cannot be achieved by their individual efforts.

In June 2011, the programme officially started with a *preparatory phase*, which will be finished in December 2011. This project phase was funded by two Dutch private foundations, by Desso Group (a Cradle-to-Cradle flooring company) and by IMSA Amsterdam (an independent think tank committed to the environment, sustainability and innovation). The objectives are (1) problem analysis, (2) a first rough design of a Plastic Marine Litter programme for the North Sea and (3) building a strong coalition and network of stakeholder organisations to implement it.

We would like to thank all the stakeholders and experts we have interviewed for their help and time in the research for this report: Rinus van den Berg (DSM), Michiel Claessens (University of Gent), Renate de Backere (Waddenvereniging), Jeroen Dagevos (North Sea Foundation), Lucia Hernandes Leal (Wetsus), Peter Nossin (DPI).

We also gratefully acknowledge the members of the scientific advisory board of the PML programme who have reviewed the report and provided valuable recommendations for further research: Jan Andries van Franeker (IMARES), Rick Nickerson (Making Waves Communications), Edward Kosior (Nextek) and Mark Anthony Browne (Chairman, University of Dublin). Finally, we would like to thank all persons involved in the programme for their valuable information and recommendations.

Executive summary

Water is the basis of life on Earth. Through water, all life on Earth is in some way or another connected to seas and oceans. People around the North Sea profit in many ways from the richness of the sea: eating its fish for food, enjoying the beautiful beaches, and using it as a medium for global transportation. Like many seas around the world the North Sea is under increasing stress from a multitude of human activities such a shipping, fishing, oil and gas production, and intensive agriculture. Plastic litter has recently moved centre-stage as another stress factor for the marine environment.

This reports makes an up-to-date, knowledge-based analysis of the causes, effects, and solutions of plastic marine litter worldwide and for the North Sea in specific.

Plastic, being a versatile, strong and lightweight material, benefits society in many ways. The negative side effects of society's growing dependence on plastic, however, are not equally shared. Due to its extreme persistence, disposed and abandoned plastic does not fully degrade. In the marine environment it only breaks down into smaller particles, thus making them available for ingestion to an ever-larger group of species. Plastic does not only spread over the surface of the waters, it also ends up on the seafloor, in sediments, is ingested by sea animals and stranded on beaches. Plastics can contain additives, sometimes up to half of their weight, and some of these additives are toxic. These additives, embedded in the plastic, also find their way to the marine environment. Moreover, plastics particles can attract already present chemicals from the seawater and thus have the potential to concentrate toxicants.

In this report we discern two types of problems.

- In regional seas, large pieces of plastic marine litter cause direct ecological and economical damage.
- Smaller particles, microplastics, can indirectly give rise to potentially large, global impacts.

Plastic marine litter directly harms marine species like seabirds and mammals. Hundreds of species have been reported to ingest or become entangled in plastic marine debris. Washed ashore or littered by bathers it also causes millions of euro of annual damages to coastal communities that have to clean up their beaches, or lose income from tourism. Also fisheries report significant losses due to e.g. restricted or damaged catches, and damaged gear.

The indirect effects include the potential impacts from microplastics. Currently too little is known on pathways and impacts: these issues require further assessment. Due to these uncertainties it can, however, not be ruled out that (micro)plastics have an impact on various food web levels in such a way that human food consumption of marine resources becomes a risk. Similarly, there is a hypothetical possibility that plastic ingestion by lantern fishes, one of the most common fish species of the open ocean, negatively affects the biological pump that influences the uptake of carbon dioxide by the oceans.

Many effects are known to exist for quite some time. As plastic production and consumption are predicted to triple until 2050, without additional measures to reduce plastic waste the impact on the marine environment will increase. This justifies immediate action to mitigate and remedy the issue. As fragmentation of larger particles appears to be a major source of microplastics, general measures to reduce large plastic items benefits the microplastic issue. Uncertainties over the indirect effects can therefore be no excuse for delaying action.

Thus far, addressing the problem proves to be hard. Plastic marine litter originates from many sources and is a multi-facetted issue. Collaboration between scientists, industry, environmental organisations and governments is required to find solutions for all phases of the plastic life cycle. The unsustainable usage of plastic as a material is at the root of the problem and as such is part of society's general resource and waste problems. A transition to a circular, zero-waste economy is the only viable alternative and requires solutions for the manufacturing, usage, and end-of-life stages of plastic products.

This report recommends launching a North Sea plastic marine litter programme. We take the North Sea as a crystallisation point for a regional programme, to develop knowledge, best practices and policy proposals at national and European scale. This report can form the starting point for such a programme.

The North Sea provides an ideal testing ground to work on effective strategies for plastic marine litter. The population density and consumption levels in the greater North Sea area are very high, resulting in a constant flow of plastic waste to the North Sea. It is also one of the most heavily exploited seas in the world. Many sectors active on the North Sea are in itself sources of marine litter, but also offer opportunities to address the problem. The area, at the same time, has relatively sophisticated waste management systems and an extensive policy framework for marine protection. There is also a strong North Sea community working on marine protection and sustainable development. The Wadden Sea ecosystem and community offer similar and other interesting starting points and should be involved in joint strategy developments for North Sea and Wadden Sea.

This is what we recommend[i].

- *Increase knowledge on ecology and health.* Develop a roadmap towards an almost plastic-free North Sea based on scenarios. Increase and integrate hypothesis-driven monitoring efforts coupled to concrete actions. Increase and integrate knowledge on long-term and indirect effects of (micro)plastics. Build on the existing marine infrastructure.

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[i] To be detailed in the next phase of the programme.

- *Enable cyclic business models.* Rethink manufacturing: design for reuse and recycling. Improve the methodology of life-cycle analyses. Avoid potential toxicants, including microplastics. Make cyclic design principles part of education programmes.
- *Promote behavioural change.* Create awareness among consumers of the value and importance of the North Sea. Improve plastic usage and disposal behaviour both on land and at sea.
- *Improve waste management.* Increase collection of plastic waste. Increase recycling rates. Close the leaks.
- *Rehabilitate habitats.* Starting in areas with high plastic concentration and high ecological value ("hotspots"): beaches, estuaries, rivers, and coastal areas. Develop low-cost technologies for cleaning up plastic marine litter without damaging habitats.
- *Develop international policies.* Connect and cooperate with formal international policy developments, improve enforcement of regulations and work towards a shared definition of "harm". Embed stakeholder knowledge and best practices in policies, building on the "the polluter pays principle" and the "precautionary principle" that are currently part of the Marine Strategy Framework Directive (MSFD) and define responsibilities for action and funding.

Summary of chapters

Causes (Chapter 2)

- Far too few products are designed for their usage phase with proper consideration for their end of life. The physical and chemical properties of plastics – including almost all current "biodegradable" plastics – make them persistent in the marine environment for a very long time, possibly centuries.
- Fragmentation does occur, and this is suspected to increase detrimental effects, including those of microplastics.
- Microplastics are also produced for direct use in specific consumer products such as cosmetics and for indirect use as precursors (pellets) for consumer products.
- Plastic products are generally inexpensive and therefore are a material of choice for single-use items.
- Combined with intentional disposal and unintentional abandoning at land and on the sea, this leads to waste streams ending in the marine environment.
- Despite 40 years of government policy making to prevent marine waste, little progress has been made on the issue of plastic marine litter.
- In part this is due to opposing views on problem definition, problem source and responsibility. These differences result in different policy proposals. This delays action.
- International law offers much more potential to manage the problem.

Spreading of plastics in the marine environment (Chapter 3)

- If plastic ends up in the marine environment, winds and currents determine its fate. In the oceans, an important mechanism is the accumulation of debris in gyres –giant garbage patches. In local seas like the North Sea, plastic accumulates in specific coastal waters, on shorelines, estuaries, ingested by sea animals, and on the seafloor. Rivers and sewage systems are expected to form important pathways for plastic marine litter.
- Concentrations of plastic marine litter are in many instances high enough to impact individual species and raise concerns for marine ecosystems.
- Of particular, and recent concern is the spreading of microplastics that can be ingested by broad range of animals. The sources, pathways and sinks of these microparticles will be different from those of large plastics.
- For both size-categories of plastic marine litter there is insufficient knowledge on how it spreads through the marine environment: what is the relative importance of land-based sources versus sea-based sources? How much debris is carried through rivers or sewage systems? This precludes the design of effective monitoring programmes, let alone the determination of the most cost-effective restoration programmes.
- Based on global resource scenarios, a threefold increase in global plastic production is expected in 2050. However, even in a more sustainable scenario where virgin plastic usage levels off, plastic in the marine environment is expected to increase if no further action is undertaken to prevent littering.

Effects (Chapter 4)

- Two distinct types of effects of plastic marine litter are identified: (1) direct effects, related mostly to the physical properties (2) indirect effects, related mostly to toxicity.
- Direct effects of plastic marine litter are mostly due to physical interactions between plastic and organisms or equipment. Sea animals get entangled; abandoned nets continue to catch fish and other sea creatures (ghost fishing) and ship's propellers are blocked. When seabirds, sea mammals or fishes ingest plastic particles, blocking of the gut is likely to harm or even kill the organism.
- The smaller plastic particles become, the higher are the potential effects related to toxicity of either built-in or adsorbed toxic substances.
- The smallest particles can be ingested by filter feeders like mussels and transfer from the gut to the tissue.
- In many waters, toxicants in fish have been found, but as yet no direct relation with ingested (micro)plastic has been established. For seabirds there are indications of plastic-related toxic effects.
- The concern with plastic microparticles and the adsorbed toxicants is that they might accumulate in tissue of marine animals and that the concentration might be magnified through the food chain.
- Although direct linkages remain to be established, potentially this is a risk for human health. Indirectly, we cannot rule out that one of mankind's nutritional sources of growing importance – seafood – is at risk from plastic marine litter.

- To illustrate the potential scale of the impact: in the North Pacific: at least 10% of lantern fish feeding on plankton in the upper water layers has plastic in their stomach. This group of animals represents millions of tons of biomass. It cannot be excluded that this affects the role of vertically migrating fish in the biological carbon pump with unknown consequences for carbon dioxide transports and global climate.

The North Sea (Chapter 5)

- The North Sea is an area rich in natural resources and with a large economic value. The impact of human activities is very large and could impair the resilience of the ecosystem.
- The ecological status of different species and habitats vary, but the overall ecological status of the North Sea is not favourable.
- The legal protection of the North Sea is relatively well regulated, but the complexity of national, European and international policy instruments hampers the implementation of effective policy actions.
- A relatively large share of plastic in the North Sea can be traced back to marine activities like shipping and fisheries.
- The pathways for the land-based sources, in particular the role of rivers and sewage systems, have not been well established. From beach clean ups and monitoring general movement and local accumulation zones have been identified.
- In general, plastic marine litter in the North Sea originates locally. An unknown fraction will be imported in and exported out of the region.
- Microplastics in the North Sea are of growing concern and large concentrations have been found in beach and estuarine sediments. Plastics pre-production pellets and microplastics in personal care products form direct sources.
- At the bottom of the food pyramid filter feeders, e.g. mussels, can ingest and incorporate plastic microparticles in their tissue.
- There is evidence for plastic ingestion by North Sea fishes. Initial pilot surveys suggest levels to be moderate in most species, but substantial further research will be required.
- Seabirds, like the fulmars, mistake plastic litter for food and have been found with large quantities of plastic in their stomach. The plastic content in fulmars is now used as an indicator to monitor the ecological status of the North Sea.
- Economic damage of plastic marine litter results mainly from beach cleaning and losses to fisheries. Direct costs to local communities are high, e.g. UK municipalities spend €18 million per year on beach cleanups to remove all litter including plastics.
- Consequences for human health are possible, although no direct linkage between plastic marine litter and fish for human consumption has been made so far.

Solutions (Chapter 6)

- A solutions framework for plastic marine litter identifies technical and societal options in all phases of the current plastic life cycle. Action on all levels is required to solve the issue. Options become progressively more expensive as we move from manufacture to restoring littered habitats.

- In the manufacturing phase, rethinking of the design is required to enable cyclic business models. Material and product must be designed in such a way that resources can be reused and recycled. An approach to avoid potential toxicants should be promoted as the industry norm: be more good instead of less bad.
- In the usage phase, consumers on land and at sea need to change their behaviour in relation to plastic consumption, recycling and littering.
- In the end-of-life stage, a hierarchy of solutions exists that start with the realisation that plastic waste is a valuable resource. Material reuse and recycling are the preferred option, followed by energy recovery. Incineration and landfilling are last resorts that should be avoided whenever possible.
- It is not just the economics of plastics per se that prevent recycling, but primarily a number of technical and logistic barriers.
- As long as plastic litter is present in the marine environment, cleaning up campaigns can assist in reducing environmental degradation, but should be in balance with costs and habitat impacts of cleaning.

Synthesis (Chapter 7)

- The plastic marine litter issue is particularly well-known by the large areas of floating plastic debris in the oceanic gyres. Plastics, however, are present in all marine and coastal compartments.
- Plastic marine litter is a waste problem that is considered to be one of the most important emerging global issues. It is occurs worldwide, but depends strongly on local conditions. It has effects on economies and on marine species. These effects are direct, mostly physical in nature and reasonably well established
- Plastic marine litter is a problem of unsustainable usage of plastic resources. The solutions require steps towards a zero-waste, cyclic economy. Solutions for sustainable use of plastics should be considered in this framework.
- Plastic marine litter has the potential to affect global ecosystem services of the earth's oceans. Microplastics might lead to accumulation and increasing concentration of toxic substances throughout the food chain. It cannot be excluded that ingestion of plastic by organisms at the bottom of the food supply ultimately has global consequences.

Recommendations (Chapter 8)

- *Increase knowledge on ecology and health.* Develop a roadmap towards an almost plastic-free North Sea based on scenarios. Increase and integrate hypothesis-driven monitoring efforts coupled to concrete actions. Increase and integrate knowledge on long-term and indirect effects of (micro)plastics. Build on the existing marine infrastructure.
- *Enable cyclic business models.* Rethink manufacturing: design for reuse and recycling. Improve the methodology of life-cycle analyses. Avoid potential toxicants, including microplastics. Make cyclic design principles part of education programmes.
- *Promote behavioural change.* Create awareness among consumers of the value and importance of the North Sea. Improve plastic usage and disposal behaviour both on land and at sea.

- *Improve waste management.* Increase collection of plastic waste. Increase recycling rates. Close the leaks.
- *Rehabilitate habitats.* Starting in areas with high plastic concentration and high ecological value (“hotspots”): beaches, estuaries, rivers, and coastal areas. Develop low-cost technologies for cleaning up plastic marine litter, without damaging habitats.
- *Develop international policies.* Connect and cooperate with formal international policy developments and improve enforcement of regulations. Embed stakeholder knowledge and best practices in policies, building on the “the polluter pays principle” and the “precautionary principle” that are currently part of the Marine Strategy Framework Directive (MSFD), and define responsibilities for action and funding. Work towards a shared definition of “harm”.

1. Introduction

"Many of the ecological maladjustments in our own society are urgent, costly, and aggravating in the extreme to those who sense them. It is a constant temptation to expend one's energy in condemnation and crusade and to satisfy one's instinct for moral indignation when the issue seems so clear-cut. But the constructive procedure, as in any ecological problem, is to analyze the processes with which we are dealing, determine the factors involved, and then go to work." Sears, 1954[2]

1.1. Plastic Marine Litter has become everyone's problem

The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program defines marine debris as "any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment". This report is about plastic marine debris or plastic marine litter[ii]. This litter consists of polymers. The debate includes the toxic substances they may contain or transport. Plastic does not only spread over the surface of the waters, it also ends up on the seafloor, in sediments, ingested by sea animals and stranded on beaches.

The environmental issue of plastic marine litter is receiving global attention. The United Nations Environmental Programme (UNEP) Yearbook 2011 highlights the subject of plastic marine litter as one of the most important emerging issues.[3] Currently, plastics are present in all of our seas and oceans. The remainders of people's everyday consumer products – bottle caps, bags, six-pack rings and large barrels – end up in the oceans and break up in ever-smaller particles; dispersed over vast areas. Plastics take a very long time to break down – possibly five centuries – and are able to affect marine organisms on every level of the food chain: from the tiniest coral polyps to giant blue whales. The range of possible effects includes entanglement, ingestion, translocation (i.e. movement of ingested plastic from the gut to the tissues and cells,[4]) transfer of toxic chemicals, habitat destruction, and spreading of non-native species. Additionally, plastic marine debris has negative effects on the economy and human safety and may form a risk for human health.

By 2011, plastic marine litter has become everyone's problem: the global scale of mankind's accumulating plastic waste has gained widespread media attention, most notably by the discovery of what has come to be known as the Great Pacific Garbage Patch. This is an immense gyre[iii] where plastic marine litter converges and accumulates in the upper water layer.[5, 6] Closer to home, many beaches and waterways are visibly contaminated with plastic items.[7, 8] The direct effects on seabirds, sea mammals and turtles have been well

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[ii] As explained in section 2.4, this report uses the term "plastic marine litter" where others prefer "plastic soup" or "marine litter".

[iii] The patch extends over an indeterminate area, with estimates ranging very widely depending on the degree of plastic concentration used to define the affected area.

documented.[9] Many of the more indirect impacts, however, are not yet understood. Depending on their actual impact, these indirect effects of plastic marine litter might have major consequences for marine life, thereby adding to the present global concern about the oceans' ecological state.

If we continue on the current path, the combination of poor product design, waste management and rates of recycling is likely to further increase the amount of plastic in the oceans in the future. With slow rates of degradation of plastic in seawater, the quantity of plastic in the oceans will accumulate and increase to reach unprecedented levels. A growing and wealthier population implies a major increase in the amount of plastic debris that ends up in the marine environment, thereby increasing the problem even further.

This report provides an analysis of the issue in order to develop effective system changes in business, technology, legislation, policy and behaviour. To do so, a hypothesis is formulated in order to arrive at a shared problem definition (see Box 1-1).

Box 1-1. Hypothesis

This hypothesis is the starting point of the Plastic Marine Litter programme. The hypothesis is formulated in order to arrive at a shared definition of the problem. It will be continuously tested, adjusted and refined based on research, analysis and insights from experts and stakeholders.

Causes

Plastics are versatile and widely used materials with many useful applications. The occurrence of plastic in marine environments is an unintended side-effect of our non-cyclic, take-make-waste production system. Plastic marine litter is man-made. Its causes are rooted in current economic, technical, design, behavioural and policy systems.

Effects

The presence of plastics in marine environments poses a threat to ecosystems, economics and human health. As yet, the effects are poorly understood and only partly quantified. Even if direct effects on the oceans are limited, they may add to and reinforce the cumulative impact from factors such as overfishing, climate change and toxic substances.

Solutions

To solve the issue, a collective effort is needed to redesign the business of plastics at all levels, including materials, products and services, life cycles, business models and usage. In other words, a system innovation is needed that makes the environmental problem manageable without discarding the benefits of plastic for society and without increasing other environmental impacts.

1.2. Brief history of plastics in our society, the issue and the scientific response

Plastics built the modern world. They are widely used materials with many useful applications. Where would we be without pacemakers, polyester, computers, mobile phones or sneakers? Plastics are generally inexpensive, light, strong, durable, corrosion-resistant materials, with good thermal and electrical insulation properties.[10] The diversity of polymers and the versatility of their properties are used to make a vast array of products in all markets and sectors. Each year we use more; plastic production during the past decade equals that of the entire twentieth century.[11]

In 1839, a German apothecary discovered the first plastic, polystyrene, which was however only made practical in 1938. The first man-made plastic, called Parkesine, was publicly demonstrated in 1862. It was an organic material derived from cellulose that once heated could be moulded, and retained its shape when cooled. In 1868, celluloid was invented as a substitute for the ivory in billiard balls and later applied in photographic film. Since then, a whole series of inventions led to the development of, for example, rubbers, polyvinyl chloride (PVC, 1872), low-density polyethylene (LDPE, 1935), nylon (polyamide, 1935), polypropylene (1951), and liquid crystal polymers (1985).[12] As a result, plastics have found their way into a multitude of applications in various markets. Plastics form a large part of the chemical industry's global output.[13]

Box 1-2. Some facts about plastic

Plastics are made of polymers – long chains of repeating chemical units (monomers) – with additives to tweak their colour, softness and other physical properties. Generally these additives are present in low concentrations, but sometimes up to half of the plastic's weight;[1] some additives are harmless, but some are toxic. The additives are not chemically bound to the material and can therefore transfer in and out of the polymer matrix.[14]

Globally, over 30% of plastics are used for packaging purposes,[15] including many single-use-items. In Europe, 39% of plastic demands comes from the packaging sector.[16] The other main sectors using plastics (about 40% of the total demand) are building & construction, automotive, and electrical and electronic equipment. Smaller markets include sectors such as furniture, agriculture, medical devices and household products (toys, leisure and sports goods).

In terms of materials, polyethylenes (PE, HDPE, LDPE, LLDPE) have the greatest share of production of any polymer type, while polypropylene (PP) has a large share as well. Together, these are called polyolefins. They are lighter than seawater and will therefore initially float. Other widely used plastics are polyvinylchloride (PVC, e.g. used for window frames and pipes), PET (e.g. bottles), PUR (e.g. insulation) and polystyrene (PS, many applications).[16] They are heavier than water and will eventually sink. Relatively new is a small but growing use of so-called biodegradable plastics. Unfortunately, most of these existing "biodegradable" plastics are *not* degradable in the marine environment. On the other hand, the development of plastics that are truly biodegradable in the marine environment might provide possible answers to the problem of plastic marine litter.

After initial enthusiasm over freedom from constraints from the material world, the relation between plastics and society has become more complicated. In the 1970s it became apparent that plastic debris accumulates in the marine environment: the United States National Oceanic and Atmospheric Administration (NOAA) discovered large amounts of plastic and oil residues in the Sargasso Sea.[17] It was the first very visible side effect of society's rapidly increasing use of plastic products. Apart from the aesthetic issues, the direct consequences for marine wild life, ingestion and strangulation, became clear. The first Honolulu Workshop on the Fate and Impact of Marine Debris was held in 1984.[18] Both the basic issue and the basic routes to prevention have been formulated in that period already.[19] The issue, however, did not attract much international attention at that time.

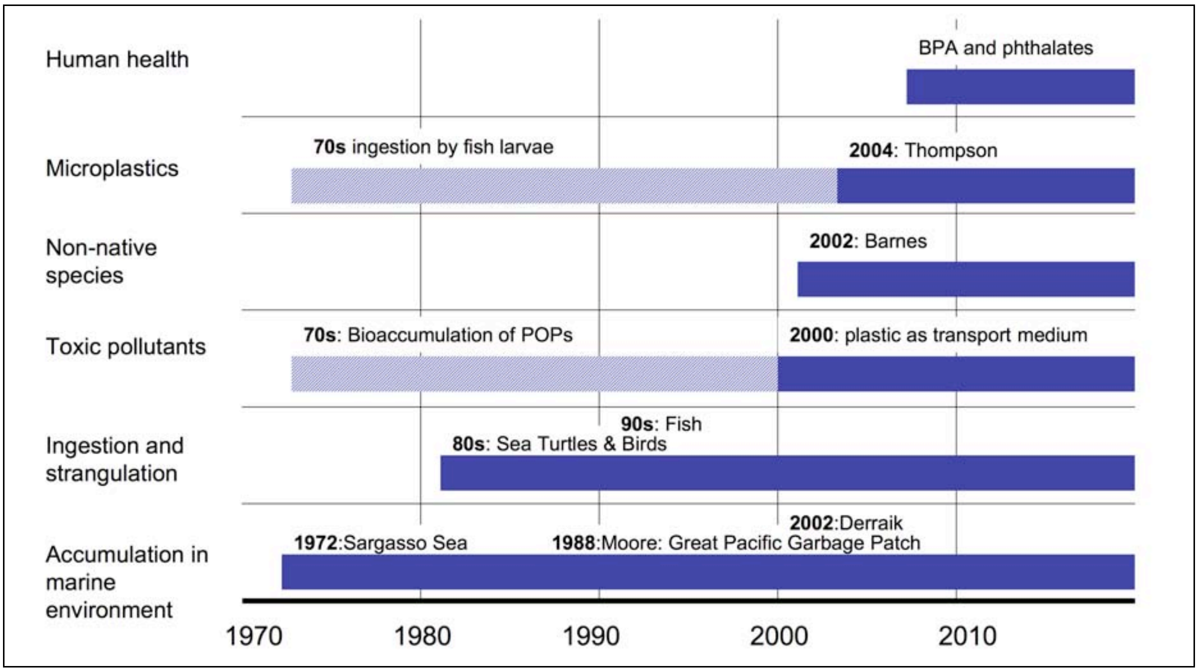

Figure 1-1. A timeline of issues related to plastic in the marine environment. Key events or publications have been inserted. A dashed bar indicates that an issue is known, but not yet generally associated with plastic marine litter. Source: IMSA analysis of literature.

This changes in 1988 when Charles Moore discovers the Great Pacific Garbage Patch. The story of a "plastic soup" raises general awareness on the environmental issues that cling to the production, usage, and disposal of plastic products. In the wake of the discovery of plastic in oceanic gyres, a number of issues related to plastics are raised; some on topics that have a long history like the toxicity of plastic additives (e.g. BPA and phthalates). Plastic marine litter thus becomes an issue with a much wider scope than the accumulation of plastic litter in itself. The chronology of these issues is displayed in figure 1-1. We see that over time, the debate has evolved from the topic of accumulation in the environment to ingestion and strangulation of animals. Later, toxic pollutants and microplastics moved up on the agenda while non-native species and human health were added to the list. Meanwhile, the associated imagery moved from affected turtles to "plastic islands" and "plastic soup".

Only recently has the issue been acknowledged as an urgent issue, requiring immediate action, e.g. by Euro Commissioner Janez Potočnik (DG Environment)[20] and the United Nations Environmental Programme.[21]

The benefits of plastics are still there: versatile, durable, inexpensive, etc. However over time, most of the strengths of plastics as a material have become accompanied by corresponding disadvantages, like the other side of the coin, that have in turn given rise to concerns over direct and indirect impacts on the environment and on human health (see Table 1-1).

Table 1-1. Fundamental strengths of plastics together with corresponding disadvantages – like the other side of the same coin – and concerns over environmental, economic and human health issues as brought up by scientist and NGOs (partly based on [22]).

Strengths	**Disadvantages**	**Concerns**
Durable, strong, relatively inert, general resistance to microbial and other degradation processes	Persistent in nature, virtually indestructible in the marine environment	Plastic (marine) litter, accumulating and degrading to microplastics[iv]. Direct negative effects on marine ecosystems and the economy.
Low cost, disposability and cost effectiveness	Many (low-value) products, easily discarded	
Light, low density	Large volume; spillage; passive transport over large distances	
Additives to tailor material properties; versatile	Transfer of additives present in and attaching to diverse plastic waste streams	Persistent, bioaccumulating and toxic materials[v] in food webs. Human exposure might lead to cancer, endocrine disruption[vi] and other toxic reactions.

In a more general sense, the concerns over plastic in Table 1-1 are the outward manifestation of an underlying problem, i.e. our current usage of plastics is *not sustainable*: today, most product life cycles including plastics are of the linear take-make-waste type, i.e. cradle-to-grave. Raw materials, primarily derived from oil are converted into products with an average lifetime of less than a year, after which they are disposed. Plastic production relies on oil, a resource that is becoming scarcer every year: *conventional* oil production peaked around 2006.[27] Only with strongly increasing amounts of unconventional oil – think of tar sands, arctic exploration, coal-to-liquids – will oil production be able to remain constant for the coming decades. Even though world wide production of resin only amounts to less than 4% of total global petroleum production,[15] this foreseen trend will increase both the price and the environmental impacts of plastic products.

[iv] Microplastics are small plastic particles[23] in the environment. This report uses the definition of microplastics as all plastic particles smaller than 5 mm.

[v] Persistent, bioaccumulating and toxic materials (PBTs) are chemicals that resist degradation in the environment and accumulate in the tissues of living organisms, where they can produce undesirable effects on human health or the environment at certain exposure levels. Persistent organic pollutants (POPs), specifically, are PBT substances likely to be transported and deposited at long distances from their original source[24]. POPs and PBTs can be embedded in plastic as chemical additives or residues or be present in the ocean as contaminant and then adhere to plastic marine litter, which can act as a sponge for toxic chemicals[25, 26].

[vi] Endocrine disruptors are chemicals that interfere with the endocrine (or hormone) system in animals or humans. These disruptions can cause cancerous tumours, birth defects and other developmental disorders.

The lifetime of plastic products is typically very short: around 30% of all plastic is used for packaging[15] and is in use for only a brief moment of time. After use, plastic is no longer considered a valuable resource, but becomes waste. What happens next depends a lot on where you live. In most industrialized countries plastic household waste is collected together with all other waste and often dumped in landfills.[28] A relatively small fraction is reused or recycled.[29] In the developing world, waste management is often less well-organized or failing altogether. In China, reportedly more than 30 billion tonnes of waste are dumped in the Yangtze River, and China's longest river is now considered to be a giant toilet bowl.[30] Unless countries manage to substantially improve their management of resources and waste, the pressure on the environment and local living standards will rapidly increase.

1.3. Oceans at risk

In order to analyse the impact of plastic marine litter on the oceans, one has to consider their current status in general (The North Sea is discussed in Chapter 5). As it turns out, the oceans are at risk by a whole range of human activities besides plastic marine litter. These impacts include overfishing, physical disturbance, climatic changes, acidification, non-native species and toxic waste. In the 2011 report of the International Programme on the State of the Ocean (IPSO), experts conclude that in many marine habitats, the activities that impact the ocean have lead to intense multiple stressors that can act together, often reinforcing each other.[31] This is already resulting in large-scale changes in the ocean at an increasing rate. In some regions, it has resulted in ecosystem collapse. The continued expansion in global population exerts ever-increasing pressures on scarcer ocean resources.

Historically, human impacts on marine habitats proceeded roughly as follows. Overfishing started centuries ago,[32] and continues to form the baseline stress for many – if not all – (coastal) ecosystems. Agricultural practices, particularly since the discovery of artificial fertilizers, have strongly contributed to the pollution of the oceans by overloading them with nutrients. Later on, persistent, bio-accumulating toxics (such as pesticides and other industrial chemicals) spread through the oceans and worked their way through food webs with potentially serious impacts for human health. For instance, the Inuit's diets consist largely of sea animals in the Arctic, where a concentrated cocktail of dioxins and other organic pollutants have moved up the food chain to a degree of toxicity that some Inuit mothers are no longer able to safely breast-feed their infants.[33]

In addition, there are growing concerns about the role of carbon dioxide causing oceans to acidify.[34] With mechanization of fisheries, a new threat for marine ecosystems arrived: damage of the seafloor by bottom trawling. On a large scale, this destroys communities at the bottom of the food chain that live in and on the bottom of the oceans. With mass transport of people and goods, the human impacts also started to include the introduction of alien species at an unprecedented scale. Finally the anthropogenic emission of greenhouse gases is causing the planet to warm, sea levels to rise, and rainfall patterns to change. Since the oceans play the major part in the global carbon cycle, changes in the balance of CO_2 uptake and release can have far-reaching consequences.

These main categories of human stresses on the oceans are further detailed in Table 1-2, which highlights the mechanisms and major impacts. These mechanisms often are strongly related: warming and acidification can increase the magnitude of hypoxia (oxygen depletion as a result of nutrient overloads). Overfishing can destabilize populations and food webs to a point where they become more vulnerable to chemical pollutants. Such effects are expressions of two types of *anticipated surprises*:[35] the first category of impending problems is that of discontinuities. These occur when ecosystems absorb stresses over prolonged periods of time without showing clear signs of harm and then reach a threshold level, tipping into an altered and often less diverse state. The second category comprises synergisms – literally, a uniting of energies. It is characterized by a multiplication rather than an addition of environmental processes. Such positive feedbacks have the potential of creating runaway processes that might not be restored.

Table 1-2. Main categories of human stress, mechanisms and impacts (Collected from: [31, 36, 37]).

Human Stress	Major mechanism	Indirect mechanisms	Major impacts
Fishing	Over-exploitation	By-catch	Severe decline in many species to the point of extinction; unparalleled rate of regional extinction of habitat types; risk of losing species and entire ecosystems like coral reefs within one generation
Pollution	Nutrient runoff (N, P)	Algal blooms resulting in oxygen depletion	Species decline
	Chemical contaminants (POPs, Hg)	Biomagnification, bioaccumulation	Species decline; human health
	Anthropogenic carbon dioxide	Acidification	Unpredictable; includes the dissolution of calcium carbonate structures and decreased calcification rates.
Mechanical damage	Bottom trawling		Habitat destruction
Introduction of non-native species	Transport		Transforms ecosystems
Climate change	Changes in primary production; Sea level rise	Influence major ocean currents	Changes in the distribution and abundance of marine species; widespread impact on the ecosystem: simplification and destabilization of food webs; reduction of resilience

Little is as yet known about the anticipated surprises that can be expected for the world's oceans. In this report we identify threats of plastic debris that have the potential to influence essential functions of oceanic ecosystems on a global scale. Knowledge on these topics is incomplete, and what is known is dispersed over many scientific disciplines. Potential risks resulting from plastic marine litter are discussed in chapter 4.

1.4. North Sea Programme: towards a roadmap

Realising that plastic marine litter is a global problem, requiring international cooperation and international laws, the question arises why we focus on the North Sea. Even with general agreements on international levels, there are specific, more localised characteristics that make this a logical choice.

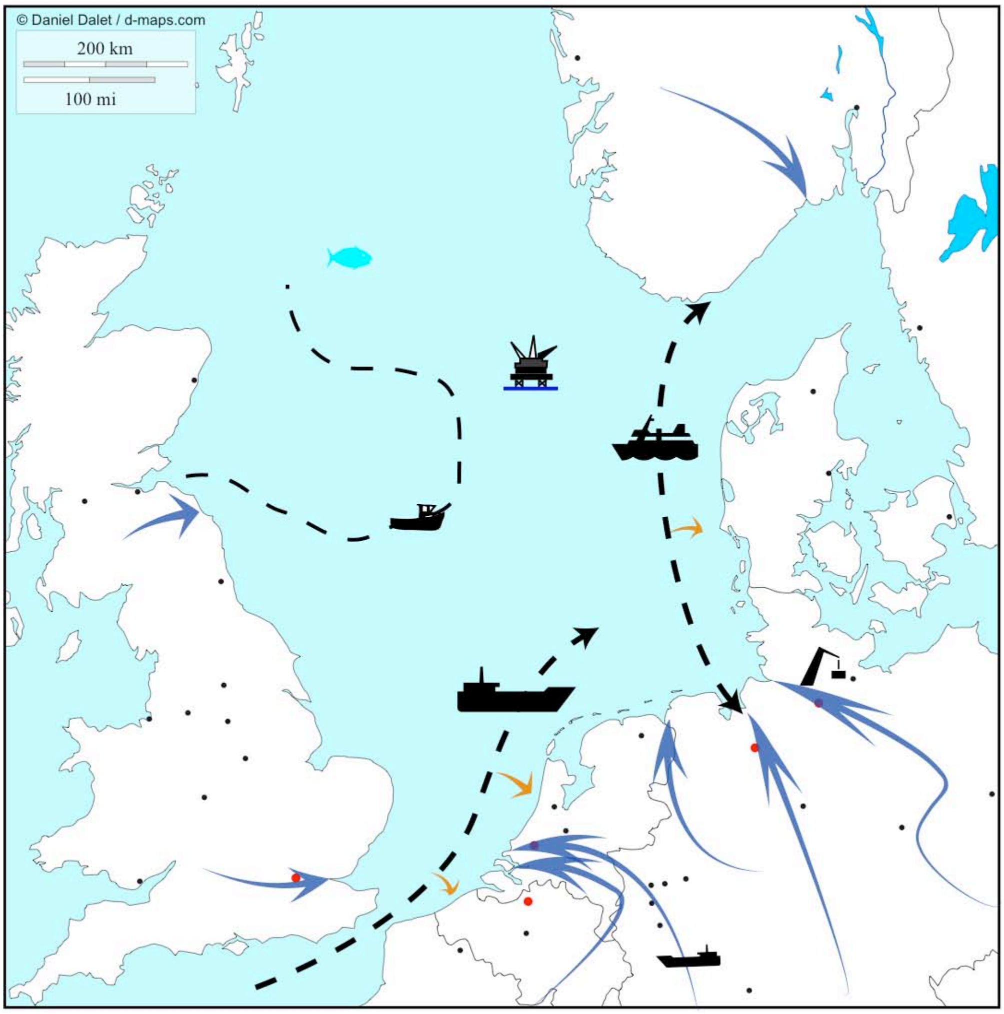

Figure 1-2. An illustration of some main characteristics of the North Sea.

The North Sea is one of the busiest seas in the world and a source of wealth for the neighbouring countries. At the same time it is also a rich natural system with a large variation in habitats: its uniqueness lies in the sandy habitats, the large productivity and the large variation in habitats, which includes a significant number and cover of rocky habitats as well. The problem of plastic marine litter in the North Sea is of a different nature than that of the gyres. The North Sea is connected to the Atlantic Ocean, the Norwegian Sea, the Kattengat and the English Channel. While its system of currents does not cause accumulation of plastic debris in a garbage patch, the west coast of Sweden is a marine litter sink.[38] Eventually all plastic litter in the North Sea ends up either buried in the sediment, deposited on beaches, buoyant in the water phase, ingested by marine organisms, or is transported elsewhere.

There is a constant flow of plastic litter from sources both on land, mainly via the rivers, sewage and wind and on the sea, from fisheries and marine transport. Compared to other regions the portion of plastic litter coming from sources at sea is in all likelihood higher than average. How big these flows are in absolute number is not known, but that they cause considerable economic and ecologic damage is well established.

The specifics of the North Sea are favourable for practical projects aimed at solving the issue of plastic marine litter. First of all, the European countries bordering the North Sea have already made great progress in solving waste problems on land. The existing knowledge infrastructure, financial and intellectual capital and legal framework is able to unleash the creativity that is needed to make plastic use more sustainable.

The North Sea geography allows for interception at various points where the plastic is not yet extremely diluted: rivers, beaches, estuaries form starting points that are close to existing infrastructure. Monitoring and restoration at these sites is therefore much less expensive than cleaning efforts at the open oceans. The high density of economic activities on the North Sea is of course one of the sources of plastic in the marine environment, but at the same time presents an opportunity to hitchhike on the existing marine infrastructure.

2. What causes plastic marine litter?

Summary

- Far too few products are designed for their usage phase with proper consideration for their end of life. The physical and chemical properties of plastics – including current biodegradable plastics – make them persistent in the marine environment for a very long time, possibly centuries.
- Fragmentation does occur, and this is suspected to increase detrimental effects, including those of microplastics.
- Microplastics are also produced for direct use in specific consumer products such as cosmetics and for indirect use as precursors (nurdles) for consumer products.
- Plastic products are generally inexpensive and therefore are a material of choice for single-use items.
- Combined with intentional disposal and unintentional abandoning at land and on the sea, this leads to waste streams ending in the marine environment.
- Despite 40 years of government policy making to prevent marine waste, little progress has been made on the issue of plastic marine litter.
- In part this is due to opposing views on problem definition, problem source and responsibility. These differences result in different policy proposals. This delays action.
- International law offers much more potential to manage the problem.

As we have seen in the previous paragraph, current plastic usage is unsustainable. That does not directly explain why that leads to a problem as plastic marine litter. Here we show that the problem results from economic, technical and behavioural factors combined with waste management, policy failure and societal debate. Some of these were already mentioned in Table 1-1. This chapter discusses in brief the causes of plastic entering the ocean as debris: many of these are explained in more detail later in the report.

2.1. Properties, technology and design

Basically, once plastics enter the marine environment, they are persistent there. The inherent properties of nearly all synthetic polymers prevent rapid degradation by microorganisms. Even most biodegradable polymers decompose very slowly under typical conditions in the sea. Plastic floating on water degrades into ever-smaller pieces by the action of UV light and waves.

On a higher level, the technical cause for plastic marine litter can be perceived as a flaw in the design of many items made from plastic. Only the short usage phase of a product is considered, without giving thought to the entire life cycle of a product. This approach collides with the very real chances that plastic waste management fails, and products end up in the environment while there are increasing concerns about their chemical and physical impact.

2.2. Economics of plastic products

One other major cause of plastic marine litter is that the direct monetary value of plastics products is low. Compare, e.g. the price of a disposable coffee cup (1-2 eurocents) to a porcelain mug (starting at 1-2 euro). Certainly, high-grade specialty plastics can be valuable and expensive, but in general, plastics are bulk materials that allow for cheap or even give-away products.

The low price makes that the users also attach little emotional value to many plastic products. Therefore they are not used for long and easily discarded. As we will show in Chapter 6 this does not necessarily mean that there is no business case for recycling. Other barriers prevent that solution from being implemented widespread. Here we focus on the reasons for the typical low price of plastic products.

In addition, market volumes of plastic are high, growing and expected to grow further over the next twenty years.

Box 2-1. Why are plastics inexpensive?

First of all, plastics are made from cheap resources. Plastics “hitchhike” on the oil infrastructure. Oil refineries run 24/7 and are continuously generating ethylene gas which can be used for the production of polyethylene.[39]

Secondly, negative effects of the consumption of plastic-containing products on the environment are hardly reflected in the price of plastic, let alone charged to consumers[vii].

Another reason for the low price of plastics is mass production. The raw materials for plastics are bulk chemicals, thus profiting from economies of scale. Highly efficient automation and cheap labour enable mass production of products.

The cheapness of plastics has in many cases led to a race to the bottom. A good example is the monobloc plastic chair. In theory a plastic chair could have an unlimited number of designs. In practice, to survive the demands of the market, the article above all needs to be cheap: it can typically be found for under €10. The economics for this chair are so tight that it is nearly impossible to deviate from its basic form. Thus, the monobloc chair becomes a symbol of cheapness, a wasteful object, not meant to last. This reinforces the unwillingness of consumers to pay more than the absolute minimum.[39]

Finally, because plastics are cheap, light, with few technical shape and colour limitations, they offer a lot of value for money, making them the material of choice over alternatives for many different applications.

[vii] The exception is for the emissions of CO_2 in the production or incineration of plastic that have a price under the European Union Emission Trading System. Note however that this price on CO_2 also has to be paid for steel, aluminium and other materials produced in the EU. And even in this exceptional case, the price charged is much lower than the possible damage due to climate change.

2.3. Behavioural patterns

Next to technical and economic causes for plastic marine litter, there are causes that are more societal in nature. This includes human psychology, preferences and behaviour connected to the issue of consumption and littering.

Without robust policies for managing waste with education and incentives, most consumers are likely to continue to litter the environment. For municipalities and companies landfills or nature for long have been the easiest form of waste disposal. This is indeed what still happens in many countries, especially developing ones. As mentioned, a large share of plastics is designed and promoted to be used only once, and to be disposed of whenever and wherever their contents are consumed. It is the logical continuation of waste disposal habits with traditional products and materials such as bamboo, banana leaves and paper, most of which are biodegradable and had never led to large accumulations of waste. In addition, modern society is encouraging consumers to consumption behaviour at unprecedented levels. In practice, most consumers decide their purchasing behaviour on price only.

2.4. Failure of waste management policies

Our “natural” behaviour of littering plastic can successfully be adjusted using a wide array of policies including (large) fines, education, awareness campaigns, deposit, increasing the number of bins, in combination with better strategies for collecting, labelling, sorting and recycling plastic. These strategies will be explored in Chapter 5. However, controlling the littering is complicated by the multitude of sources. Land-based sources include tourism, recreation, illegal dumping, waste disposal and industrial activities. Sea-based activities include fisheries, offshore industry, shipping and recreation, each of which forms a source of plastic marine litter (Chapter 3). Setting up a proper waste management system takes considerable resources, cooperation and time. In addition, it is necessary that nature be no longer viewed as infinitely resilient, able to cope with large disturbances caused by humans and without much intrinsic value. In many countries, waste management approaches and policies are failing.

2.5. Failure of international policies

As plastic marine litter is a global problem, international management of the problem is required in addition to national and regional approaches. First of all, plastic debris can be found in any ocean and sea worldwide. Second, as all seas and oceans are connected to each other, plastics are transported from one regional sea to another. Plastics are also concentrated in some regions, including coastlines and the oceanic gyres or *garbage patches*, which are located in the open ocean. Since these gyres are located far from the territorial waters of countries, they fall under jurisdiction of international law and can only be addressed by *international cooperation* and further development of *international law*.

Trouwborst has reviewed the role of international law in managing the problem of marine litter.[40] The legal framework for marine litter is vast and complex, consisting of a wide range of global, regional, national and local regulations. The United Nations Environmental Programme (UNEP) has stated that "the problem of marine litter has steadily grown worse, despite both national and international efforts to control it". Legislation is also expected to have had "a limited effect".[41] Trouwborst, however, states that international law is "a useful, and probably indispensable, ingredient of the larger toolbox (politics, economics, technology, public awareness) needed to adequately manage marine litter". Without international law the situation would have been worse and international law offers much more potential to manage the problem, than currently fulfilled. International law and institutions could contribute to: new legislation for areas beyond national jurisdiction; harmonisation of national legislation; encouragement of countries that are lagging behind with their national legislation; agreements on liability and compensation for countries affected by pollution; and damage caused by other countries; and so on.

For *sea-based sources* of marine litter important regulations have come into effect, among which the MARPOL Convention (International Convention for the Prevention of Pollution from Ships) which was adopted in 1973 and prevents dumping of litter at sea. Although the convention is still widely ignored, these regulations are shown to be successful to some extent. Legislation on *land-based sources of* marine litter, however, is even more complicated, is lagging behind and offers much room for improvement.[40]

Several institutions have also tried for years to enhance *international cooperation*. UNEP has recently brought attention to the issue of marine litter in the context of its *regional seas programme*. More than 140 countries participate in one or more Regional Seas Conventions or Action Plans.[42] It is not yet clear however to what extent these conventions and action plans will lead to concrete measures on marine litter. UNEP and NOAA are also working on global strategies, among others by publications on marine litter and by organisation of international conferences on plastic marine debris. In practice, most of these initiatives fail because of poor science and the use of ineffective programmes of monitoring. They are not based on a hypothesis about the nature of the problem, lack a prediction of the expected result and/or do not have the statistical power to determine whether a particular management action/policy has reduced or increased plastic debris.[43, 44]

An additional factor delaying action is the lack of a shared definition of "harm". The MSFD mentions the term in the definition of (marine) pollution. It has an economic and an ecological component. But when is the harm so severe that measures are to be taken? For instance, must ecological impact be demonstrated at the level of individual animals, species or entire ecosystems? And given a certain impact, what would be an appropriate response?

During the Fifth International Marine Debris Conference, co-organised by the UNEP and the NOAA in March 2011, the Honolulu Commitment was adopted, which expresses the intention to establish a cross-sectoral approach to address the issue of marine debris.[45] This Commitment is the first step towards a Honolulu Strategy, which will be developed by UNEP, NOAA, international marine debris experts and representatives of industry and governments, and will provide a strategic framework for coordinated action plans to prevent, reduce and manage sources of marine debris. It remains to be seen if this declaration will result in a global strategy and action plan.

Since the legal protection status of open oceans is currently poor and the international law on marine litter contains significant gaps, further efforts need to be made to improve general *ocean governance* and to develop of a more stringent international legal framework for marine litter.

Finally, at the regional EU level, The European Commission recognises the problem and is working on an action plan. In November 2010, DG Environment issued the report "Plastic waste in the environment".[46] This report discusses directives for sustainable packaging, recycling and prevention, as well as the necessary research into innovative solutions. In the EU, 24% of plastic waste is recycled and 32% is used for energy recovery (2010 figures).[16] In 2008, the Waste Framework Directive set a target for the recycling of waste from households (such as plastic) of 50 percent by weight in 2020. This means that some EU member states still have a long way to go. Besides the above instruments, the EU Marine Strategy Framework has included the problem of (plastic) waste as one of the elements for which a "good environmental status" must be achieved in 2020. With respect to litter, the directive specifies as a qualitative descriptor for determining this status that "properties and quantities of marine litter do not cause harm to the coastal and marine environment". What a good environmental status is with respect to waste at sea, and how to measure this, is currently being discussed in a European context.[47]

2.6. Societal debate

Plastics do not belong in the ocean. There is consensus about this fundamental statement between all parties involved: industry, NGOs, government and scientists. Since plastics are man-made, there is no debate about the anthropogenic origin of the issue. Yet on other aspects there is less consensus: there are different views on the scale of the problem and the impacts of plastic marine litter. When it comes to responsibilities and solutions, there is considerable debate on who should do what and when.

The lack of consensus has many underlying causes, but to a large degree it can be explained by the fact that different stakeholders use different *frames*. Frames are thought shortcuts for making sense of the complex world around us, and for decision making. People create frames to name issues they are confronted with, to identify and interpret aspects that seem *key* in understanding the issue and to communicate their interpretation to others. Frames give meaning to some observed aspects, while discounting others that appear irrelevant at the same time. This selective simplification filters people's perceptions and defines their fields of vision.[48]

Plastic marine litter is framed in many different and divergent ways. The *littering frame* and *consumption frame*, as presented in table 1-3, summarise the most polarised positions in the debate on plastic marine litter. For those expressing the problem as a general littering issue, plastics are a valuable and essential building block of modern day society, which only poses environmental problems if not disposed of properly. Since this counts for all other materials or types of marine litter, the littering frame therefore stresses the need for a general marine litter policy, not specifically focused on plastics.

The consumption frame stresses a different aspect of the issue. The modern day society is not only depending on, but also addicted to plastics. The ever-growing production of single-use plastics and low-value plastic products are a serious burden for our oceans, as plastic waste is harming marine life and threatening human health. Within this view, the issue is framed as "plastic soup" to convey the concern of the widespread distribution, accumulation and dispersion of plastic waste. This implies that the problem can only be addressed by constraining production and use of plastics.

The framing table presents a characterization of the two most opposing views. In reality, there are more frames that will not be detailed here, e.g. plastic marine litter as a toxicity issue, a business opportunity, an environmental hype and so on. It should also be stressed that in the current debate parties seldom adopt a pure frame, but use arguments and ideas from several frames or switch frames over time. In fact, the characterization of the issue in this report as *plastic marine litter* is a deliberate attempt to encompass most of the existing frames in a single frame.

Table 2-1 explains how policy development can be troubled, as persistent and widely diverging frames can result in different policy proposals and can delay action despite the general consensus that plastic marine litter is a serious issue demanding a solution. The Plastic Marine Litter programme intends to acknowledge all frames and resolve conflicts using establishing and sharing of a scientific base. We look for combining all types of approaches into integrative solutions to this complex problem.

Table 2-1. Table representing the two most opposing frames, the *littering frame* and *consumption frame*.

	Littering issue	**Consumption issue**
Language	Marine debris "The simple fact is that waste (plastics or otherwise) does not belong in the sea. Litter is primarily a result of human neglect and poor waste management and if we all acted responsibly there would be no reason for the large majority of it to be there." [49]	Plastic soup, plastic marine pollution "Plastic pollution is a genuine crisis. No amount of political tactics, business greed, or disinformation can change the fact that there are almost no places on the planet that remain untouched by plastic trash."[50]
Problem definition	Plastics are valuable and diverse materials with many useful applications, but as with all materials problems can occur if not disposed of properly.	Plastics are inherently toxic and non-degradable materials, which last forever, poison our food chain and affect human health.
Problem source	Littering "consumers", e.g. during beach recreation, and littering "industries", e.g. shipping and fisheries.	Industry deliberately produces toxic and wasteful products to maximise profits.
Responsibility	Consumers, all users of plastic products.	Producers, including plastic industry, packaging industry and other industries. Governments. To a lesser degree non-sustainable consumers.
Role of policy	Prevent plastics ending up in the ocean	End global dependence on (disposable) plastics.
Policy solution	Policy based on risk-based approach • Recovery of plastic waste during production and transport • Improve waste infrastructure • Market-based measures • Design for recycling • Government enforcement of waste reduction policies and conventions	Policy based on precautionary principle • Refuse or ban disposable products • Substitution with other materials • Encourage consumers and companies to reduce their plastic footprint. • Government regulation and enforcement

2.7. Plastic marine litter as a complex problem

Plastic marine litter can be characterised as a "poorly structured problem": it is not fully understood while information is ambiguous and incomplete. In general, one must fully understand the issue in all its aspects before proposing a system solution to address them.

As for many environmental problems, plastic marine litter is a "Tragedy of the Commons". [51] This well-known dilemma arises from the situation in which multiple individuals, acting independently and rationally within their own self-interest will ultimately deplete a shared limited resource like the ecosystem functions of the oceans. Even when it is clear that it is not in anyone's long-term interest for this to happen. Simply put: because is it everyone's problem, no one takes action. The effect is reinforced by the diffuse nature of the source (see also Chapter 3) and by the lack of knowledge of the consequences of plastic litter in a removed location. Furthermore, the resulting societal debate, amplified by the lack of solid information, is delaying taking action.

Plastic marine litter is therefore a complex problem. As a result, it requires implementation of a wide variety of approaches and strategies if the oceans are to receive a reduced load of (plastic) marine litter.[21] Isolated measures will have little effect. Without sufficient clarity in the relevant knowledge base to make informed decisions from a systems perspective, a proposed solution may even create more problems than it solves. If the problem was simple, it had already been solved by now. Only a systematic, integral approach involving a clever mix of effective measures can truly solve the problem of plastic marine litter. These circumstances suggest a need for an independent knowledge broker between industry, scientists and policy makers using systems analysis.[52]

Meanwhile, all measures clearly addressing the problem while providing a minimal or non-existent chance of adverse effects should be taken immediately.

2.8. Conclusion

Plastic marine litter is a complex problem. Its persistent nature is rooted in the interdependence of economic, technical and behavioural aspects, in combination with lack of understanding and knowledge. Plastics are generally cheap while the design only considers the short usage phase of a product. Consumption is encouraged while our natural littering behaviour is generally not corrected by policy measures while waste management fails. Societal debate and the “Tragedy of the Commons” are delaying action.

Only a systematic, integral approach involving a clever mix of effective measures can truly solve the problem of plastic marine litter. Meanwhile, all measures clearly addressing the problem while providing a minimal or non-existent chance of adverse effects should be taken immediately.

3. Spreading of plastic into the marine environment

Summary

- If plastic ends up in the marine environment, winds and currents determine its fate. In the oceans, an important mechanism is the accumulation of debris in gyres –giant garbage patches. In local seas like the North Sea, plastic accumulates in specific coastal waters, on shorelines, estuaries, ingested by sea animals, and on the seafloor. Rivers and sewage systems are expected to form important pathways for plastic marine litter.
- Concentrations of plastic marine litter are in many instances high enough to impact individual species and raise concerns for marine ecosystems.
- Of particular, and recent concern is the spreading of microplastics that can be ingested by broad range of animals. The sources, pathways and sinks of these microparticles will be different from those of large plastics.
- For both size-categories of plastic marine litter there is insufficient knowledge on how it spreads through the marine environment: what is the relative importance of land- based sources versus sea-based sources? How much debris is carried through rivers or sewage systems? This precludes the design of effective monitoring programmes, let alone the determination of the most cost effective restoration programmes.
- Based on global resource scenarios, a threefold increase in global plastic production is expected in 2050. However, even in a more sustainable scenario where virgin plastic usage levels off, plastic in the marine environment is expected to increase if no further action is undertaken to prevent littering.

Plastics do not belong in the oceans, yet they are found in nearly all the oceans, seas, and beaches. The occurrence of plastic marine litter is not homogenous: there is a large variability in amounts that are found world-wide. There is no global image of all oceans: remote sensing is impossible or extremely limited, while ocean current models give only large-scale patterns of where plastic might end up. Much of what we know is therefore reconstructed from beach cleanups and scattered information is available from ocean surveys. The fate of plastic sinking to the seabed and disappearing in the sediment has only recently been investigated and is mainly confined to near-shore areas.

What we do know are the sources of plastic marine litter. These are waste streams of man-made plastic products. This sounds trivial, but is an important characteristic of the problem. Plastic marine litter originates from a multitude of diffuse sources and is therefore more difficult to control than the emissions from a point source like a smokestack.

This chapter explains the current state of knowledge on where plastics marine litter occurs, and what controls its presence. Next we discuss where it comes from: the sources and pathways. Microplastics are treated separately, as their sources, pathways and sinks prove to be distinctly different from the large and visible plastic debris. Finally, we discuss a scenario for the future development of the problem. This chapter takes a global scope, in chapter 5 more details on the situation in the North Sea will be provided.

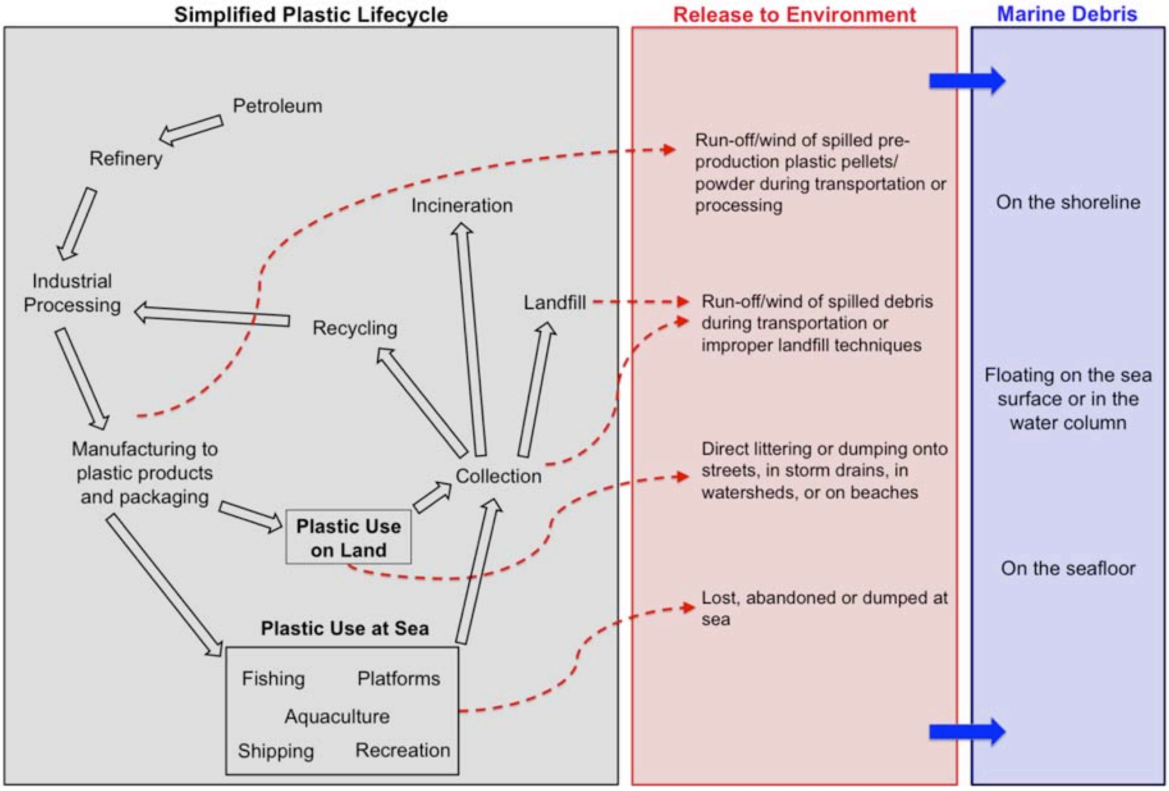

Figure 3-1. A simplified diagram of the lifecycle of plastic and a selection of ways in which it becomes marine debris. Source: [53].

3.1. Occurrence

The longevity of plastic

Mass production of plastics took off after the Second World War and some items from that period can still be retrieved from the oceans.[39] This is testimony to the fact that plastics only very slowly degrade in the marine environment. Most common plastics are resistant to microbial degradation, leaving solar radiation and thermal oxidation as the main mechanisms that influence the material properties over practical timescales.[22] Light-induced degradation can significantly reduce the mechanical strength of floating plastic. For plastic that sinks to the bottom, degradation is slower as any degradation on the dark and cold ocean floor is solely due to thermal oxidation. The weathering of plastic leads to embrittlement and disintegration of plastic materials. In photo- or oxo-degradable plastics these properties are artificially enhanced. While this helps to ease entanglement-related impacts, it is important to note that disintegration into smaller particles does not alleviate the risk of ingestion by marine species. In fact with ever-smaller plastic particles the risks for ingestion by smaller animals increases.[22]

Because plastic in the ocean last for a very long time it can be transported over large distances. Rubber ducks that were lost from a container in the middle of the Pacific Ocean in 1992, are since circumnavigating the globe, and have actually contributed to the knowledge of oceanic currents.[54] Once plastic debris has entered the sea, its fate is determined by a number of factors. Plastic debris is known to accumulate on beaches, in the open ocean and on the sea floor. The pathways of particles are dependent of their size, shape and density, which determine their vertical position in the water column. Wind, waves, and currents then affect the transportation patterns of plastic particles.[7]

Floating in oceanic gyres

The most common plastic, polyethylene (PE) has a density slightly lower than seawater. Thus, the debris remains buoyant in the upper water layer and surface currents determine the transport of debris. On a global scale this transport is dominated by the "oceanic gyres", massive, slow rotating whirlpools that are formed by prevailing winds and currents. There are five major oceanic gyres worldwide in every ocean (see figure 3-2). In the centres of these gyres, surface velocities are low which causes them to act as convergence areas for all types of floating debris, including plastics (see also modelling results in figure 3-3). Since it has been discovered that the gyres collect debris over vast areas they have also been come to known as *garbage patches*.[54]

Early reports of floating plastic in the North Pacific revealed high densities of floating plastic debris in Transnational Water east of Japan.[5] The highest total density found between 1985-88 was 316,800 pieces per square km. The highest concentration was almost 3.5 kg/km^2. In 2001, Charles Moore found comparable amounts of plastic in the North Pacific Ocean halfway between the west coast of the USA and Hawaii: approximately 334,000 pieces/km^2, but with a higher total mass of 5.1 kg/km^2 .[56]

In absolute numbers this represents a dilute situation: approximately 1 piece of plastics per 3 m^2. Therefore, cleaning up – if possible at all – is expected to be extremely energy intensive. Even though plastic in the gyres is diluted, the concentrations represent a significant potential for ingestion by organisms that feed on plankton. This is illustrated by the comparison between plastic and plankton collected from the surface of the North Pacific Ocean: plankton abundance was 5 times higher than that of plastic, but the mass of plastics was approximately six times that of plankton.[56] These findings cannot be generalised as the sampling took place in the centre of the North Pacific gyre where plastic concentrations are highest and natural abundance of plankton is low. In this same region, plastic is found in fish feeding on plankton.[57, 58] Judged from the amounts of plastic found in the stomachs of these fishes, it has been extrapolated that 12,000-24,000 tons of plastic are ingested per year.[58] Again such findings need to be interpreted as illustrative for the areas that are worst affected. The extrapolations to larger areas therefore have a large uncertainty.

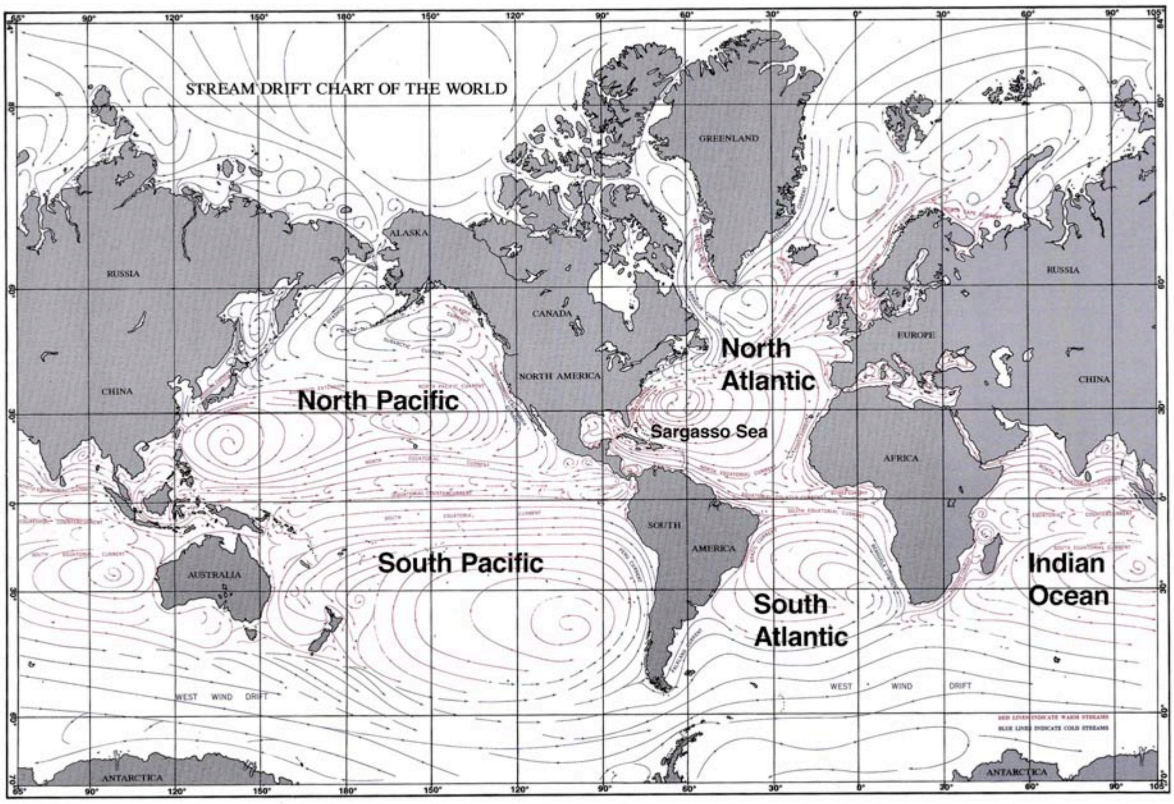

Figure 3-2. Ocean surface currents generate the five main gyres[55].

A similar patch of floating plastic debris is found in the North Atlantic gyre. This region, which contains the Sargasso Sea, has been sampled in detail between 1986 and 2002.[59] In this region, concentrations up to 580,000 pieces per km^2 were found, at least 5 times more than were reported in the earliest reports from the 70s for the same region.[17, 60] Law et al. estimated that the total amount of plastic in the domain was 1,100 tons.[59] Surprisingly, their analysis revealed that *on average*, the amount of floating plastic in the North Atlantic gyre had not increased from 1986-2008, despite a strong increase of discarded plastic in the USA.

Floating plastic debris has also been found in the South Atlantic[62] and Indian Ocean.[63] Generally, there is less information available for these regions. To fill in the missing pieces and to better understand the experimental findings from oceanic expeditions, modelling studies of oceanic currents are performed to elucidate the spatial patterns of marine debris in the world's oceans and seas. Maximenko, for instance, has used known trajectories of satellite-tracked drifters to model the pathways of marine debris.[64] Starting from a homogeneous distribution of flotsams, the model shows where the larges concentrations of floating debris can be expected (figure 3-3).

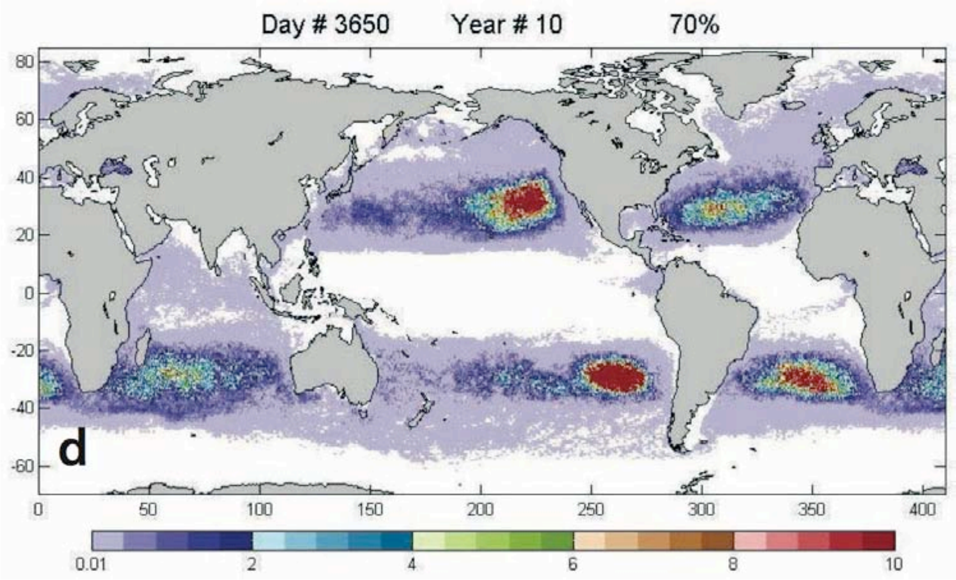

Figure 3-3. Simulation of drifter densities after a 10-year period from an initially homogenous state[61].

Washed up on beaches

The oceanic gyres determine the broad spatial distribution of plastic marine litter floating around the globe. Outside these oceanic gyres, most information on plastic in the marine environment comes from surveys of litter stranded on beaches.[65, 66] Results from these surveys show wide geographical and seasonal variability caused by local wind and current conditions, coastline geography and the point of entry into the system. Typically, about 200 and 50 items of man-made debris per 100 m beach strand annually on north and south Atlantic shores respectively. Enclosed seas, like the Mediterranean, typically have much higher densities of plastic debris.[65] Though interpretation is often hampered by differences in sampling protocols, two general patterns are clear: it is found that 60-80% of the stranded marine litter items is plastic[9] and litter loads are greater close to urban areas.[66]

Since 1998 OSPAR has monitored levels of beach litter in the North East Atlantic region with a standardized protocol.[8] This monitoring has shown that plastic is the most dominant source of waste in the greater North Sea region with the highest level of 80% on beaches in the northern North Sea and 75% in the southern North Sea. Beaches in the OSPAR region have between 200-1400 litter items per 100 m depending on the location. Levels have remained consistently high from 2001-2006.

Sinking to the seabed

Compared to floating debris, the presence of plastic litter on the seabed is much less widely investigated. For a start, it is not well established which fraction of plastic marine litter sinks to the seafloor. It is often quoted that 70% of all plastic marine litter ends up on the seafloor, but there seems to be no scientific foundation for this claim. Part of the plastic litter, like PVC, is dense enough to sink directly to the bottom. Also floating plastic debris can sink as the density of increases by weathering and biofouling.[67, 68] As the amount of plastic marine litters continues to increase, concerns have been raised that this might lead to a plasticizing of the seafloor.[69]

Most studies of plastic on the seabed have focussed on the continental shelves.[70, 71] The distribution is influenced by hydrodynamics, geomorphology and human factors. Also notable seasonal variations can exist in some zones. In general, bottom debris tends to become trapped in areas of low circulation and high sediment accumulation. The spatial patterns of plastic on the seafloor therefore do not necessarily follow the patterns of floating debris.[65]

Along the European coasts, the greatest densities were found in the Mediterranean, [70] which is caused by a combination of a densely populated shoreline, shipping activities and little tidal movement. At some points, particularly near large cities or in offshore canyons the densities could exceed 100,000 pieces/km^2; the same order of magnitude as plastic marine litter in the gyres.

3.2. Sources and dispersion

Points of origin

All plastic litter is man-made and originates from a large multitude of sources. Consider for example throwaway plastic lighters: at least 5 million of these are sold every day,[72] creating numerous potential sources for marine litter. Global production of plastics amounted to 265 million tonnes of plastic in 2010,[16] but this provides little details as to how the material flows through societies. Plastic loss from the production process and transport is found worldwide on beaches.[25, 26, 73]

The use of plastic shows a strong positive relation with economic living standards, expressed as Gross Domestic Product (GDP).[15] Plastic use therefore peaks in regions where GDP is high, which approximately corresponds to the regions of the earth that are well-illuminated at night (figure 3-4). High plastic usage is likely to also correlate with plastic getting displaced into the marine environment. However, there are large regional differences in how societies regulate and control the flow of waste that can modify the actual flux.

Next to land-based sources, a significant fraction of plastic marine litter comes from sea-based sources. The ratio between land-based and ocean-based sources is not known from measurements or observations and varies from sea to sea. Expert judgements have come forward with an 80-20 ratio globally.[74] By looking at global shipping routes, an indication can be provided of which seas show the busiest traffic (figure 3-5). This map does not include other sea-based points of origin, namely commercial fishing, recreational boating, and offshore oil and gas platforms.

Figure 3-4. Earth at nigh. The most illuminated areas are densely populated and/or have a high living standard. Source: NASA.

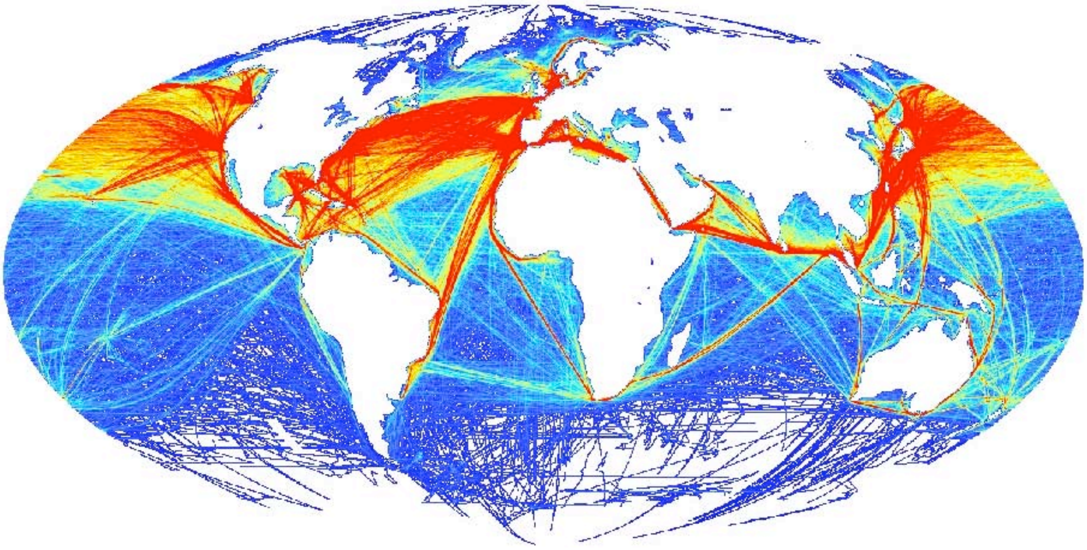

Figure 3-5. Global shipping routes[75].

Pathways

The movement of plastic litter through the Earth's water system is highly dynamic. In 3.1 we saw that once plastic reaches the ocean it can be trapped for prolonged period of time in oceanic current systems before returning to the coasts. Here we discuss other pathways that transport plastic marine litter from its point of origin. A number of these pathways have been identified, but quantitative information is scarce.

Transport of plastic litter from land to the seas can occur via the air, e.g. from waste dumping sites, for lightweight products like plastic bags. A more general pathway for many types of plastics is via waterways: rivers, storm water discharges and sewer overflows. Galgani suggested that large rivers are responsible for plastic found at the seafloor around estuaries.[70] However, standardized monitoring of litter in rivers is still in its infancy.[76] Measurements in the river Cynon in Wales (UK) show that stranding of riverine litter along a 100 m bank is strongly influenced by the water level in the river and could reach values of approximately 400 items.[77]

Sewer systems typically filter larger plastic debris, but not microplastics, before discharging into surface waters, but when there is an overflow during heavy rainfall this system is bypassed and debris ends up in beaches and seas. During such events large amounts of debris can end up on beaches and enter the seas. According to Nollkaemper, sewer overflows form one of the major pathways of plastic marine litter in the USA.[78]

Finally, marine animals like sea birds and large marine animals can transport plastic. These organisms are known to ingest plastic debris and some organisms are known to have a role in the fragmentation of debris. Fish that are feeding primarily on plankton in the North Pacific are estimated to ingest 12,000-24,000 tonnes of plastic each year.[58] Northern Fulmars from around the North Sea reshape and redistribute about 630 million plastic particles, representing circa 6 tons of plastic mass.[79]

Ingestion by marine organisms may be useful *indicators* to assess the abundance and spatial patterns of plastic debris in a marine environment. In many different North Sea areas dead *fulmars* have been collected since the 1980s to assess the quantities of plastic within their stomach (see figure 3-6). As fulmars feed only at sea and indigestible plastics wear down slowly in their stomachs, the abundance of plastics remaining in the stomachs gives a good idea of ingestion of plastics over a period of time before death. The ecological indicator EcoQO was developed by ICES and the North Sea ministers and will be adopted both by OSPAR and by the European Marine Strategy Framework Directive.[80]

3.3. Microplastics

The occurrence of plastic microparticles in the world's oceans is an issue of growing concern.[81] An up-to-date review of microplastic occurrences in both surface waters and sediments has recently been published.[82] The potential ecological impacts will be discussed in Chapter 4, here we discuss the sources, pathways, and sinks. In 2008, an expert panel agreed to define microplastics as plastic particles that are smaller than 5 mm.[23] Other researcher prefer a maximum size of 1 mm as a definition.[7] The commonly found virgin plastic pellets that are of 2-5 mm size are thus included in our definition. Some authors refer to this latter size category as small- or meso-plastic.

Sampling of plastic marine litter in surface waters commonly takes place with nets that have a minimum mesh size of approximately 300 μm (= 0.3 mm), giving a practical lower boundary to what can be considered microplastics. Since in many monitoring surveys no further size analysis is made, it is not clear which fraction of the detected plastic debris consists of microparticles, meso-particles and macro-particles. For impact studies under laboratory conditions particles of far smaller dimensions are used (e.g. 3.0 or 9.6 μm plastic spheres[4] and 0.020 μm beads[83]) than can be collected with even the finest-meshed nets, making it difficult to relate potential ecological impacts to experimental concentrations.

Definition issues aside, it is quite clear what are the sources of microplastics. The origins are attributed to two main sources: (1) direct introduction with runoff and (2) weathering breakdown of larger plastic debris.[81] Some microplastic particles are used in cosmetic products.[84, 85] Others uses of microplastics are in synthetic "sandblasting" media. Recently also polyester and acrylic fibres from washing clothes were identified as a source of microplastics.[86] These plastic fibres and particles are flushed down the drain without being captured by sewage treatment facilities. However, these direct sources are believed to be minor compared to the weathering of meso- and macro-plastics in the marine environment.[81]

At the water surface, microplastics (> 280 μm) abundance in the North Sea increased significantly since the 1960s in accordance with increased plastic production.[87] A study by Law and others in the North Atlantic gyre, however, did not find such a trend for the period 1986-2006, suggesting that the ultimate fate of plastic marine litter is to either further degrade or sink.[59] A study of the entire water column in Santa Monica Bay indeed showed that the density of debris was greatest near the bottom and least in midwater. Debris density furthermore strongly increased after a storm, which could relate to inputs from land-based run-off.[88] When in coastal Swedish waters 80-μm mesh nets were used instead of the more common 330-μm nets much more plastic particles were found: approximately 100,000 times more.[89] This suggests that the actual number of microplastic particles at the surface is much more than commonly sampled.

The small size of microplastics means that transport properties of the plastic are distinctly different from larger plastic debris. This is evident from the composition of plastics in sediments. Macro-plastic debris consists predominantly of PE, PP, and expanded PS, whereas for microplastics mainly denser types of plastic are found like polyester and PVC.[7] The study of microplastics in marine sediments of the UK has shown that the highest abundance is found in subtidal habitats[viii], followed by estuarine and sandy habitats.[87] In Belgian marine sediments even higher concentrations were found.[90] By making depth profiles of sediment cores it could also be shown that microplastic concentrations follow global plastic production increase.

[viii] The shallow region not far from the shore that is always covered by water.

3.4. Future trends

Scenarios for the future development of plastic usage and waste have not been found. Assuming that plastic production follows the general trend for raw materials, global levels of overall usage could triple by 2050.[91] Figure 3-7 shows two scenarios for plastics production during the next decades.

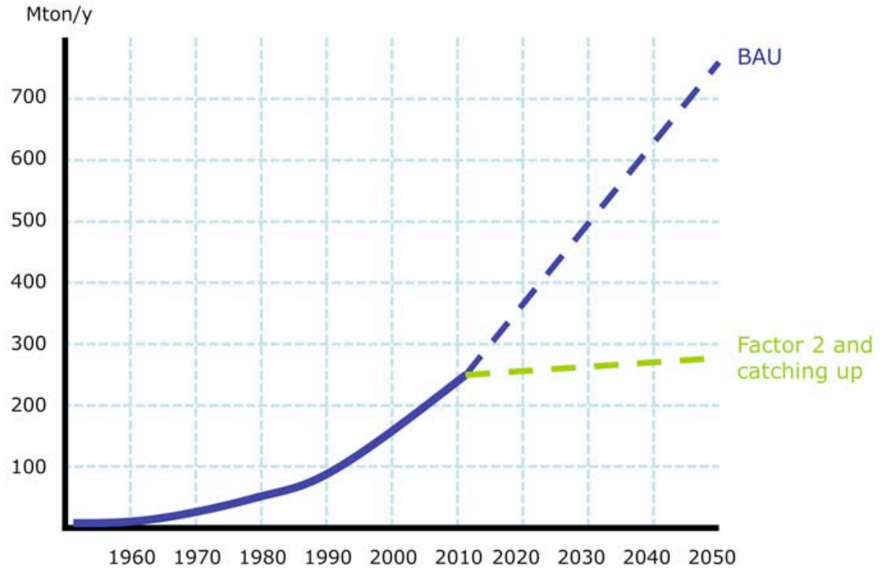

Figure 3-7. Projection for the global plastics production according to two different scenarios for global consumption. In the Business As Usual (BAU) scenario, industrial countries freeze their average consumption levels ("metabolic rates") at 2000 levels, while developing countries catch up. In the "Factor 2 and catching up" scenario, industrialized countries reduce resource consumption by factor of two, while developing countries catch up to average consumption. Based on PlasticsEurope[92] and UNEP.[91]

For marine litter, the Business-as-Usual (BAU) scenario means that a serious aggravation of the existing problems is to be expected. Assuming that a comparable fraction of plastics ends up in the marine environment, the plastic ending up year after year in the marine environment would grow in parallel with the plastic production. With the very slow degradation in seawater, this effectively means the plastic present in the oceans will accumulate and increase to unprecedented levels.

In a more sustainable scenario (Factor 2 and catching up) the annual global consumption of virgin plastics stabilises at half the current levels of the industrialised world. Even under this optimistic assumption, without further action, the resulting litter will accumulate in the seas and oceans. These tentative scenarios therefore underscore the need for solutions at all levels: from manufacture to waste management, and from consumer awareness to restoration programmes (see further Chapter 5).

3.5. Conclusions

The persistent nature of plastic in the marine environment makes that plastic litter can now be found almost everywhere that researchers have cared to look. This also means that as long as the sources of plastic marine litter are not addressed, the problem will increase. Still, even in the worst affected places at sea or in the oceans, the typical physical situation should be characterized as dilute, in contrast to portrayals in the media that point the camera to plastic waste hot spots. For the ecosystem, however, the concentrations are already high enough that stomach contents of seabirds can be used as monitoring tools. Another consequence of the dilute nature of plastic marine litter is that cleaning-up will be energy intensive and costly. Only at beaches or when plastic is "bycatch", such as in KIMO's Fishing For Litter programme, the costs of plastic removal are not prohibitive.

In devising effective strategies for the prevention of plastic marine litter, quantitative knowledge on points of origins and pathways is essential. Of particular, and recent concern is the spreading of microplastics that can be ingested by broad range of animals. The sources, pathways and sinks of these microparticles will be different from those of large plastics. How much litter is contributed per sector? What is the role of rivers in transport? Currently, answers to these questions come from expert judgments and patchy scientific evidence.

Based on global resource scenarios, a threefold increase in plastic production is expected in 2050. However, even in a more sustainable scenario where plastic usage levels off, plastic in the marine environment is expected to increase if no further action is undertaken to prevent littering.

4. Effects and risks of plastic marine litter

Summary

- Two distinct types of effects of plastic marine litter are identified: (1) direct effects, related mostly to the physical properties (2) indirect effects, related mostly to toxicity.
- Direct effects of plastic marine litter are mostly due to physical interactions between plastic and organisms or equipment. Sea animals get entangled; abandoned nets continue to catch fish and other sea creatures (ghost fishing) and ship's propellers are blocked. When seabirds, sea mammals or fishes ingest plastic particles, blocking of the gut is likely to harm or even kill the organism.
- The smaller plastic particles become, the higher are the potential effects related to toxicity of either built-in or adsorbed toxic substances.
- The smallest particles can be ingested by filter feeders like mussels and transfer from the gut to the tissue.
- In many waters, toxicants in fish have been found, but as yet no direct relation with ingested (micro)plastic has been established. For seabirds there are indications of plastic-related toxic effects.
- The concern with plastic microparticles and the adsorbed toxicants is that they might accumulate in tissue of marine animals and that the concentration might be magnified through the food chain.
- Although direct linkages remain to be established, potentially this is a risk for human health. Indirectly, we cannot rule out that one of mankind's nutritional sources of growing importance – sea food – is at risk from plastic marine litter.
- To illustrate the potential scale of the impact: in the North Pacific: at least 10% of lantern fish feeding on plankton in the upper water layers has plastic in their stomach. This group of animals represents millions of tons of biomass. It can not be excluded that this affects the role of vertically migrating fish in the biological carbon pump with unknown consequences for carbon dioxide transports and global climate.

4.1. Direct effects of plastic on marine species

Plastic debris in the marine environment hurts or even kills a wide range of species through entanglement, ghost fishing or ingestion.

Entanglement

Large marine organisms, particularly whales, seals, dolphins, turtles, and seabirds, become entangled in plastic debris. The biological harmful effects of entanglement that have been identified include death, deformation, suppurating skin lesions, ulcerating body wounds and other injuries, as well as general debilitation from interruption to feeding activities or through failed predator avoidance.[9] Six out of the seven known species of sea turtles have entanglement records. For marine mammals this is 32 out of 115 species, while 51 out of 312 sea bird species are affected.[93] Note that these numbers indicate which *species* are affected, not what percentage of each *population* is affected. Effects on population levels have rarely been quantified and long-term trends are often unavailable.

Figure 4-1. Entanglement: Antarctic fur seals with a collar of plastic sheeting. Credit: British Antarctic Survey. Ghost fishing: turtle entangled in a fishing net. Source: NOAA. Ingestion: plastics found in a 5-week old rainbow runner. Source: Algalita.

Ghost fishing

Ghost fishing is a common form of entanglement. It kills both the target and non-target species of derelict fishing nets, lines, and pots.[94] Derelict fishing gear can continue to ghost fish for months to several years, depending on the type of gear. In isolated cases damage to coral reefs has also been established. Recent estimates of fishing gear lost at sea world-wide is lacking. There is a crude estimate that 10 percent of global marine litter consists of fishing nets.[94] Ghost fishing also leads to economic losses for fisheries, as is discussed in section 4.4.

Ingestion

Ingestion of plastic particles has been found in seabirds,[95] seals,[96] sea-turtles,[97], and fish.[57, 58, 98] Ingestion is widespread in some populations (>95% of individuals) and can compromise feeding.[52] Seabirds ingest plastic because it resembles prey, or because it is already present in the gut of the prey. It has furthermore been shown that plastics can be passed on to their chicks. For some seabirds long-term trends have been established: in the Netherlands since the 1980s a decrease of industrial, but an increase of user plastics is found in fulmar stomachs, with shipping and fisheries as the main sources. Overall, the trend is relatively stable, with 90-100% of beached fulmars having plastic in the stomach: on average 35 pieces weighing 0.31 g.[95]

Observed effects of ingestion of plastic marine litter are starvation or weight loss of birds, caused by satiation (the plastic accumulating in their stomach creates a false sense of fullness) or by blockage of the digestive tract and damage to delicate internal tissues through sharp objects, leading to infection, pain or death. Again these are all physical effects. In one case, clues have been found for hormonal disruption in fulmar birds.[99]

Plastic ingestion by fishes has been studied less frequently. Direct ingestion of plastics is demonstrated for those species that feed in areas where plastic accumulates, i.e. in the upper water layers in the North Pacific central gyre[57, 58] or in mangrove forests.[98] The fish from the North Pacific gyre lives in the twilight zone of the oceans between 200 and 1000 m deep (mesopelagic zone) and feed on zooplankton in the upper water layers at night. They represent an enormous biomass: 3.5-7.1 million tons in the North Pacific Subtropical Gyre alone.[58] For this reason, plastic ingestion by these fishes is relevant for the global, more indirect effects that are discussed in section 4.2.

Figure 4-2. Drawing of a lanternfish; the most common of fishes that live in the twilight zone of the Pacific Ocean. Their abundance is so great that they are largely responsible for the deep scattering layer that can be observed with sound echoes in many ocean areas that can be confused for the sea bottom. Image source: Résultats des campagnes scientifiques accomplies sur son yacht par Albert Ier, prince souverain de Monaco Albert I, Prince of Monaco, 1848-1922, p. 184.

Here, we confine the discussion to the direct effects on lantern fishes,[100] a member of the so-called mesopelagic fish (fig 4-2). A study by the group of Moore found that approximately 35% of the fish that they caught in their nets in the North Pacific central gyre had ingested plastic.[57]. A later study found that 9% of the fish has plastics in their stomachs[58] and attributed the difference to net feeding.[ix] The implications for the health and survival of the twilight zone fishes are uncertain.

Seafloor

With regard to plastic litter, the ocean and seafloors are nearly terra incognita. All previously described effects – ingestion, strangulation, exposure to toxicants, can still occur when the plastics rest on the seafloor. Marine creatures like starfish, snails, oysters, sea cucumbers, and sea anemones live in and on the seafloor and are a specific, but hardly studied concern with regard to plastic on the ocean floor. Such organisms have an important role as food source for fish and humans. When present in large enough concentration, plastic might induce changes in their ecosystem and inhibit gas exchange between the sediments and the overlaying water.[69] Experimental proof or a quantitative estimate for these effects has, to the best of our knowledge, not been given. Plastic on the seafloor might even provide artificial hard substrate for marine organisms like shells.

[ix] The term "net feeding" refers to the ingestion by fishes of organisms or debris that are concentrated in the end of a net while deployed. Net feeding can bias studies of fish diet by altering the composition of prey items and leading to overestimation of ingestion rates.

4.2. Effects with global consequences

Effects of microplastics

Partly, the effects of microplastics overlap with the ingestion effects discussed above. However, with their small size come specific properties that might increase the harmful effects.[81]

Because of their small size, microplastics are available to a range of smaller species at the bottom of the food chain. Under laboratory conditions, filter feeders like mussels and sea cucumbers ingest the microplastics, because they do not discriminate between sediment and plastic particles. In mussels, particles of a micrometer (1/1000th of a millimetre) size were found to move from the gut into the circulatory system and did so more effectively if the particles were smaller.[4] How much plastic is ingested in open waters remains to be established.

A second cause for concern regarding microplastics is their relatively large active surface. Imagine cutting a piece of plastic in small fragments: the total volume remains the same, but collectively, the fragments will have a much larger surface area. This is relevant for their behaviour with respect to toxic additives. Plastics act like sponges for persistent toxic compounds present in water, and in smaller plastics more surface area is available.[25] These toxic compounds not only originate from plastics, but can also originate from e.g. pesticide use. In a worldwide survey, plastic pellets collected from beaches all over the world have been analysed for persistent organic pollutants.[26] It was found that concentrations of toxic compound in the microplastics were orders of magnitude up to 1 million times greater than in the surrounding waters.[100] The precise concentrating effect depending on the toxin and location.

How much of these toxics attached to microplastic are transferred to marine organisms is not easy to establish. Modelling equilibrium distributions, suggest that compared to air and water, plastics carry only a very small fraction of the total amount of toxics.[101] However they are carried at such high concentrations and in easily ingestible size that this small fraction can adversely interact with the food web. Bio-accumulation and –magnification[x] can cause larger effects, higher up the food chains, potentially damaging human health. The precise effect will depend on many circumstances: type of toxin, plastic, age of the plastic, concentrations, et cetera.

Both in mathematical models and in feeding experiments has it been shown that contaminants can transfer from plastic to organisms.[102] In a recent theoretical model study, however, it was predicted that microplastics were not very likely to be an important vector

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[x] When toxins accumulate in tissues of organisms because the rate of intake (from food or from environmental media such as water) exceeds the organism's ability to remove the substance from the body, we speak of bioaccumulation. When intake is primarily from food, we speak of biomagnification; when primarily from the environment (e.g. air or water) the term bioconcentration may be used. Through these mechanisms, toxins can ultimately end up in high concentrations in the human population or top predators.

of toxic substances to cold-blooded biological organisms, relative to other pathways.[103] Although this study is an important first step in understanding the effects of toxics in plastic, it cannot be used for overly generalized conclusions. In order to be able to do so, the critical role of kinetics would need to be addressed not only for fish-eating fish, but also for the smaller plankton species (Pers. comm. Andrady) and a range of sizes and types of microplastic.

Box 4-1. The general issue of plastics usage and toxicity

The issue of plastic marine litter lies at the intersect of ocean health and plastic usage (see figure 4-3). On the one hand, ocean health is under stress from factors such as overfishing that have no link with plastic usage. On the other hand, plastic usage is linked to the more general issue of finite resources, that stands apart from ocean health. However, the central plastic usage issues of toxicity and unsustainable life cycles are partly affecting the oceans health, while ocean pollution covers both plastic and non-plastic marine debris. For instance, the issue of toxicity plays an important role in the public discussions on plastic usage and also in the plastic marine litter debate, particularly for the discussion on microplastics. Exposure to harmful compounds in plastics can take place via numerous pathways, plastic in the marine environment being only one of them. In addition, the impact of non-native species is amplified by plastic marine litter while we cannot exclude that global warming is enhanced as well. For each of the cross-sectional issues, special care must be taken if a specific concern is related to plastic marine litter or to plastic usage or ocean health alone.

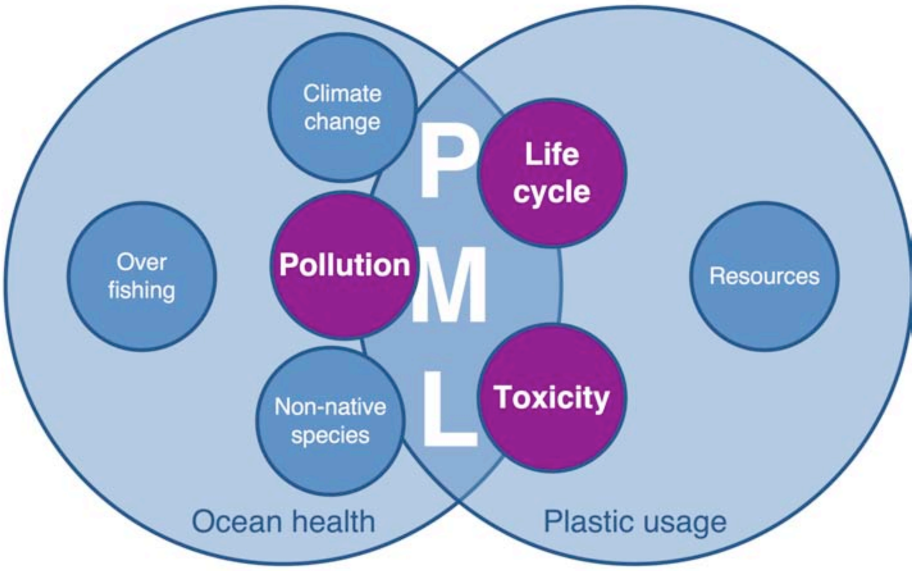

Figure 4-3. The issue of plastic marine litter as the overlap of ocean health and plastic usage issues.

With respect to the general issue of plastic usage, most polymers in plastics like polyethylene are chemically inert and are not considered toxic. A number of plastic additives however have been identified as endocrine disruptors (such as phthalate plasticizers) or have been shown to be toxic (such as brominated flame retardants). Because these compounds are not chemically bound to the plastic they may easily leak out of plastic

products in various stages of their life cycle. Currently, bisphenol A (BPA) is topic of heated debates. BPA can be released when polycarbonate is exposed to heat or acidic or basic compounds. BPA is an artificial oestrogen that interferes with the hormone system and has been implicated in a laundry list of illnesses with particular risks for developing embryos and babies. The toxic effects of BPA have become a scientific controversy and issue in itself.[104]
Ever since Rachel Carson's book Silent spring,[105] the presence of toxic substances in the environment has been recognized as a problem. Bio-accumulation and bio-magnification are the mechanisms that are of particular concern. The controversy surrounding the toxicity of additives in plastics is ongoing. The reason behind it is a fundamental difference of opinion between industry and environmentalists concerning the management of toxicity: risk assessment versus the precautionary principle. While the risk-assessment approach focuses on one chemical substance at a time and expects public institutions to scientifically prove harmful effects, the precautionary principle demands a more open evaluation of an entire class of chemicals and places the burden of proving safety on industry, using robust statistical approaches used in the drug industry (Browne, pers. communication).

Plastic marine litter as a threat to food supply

The world is increasingly dependent on fish protein for nutrition: fish consumption grew twice as fast as the population. In 1960, the average consumption was 9 kg per person per year. This figure was nearly doubled in 1997 (16 kg) and is expected to rise to 20 kg in 2030.[106] Plastic marine litter can compromise this food source, as a result of toxics that enter the foodweb via microplastic particles (section 4.2.1). Although such linkages have thus far not been directly established, the known amounts of plastic ingested by lanternfish in the North Pacific combined with their large biomass gives cause for concern. Similar effects may occur in other food chains.

Lantern fish live in the twilight zone of the oceans at a depth of 200-1000 m where daylight hardly penetrates. At night they feed on plankton in the upper water layers. During the day, they return to the dark, cold waters. Even though they are tiny and fragile – they are seldom bigger than 15 cm – and are of little direct commercial value, collectively they represent hundreds of millions of tons of biomass in the world's oceans.[107]. A volume that is significantly larger than the global annual capture from commercial fisheries (approx 90 million tons[108]).

The plastic that accumulates in the Pacific gyre finds an entry point into the food chain, through the twilight zone fishes. If, according to the latest estimates, circa 10% of these fish have plastic ingested; we cannot rule out that these particles or the chemicals within them are passed on to predator animals such as seabirds, larger fishes and dolphins. The ecological linkages with the commercially important fish species are poorly known. Assuming that predatory fishes are similarly affected by ingested plastic as the lanternfish, an impact on commercial fish is possible.

Although these examples show that an entry point into the marine food web has been established for plastics, much remains unknown about the possible consequences. Little research has been done yet: lantern fish live in a remote place that is difficult and expensive to investigate. Samples have been taken from the most plastic-rich areas in the gyre, therefore care must be taken to extrapolate the findings to other areas. Little is furthermore known about the effects that toxic substances in the plastic particles may have on the fish themselves and on the wider food web. Also effects in other types of fish – particularly for human consumption – remain largely unexplored.

Plastic marine litter from an Earth system perspective

The vertical migration of lantern fish plays a role in the so-called "biological pump" function of the oceans. This is the name given to the total effect of a whole range of biological processes that influence the transport of carbon from the upper zone into the deeper ocean, where part of it is stored in the sediments – hardly available for the biological cycles. This biological pump is a major mechanism contributing to the function of the oceans as a sink for carbon. To illustrate the importance of the biological pump: oceans have sequestered up to 30% of the additional carbon dioxide emitted to the atmosphere since the start of the Industrial Revolution,[109] thus slowing down global warming.

The biological pump process starts with the conversion of CO_2 and inorganic nutrients by plant photosynthesis into particulate organic matter. The small plants (phytoplankton) form the base of the food pyramid. When they die they sink to the bottom where part of the carbon is stored in the sediment. Higher up the food chain, zooplankton and many fish species contribute actively to the biological pump.[110] This is because they perform a daily vertical migration: moving hundreds of metres up at night to feed to return to the deeps of the ocean during the day. This process has been described as the biggest animal migration, in terms of biomass, on the planet.[111] Doing so, the transport of faeces to the seafloor occurs faster than when faeces would be produced in the upper layers and have to be transported to the bottom in a passive way.

Via the biological pump, fish and zooplankton are an integral part of the feedback loops that determine the rate of global warming. If and how the expected further increase in greenhouse gases will influence these essential oceanic processes is difficult to quantify.[112] "Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future".[113] But if ingestion of plastic by fish or plankton would be found to impair the biological pump (for example by reduced fitness of the organisms), then there is a possibility that plastic marine litter might disrupt the "circulation as usual".

There are some indications that the amount of plastic in the Pacific Ocean is large enough to disturb the role of lanternfish in the biological pump. At the centre of the North Pacific gyre, Charles Moore found more plastic than plankton in his nets.[56] In the same region also lantern fish were found with plastic in their stomachs.[57, 58] There is limited information on the situation in the Pacific Ocean at large. If plastic marine litter is present in sufficiently large quantities to compete with plankton in the biological pump function, in the worst case, acceleration of global warming might occur.

Non-native species

On top of all human activities that spread species from their original habitat to all corners of the world, plastic marine litter provides a new mode of transport. Where the newcomer does not find any natural predators, rapid and uncontrolled population growth might occur, risking harm to the original habitat or damaging industrial cooling water supplies.

Plastic in the marine environment attracts "hangers-on and hitch-hikers" like bacteria, algae, and barnacles (fig 4-4). The surfaces are covered with a biofilm in hours and fouling is evident within a few days.[68] Thus, plastic provides a pathway for the introduction of non-native species to sensitive marine areas.[9, 114] The concern raised here is that plastic debris is long lasting, pervasive and travels slowly. Factors that could favour the survival of colonists.

Figure 4-4. An example of hitchhiking: a buoy with a barnacle fouling community on it. Source: http://www.diveintoyourimagination.com/news/the-garbage-patch/surprising-marine-debris-327.html

The precise impact of marine debris on species distribution is difficult to establish, and this is even more so when trying to compare it with other pathways (like e.g. shipping or natural driftwood).[115] Earlier, it has been estimated that human litter more than doubles the rafting opportunities for ocean plants and animals.[114] As for the specific effects introduced by species floating on plastic particles, there is insufficient data to draw any conclusions.

Box 4-2. Biodiversity scepticism

In a general sense, it has recently been questioned whether non-native species should always be regarded as a threat.[116] This has elicited a strong response of a group of 141 scientists,[117] claiming that this is a misleading argument: most conservation biologists and ecologists do not oppose non-native species per se, nor do they ignore the potential benefits of such species. By advocating a change in environmental management they fear that the potential severe impact of non-native species on biodiversity is being downplayed.

4.3. Effects on human health

Most discussions on the effects of plastic on human health in scientific literature deal with direct exposure to toxicants (see box 4-1 for possible harmful effects). Direct exposure routes include for example additives leaking out of plastic food containers[14] or plastic nanoparticles inhaled through the lungs.[118] Whether humans are exposed to plastic or associated toxicants indirectly via a marine litter route has thus far not been established. As the previous sections show, there are many pieces of the puzzle to suspect that such a route is possible, but at this point it cannot be established how important this pathway is in relation to other exposures.

That does not mean that indirect effects might not have far-reaching consequences. Marine ecosystems provide a myriad of functions for human well being, and seemingly small causes can have large effects, particularly in regions that are already under large pressures from human activities. Toxics substances transported by plastics could accumulate through the food chain in consumption fish, making it unsafe to eat. Plastics, in this scenario, add to the toxic loads that are already present in different areas. Another cause for concern is that the combined effects of overfishing and climate change cause a change from a fish-dominated to a jellyfish-dominated ecosystem.[119] Such a transition will be reached quicker if essential species are weakened or killed by plastic. It is effects like this that justify the conclusion that plastic marine litter poses an unknown, but potentially large risk for human health and the availability of food from the sea.

4.4. Socio-economic effects

The seas have been and still are an important source of wealth for countless (coastal) communities. Ports, fisheries, shipping, tourism and many other activities create jobs and income for the billions of people that live near coasts. Plastic marine litter causes substantial damages to these sectors, summarized in table 4-1.

A main impact is the cost for coastal communities that are responsible for the removal of beach litter. The city of Long Beach in California alone spends $2.2 million per year in maintenance cost,[121] while UK municipalities spend approximately €18 million each year. For the Netherlands and Belgium these costs are €10.4 million.[120] Moreover these costs are sharply rising. Taking the UK with its coastline of over 12,000 km to be representative, we can estimate an approximate annual cleaning cost of €1500 per km. Then globally, a theoretical figure for the cost required to keep all coastlines (34 million km) clean emerges of €50 billion per year (coastline data from: [122]).

Table 4-1. Economic impacts of plastic marine litter[120].

Sector	Major damages
Tourism	Fouled beaches
Fishing	Contaminated catch; restricted catch; damaged gear
Aquaculture	Fouled propellers on workboats
Ports and harbours	Fouled facilities; vessel damages due to fouled propellers
Shipping	Navigational hazards
Coastal agriculture	Property and machinery; harm to livestock; litter removal

Fishing vessels can also experience a variety of issues due to marine litter as can be exemplified for the Scottish fishing fleet: of all vessels surveyed, 86% had experienced a restricted catch due to marine litter, 82% had had their catch contaminated and 95% had snagged their nets on debris on the seabed. Marine litter costs this fleet between €11.7 million and €13 million on average each year, which is the equivalent of 5% of the total revenue of the affected fisheries.[120] Considering that the worldwide fishing industry generates $94 billion per year,[108] the potential economic damage due to plastic marine litter is also in the order of billions.

The economic costs for other sectors are generally lower, but as a general conclusion it is justified to assert that plastic marine litter causes economic damages to a wide variety of industries with total, global costs adding up to billions of Euros each year.

4.5. Discussion: assessing the risks

While a direct, quantitative comparison between the effects of plastic on marine ecosystems cannot be given, some clues on how to compare these different risks will be provided here. Based on the preceding sections we give a tentative assessment of ecological risks, which has both a probability and an impact (Figure 4-5).

The distinction made here is between direct effects on species level and effects that could possibly have global consequences and form a potential risk for human health. We see that for larger particles entanglement and ingestion by birds and mammals are the primary effects. The physical effects of plastic are the most visible. These direct effects have been reasonably well established in the scientific literature and are likely to continue in the absence of effective waste policies. The impacts considered here are confined to the species that eats the plastic or gets entangled in the debris. The impact on biodiversity is therefore assessed as moderate, but almost certain to occur. As these effects have been occurring for over 40 years, a much higher potential impact is difficult to justify (figure 4-5).

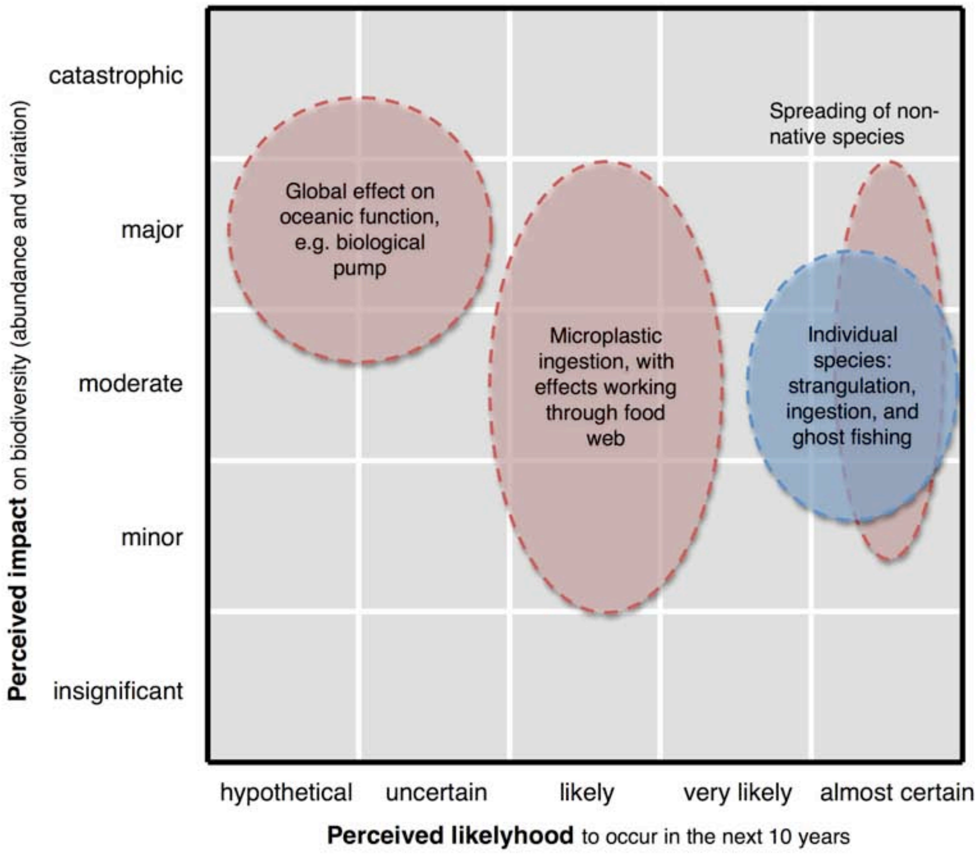

Figure 4-5. A risk assessment of the ecological effects of plastic in the marine environment. The size of the ovals indicates the estimated uncertainties. Direct, local effects in blue, effects that occur through more indirect mechanisms and have a global scope in red.

Next we assess the more indirect effects with potential global impacts. The effect that plastic litter provides a pathway for species to cross oceans and seas is well established. The potential impact of non-native species however is much harder to establish, particularly when comparing it with many other possible transport routes. Until more quantitative data becomes available, the impact could be minor as well as major.

For microplastics, there is an increasing body of literature indicating that ingestion of small particles or fibres is possible for species at the bottom of the food chain, e.g. the lantern fish. For a number of other species like mussels it has yet to be established that ingestion also occurs outside a laboratory setting. Risk related to microplastics are therefore assessed too be likely to occur. The impact is a matter of large uncertainty: it is possible that the effects of microplastics remain confined to the species that ingest it. If toxicants concentrate and magnify through the food chain the potential impact can be much higher.

Effects of plastic influencing global oceanic functions such as the biological pump (section 4.2.3) cannot be ruled out, but with current knowledge have to be assessed as unlikely. However, if such effects of plastic marine litter occur their impact will be major.

At this point there is no direct evidence that links plastic marine litter to human health. However, the ecological risks identified above, can influence human health as well. As the human population increasingly relies on seafood for nutrition, impacts for human health cannot be excluded.

For economic effects of plastic marine litter, it is clear that all sectors described in section 4.4, are already impacted. Total economic damages for tourism and fisheries are highest and can be estimated to be in the order of billion Euros per year.

5. Plastic and the North Sea

Summary

- The North Sea is an area rich in natural resources and with a large economic value. The impact of human activities is very large and could impair the resilience of the ecosystem.
- The ecological status of different species and habitats vary, but the overall ecological status of the North Sea is not favourable.
- The legal protection of the North Sea is relatively well regulated, but the complexity of national, European and international policy instruments hampers the implementation of effective policy actions.
- A relatively large share of plastic in the North Sea can be traced back to marine activities like shipping and fisheries.
- The pathways for the land-based sources, in particular the role of rivers and sewage systems, have not been well established. From beach clean ups and monitoring general movement and local accumulation zones have been identified.
- In general, plastic marine litter in the North Sea originates locally. An unknown fraction will be imported in and exported out of the region.
- Microplastics in the North Sea are of growing concern and large concentrations have been found in beach and estuarine sediments. Plastics pre-production pellets and microplastics in personal care products form direct sources.
- At the bottom of the food pyramid filter feeders, e.g. mussels, can ingest and incorporate plastic microparticles in their tissue.
- There is evidence for plastic ingestion by North Sea fishes. Initial pilot surveys suggest levels to be moderate in most species, but substantial further research will be required
- Seabirds, like the fulmars, mistake plastic litter for food and have been found with large quantities of plastic in their stomach. The plastic content in fulmars is now used as an indicator to monitor the ecological status of the North Sea.
- Economic damage of plastic marine litter results mainly from beach cleaning and losses to fisheries. Direct costs to local communities are high, e.g. UK municipalities spend €18 million per year on beach cleanups to remove all litter including plastics.
- Consequences for human health are possible, although no direct linkage between plastic marine litter and fish for human consumption has been made so far.

This chapter gives an introduction into the most important ecological, economic and socio-political characteristics of the North Sea ecosystem. This chapter also describes the main ecological impacts in the North Sea and the additional stress caused by plastic marine waste.

5.1. Introduction

5.1.1. General features

The North Sea is a very young sea: it developed 11,000 years ago after the last ice age. The movements of the ice masses can still be detected on the seabed in the form of boulders and gravel patches. The largest part of the North Sea bottom however is covered in sandy and muddy sediments. The North Sea is shallow (mean depth 90 m; only 50 m in the South) and many rivers drain into it. This results in a large availability of light and nutrients, which together cause the North Sea to have a very high production of organic matter (all micro-organisms, flora and fauna together). Apart from having an intrinsic value, this high productivity is important for fisheries and thus gives the sea a high economic value: the North Sea is “rich” in more than one way.

Such a shallow, sandy and highly productive sea can only be found in two or three other places in the world. Another special feature of the North Sea is the large variation in habitats and, consequently, species. There are rocky shores, sandy beaches, estuaries and all sorts of subsurface structures.

5.1.2. Rivers and currents

There are eleven major rivers discharging into the North Sea, of which Rhine and Elbe are the largest[xi]. In figure 2.1, rain that falls on the “North Sea side” of the red lines through the UK, Norway, Belgium and Norway is eventually discharged into the North Sea.
The North Sea has a very dynamic coastline. As a result of winds and currents, there is a continuous flow of water and sand parallel to the Belgian/Dutch/Danish coast, in a northerly direction. Rivers and seawater flow of course have an important effect on the distribution of plastic marine litter.

5.1.3. Animals living on and in the seabed[xii]

Because of the sandy and muddy sediment, the North Sea has many worm species and burying shellfish such as cockles. These can reach densities of several hundreds to even a few thousands of animals per m^2. Mussels and oysters live on top of the seabed or attached to hard surfaces. Most of the species mentioned eat plankton, which they filter out of the water (filter feeding). Species such as starfish, lobster, crab and shrimp are mobile but stay close to the seabed. In an adult stage, they eat larger animals than plankton.

Seabed communities in the North Sea are affected by several human activities and their impact, of which habitat destruction by fisheries (bottom trawling), pollution and aggregate extraction are most important. For the future, seawater acidification from rising CO_2 levels

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[xi] They have the largest river basin: almost 200.000 and 150.000 km^2, respectively.

[xii] Technically these soil organisms are called “benthic” animals as opposed to those living higher up in the water column (“pelagic animals”).

is a large threat, especially for species with a calcareous shell or exoskeleton. Some of these species may develop thinner shells.

Figure 5-1. The main watersheds of Europe, shown by red lines. Source: Wikipedia.

5.1.4. Fish, birds and mammals

The North Sea, and especially the estuaries and coastal areas, has an important nursery function for young *fish*. There are approximately 230 species of fish in the North Sea. Because of the large area of sandy substrates, there are large populations of flatfish, such as sole and plaice. A key prey species for birds is sandeel. Other important fish species are herring, mackerel, dab, cod, haddock and whiting. The main pressure on fish is overfishing.

Some 10 million *seabirds* are present in the North Sea at most times of the year, of dozens of different species. None of these species is endemic (that is, not living elsewhere than in the North Sea), but many species are present in numbers that represent substantial proportions of their world population. Although some bird species are declining, some others are doing very well. Factors that negatively impact birds are reduction in prey by overfishing, pollution (for some species like fulmars plastic particles are a threat) and human disturbance.

Of the *marine mammals*, the harbour porpoise, harbour seal and grey seal are common. Several other types of whales and dolphins are also regularly observed.[123] Threats to marine mammals include bycatch, entanglement in fishing gear, habitat and feeding ground degradation, ship collisions, hunting and noise (for example from oil and gas exploration, shipping, and increasingly from the construction of wind parks).

5.1.5. Main pressures on the North Sea ecosystem

Below are the most important economic sectors in the North Sea. Their economic activities cause a wide range of pressures on the North Sea ecosystem, including plastic marine waste. Most of these sectors are in itself *sources* of plastic marine waste, which will be further explained in paragraph 5.3.

Fisheries

Fisheries are of significant economic importance to many North Sea countries. Damage is done to the ecosystem by the high fishing pressure, discards, and disturbance of the ocean floor. There are positive signs of decreasing impact (decreasing fishing effort, less discards, less damaging fishing techniques), but large problems remain.

Offshore industry

With approximately 500-600 installations, offshore oil and gas production in the North Sea represents an important sector. As the oil and gas fields become depleted in the coming decades, their relative importance will become smaller. Oil and gas production impacts the ecosystem in two ways: during exploration and production (e.g. by leakages and discharges of oil, oily waste and other chemicals, shipping movements, marine litter, noise and light) and during decommissioning of old platforms. In addition, the offshore renewable energy industry is upcoming and has a growing impact via noise, bird collisions and possibly other mechanisms.

Shipping

There is heavy shipping traffic in the North Sea because of the dense population of the surrounding countries and their wealth, and the fact that there are some very large harbours (Rotterdam, Antwerp, Hamburg, Grimsby & Immingham, Oslo).
The impact of shipping is mainly via ballast water and fouling (introduction of exotic species), calamities (oil, other chemicals) and dumping of litter. Other impacts are pollution through loss of ships and cargo, noise and collisions with marine mammals.[124]

Intensive agriculture

Intensive agriculture covers up to 70% of the land that drains into the North Sea. The runoff of fertilisers (phosphates and especially nitrates) causes eutrophication in large parts of the North Sea, especially along the east coast from Belgium to Norway, and in some small estuaries and bays of eastern England and northwest France. Associated problems include algal blooms causing oxygen deficiency and toxic breakdown products, fish dying in the Danish and Swedish fjords and the decline of biodiverse kelp (seaweed) “forests” in

Norway. There has been a clear decrease in the amount of nitrogen carried by rivers since 1990, but the problem is still very large, also because nutrients are released from sediments and soil long after reductions have been achieved at the source. Next to agriculture, other causes of eutrophication are atmospheric deposition from traffic and industry, and sewage effluents.

Sand and gravel extraction, erosion control and other artificial sand movements

Sand and gravel extraction is especially important in the shallow south-eastern part of the North Sea. The main impacts of extraction are the removal of substrate and organisms living in or on this substrate, which can affect the stability of the seabed and lead to changes in food webs. As sea levels rise and there is a growth in infrastructure projects, the demand for marine sand and gravel is also likely to increase. Sand is also moved artificially, for example for land reclamation or erosion control.

Tourism

Because of the long varied coastline, tourism is an important economic sector in the North Sea. Tourism is growing, leading to increases in coastal infrastructure and an increasing demand for resources.[124] Especially the fragile ecosystems such as dunes, cliffs and wetlands suffer from the increased pressure. Tourism contributes to pollution, marine litter, coastal erosion, habitat fragmentation and direct disturbance.

5.1.6. Status of the North Sea ecosystem

The OSPAR Quality Status Report 2010 assessed the status of different North Sea ecosystem components and investigated the main pressures. Most ecosystem components, such as fish and seabirds, were found to be of a moderate quality. The quality status of the shallow seabed habitats was assessed as “poor”. Seals and part of the deepest seabed habitats were found to be in a good state. Some specific problems were identified: average fish length is smaller because of overfishing, there is an excess of nutrients[xiii] causing harmful algae blooms, several hazardous substances exceed reference levels – and marine litter is a problem.[124]

The cumulative effects of the many economic activities cause a pressure on the ecosystem. This pressure shows an increasing trend, since there are new users and the activities of existing users are intensified. There are, however, also improvements in individual human pressures: fisheries impact and pollution are diminishing, and the oil and gas industry is on its way back as reserves become exhausted.

[xiii] From an ecological point of view, high levels of nutrients are only good up to a certain point; in the North Sea they are actually too high (this is called eutrophication), caused by the large use of fertilizers on the agricultural land surrounding the North Sea. Algae blooms use up much of the oxygen and may cause “dead zones” in the sea.

Ecosystems have a significant resilience towards outside pressures. They are never static; they can tolerate insults, however, sometimes they change very suddenly (from one year to the next). This is called a regime shift. Regime shifts are attributed to a range of factors, climatic, geomorphological as well as anthropogenic. Substantial regime shifts occurred in the North Sea ecosystem in 1977/79 and 1987/89[125] and in 2001/2.[126] The exact causes are not always clear and a regime shift is also difficult to predict. Because the resilience of the North Sea ecosystem is already being put to the test because of the many human activities, pressures should be minimised as much as possible to prevent future unwanted regime shifts.

5.2. Causes of plastic waste in the North Sea

5.2.1. Social-economical causes

Population density and consumption level

Most of the North Sea countries are densely populated and there are relatively large cities situated directly at the coast or river mouths. GDP and consumption levels are among the world's highest. As illustrated by figure 3-4 (chapter 3), the GDP per area around the North Sea is very high. The use of plastic, on its turn, shows a strong positive relation to the GDP and to population density, and is therefore expected to peak in regions of high GDP per km^2.

Plastic production and consumption

Europe produces approximately 57 million tonnes of plastics, representing 22% of global plastics production (see figure 5-2).[16] Many Western-European countries situated close to the North Sea, like Germany, the Benelux and France, are major producers. The EU is a net exporter of primary plastics and converted plastic products. Plastics consumption in Europe, and in specific Western Europe, is also significant. Plastics materials consumption per capita has grown to 100 kg per year in Western Europe,[92] consisting mainly of packaging which is by far the largest contributor to plastic waste at 63%.[46] It is projected that the overall generation of plastic waste in Europe will increase with 23% up to 2015, driven largely by the packaging sector.

Waste management

Over the years governments and (waste) industries have steadily improved the waste disposal options of different plastic waste streams. In 2008 51.3% of post-consumer plastics was recovered of which of 30% energy was recovered and 21.3% was recycled. [46]

Although overall recovery and recycling rates increase, its share remains relatively stable due to the increase in plastic waste generation.[46] And despite the fact that waste management is relatively well-regulated and waste management infrastructure is well-developed in (Western-)Europe leakages and dumping still occur throughout the entire life cycle of plastics. This share of plastic waste, which is not presented in or quantified by statistics, ends up in the (marine) environment. As the production and consumption of plastics in Western Europe is expected to grow, it can only be assumed that the plastic waste streams flowing into the North Sea Waste will grow in parallel.

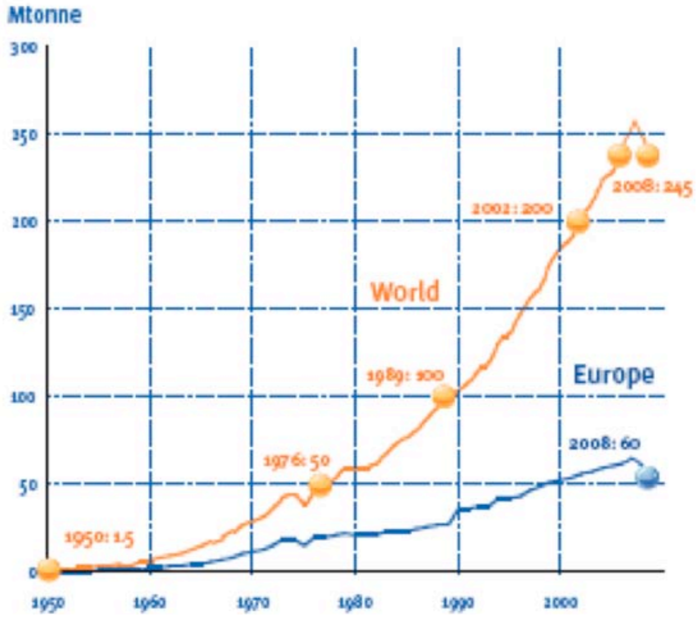

Figure 5-2. Global and European plastics production 1950-2008 [92].

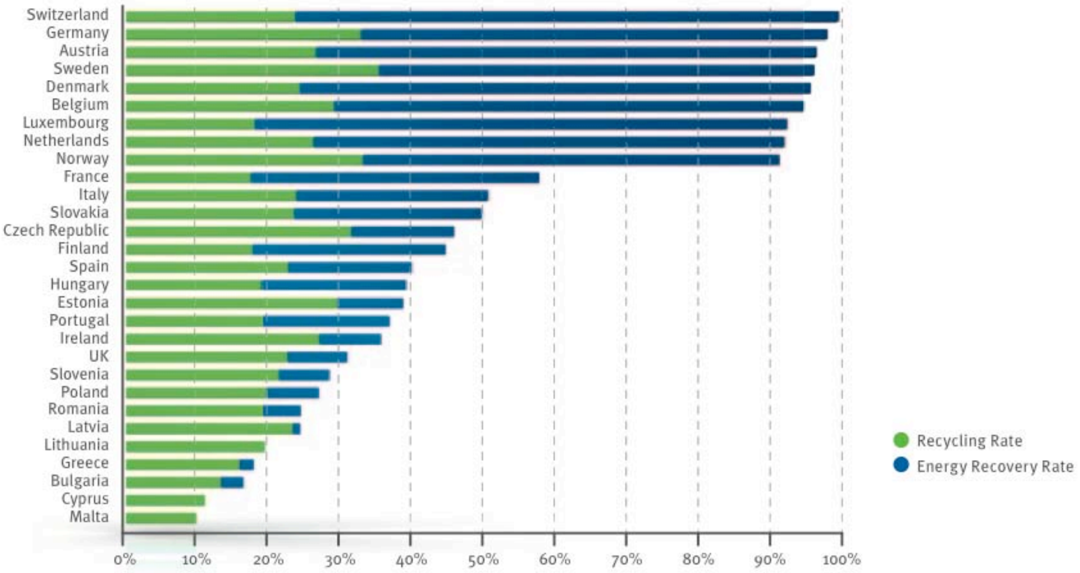

Figure 5-3. Total recovery rate of post-consumer plastic waste by country in 2010[16].

Legal causes

In theory, the legal protection of the North Sea is better than that of many other places. However, the legal regime of national, European and international policy instruments is very complex and the different instruments are poorly coordinated. Enforcement is often a bottleneck, particularly at open sea but also on land.

The main legal instruments governing the North Sea are the OSPAR Convention and the European Marine Strategy Framework Directive. The *OSPAR Convention*, the Convention for the Protection of the Marine Environment of the North-East Atlantic, sets quality objectives and standards and promotes assessment and monitoring of the quality of marine ecosystems. Participating countries are required to undertake joint assessments about the quality of the habitats and to identify priorities for further action [127]. The OSPAR Convention is a relatively clear legal framework, which obliges parties to implement decisions in their national legislation. However, enforcement appears to be problematic since the OSPAR organisation has little means to impose sanctions and the step to the International Court of Justice is not one easily taken.

The *Marine Strategy Framework Directive* (MSFD) was developed by the EU "to achieve and maintain good environmental status in the marine environment by the year 2020" which is defined by ten "qualitative descriptors for determining good environmental status".[128] This status should be achieved by the development of measures which are based on the precautionary principle and an ecosystem-based approach to the management of human activities (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0056:EN:NOT).[xiv]

Member states are obliged to reach "Good Environmental Status" of their part of the sea, but they are until now uncertain about how to achieve this, since the qualitative descriptors and the resulting objectives are not yet set. The MSFD indicators have to be agreed on in 2012, the monitoring programme in 2014 and the programme of measures settled by 2014, leading to a GES in 2020. Since these deadlines are very tight, there is a risk for either poor standards or the necessity of phased introduction of standards (pers. comm. J.A. van Franeker).

Descriptor 10 of the MSFD states that in 2020 "properties and quantities of marine litter do not cause harm to the coastal and marine environment" **(Directive 2008/56/EC)**. There is some discussion about the definition of harm in this sense: some (scientific) assessment in

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[xiv] The OSPAR convention defines the requirement of the precautionary principle as "preventive measures are to be taken when there are reasonable grounds for concern that human activities may bring about hazards to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea, even when there is no conclusive evidence of a causal relationship" and the ecosystem approach as "the comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take action on influences which are critical to the health of marine ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity" (http://www.ospar.org/content/content.asp?menu=00320109000000_000000_000000).

the future will be needed to establish what amount of properties and quantities would cause harm to the marine environment.

OSPAR has taken a collective approach on the regional aspects of the implementation of the MSFD and consequently is working on a Regional Action Plan through its Intersessional Correspondence Group on Marine Litter.

The European Commission also aims to publish a Green Paper on waste by the end of this year and a specific announcement on marine litter next year, which will probably be followed by policy proposals (pers. comm. Christa Licher). The contents of the Green Paper and the announcement are currently unknown.

The complexity of legal instruments and integral coordination hampers the implementation of the aspired "Ecosystem Approach", the strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way.[129] In the future, the Ecosystem Approach will be further developed.[127] The main obstacle for management of the North Sea is the use of poorly designed programmes of monitoring without any hypotheses.[44] This creates a major challenge for the joint implementation of a wide range of EU regulations (including the Habitat Directive, Water Framework Directive, Marine Strategy Framework Directive and the Integrated Coastal Zone Management Decision) and the translation into clear, integral action plans.[127] Also, alignment between the complex EU regulations and OSPAR is a complicated issue that needs attention.

5.3. Spreading of plastics in the North Sea

5.3.1. Degradation

The presence of light is likely to be one of main decisive drivers for degradation of plastics. The North Sea is a shallow sea with large tidal currents, which cause a lot of upwelling and mixing of sediments. Plastic in large part of water column therefore gets exposed to light. Is the relatively shallow seabed of the North Sea leading to quicker degradation of plastics due to solar radiation? What other factors have impacts on degradation rate and products? Do plastics, for instance, break down faster in warmer marine or more saline environments? The influence of these factors on the degradation of plastics is a major knowledge gap.

5.3.2. Occurrence

Plastics, both macro- and microplastics, are found on the water surface of the *North Sea* but also at the seafloor, in coastal sediments and ingested by marine species. Surface waters have been sampled since the 1960s with a Continuous Plankton Recorder. Between Aberdeen and Shetland and between Sule Skerry to Iceland, plastic fibres were found with an abundance in the order of several plastic fibres per 100 cubic meters seawater. The abundance increased significantly over time.[87] Similar abundances were found in Swedish coastal waters. However, when a net with a finer mesh was used – 80 μm instead of a 450 μm – up to 100,000 times higher concentrations of small plastic fibres was retained, i.e. 150-2400 particle per m^3.[89]

Litter washed ashore is one of the most obvious signs of marine litter pollutions. Relatively much is known about quantities, types and sources of beached waste items as OSPAR has developed standardised protocols for monitoring beaches. This monitoring has shown that plastic is the dominant source of waste in the greater North Sea region with 80% on beaches in the northern North Sea and 75% in the Southern Sea.[8] OSPAR beach monitoring also indicates that there is no change in the number of beach debris items since 2002. Note that this does not include microplastics.

In 1998, the seafloor of the North Sea has been mapped for debris: on average approximately 1.5 items of large debris (>20 mm) per hectare (100m x 100m) were collected, half of which were plastics.[70] As shown in figure 5-4, accumulation zones can be found far from potential waste sources and may be the result of the influence of hydrodynamics. For large debris at the seafloor, the influence of rivers seems to be slight in comparison with that of general water movements. Factors influencing sedimentation appear to dominate the accumulation of debris in the northern part of the channel that corresponds to a zone of very low turbulence and is the convergence zone of seabed sediment movements.

In sediments of beaches, ports, and estuaries microplastics have been found. Along the UK coast concentrations of up to 10 plastic particles per 50 ml sediment were measured, mostly fibres.[87] The highest concentrations occurred in subtidal areas. A more detailed study in the Tamar estuary found similar concentrations and revealed that microplastic (<1 mm) in terms of abundance accounted for 65% of the debris and consisted mainly of polyvinylchloride, polyester and polyamide.[7] In Belgian coastal waters concentration of microplastics were reported up to 390 particles per kg dry sediment, which is 15-50 times higher than the reported maximum concentrations in other study areas. The depth profile of sediment cores show that microplastic concentrations on the beaches have increased over time, in line with increased global plastic production (see also figure 3-6 in chapter 3).[90]

Plastic in stomachs of fulmars is an ecological indicator (EcoQO) of surface plastic in the North Sea region.[80, 95] The EcoQO allows less than 10% of fulmars to have more than 0.1% g of plastic in their stomachs. The range of fulmars in different North Sea areas exceeding the target varied from 48 to 78% depending on the area. In general the abundance of plastics was highest in fulmars in the Channel area, gradually decreasing northwards. The amount of litter in the stomachs of fulmars have not decreased in the period 1979-2007 implying that the amount of litter in sea has not decreased since then. Two major types of plastics are present: industrial plastics have steadily decreased but have been replaced by user plastics. As shipping and fisheries are important sources of plastic debris, the majority of plastics is of relatively local origin and cannot be attributed to distant sources.[130]

5.3.3. Sources and dispersion

Beach clean ups enable a partial identification of the origins of marine litter. Coastwatch projects typically find that 40% of the counted objects found on Dutch beaches originates from sea, 20% originates from land, while 40% has an unknown origin. Measured by weight it can be reasoned that the majority of beach litter originates from fisheries and shipping [130] The larger proportion of litter recorded on German North Sea beaches certainly originates from shipping with a considerable proportion of this originating in the fisheries industry. This has not changed since the 1980s[131] For the UK, Beachwatch actions provide a very different impression with the largest share of litter coming from public sources:[132] 37% of all items found belong to this category. The types and location of beaches being cleaned can probably explain these differences. Although the numerous activities at the North Sea gives rise to the expectation that marine litter originates more than averagely from sea-based sources, this has yet to be firmly established.

Land-based sources in the North Sea

The main land-based sources of plastic marine litter are inland shipping, inland fisheries, street litter, sewage overflows, industry, and agriculture. Trends in the distribution of user and industrial plastics as measured by the stomach content of fulmars are very different. The mass of industrial plastic has decreased significantly between while user plastics have increased.[95]

Some of Western Europe's most impressive rivers flow into the North Sea, covering water basins from Switzerland to Sweden and the UK. These rivers do not only discharge fresh water into the North Sea, but also the many types of waste they carry with them, including plastic waste. There are not enough studies on river-based sources of plastic marine litter, to provide a clear picture of the amount and composition of plastic particles transported to sea by rivers. A recent study identified plastic fibres from clothing in sewage water as an important source of microplastics.[86]

Sea-based sources in the North Sea

The large amount of sea-based sources in the North Sea can be explained by the fact that the North Sea is used by a lot of ships. *Shipping* is one of the main "contributors" of plastic marine litter at sea, with major shipping traffic passing through the North Sea and over 260,000 shipping movements made per year (see figure 3-2). As for land-based sources, quantitative data on plastic litter sources is lacking.

Fisheries and *offshore industry* are other major sources of plastic debris and cause many different types of waste. Abandoned or discarded fishing nets are the second source of waste found on North Sea, pieces of nets, buoys, and protective gloves are also commonly found on beaches.

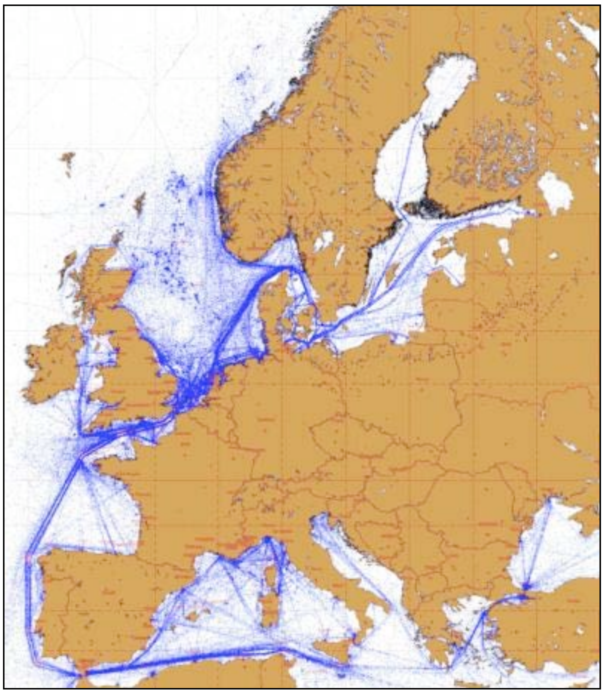


Figure 5-5. Shipping routes in the North Sea (Credits: CLS - KNMI - ESA).

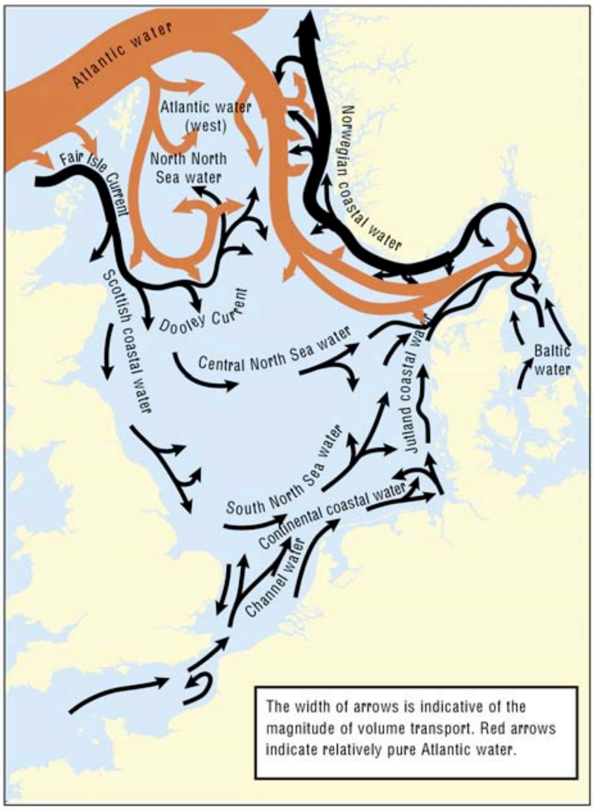
Although there are several examples of marine litter import originating from the east coast of North America,[8] most plastic waste has a local origin. Of all the traceable waste 80% come from the North Sea area itself.[46]

Spreading

The surface currents of the North Sea determine the fate of floating debris. Two major currents dominate the circulation in the North Sea. The Northern North Sea receives Atlantic inputs from the North Atlantic Ocean flowing in from the north following the coastline of Norway. The southern North receives Atlantic inputs via the English Channel following the coastline of Belgium, the Netherlands and Denmark (see figure 5-6).

As the North Sea is an open system and currents from the North Sea also flow back to the Atlantic Ocean, part of the plastic debris from the North Sea is exported into the North Atlantic where it may end up in gyral accumulation areas. Relatively high concentrations of plastic can be found in the Skagerrak area,[8] as both currents come out near the Scandinavian coastline. The west coast of Sweden has been described as a marine litter sink.[38]

Plastics found on the seafloor and microplastics in sediments show different distribution patterns from floating debris. For microplastics, studies indicate that concentrations are higher in downwind sites in an estuarine situation. Small particles of sediment and plastic are transported by the flow of water and are both likely to settle slowly. Sedimentation of microplastics can however not directly be inferred from sedimentation of sand and clay.[7]



The width of arrows is indicative of the magnitude of volume transport. Red arrows indicate relatively pure Atlantic water.

Figure 5-6. General circulation in the North Sea. After Turrell et al. (1992) [123].

5.4. Effects of plastic marine litter on North Sea ecosystems and economies

The North Sea is important both for the economies of the surrounding countries and because of its unique ecosystem. The costs of plastic marine litter to the North Sea *economies* have been estimated to be in the order of hundred million Euros annually.[120] For example, UK municipalities spend €18 million per year on beach cleanups to remove all litter including plastics. A disproportional large share of these costs is born by coastal communities (see also section 4.5).

The impacts of plastic on the North Sea *ecosystem* are less well known. Some high-quality data is available for certain species, like the fulmars,[79, 95, 99, 133] but this is insufficient to make a general, quantitative assessment of the risks for the entire ecosystem.

This leaves us with two possible routes for discussing the effects of plastic marine litter on the North Sea ecosystem: one based on the amounts of plastic present and another based on the specifics of the ecosystem. The first approach considers the quantities of plastic found in different locations. The North Sea has an open connection to the Atlantic Ocean and therefore does not act as a trap. Consequently there is no large-scale *accumulation* of marine debris, as is the case for the Mediterranean Sea. The North Sea does have a constant influx from land- and sea-based sources. Well-founded numbers are not known, but it has been estimated that 20,000 tonnes of marine litter are dumped annually in the North Sea.[134] The input of plastic continues to increase with increased plastic production, as can be seen from microplastic concentrations in sediment records. [87, 90]

The first indication that the ecological state of the North Sea is negatively affected by plastic comes from the monitoring of the stomach content of fulmars. This is used as an OSPAR indicator for marine litter. An acceptable ecological quality with regard to marine litter (the Ecological Quality Objective or EcoQO) is defined as a situation where less than 10% of this bird population has more than 0.1 g of plastic in its stomach. Since the 1980s this percentage lies between 57% and 67% with no clear indication of improvement.[80, 95]

Another cause for concern is the fact that persistent and organic pollutants (POPs) are widespread and accumulating in marine life in the North Sea.[124] Already, it has been shown that heavy seafood consumers can be at risk for a too high intake of dioxin-like compounds.[135] As plastic particles may act as sponges for pollutants in sea-water, this can increase health risks. Ingestion of plastic microparticles is possible by the less glamorous but essential species that live in and on the bottom of the North Sea, the "benthic species" or soil organisms. Because the North Sea is shallow, sandy and rich in nutrients it has large populations of soil organisms that are vital for many other species higher up the food chain. Many soil organisms, such as mussels and worms, are filter feeders that simply pass the seawater through their body to take up nutrients. It has been established that under laboratory conditions these animals also take up microplastics (see section 4.2.4). Knowing that sediments are increasingly contaminated with microplastics,[7, 86, 87, 90] the potential for ill effects grows.

Our understanding of the fate and effects of plastic in the soil organisms is far from complete. What happens under natural conditions is largely unknown. Which species are most affected? What parts of the populations are affected? What are the consequences for species higher up the food chain? The last question is of particular relevance for North Sea fish, whose importance for the human food supply is large. Some preliminary findings suggest that plastic debris does not form a *direct* threat for North Sea fish species.[136] The indirect pathways however have remained largely unexplored.

5.5. Short introduction to the Wadden Sea

Fig 5-7. Map of the Wadden Sea. Source: Wikipedia.

The Wadden Sea is formally considered as a shallow part of the North Sea, but has its own distinctive features and is viewed as being of special environmental significance.

The Wadden Sea is an intertidal sea[xv], a shallow body of water, famous for its tidal flats, salt marshes, wide beaches, dune islands and abundance of wildlife.[137] The Wadden Sea is a very dynamic ecosystem, shaped by the influences of tides, sedimentation, weather and the mixture of fresh river water with salty seawater. The biodiversity in the Wadden Sea is high, due to the ever-changing circumstances and the variation in biotopes. The Waddensea is home to thousands of permanent and migratory species. Each year 10-12 million migrating birds find shelter and food in the wadden region. These were the main reasons to appoint the Wadden Sea as a Natura 2000 area, the highest legal protection status for nature conservation in Europe, and as UNESCO World Heritage.

There are many unknowns on the occurrence, pathways and effects of plastic waste in the Wadden Sea. Monitoring of and research on plastic marine litter in the Wadden Sea area is still very limited and mostly follows from monitoring programmes developed for the North Sea. Some German and Dutch Wadden Sea beaches were monitored as part of the OSPAR Beach Litter Monitoring Programme to assess the presence of marine litter, including macro-plastics on beaches,[131] but research in other water compartments is still absent. Monitoring of the effects on marine species mainly consisted of investigating the stomach contents of beached fulmars, seals and porpoises.

[xv] An intertidal zone is the area that is above water at low tide and under water at high tide.

Studies on the occurrence of microplastics in sea water and sediments in the Wadden Sea and potential ecological effects are also absent. As the Wadden Sea is known for its large sand demand, the Wadden Sea could act as a potential sink for microplastics. Microplastics might be imported from the North Sea together with the continuous influx of fine sediments. If these microplastics settle down in sediments in the Wadden area, they could pose a serious ecological risk as the Wadden Sea ecosystem is strongly dependent on sediments and the soil organisms living on and in it. Mussels, oysters and other suspension feeders, for instance, filter the entire volume of tidal waters within two weeks and over a billion lugworms recycle the upper layer of sediments 10-20 times per year. If microplastics are taken up by these soil organisms, this could disturb the food chain as these species provide food for many, often vulnerable or protected, species higher in the food chain which are breeding and foraging in the Wadden Sea area.[137]

6. Solutions

Summary

- A solutions framework for plastic marine litter identifies technical and societal options in all phases of the current plastic life cycle. Action on all levels is required to solve the issue. Options become progressively more expensive as we move from manufacture to restoring littered habitats.
- In the manufacturing phase, rethinking of the design is required to enable cyclic business models. Material and product must be designed in such a way that resources can be reused and recycled. An approach to avoid potential toxicants should be promoted as the industry norm: be more good instead of less bad.
- In the usage phase, consumers on land and at sea need to change their behaviour in relation to plastic consumption, recycling and littering.
- In the end-of-life stage, a hierarchy of solutions exists that start with the realisation that plastic waste is a valuable resource. Material reuse and recycling are the preferred option, followed by energy recovery. Incineration and landfilling are last resorts that should be avoided whenever possible.
- It is not just the economics of plastics per se that prevent recycling, but primarily a number of technical and logistic barriers.
- As long as plastic litter is present in the marine environment, cleaning up campaigns can assist in reducing environmental degradation, but should be in balance with costs and habitat impacts of cleaning.

This chapter will provide a general solution framework aimed at making a transition from a linear to a cyclic economy for plastic. These solutions primarily address the options to reduce the amount of plastics in the seas and oceans. As such they will of course contribute to diminishing in the toxic loads in the marine environment. In depth covering of the solutions for the more general problem of plastic and toxicity lie outside the scope of this chapter.

6.1. A general solution framework

Towards a cyclic economy

The current usage of plastic is unsustainable in the sense that most product life cycles are of the linear take-make-waste type (see figure 6-1). About 50% of plastic is used for single-use disposable applications[138]. This means raw materials, primarily derived from oil are converted into products with an average lifetime of less than a year, after which they are disposed.

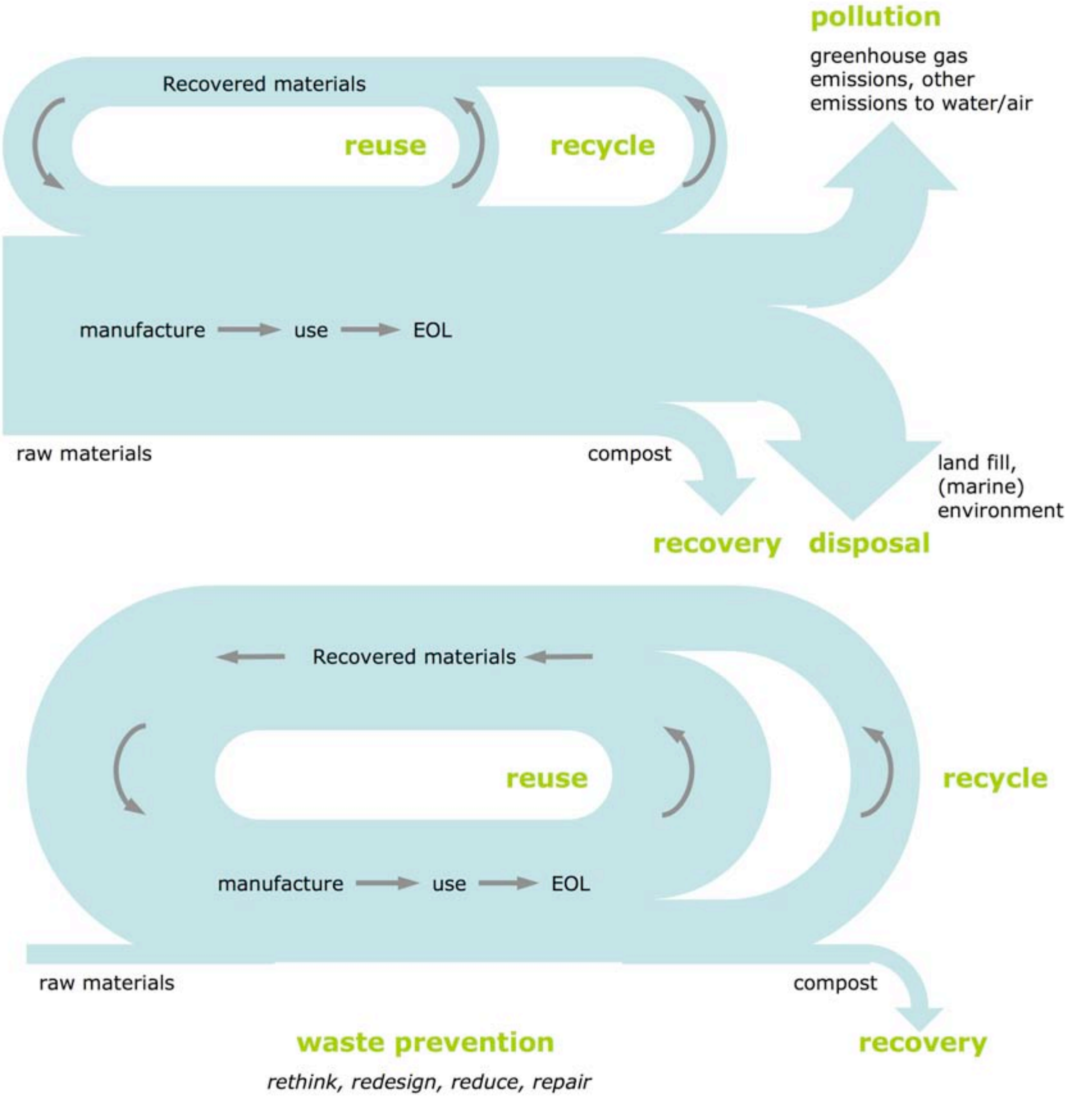


Figure 6-1. Current resource usage is predominantly linear (top). In a cyclic, zero-waste situation less raw materials are required and waste and pollution are eliminated (bottom).

To have a truly sustainable use of resources, the use of raw, non-renewable materials (oil in the case of plastic) should be avoided altogether. At the same time reusing and recycling valuable resources eliminates waste and the associated burdens for the environment (figure 6-1). The conceptual foundations for a cyclic, zero-waste economy have been known for quite some time. In order to achieve this, attention should be placed not only on waste management, but also on how to prevent (the concept of) waste in the first place. The next section explores what kinds of solutions are necessary to reach this ultimate goal.

Box 6-1. Evaluating the alternatives for plastic: life-cycle analyses

There is no doubt that plastic brings many benefits to society. Plastics are lighter than most other materials and thus contribute to energy savings in many products.[139] In terms of emissions to air and water during production, plastics also compare favourably to other products.[15] Such considerations are typically the domain of life-cycle analyses (LCAs).

LCAs are no exact science and need continuous improvement to reflect the best available assessment of all relevant impacts. Traditionally LCAs have been most reliable with respect to energy and emission comparisons. For plastics, however, another important parameter is toxicity, which is only partly included in LCA evaluations. Up to 2008, the human toxicity potential and fresh water eco-toxicology were subject to scientific debate and could not be established reliably.[140] This situation improved by the application of USETox that leads to a reduction of the uncertainty in toxicity characterisation factors by a factor of one million.[141] While the implementation of USETox may lead to considerable improvements in this area, even this new model will not provide the final answers: e.g., the ocean is modelled as a sink only, with no effects considered, whereas in reality toxics in, for example, plastics will affect marine life for many years.

Even when using USEtox, an LCA should be preceded or complemented by, e.g., an Environmental Risk Assessment. If this qualitative and/or Environmental Risk Assessment yields a serious risk, a “red flag” should be given regardless the outcome of the LCA.

With regard to the (marine) litter issue itself, i.e. irrespective of toxicity; LCAs often do not take that into account. Some first steps in this direction are being made.[142] Finally, it should be noted that an LCA also does not give an answer to the question if a product is needed in the first place.

Solutions model

In order to make plastic waste a thing of the past, solutions are required on many different levels (figure 6-2). Following the linear life cycle of a plastic product from production via usage to end-of-life, we seek the ways in which plastic usage can become more sustainable. While these measures might be expected to steadily decrease the amount of plastic litter ending up in the oceans, the existing marine litter will not disappear. Therefore also restoration activities should be considered.

In the following sections, we will discuss possible solutions following the scheme of figure 6-2. As we move from top to bottom, we note that it becomes increasingly harder and more costly to solve the plastic issue, as products diffuse from production sites into society and eventually into the environment. With different stages also come different responsibilities: in the manufacturing stage this lies predominantly with industry, the use phase is influenced by consumer behaviour, and the end-of-life stage is regulated by government waste policies. Largest progress can be expected if the plastic marine litter issue is tackled at all levels simultaneously. This is not to say that all issues can be solved in a sufficiently short timeframe: the sustainable transition might take decades. This might be an argument to ban certain products or practices altogether if potential damages are large while there is no short-term prospect of a solution and better alternatives are available.

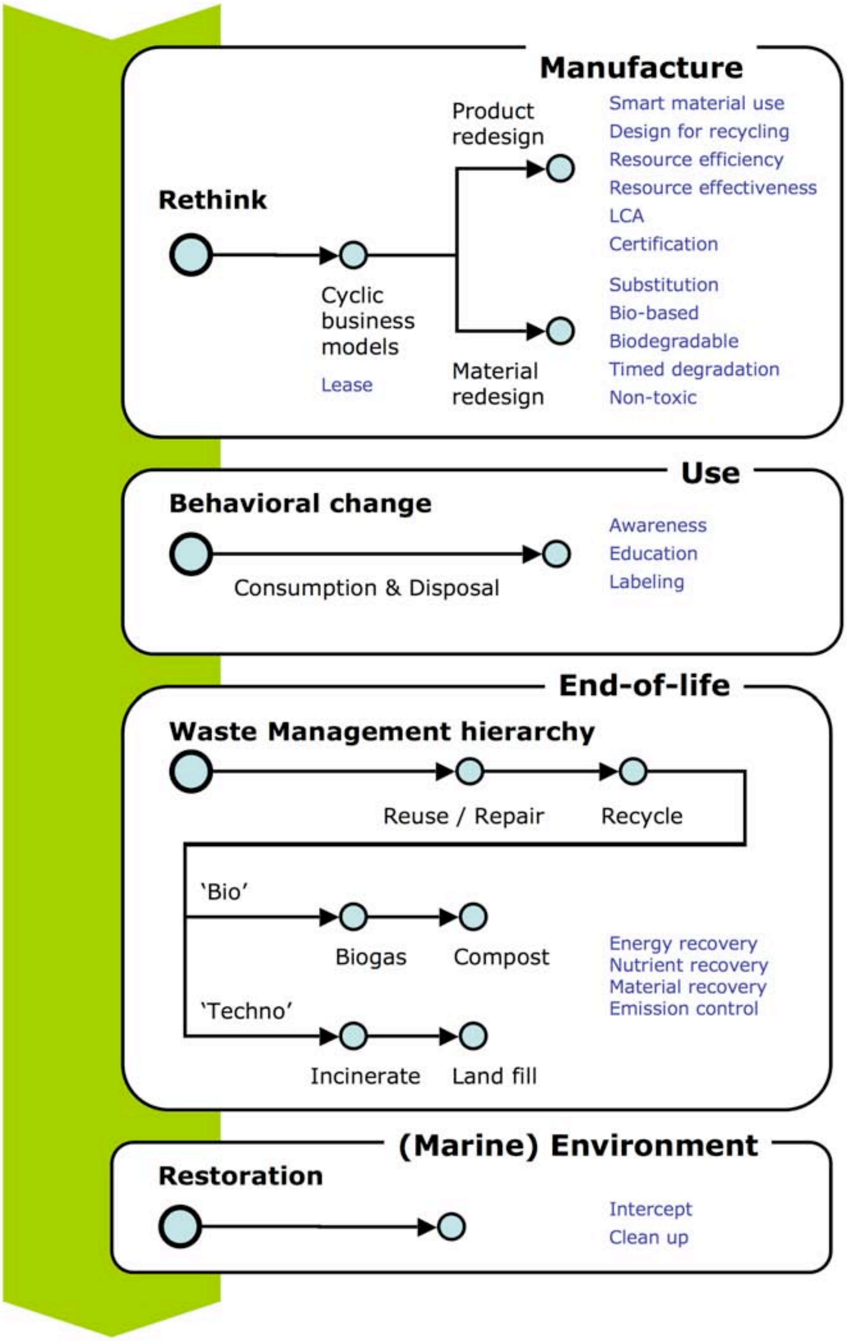


Figure 6-2. A general solutions framework towards cyclic use of resources

6.2. Rethink manufacturing

To close the plastic product chain, rethinking is required early in the manufacturing stage. This means that the end-of-life stage of a material product is taken into account from the very first design phase: the design should not only consider the usage phase, but also include a design for reuse and recycling. Also the business model could reflect a cyclic way of thinking about a product, including e.g. leasing instead of buying.

Developing cyclic business models is primarily the responsibility of industry with governments providing the limits and conditions under which they operate. In the manufacturing stage of a product's life cycle, profitable solutions can appear. As many companies show, incorporating sustainability in the core of the business can combine market leadership with corporate social responsibility.

How do these general concepts apply to plastic materials and products? For plastic products, this means a smarter usage of resources: it includes doing more with less plastic (resource efficiency), but also making constructions such that materials can be easily separated at the end of their lifetime (resource effectiveness) An important aspect is furthermore to designing for a longer lifetime. If products are easily repaired, valuable resources stay longer in the loop. It could also simply mean designing something so beautiful or useful that people rather keep it than throw it away.

Of course there is a whole category of plastics products for which such considerations do not easily apply. Many items like plastic bags, plastic coffee cups, plastic bottles, or food packaging are – by design – meant to be used only once. All efficiency improvements will be negated by the projected growth in of the total market for these products. Non-plastic alternatives are in many cases available for these products, but these might score worse on other environmental aspects (box 6-1). To keep the benefits of these products (lightweight, transparent, cheap), new plastic materials are being developed with improved environmental characteristics. Some will argue that these material improvements do not solve the fundamental error of producing products for single use, and promote to minimize the use such products altogether, either through customer awareness, by pricing incentives, or ultimately by a legal ban on certain products like the plastic bag.

Rethinking of the design can also be done at the material level. For the plastics this means e.g. finding substitutes for current plastics that can be composted. The wish list *sounds* simple: non-toxic and fully recyclable, made from renewable materials and biodegradable. In real life, technical and economic trade-offs have to be made: the perfect material (box 6-2) does not yet exist and is unlikely to be developed any time soon. Therefore, action on all other phases of a product life cycle (see fig 6-2) remains necessary.

Box 6-2. Bioplastics: biobased or biodegradable?

With bioplastics two broad, not necessarily overlapping, categories of plastic are meant:

- plastics that are derived from renewable resources, i.e. *bio-based*
- plastics that are able to degrade to harmless components, i.e. *biodegradable*.

Both bio-based and biodegradable plastics have environmental benefits over traditional plastics,[143] although for the issue of marine litter these benefits at present are small. Bio-based, means a biological origin and as such has benefits in reducing the depletion of fossil resources, and a reduction in the emission of greenhouse gasses. The latter is only true if over the whole life cycle the benefits of using renewable resources are outweighed by the fossil fuels used for planting, harvesting, fertilizing, transport, etc. It should be stressed that bio-based tells us nothing about the behaviour of plastics in the environment. In fact, using plant-based materials, the same plastics like PET and PE can be produced that take centuries to degrade.

Figure 6-3. The Coca Cola PlantBottle is partly bio-based, but not biodegradable.

Biodegradable plastics – as the name implies – do break down in the environment and as such are an improvement over most current plastics. Many have a biological basis in either the raw materials or the process (bacterial). Biodegradable polymers, however, can also be synthesized from petrochemical sources. The questions related to the degradability are: which environment and what are the degradation products? To break down a plastic into smaller molecular units, requires the action of microorganisms. Relatively high temperatures (40-50°C) and specific composting conditions promote rapid breakdown. The marine environment generally is far away from these optimal conditions. As numerous shipwrecks demonstrate: dead wood (containing the natural polymer cellulose), which disappears completely within a few years in a forest, survives for centuries at the bottom of the sea.

Many biodegradables contain additives to make them oxo- or photo-degradable. This however only speeds up fragmentation, not degradation. In addition, it introduces new additives. Therefore doubts have been raised if biodegradable plastics will provide a solution for the problem of plastic marine litter. Even if products are developed that degrade completely in the marine environment, and there are some examples on the market, a more fundamental issue remains. If plastic products are perceived as harmless to the environment, the incentive to collect used plastic might disappear, and actually more plastic is discarded rather than recycled.

6.3. Behavioural change

Between the manufacturing of a product and its end of life, is the stage where a consumer owns a plastic product. Changing consumption and littering behaviour is one of the keys to prevent plastic marine litter. Raising awareness of the consequences of careless plastic usage and disposal can help, but should always be accompanied with on the one side a proper waste management system and on the other side by smarter materials and products (see fig 6-2).

Our attitudes towards waste have been shaped by the values in our society. This explains why littering behaviour can be very different across the world. Some might claim that throwing away items that are no longer of use to us is part of human nature. Observing how difficult it sometimes is for small children to throw away items – for adults it is rubbish; the child sees a world full of magical possibilities for reuse – shows that at least partly our behaviour is an acquired skill.

To change deeply engraved attitudes is not easy. Even though most people know the right thing to do – use the rubbish and/or recycling bins – litter still finds its way into our environment. Although it is important that correct disposal of waste is facilitated through collection systems, this is not the whole story. A North American study showed that despite widespread availability of trash receptacles in public space, litter was still common. Even more worrisome was that the majority of littering behaviour occurred with notable intent.[144]

Fig 6-4. Examples of littering fines throughout the world: Borrow UK, Georgia USA, Orilia Canada, and Singapore Malaysia

Ever since litter in the public space was perceived as problematic, campaigns have been set up to correct the public behaviour: stimulating correct disposal and motivating recycling. These campaigns have included informing and education, prompting in combination with labelling ("place this paper in a bin"), environmental design (have enough and well-placed bins), rewards, and fines (figure 6-4). While all of these techniques can have at least a temporary effect, the biggest challenge is to make *durable* changes in behaviour.[145, 146]

For plastic marine litter, reducing littering by the maritime profession is an additional challenge. Recently, the International Maritime Organisation has decided to completely ban the dumping of shipping waste on sea (MEPC 62). Enforcing such measures in international waters, however, is complicated and hence strong emphasis should be placed on changing the behaviour through other incentives as well. An example is the educational campaign started by the Port of Rotterdam, “Any waste, Any time”, promoting the handing over of ship’s waste at the proper waste reception facilities.[147]

Box 6-3. Convenience cannot be substituted

One possible explanation why it is so difficult to change behaviour towards more environmentally conscience attitudes is that convenience cannot be substituted. We have come to rely on the convenience of being able to satisfy our material needs almost instantly. Plastics are often the package of these convenient items. Take for instance the free plastic bag at stores. Knowing that this is available makes it possible to forget your own bag if you feel the desire to shop. The only substitute for this convenience is less convenience: you either have to buy a more expensive durable bag, or go home first to pick up your own bag.

Raising awareness over the issue of plastic marine litter and correcting behaviour will need to be a continuous effort, directed both at consumption *and* littering. With no general agreement on the most effective ways to influence people, a multi-target, multi-channel approach seems to make the most sense. An example of such a broad campaign is the Dutch Plastic Heroes campaign, aimed at increasing the amount of recycled plastic packaging material. Other initiatives that increase awareness are various ban-the-bag initiatives, and beach clean-ups. The message should also be included in education programmes. In addition, raised awareness needs to be accompanied by increased options for action, e.g. by labels informing the consumer of the risks that plastic poses to themselves and the environment (like on cigarettes) and by improving waste management (see 6.4.).

6.4. Waste management: a focus on recycling

After use, plastic need not be considered waste, better to think of it as a valuable resource. If a product can be reused, this is in most cases the best option from an environmental point of view. When this is impossible, mechanical recycling is often the next best option, recovering the material resources. Additionally, the energy content of plastic can be recovered in the form of electricity and heat. After all, plastics are a different chemical form of oil and can be considered a fuel. For biodegradable plastics, the preferred method would be composting, recovering both nutrients and possibly energy in the form of biogas. To do so separate collection or automated sorting of biodegradable plastic is a prerequisite. As a last resort, plastic should be considered waste and end its life in an incinerator or landfill. This waste hierarchy is visualised in Fig 6-2.

A detailed overview of waste regulations falls outside the scope of this report. Instead we focus here on recycling as one of the most important options for closing material cycles in plastic. Furthermore attention is given to why recycling of plastic is so much less common then paper and glass recycling.

Initially, we should answer what we mean by closing the loop (see Fig 6-5). Two broad categories were already mentioned: material recycling and energy recovery. The most common form of material recycling is mechanical: after cleaning and separation, the plastic is shredded into small particles that can be used as input for new plastic products. Depending on the composition of the waste plastic this leads to a high-grade material with at least the same quality (primary) or to a lower-grade material (secondary). The latter option is sometimes referred to as downcycling. A specific concern for recycling plastic waste lies with so-called legacy plastics: additives that have been banned at some date can be present in recycled material from before that period. As long as the loops remain closed and these additives are not released during production or use this does not need to be a problem.

As an alternative for mechanical recycling, there are different methods to recover chemical building blocks from the polymers through liquefaction, gasification or chemical depolymerisation. Chemical recycling offers the possibility to remove unwanted or toxic additives. These options have yet to be employed on a large scale.

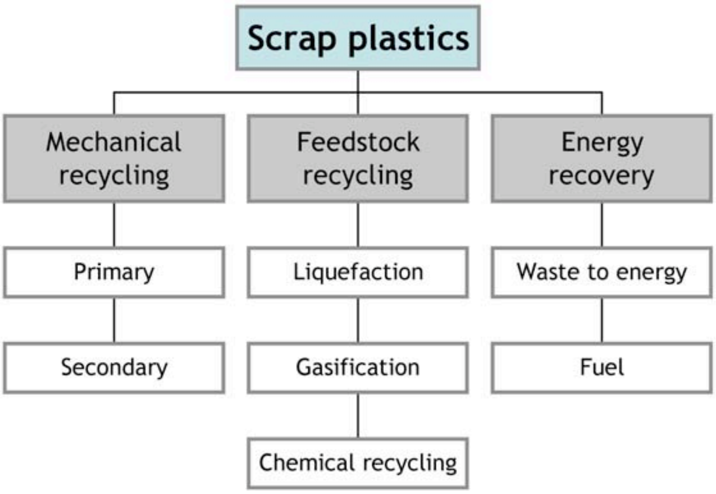


Figure 6-5. Recycling options for post-use plastic (based on [148]).

With energy recovery plastic is burnt to produce electricity and/or heat. Alternatively, the plastic can be process engineered to fuels for transport or other applications. It should be understood that from a life cycle perspective, energy recovery is always incomplete. Simply put: with two units of oil, only one unit of plastic is made, the other unit is needed as energy in the production process. Therefore, at best only half of the energy is recovered, in practice it is even less due to energy conversion losses.

As noted in the introduction of this chapter, recycled plastic still forms a relatively small fraction of the input for new products. Most plastic products are still produced from virgin plastic. For other materials, like glass or paper, much greater recycling rates are generally achieved. Why is this so? Economically, it makes sense to recycle plastics when the price of production from raw material, i.e. oil, exceeds the price of production from scrap plastic. Particularly when oil prices are high, recycling plastic presents a favourable business case. The reason that plastic is not recycled on a much larger scale has to do with a number of barriers that go further than the basic economics.

Foremost, plastic recycling has to compete economically with other end-of-life options that are generally cheaper from a waste perspective: land filling or incineration. Recycling of plastics furthermore has a number of logistic hurdles: an effective system of collection needs to be maintained, while at the same time the consumer needs to be persuaded to use it. The large variety of plastic types makes it necessary to find a balance between the easy of collection and the quality of the recycled plastic. From a technical perspective, there are some additional problems, inherent to plastic recycling: waste streams are often contaminated, and with recycling the polymer chains in the plastic shorten. In contrast to metals and glass, very high temperatures – to burn off organic contaminants – cannot be used. Quality sorting is expensive which makes it necessary to either down-cycle, or to add virgin materials to the recycled fraction in order to maintain the desired properties.

Finally, there are possible barriers between supply and demand: if a producer wants to use a recycled plastic, will he be able to find the right material in the right colour and with the right properties? And can he be assured of a continuous supply, even if demand increases? In part these barriers will become less important as recycling volumes increase. In order to get to this point, recycling should be stimulated through government targets and the raising of public awareness.

6.5. Restoration

As long as material loops are not sufficiently closed, a need for restoration of the marine environment will remain. This can take many forms: beach cleaning, fish net recovery, fishing for litter, reef cleaning, and interception at sewage facilities. Although such initiatives generally have no direct economical benefit, they are one of the strongest methods of creating public awareness on the topic of plastic marine litter. A motive that is almost equally important in these initiatives (e.g. the MyBeach campaign of the North Sea Foundation makes beach users responsible for the litter on the beaches.[149] At the same time, the impact of these measures on the global problem is negligible in most cases. Viable long-term solutions come from the closing of the material loop.

Box 6-4. The benefits of removing derelict fishing gear

It is not always the case that removal of plastic marine litter from open sea is prohibitively expensive. In the case of derelict fishing gear it has been shown that it makes very good economical sense to remove these nets and pots from open sea. The reason being that the nets that are lost at sea continue to fish for quite some time. This can be expressed as an economic loss. In a case where crab entanglement was studied it was found that the cost of removing a net was compensated more than 14 times by the economic loss of crabs to commercial fishery.[150]

Because it is costly to remove plastic from the open sea, many initiatives focus on spots where plastic is relatively concentrated: beaches, but increasingly also rivers, estuaries, harbours, and ports. For example, the European Waste Free Oceans initiative collects floating debris along coast lines.[151] An alternative approach is to “hitchhike” on existing marine infrastructure. The best example is the fishing for litter programme, where fishermen can return plastic to shore without waste charges.

7. Synthesis

In the previous chapters we analysed the most up-to-date knowledge on causes, effects, and solutions of plastic marine litter and identified the existing knowledge gaps. Here, we take the analysis one step further to disentangle the different levels of the issue from a systems perspective.

The plastic marine litter issue is particularly well-known by the large areas of floating plastic debris in the oceanic gyres. Monitoring studies show, however, that plastics are present in all marine and coastal compartments. Macro-plastics are present in seawater in oceans and seas worldwide, wash up on beaches and settle down to the seabed. More recently, it also became known that microplastics are widespread in seawater and in sediments of rivers, beaches and seas. These macro- en microplastics behave very differently, depending on the circumstances of the places where they end up. Even after long-term monitoring programmes there are still many unknowns about the origin of sources and the processes determining dispersion, concentration and degradation. For the microplastics, where monitoring has just started, there are even more uncertainties.

Better knowledge on the quantities and pathways of plastic marine litter is essential in devising optimal solutions mitigate and remedy the problem of plastic marine litter. This problem manifests itself on three different levels.

1. Plastic marine litter is a waste problem that is considered to be one of the most important emerging global issues. It is occurs worldwide, but depends strongly on local conditions. It has effects on economies and on marine species. These effects are direct, mostly physical in nature and reasonably well established

2. Plastic marine litter is a problem of unsustainable usage of plastic resources. Unsustainable usage of resources is a wider problem that has recently been recognized for many materials (see e.g. the EU Critical Raw Materials Initiative). This wider problem has repercussions that extend far beyond the realm of the plastic marine litter issue, including material scarcity, climate change, and production of food. The solutions require steps towards a zero-waste, cyclic economy. Solutions for sustainable use of plastics should be considered in this framework.

3. Plastic marine litter has the potential to affect global ecosystem services of the earth's oceans. Microplastics might lead to accumulation and increasing concentration of toxic substances throughout the food chain. It cannot be excluded that ingestion of plastic by organisms at the bottom of the food supply ultimately has global consequences.

This section puts forward the main conclusions at each level of the issue. In the next chapter we detail the specific recommendations.

7.1. Plastic marine litter as a worldwide waste problem

Plastic marine litter is found in almost every sea and ocean. The local characteristics of the problem depend on (1) the population density near the coast and the economic welfare (GDP density), (2) traffic density from shipping, (3) effectiveness of the local and marine waste management systems, and (4) the ocean currents and patterns of weather accumulating the material.

At this level the direct effects of plastic marine litter are both economical and ecological. The direct economic damage is mainly in beach cleanups and damage to fisheries. If the costs for cleaning the UK can be taken as a standard, the worldwide cleanup of beaches would amount to 50 billion Euros per year. Impact of plastic on fisheries has been estimated to be 5% of total revenues each year, i.e. amounting to a global impact of almost €5 billion dollar each year. Direct ecological effects are the weakening and ultimately death of seabirds; sea mammals and turtles through plastic ingestion and strangulation.

These direct effects are without question man-made and will continue and grow in the absence of preventive measures. They make for a highly visible impact that is aggravating for those who sense them. Some remedies are already in place (OSPAR EcoQO indicators, beach cleaning, fishing for litter). However, without addressing the other problem levels, this is likely to have only limited results.

7.2. Plastic marine litter as a sustainability problem

At a higher level, plastic marine litter is a side effect of the unsustainable, linear use of resources: take-make-waste. Improving the sustainable use of plastic has the effect of reducing plastic in the marine environment, but can also create other benefits like a reduction in greenhouse gas emissions over the entire life cycle.

Working towards a cyclic, zero-waste economy is a key solution that needs to become enshrined in profitable business models. Biodegradable plastics are expected to play an important role in making plastic more sustainable, but have as yet few benefits for the plastic marine litter issue. As long as fully sustainable plastic products and services are not realized, all other solutions to reduce plastic marine litter should simultaneously be explored and implemented. This includes all solutions in the product chain: rethink manufacturing, influence consumption and littering behaviour, effective systems for managing waste plastic (reusing and recycling, not burning) and rehabilitation of affected marine habitats. The effectiveness of these potential solutions needs to be measured using robust experimental designs with sufficient replication in time and space than has previously been used.[43]

The North Sea region is an ideal testing ground for developing all necessary solutions that are defined in the general solutions framework discussed in Chapter 6. The reasons are the following: (1) the North Sea has a good economic and ecological value, (2) it has a manageable scale, (3) the presence of innovative industry and (4) basic waste management is already in place. Technical and social innovations developed in the North Sea region could serve as an example (e.g. a practical step-by-step approach) for other regions as well.

Plastic marine litter as a global problem for oceanic ecosystem services

At the global level, we have identified effects that might disrupt essential ecosystem functions for human welfare. These effects differ in likelihood as discussed in section 4.5. For all effects, the potential impacts are currently highly uncertain.

The effect that plastic litter provides a pathway for species to cross oceans and seas is well established. The potential impact of non-native species however is much harder to establish, particularly when comparing it with many other possible transport routes. Until more quantitative data becomes available, the impact could be minor as well as major.

Persistent bio-accumulating toxics inside plastics or adhering to plastic can move up the food chain and enter the human body through this route. Through microplastics, an entry point in the food web has been identified as a first step of such an indirect mechanism. Much less is known about the indirect mechanisms that might lead up to toxicological effects for humans.

The more general issue of toxicity in plastics overlaps partly with the microplastic issue, but is much more general in its causes (chemical composition of plastic), effects (human toxicity through many more pathways than via plastic litter alone) and solutions (aimed at regulating the usage of toxic chemicals).

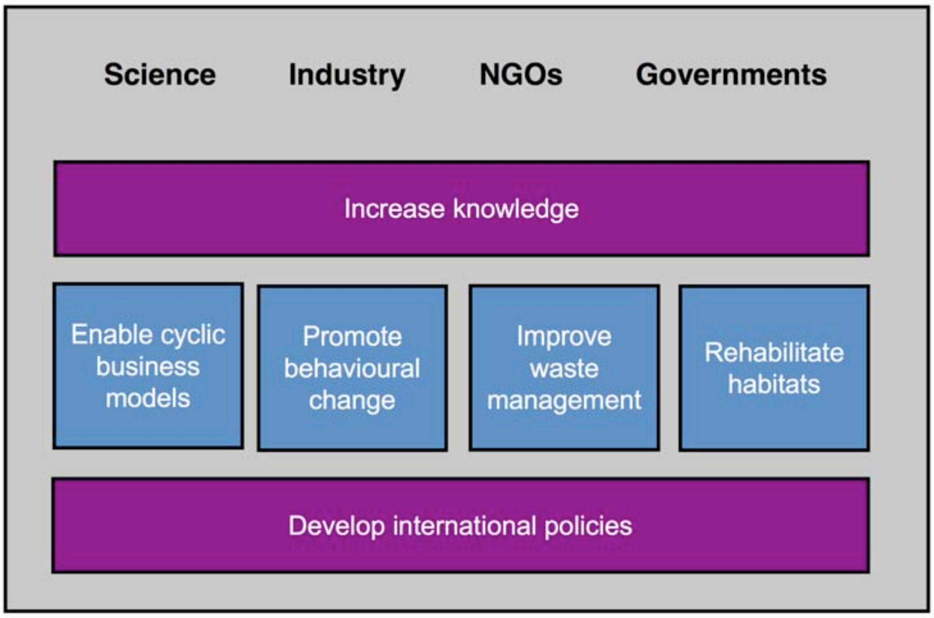
Even though lanternfishes are not (yet) commercially exploited, it represents an enormous biomass. Little is known about significance to human protein consumption. Links to human food intake have not been firmly established, however given the fact that these have been shown to ingest plastic, such effects cannot be excluded.

In the North Pacific Ocean, local plastic abundance in the centre of the gyre is so high that it is conceivable that it disrupts the biological pump function. Vertically migrating fish play a role in the carbon dioxide uptake of the oceans. When impaired by ingesting plastic it cannot be excluded that carbon dioxide fluxes might change, which – in the worst case – might accelerate global warming.

8. Recommendations

The fact that there is still a lot unknown about the scale and effects of plastic marine litter is no excuse for inaction. Where possible, measures could and should be implemented without further delay. The North Sea forms an ideal starting place for such practical initiatives as detailed in chapter 5.

We propose that a coalition of scientists, representatives from the plastic industry, governments and NGOs establish concrete projects to work on solutions for plastic marine litter. Together they form a programme with a roadmap aiming at an almost plastic-free North Sea and Wadden Sea. The components of this programme are derived from the general solutions model developed in chapter 5. They aim at innovation on land towards a circular economy for plastics as well as habitat restoration, and are supplemented with research ("increase knowledge") and policy development.



These themes all interact, require the combined efforts of all stakeholders involved and are linked to broader developments in resource and waste management. An independent knowledge broker continuously ensures the dissemination of insights throughout all projects. To guarantee societal support for the development and implementation of effective policies for plastic marine litter, a broad international and North Sea coalition has to be built and a collective agenda has to be set, in cooperation with other initiatives where possible.

The recommendations provided in this chapter need further expansion into concrete measures and pilots. Some specific examples are already given, but should be treated as suggestions in need of further discussion and refinement.

8.1. Increase knowledge

Increase and improve monitoring efforts

Major knowledge gaps exist in the pathways (from sources to sinks) of plastic marine litter. The rivers that discharge into the North Sea might be important carriers of plastic litter, but little is as yet known about the quantities of plastic that they transport to the sea. The knowledge gaps in the Wadden Sea on plastic marine waste, and in particular microplastics, are even bigger. Studies should be set up to monitor if microplastics are present in the water and sediments in the Wadden Sea and to assess potential (specific) ecological risks for the Wadden Sea.

Hypothesis-driven monitoring leading to improved protocols should establish long-term trends for major rivers, ports, beaches and estuaries. The monitoring should be coupled to concrete actions aiming at reducing plastic marine litter in order to establish cause and effect. For microplastics, technologies should be developed that allow for rapid, automated measurements. In addition, maps should be constructed that combine measurement and modelling results on the concentrations of plastic marine litter with ecological data. Thus high-impact regions can be identified, and appropriate protection measures taken.

Identification of major sources of plastic litter is needed, particularly for microplastics. Specifically, the question in how far microplastics pass through sewage systems needs to be addressed.

A separate programme should be developed to monitor those sea animals where high impacts are expected. Fulmars are already closely monitored and provide an indicator for ecological quality in the North Sea.

Risks for human health from seafood cannot be ruled out, but await scientific assessment. In order to assess if these risks exist, mussels, fishes or other commercial seafood that directly or indirectly ingests plastic should be monitored for plastic or plastic-related toxicants. More research is needed to establish where to look, what to look for, and how to measure it.

Increase and integrate knowledge

There are still many unknowns, specifically on long-term effects of the smallest particles of plastics, the so-called (micro)plastics, on populations, food webs and biological functions. Potentially the impacts can be very high. To increase the knowledge base, a synthesis of knowledge from different disciplines and sectors is needed. The field of plastic marine litter is restricted to a limited number of researchers. A stronger integration with other scientific fields may bring new perspectives and knowledge.

Develop scenarios for plastic marine litter in the North Sea

In order to develop a roadmap to a plastic-free North Sea, a scenario needs to be developed, outlining the current trend and the setting of what could be a realistic path towards an almost plastic-free North Sea. Such scenarios currently do not exist and this seriously complicates setting initial and intermediate targets. They are especially needed for insight into the magnitude of the task at hand and for the first estimates of the cost involved in reducing plastic marine litter. This needs to be an iterative process as, clearly, there is currently insufficient data to allow for more than crude estimates. Over time these estimates can be refined using the latest data and insights from monitoring and modelling studies.

Build on marine infrastructure

The busy North Sea forms an opportunity to set up cost-effective monitoring. Well-known examples include fishing for litter and the SAHFOS Continuous Plankton Recorder that can be towed from merchant ship in the North West Atlantic and provides valuable time series on microplastics [87]. Thinking about all commercial activities, a number of new ideas might emerge that prompt further investigation. Nets or other devices need to be developed that can retrieve plastic from open sea. These can be attached to existing structures like oil platforms or wind turbine poles.

8.2. Enable cyclic business models

Rethink: design for reuse and recycling

Promote rethinking of plastic products on all levels. Design for reuse and recycling needs to become the industry norm to phase out the production of single-use items. This means treating plastic waste as a valuable resource; design business around the service rather than on the material (leasing); and collaborate with other industrial partners in the chain. Simplifying products and design for disassembly are key ingredients. E.g., the number of different plastics and plastic varieties used in consumer products should be reduced when possible. The development of material passports, making available information on material specifications for reuse and recycling, is an important enabler for such schemes. Similarly companies need to be encouraged to use recycled plastics rather than virgin plastic.

Attention needs to be given to the financial aspects of cyclic economies. How can financial barriers be removed, and a level playing field promoted?

Currently, virtually all plastics, including oxo-degradable and most biodegradable variants, are persistent in the marine environment. Therefore, design for reuse and recycling should be interpreted as keeping resources in a technological cycle: collecting plastic waste, reuse when possible and recycle the material content with as little loss of material quality as possible (upcycling).

Development of truly biodegradable plastics should include assessment of the persistence in the marine environment. Only when plastics are developed that are truly biodegradable, can cyclic business models be developed where plastic is part of a biological cycle.

Improve life-cycle analyses

In order to compare the shift of burdens in environmental impacts of different materials, life-cycle analyses (LCA) are a useful tool. The limitations lie in the treatment of toxicity and the potential littering of the product. LCAs take regular / intended disposal routes for granted. These limitations need to be addressed. Either by developing additional screening protocols for these issues, or by improving current LCA methods. The development of open-source LCA software might be a suitable platform for such initiatives.

Avoid potential toxicants

Promote an approach to avoid potential toxicants as the industry norm. A company like LEGO for instance has started a programme to collaborate with stakeholders in substituting environmentally undesirable substances.[152] Other examples are provided by companies that apply Cradle to Cradle principles, putting "be more good instead of less bad" into practice. Microplastics in scrub creams and other cosmetic products need to be substituted by more environment-friendly alternatives.

Cyclic design principles as part of the curriculum

Many design studies integrate eco-design subjects in their curriculum. The principles of cyclic business models also need to be incorporated in other studies, particularly business schools and chemical engineering. Companies should also be encouraged to increase their range of eco-design products. Different disciplines within companies, e.g. designers, engineers and marketers, should be involved to develop attractive, ecologically sound alternatives.

8.3. Promote behavioural change

Awareness of the North Sea

Many people are aware that somewhere in the North Pacific there is a lot of plastic floating around. Less known is that plastic marine litter poses a risk to the North Sea ecosystem and local economies as well. Raising awareness among consumers – and we are all consumers – should start by communicating the value and importance of the North Sea to society. Cleaning up beaches, furthermore, is a good way to show the magnitude of the problem and can establish a long-term awareness of the consequences of plastic littering. The MyBeach project takes this one step further by making beach visitors responsible for keeping their own beach clean.

Plastic usage and disposal on land

To promote behavioural change in the way people use and dispose of plastics, technical and social innovations go hand in hand. Raising awareness needs to be complemented by practical ways and methods that enable consumers to make the right choice. E.g. clear labelling and online environmental product evaluations should help people to make an informed choice in what they are buying and how they should dispose of it. Alternatively, applications could be developed that give consumers insight into their plastic footprint. Improving plastic usage behaviour could focus on hot spots such as retailers, busy events like public concerts and zones with much littering like parks. The impact of voluntary schemes such as “Nederland Schoon” and Plastic Heroes should be evaluated and improved, while the extension to more stringent government measures such as deposits, bans and fines should be seriously considered.

Prevent disposal practices at sea

Though littering of plastic in open sea is forbidden under national and international law, still a lot of plastic intentionally or unintentionally is lost at sea. Since improving enforcement in open waters is complicated, the fisheries and marine transport sectors deserve special attention. Again general awareness programmes need to be complemented by practical collection systems that make it easy to do the right thing. Further promote the handing over of waste at port reception facilities, and expand the fishing for litter programmes.

8.4. Improve waste management

Increase collection of plastic waste

Illegal dumping must be discouraged by strict enforcement. Particularly from ships, waste collection needs to be further improved. All ports have waste reception facilities, but it difficult to ensure that these facilities are used. Better waste collection schemes, supported by effective waste tax regimes, and stricter enforcement are needed to avoid illegal dumping on land by households and companies.

Increase recycling rates

All initiatives to improve waste management need to start from the notion that plastic waste should be treated as a valuable resource. From that principle, a logical waste hierarchy follows, giving priority to reuse and material recycling over energy recovery. Land filling and incineration need to be avoided. This line of thinking needs to be clearly reflected in targets for recycling, for which the EU and the member states should set increasingly ambitious targets.

To enable higher recycling rates waste collection schemes and regional waste processing and recycling units need to be optimised and harmonised. Separation technologies need to be further developed to handle large, mixed plastic waste streams and to filter out microplastics and biodegradable plastics.

Close the leaks

Known sources of plastic marine litter need to be addressed. For instance waste water from plants needs to be completely free of (micro)plastics. Water from sewage treatment needs to be similarly free of plastics. Currently microplastics are not filtered, and this requires attention. Similarly, losses during transport need to be minimised.

8.5. Rehabilitate habitats

Completely clearing the seas and oceans from plastic is prohibitively expensive and in all likelihood highly energy-intensive. Interception and removal should therefore commence from locations that have a combination of high ecological or economical value and a high concentration of plastics litter (“hotspots”). Such locations include beaches, estuaries, coastal areas, and nature conservation areas such as the Wadden Sea. If rivers prove to be major pathway for marine litter, than interception in rivers could be developed.

Low-cost technologies need to be developed to tackle the removal of dilute plastics from open waters. Ecological assessments are needed to guarantee that these technologies do not cause ecological harm, have no adverse effects on other environmental issues, thus have a net ecological benefit in themselves. One way to keep costs low is to combine removal of plastic with other activities at the North Sea. Fishing for litter is a well-known example of approach.

As clean-up and recovery of microplastics and toxicants is even more challenging, new technologies for separation and absorption technologies could be explored.

8.6. Develop international policies

Embed stakeholder knowledge and best practices in policies

Policy assessments, founded by a broad range of stakeholders, can identify gaps and flaws in the current policy framework and can list options to overcome regulatory or financial boundaries for sustainable usage of plastics. These assessments provide policy makers with more informed options, for instance on potential consequences of future policy decisions, effective incentive structures, standardised and objective-driven monitoring programmes and so on. A broad stakeholder programme also contributes to defining acceptable levels of uncertainty.

The programme, as described above, aims to build a solid knowledge base on plastic marine litter and develops best practices to address the problem. Once proven, best practices should be adopted and embedded in policies on regional or even global scales. Close cooperation with regional and international regulators is needed in the early stages of pilot projects to enable the development of feasible projects that could be integrated in policy in a later stage.

Improve regional and international policies and the enforcement of regulations

Regional policy efforts should mainly focus on source reduction and control. Options to minimise plastic waste include setting challenging policy goals, embedding “the polluter pays” principle in financial regimes, further embedding the precautionary principle in marine policies (with implications for land-based sources of pollution), optimising waste management strategies, implementing best management practices, monitoring to assess effectiveness of measures taken and strict enforcement of regulations. Many of these policy options need to be further explored.
International policy efforts should, in addition, address the pressing problem of plastic pollution of global marine ecosystems. As oceans and seas are open systems plastic waste is exported from one area to the other and some areas are disproportionately burdened, e.g. Hawaii and the Antarctic region. Areas of responsibilities for restorative programmes need to be defined and funds should be provided. An assessment is needed to see which international policy tools or institutional structures are fit to address these issues.
International regulators should also develop long term policies, coupling long term scenarios/prognoses for plastic marine waste to the concept of “ecosystem boundaries”.

Finally, efforts should be made to arrive at a shared definition of “harm” indicating if and when ecological impact needs to be demonstrated at the level of individual animals, species or entire ecosystems.

Enhance global cooperation

Policy makers play a decisive role in stimulating and enabling the development of cyclic business models, improved waste management systems and restorative practices. The issue of plastic marine litter has gained much political attention recently and policy makers have initiated several regulation-driven, multi-stakeholder initiatives. Multi-stakeholder initiatives originating from industry, NGOs, science and other societal parties, however, are a valuable complement to these formal initiatives. By continuous exchange between these initiatives plastic marine litter can be kept high on the political and societal agenda.

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