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REPORTS AND STUDIES

GESAMP
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

SOURCES, FATE AND EFFECTS OF MICROPLASTICS IN THE MARINE ENVIRONMENT: A GLOBAL ASSESSMENT

IMO FAO UNESCO IOC WMO UNIDO IAEA UN UNEP UNDP

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Cover photo: Microplastic fragments from the western North Atlantic, collected using a towed plankton net.
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Notes:

GESAMP is an advisory body consisting of specialized experts nominated by the Sponsoring Agencies (IMO, FAO, UNESCO-IOC, UNIDO, WMO, IAEA, UN, UNEP, UNDP). Its principal task is to provide scientific advice concerning the prevention, reduction and control of the degradation of the marine environment to the Sponsoring Agencies.

The report contains views expressed or endorsed by members of GESAMP who act in their individual capacities; their views may not necessarily correspond with those of the Sponsoring Agencies.

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Contents

EXECUTIVE SUMMARY

Society has used the ocean as a convenient place to dispose of unwanted materials and waste products for many centuries, either directly or indirectly via rivers. The volume of material increased with a growing population and an increasingly industrialized society. The demand for manufactured goods and packaging, to contain or protect food and goods, increased throughout the twentieth century. Large-scale production of plastics began in the 1950s and plastics have become widespread, used in a bewildering variety of applications. The many favourable properties of plastics, including durability and low cost, make plastics the obvious choice in many situations. Unfortunately, society has been slow to anticipate the need for dealing adequately with end-of-life plastics, to prevent plastics entering the marine environment. As a result there has been a substantial volume of debris added to the ocean over the past 60 years, covering a very wide range of sizes (metres to nanometres in diameter). This is a phenomenon that has occurred wherever humans live or travel. As a result there are multiple routes of entry of plastics into the ocean, and ocean currents have transported plastics to the most remote regions. It is truly a global problem.

The GESAMP assessment focuses on a category of plastic debris termed 'microplastics'. These small pieces of plastic may enter the ocean as such, or may result from the fragmentation of larger items through the influence of UV radiation. Section 1 provides an introduction to the problem of microplastics in the marine environment, and the rationale for the assessment. The principal purpose of the assessment is to provide an improved evidence base, to support policy and management decisions on measures that might be adopted to reduce the input of microplastics to the oceans. The GESAMP assessment can be considered as contributing to a more formal Assessment Framework, such as the Driver-Pressure-State-Impact-Response (DPSIR) Assessment Framework, which is introduced in Section 2.

The nature of man-made polymers, different types and properties of common plastics and their behaviour in the marine environment are introduced in Section 3. There is no internationally agreed definition of the size below which a small piece of plastic should be called a microplastic. Many researchers have used a definition of <5 mm, but this encompasses a very wide range of sizes, down to nano-scales. Some microplastics are purposefully made to carry out certain functions, such as abrasives in personal care products (e.g. toothpaste and skin cleaners) or for industrial purposes such as shot-blasting surfaces. These are often termed 'primary' microplastics. There is an additional category of primary particle known as a 'pellet'. These are usually spherical or cylindrical, approximately 5 mm in diameter, and represent the common form in which newly produced plastic is transported between plastic producers and industries which convert the simple pellet into a myriad of different types of product.

The potential physical and chemical impacts of microplastics, and associated contaminants, are discussed in detail in Section 4. The physical impacts of larger litter items, such as plastic bags and fishing nets, have been demonstrated, but it is much more difficult to attribute physical impacts of microplastics from field observations. For this reason researchers have used laboratory-based experimental facilities to investigate particle uptake, retention and effects. Chemical effects are even more difficult to quantify. This is partly because seawater, sediment particles and biota are already contaminated by many of the chemical substances also associated with plastics. Organic contaminants that accumulate in fat (lipids) in marine organisms are absorbed by plastics to a similar extent. Thus the presence of a contaminant in plastic fragments in the gut of an animal and the measurement of the same contaminant in tissue samples does not imply a causal relationship. The contaminant may be there due to the normal diet. In a very small number of cases, contaminants present in high concentrations in plastic fragments with a distinctive chemical 'signature' (a type of flame retardant) can be separated from related contaminants present in prey items and have been shown to transfer across the gut. What is still unknown is the extent to which this might have an ecotoxicological impact on the individual.

It is recognized that people's attitudes and behaviour contribute significantly to many routes of entry of plastics into the ocean. Any solutions to reducing these sources must take account of this social dimension, as attempts to impose regulation without public understanding and approval are unlikely to be effective. Section 5 provides an opportunity to explore issues around public perceptions towards the ocean, marine litter, microplastics and the extent to which society should be concerned. Research specifically on litter is rather limited, but useful analogies can be made with other environmental issues of concern, such as radioactivity or climate change.

Section 6 summarizes some of the main observations and conclusions, divided into three sections: i) sources, distribution and fate; ii) effects; and, iii) social aspects. Statements are given a mark of high, medium or low confidence. A common theme is the high degree of confidence in what we do not know.

The assessment report concludes (Section 7) with a set of six Challenges and related Recommendations. Suggestions for how to carry out the recommendations are provided, together with a briefing on the likely consequences of not taking action. These are divided into three Action-orientated recommendations and three recommendations designed to improve a future assessment:

Action-orientated recommendations:

- Identify the main sources and categories of plastics and microplastics entering the ocean.
- Utilize end-of-plastic as a valuable resource rather than a waste product.

- Promote greater awareness of the impact of plastics and microplastics in the marine environment.

Recommendations for improving a future assessment:

- Include particles in the nano-size range.
- Evaluate the potential significance of plastics and microplastics as a vector for organisms.
- Address the chemical risk posed by ingested microplastics in greater detail.

ACKNOWLEDGMENTS

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The following organizations provided in-kind or financial support to the working group: IOC of UNESCO, IMO, UNIDO, UNEP, NOAA. In addition, the American Chemistry Council (ACC) and Plastics Europe (PE) provided financial support, without which the Working Group could not have functioned. Luis Valdes (IOC), Edward Kleverlaan, Fredrik Haag and Jennifer Rate (IMO) provided invaluable encouragement and in-kind support.

Ashley Carson (ACC), Keith Christman (ACC), Roberto Gomez (PE) and Ralph Schneider (PE) provided encouragement and technical advice on the plastics industry and related matters.

1 BACKGROUND TO GESAMP ASSESSMENT

1.1 Microplastics in the ocean – an emerging issue of international concern

Marine debris from natural sources, such as floating vegetation or volcanic ash deposits (tuff), is commonplace in the ocean. Unfortunately, man-made debris has increased substantially, particularly in the past hundred years. Marine debris, or litter, from non-natural sources is usually defined as 'any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment' (Galgani et al. 2010). This includes items that have been made or used by people and deliberately discarded or unintentionally lost directly into the sea, or on beaches, and materials transported into the marine environment from land by rivers, drainage or sewage systems or by wind transport. Such items may consist of metal, glass, paper, fabric or plastic. Of these, plastic is considered to be the most persistent and problematic.

Larger plastic objects are readily visible and many types of negative social, economic and ecological impact have been demonstrated, ranging from the entanglement of wildlife in fishing gear to the blockage of cooling water intakes on boats, requiring intervention by the rescue services. Smaller plastic objects, by definition, are less visible to the casual observer. Potential negative impacts are less obvious. However, reports of floating plastic micro-debris in the North Atlantic were first published in the scientific literature in the early 1970s. These publications raised concerns about the likelihood of ingestion of plastic particles by organisms and the potential for adverse physical and chemical impacts. A number of further publications, some in the 'grey' literature, in the 1970s and 1980s confirmed the occurrence of plastic particles in the North Pacific, Bering Sea and Japan Sea. But, the topic was largely ignored by the wider scientific and non-scientific community for many years.

Up until relatively recently, there has been a widespread tendency to treat the ocean as a convenient place to dispose of all sorts of unwanted material, either deliberately or unwittingly. Of course, the ocean is of finite capacity and persistent substances will tend to be transported globally and accumulate in certain locations, under the influence of oceanic and atmospheric transport. Plastics began to enter the ocean in increasing quantities from the 1950s, from a wide variety of land- and sea-based sources. There are no reliable estimates of inputs at a regional or global scale, but it is reasonable to assume that the total quantities have increased, even if the rate of increase is unknown.

National and international concern started to increase in the mid 1980s. For example, the National Oceanic and Atmospheric Administration (NOAA) of the USA initiated the first of a series of international conferences of marine debris, held at regular intervals with the most recent (the fifth, 5IMDC) taking place in 2011. Increasingly this has included plastic particles as an important category of marine litter. The Honolulu Strategy was launched at 5IMDC.[1] NOAA has been at the forefront of developing assessment guidelines and funding initiatives designed to reduce the impact of marine litter (Arthur & Baker 2009; 2012).[2] At a regional level the European Union has adopted the Marine Strategy Framework Programme, with marine litter as one of 11 descriptors of environmental state. A Technical Support Group was set up to guide the selection of sampling methods and assessment strategies, including microplastics.

At an international level, marine litter was one of the categories incorporated in the 1995 Washington Declaration concerning a Global Programme of Action (GPA) for the protection of the marine environment from land-based sources (UNEP 1995). It was listed as being of concern in the GESAMP 71 report on land-based activities (GESAMP 2001). More recently, the problem of marine debris, and the need for increased national and international control, was dealt with at the 60th session of UNGA within the Oceans and the Law of the Sea session ((UNGA 2005); paragraphs 65-70).

A more definitive assessment was provided by the analytical overview of marine litter, initiated by UNEP with input from IOC, IMO and FAO (UNEP 2005). This provided a useful overview of the issue, including type, source and distribution of litter, and measures to combat the problem. FAO has expressed concern over lost, abandoned or otherwise discarded fishing gear and has addressed this issue through a correspondence group with IMO and in a joint study with UNEP (Macfadyen et al. 2009). UNEP pursued this issue within the Regional Sea Programme and published a review of their global initiative on marine litter in 2009 (UNEP 2009) together with a series of Regional Sea status reports with regards to marine litter. Subsequently, marine debris was one of three topics selected for inclusion in the 2011 UNEP Year Book, with specific emphasis on microplastics as an emerging issue of environmental concern (UNEP 2011). The MARPOL Convention (International Convention for the Prevention of Pollution from Ships; MARPOL 1973), governed by IMO, covers the disposal of solid wastes under Annex V. Annex V specifically prohibits the disposal of any plastic waste anywhere in the world ocean.

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1 http://5imdc.wordpress.com/about/honolulustrategy/
2 http://marinedebris.noaa.gov

Marine litter was raised as an issue of concern at the UN Conference on Sustainable Development in 2012 (Rio+20). This resulted in a specific reference to marine litter in the outcome document (paragraph 163, A/RES/66/288), 'The future we want':

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

The Global Partnership on Marine Litter[3] was launched during Rio+20. This UNEP-led initiative is designed to encourage all sectors of governance, business, commerce and society to work together to bring about a reduction in the input of marine litter, especially plastics, into the ocean. The problem of marine litter and microplastics was raised at the First UN Environment Assembly, which took place in Nairobi in June 2014. This resulted in agreement on a Resolution on 'Marine plastic debris and microplastics' (UNEP 2014). The resolution referred specifically to the GESAMP assessment on microplastics (the subject of this report):

> '13. Welcomes *the initiative by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection to produce an assessment report on microplastics, which is scheduled to be launched in November 2014;*
>
> 15. Requests *the Executive Director, in consultation with other relevant institutions and stakeholders, to undertake a study on marine plastic debris and marine microplastics, building on existing work and taking into account the most up-to-date studies and data, focusing on:*
>
> > *(a) Identification of the key sources for marine plastic debris and microplastics;*
> >
> > *(b) Identification of possible measures and best available techniques and environmental practices to prevent the accumulation and minimize the level of microplastics in the marine environment;*
> >
> > *(c) Recommendations for the most urgent actions;*
> >
> > *(d) Specification of areas especially in need of more research, including key impacts on the environment and on human health;*
> >
> > *(e) Any other relevant priority areas identified in the GESAMP assessment of the Joint Group of Experts described in paragraph [13].'*

In a related development, the Global Partnership for Oceans was also launched at Rio+20.[4] The World Bank acts as the Secretariat, with over 140 partners representing governments, NGOs, international organizations and the private sector. Marine litter is one of three (waste water and excess nutrients) priority topics under the pollution theme.

An assessment of floating plastic marine debris, and contaminants contained in plastic resin pellets, forms part of the Transboundary Waters Assessment Programme (TWAP), a full-size project (2013–2014) co-financed by the Global Environmental Facility.[5] There has been coordination between the work on marine plastics and microplastics carried out under the TWAP and the work of WG40. The TWAP report is due for publication in early 2015.

Concern at an institutional level has been matched by a surge in interest amongst the academic community, with publications increasing almost exponentially over the past 5 years (Figure 1.1). The term 'microplastics' entered the popular lexicon at the start of this period of increased activity. Several regional seas organizations (e.g. NOWPAP, UNEP-MAP, OSPAR, HELCOM) have produced guidelines for assessing marine litter, including microplastics, in recent years, and some have organized regional workshops to encourage capacity building and the spread of good practice. The plastics production industry has developed a Joint 'Declaration of the Global Plastics Associations for Solutions on Marine Litter',[6] launched at the 5IMDC in 2011. This includes a commitment to support a number of litter assessment and litter reduction programmes.[7] Several Non-Governmental Organizations (NGOs), also referred to as Not-for-Profit organizations, have developed programmes both to raise awareness and help to quantify the extent of microplastic contamination and effects, at a national, regional and international scale. This has provided valuable additional information, often in a very cost-effective manner.

[3] http://gpa.unep.org/index.php/global-partnership-on-marine-litter

[4] http://www.globalpartnershipforoceans.org/about

[5] http://geftwap.org

[6] http://www.marinelittersolutions.com/who-we-are/joint-declaration.aspx

[7] Plastics Europe and the American Chemistry Council have jointly supported the GESAMP Working Group 40 on microplastics.

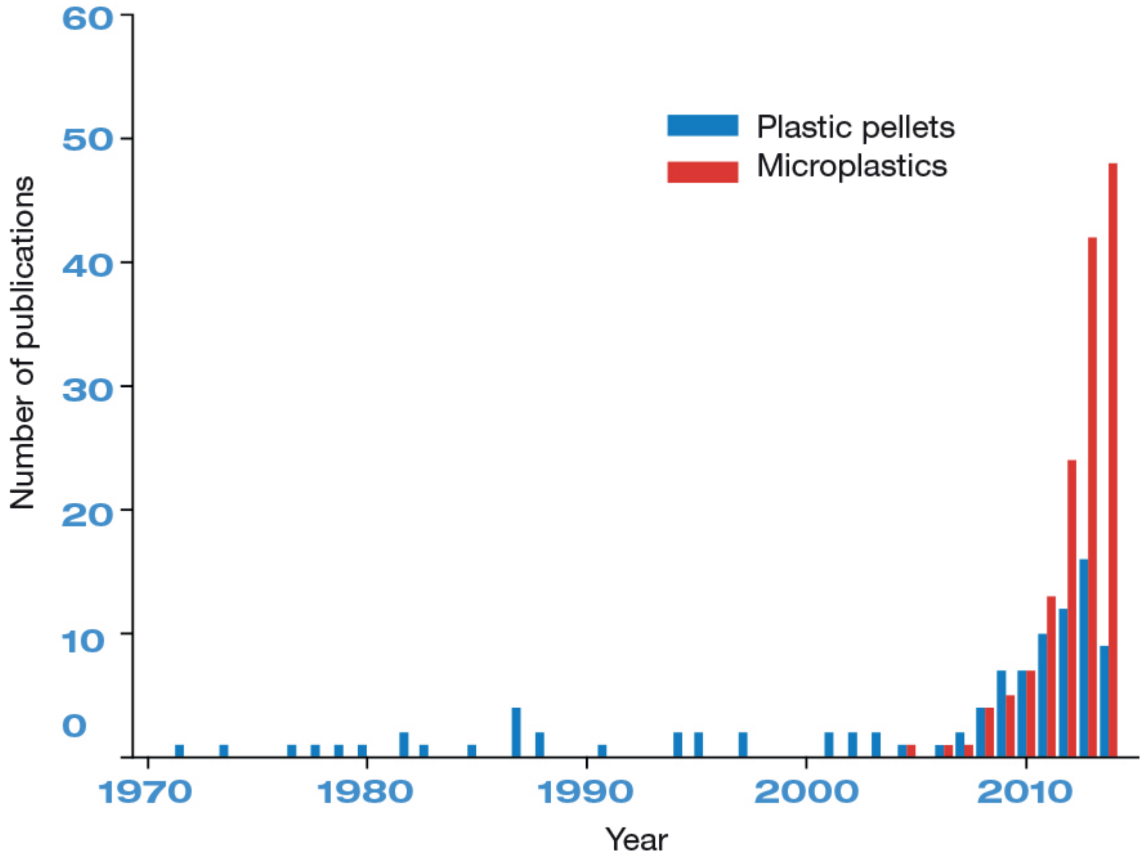

Figure 1.1 *Publications by year, 1970 – July 2014, using the search terms 'plastic pellets' and 'microplastics' – compiled by Sarah Gall, Univ. Plymouth, UK.*

1.2 GESAMP response

1.2.1 *Scoping activities*

The topic of microplastics in the marine environment was raised as part of GESAMP's Emerging Issues programme in 2008. It was agreed to produce a scoping paper, published as an internal document in 2009. This was followed by a scoping workshop in June 2010, hosted by UNESCO-IOC in Paris, entitled: 'International Workshop on Microplastic particles as a vector in transporting persistent, bioaccumulating and toxic substances in the ocean'. The proceedings were published in the GESAMP Reports & Studies Series (GESAMP 2010). One of the recommendations of the workshop was GESAMP should initiate a Working Group to conduct an assessment of microplastics in the coastal and open ocean, resulting in the setting up of WG40.

1.2.2 *Working Group 40*

Institutional support

Lead Agency: UNESCO-IOC

Other supporting UN Agencies: IMO, UNIDO

Other supporting organizations: NOAA, American Chemicals Council, Plastics Europe

Terms of reference

(as agreed at the 39th Session of GESAMP, April 2012, UNDP, New York)

1. Assess inputs of microplastic particles (e.g. resin pellets, abrasives, personal care products) and macroplastics (including main polymer types) into the ocean; to include pathways, developing methodology, using monitoring data, identifying proxies (e.g. population centres, shipping routes, tourism revenues);

2. Assess modelling of surface transport, distribution & areas of accumulation of plastics and microplastics, over a range of space- and time-scales;

3. Assess processes (physical, chemical & biological) controlling the rate of fragmentation and degradation, including estimating long-term behaviour and estimate rate of production of 'secondary' microplastic fragments;

4. Assess long-term modelling including fragmentation, seabed and water column distribution, informed by the results of ToR 3;

5. Assess uptake of particles and their contaminant/additive load by biota, as well as their physical and biological impacts at a population level;

6. Assess the socio-economic aspects, including public awareness.

Details of the working group members are provided in Annex I.

2 ASSESSMENT FRAMEWORK

2.1 DPSIR Conceptual model

The Driver-Pressure-State-Impact-Response (DPSIR) model has been used quite widely as a conceptual framework on which to base assessments of human impacts on both the terrestrial and aquatic environments (Ness et al. 2010). Drivers refer to high level demands society places on the environment, for example: energy supply, food security, transport, housing and recreation. In turn this may result in Pressures, or stresses, on the environment such as fisheries, shipping, coastal tourism and waste generation. The State of the environment may change, for example by increasing levels of noise or introducing litter. This may lead to an Impact, for a Response may be implemented. Any response has to consider the cost-benefit trade-offs between the overriding Drivers and the desired reduction of the Impact. An example of the DPSIR model applied to the generation and impacts on marine litter, including microplastics, is provided in Figure 2.1.

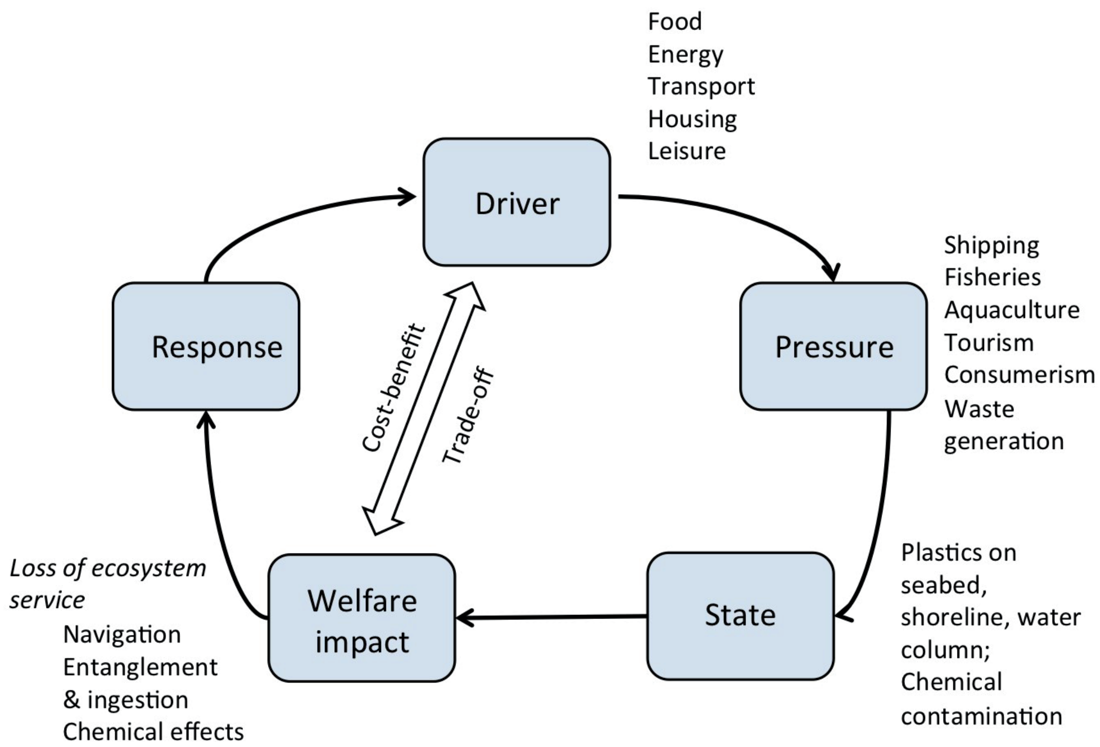

Figure 2.1 *DPSIR/DPSWR model as applied to the generation and potential impacts of marine litter.*

There has been considerable debate, largely between natural scientists and social scientists and economists, about what constitutes an Impact. In natural sciences the injury or death on an organism might be construed as an Impact, whereas in socio-economics it is usually argued that Impacts imply a loss of an ecosystem service, i.e. a welfare Impact that society is concerned about. Attempts have been made to clarify this by replacing 'Impact' with 'Welfare impact' (i.e. DPSWR) (Cooper 2013), but this has not been universally accepted. The Response may include several formal and informal measures to mitigate the Impact, acting on one or more of the Driver, Pressure, State or Impact (Figure 2.2). The example used to illustrate this involves the impact of larger plastic items on turtles, as this provides an easily understood set of relationships. However, the model can also be applied to microplastics, although the Response pathways are likely to be much more complex.

2.2 Scope of assessment

The assessment was constrained by the Terms of Reference, to consider the sources, fate and effects of microplastics in the marine environment. It was designed to provide an improved evidence base for the intended audience, summarized as follows:

- UNESCO-IOC, IMO, UNIDO – main WG40 supporting agencies
- Other international agencies: e.g. UNEP, UNDP, FAO, World Bank, GEF, WHO, IWC
- Regional Seas Organizations, e.g. NOWPAP
- National and local governance bodies
- Other funding/development bodies
- Industry/commercial sectors, e.g. tourism, aquaculture, fisheries, retail, plastic producers, plastic recyclers
- General public, NGOs, school children etc.
- Social and natural scientists, economists

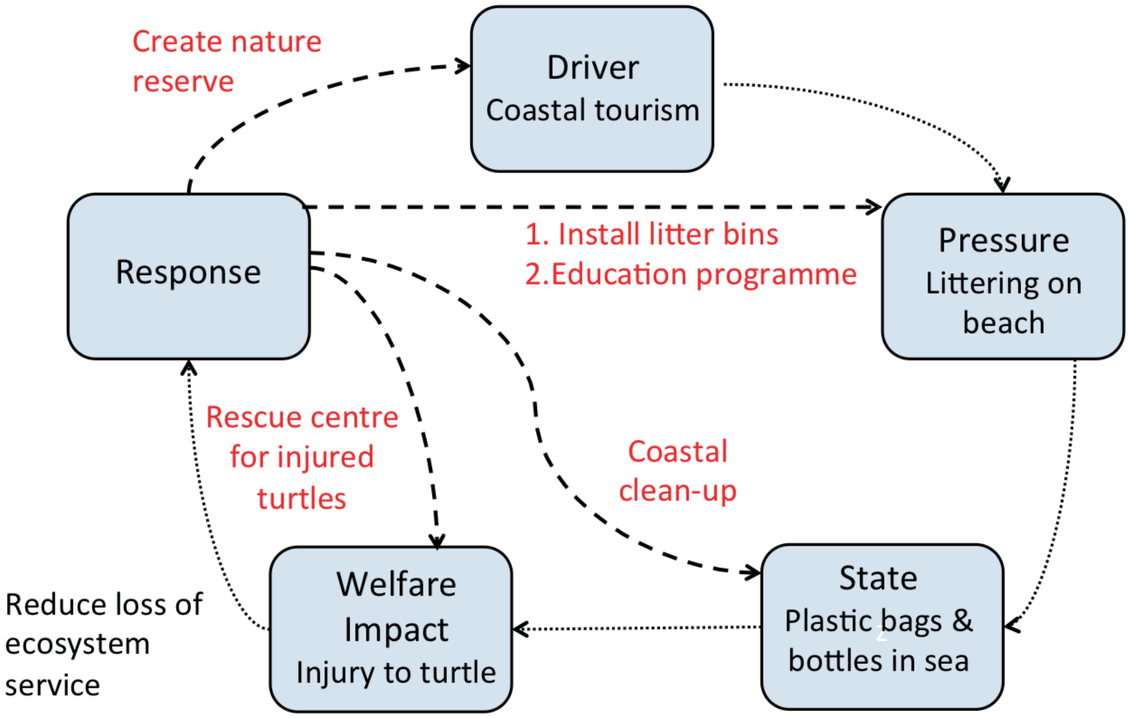

Figure 2.2 *DPSIR/DPSWR model showing an example of potential Responses to reduce the Impact of marine litter on turtles.*

The scope did not include providing recommendations for implementing specific measures to reduce the input of plastic and microplastics into the ocean. But, it is anticipated that the improved evidence base will inform such processes. One critical aspect of designing measures is to consider the potential economic loss associated with the loss of an ecosystem service, to allow a reliable cost-benefit analysis of any trade-offs that will be necessary. This was outside the scope of the present assessment.

The working group considered three main topics, reflected in the structure of this report: Section 3 – sources and fate of microplastics; Section 4 – physical and chemical effects of microplastics; and, Section 5 – social aspects. These have been mapped onto the DPSIR model in Figure 2.3.

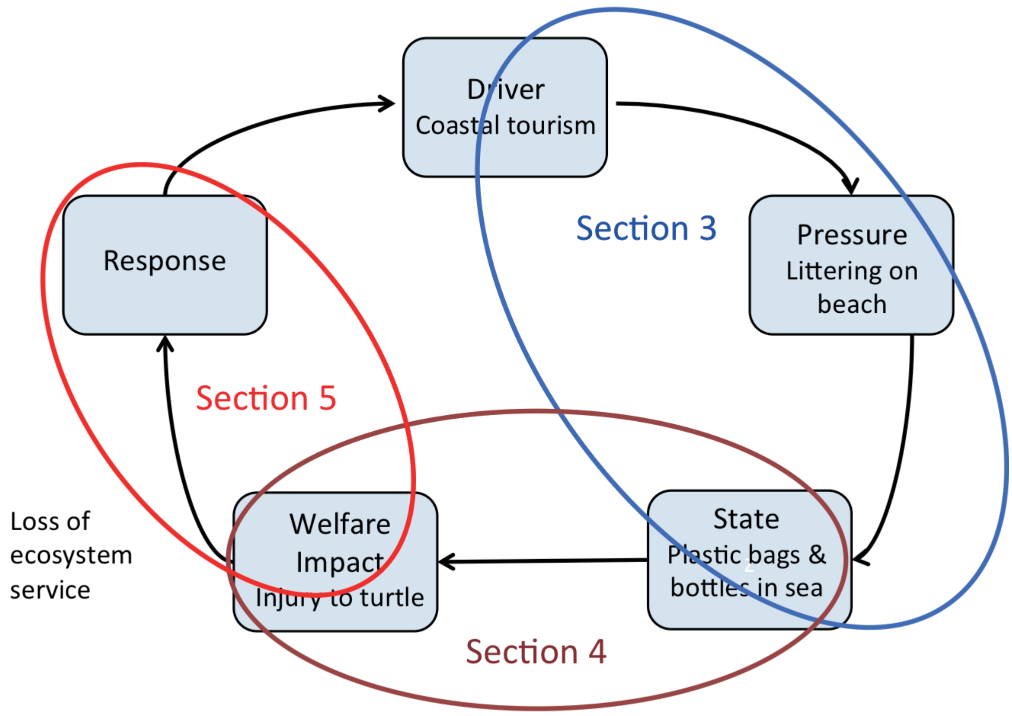

Figure 2.3 *Coverage of the DPSIR/DPSWR model by the three main sections of the report: Section 3 – sources and fate of microplastics; Section 4 – physical and chemical effects of microplastics; and, Section 5 – social aspects.*

3 SOURCES AND FATE OF MICROPLASTICS IN THE MARINE ENVIRONMENT

3.1 Introduction

3.1.1 *Defining 'plastic'*

Plastic is a term used in many fields, to describe the physical properties and behaviour of materials (e.g. soils, geological formations) as well as the name of a class of materials. The term 'plastic' is used here to define a sub-category of the larger class of materials called polymers. Polymers are very large molecules that have characteristically long chain-like molecular architecture and therefore very high average molecular weights. They may consist of repeating identical units (homopolymers) or different sub-units in various possible sequences (copolymers). Those polymers that soften on heating, and can be moulded, are generally referred to as 'plastic' materials. These include both virgin plastic resin[8] pellets (easily transported prior to manufacture of plastic objects) as well as the resins mixed (or blended) with numerous additives to enhance the performance of the material. Additives may typically include fillers, plasticizers, colorants, stabilizers and processing aids. In addition to the thermoplastics, marine debris also includes some thermoset materials such as polyurethane foams, epoxy resins and some coating films. Thermosets are cross-linked materials that cannot be re-moulded on heating. However, these too are generally counted within the category of 'plastics' in marine debris.

3.1.2 *Defining 'microplastics'*

Small pieces of floating plastics in the surface ocean were first reported in the scientific literature in the early 1970s (Carpenter and Smith 1972; Carpenter et al. 1972), and later publications described studies identifying plastic fragments in birds in the 1960s (Harper and Fowler 1987). It is unclear when the term 'microplastic' was first used in relation to marine debris. It was mentioned by Ryan and Moloney (1990) in describing the results of surveys of South African beaches, and in cruise reports of the Sea Education Association in the 1990s and by Thompson et al. (2004) describing the distribution of plastic fragments in seawater. No formal size definition was proposed at the time but generally the term implied material that could only be readily identified with the aid of a microscope. It has since become widely used to describe small pieces of plastic in the millimetre to sub-millimetre size range, although it has not been formally recognized.

> Particles in the size range 1 nm to <5 mm were considered microplastics for the purposes of this assessment

A more scientifically rigorous definition of plastic pieces might refer to nano-, micro-, meso-, macro- and mega-size ranges, although this has not yet been formally proposed for adoption by the international research community (Figure 3.1). At present, the lack of an agreed nomenclature, together with practical difficulties of sampling and measuring different size ranges in the field, has encouraged the widespread adoption of microplastics as a generic term for 'small' pieces of plastic.

The size definition of microplastics was discussed at the first international research workshop on the occurrence, effects and fate of microplastic marine debris in 2008, hosted by NOAA (Arthur et al. 2009). The participants adopted a pragmatic definition, suggesting an upper size limit of 5mm. This was based on the premise that it would include a wide range of small particles that could readily be ingested by biota, and such particles that might be expected to present different kinds of threat than larger plastic items (such as entanglement).

It was also recognized that the size ranges reported in field studies are constrained by the sampling techniques employed. For example, many studies have reported concentrations and size ranges of microplastics based on sampling with a plankton net, typically with a mesh size of 330 microns. Material <330 microns will be under-sampled. In this report we consider all available evidence; for example, including that relating to impacts of nano-particles, even though such particles cannot be detected at present in the environment on a routine basis.

3.1.3 *Origin and types of plastic*

Many different types of plastic are produced globally, but the market is dominated by 6 classes of plastics: polyethylene (PE, high and low density), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS, including expanded EPS), polyurethane (PUR) and polyethylene terephthalate (PET). Plastics are usually synthesized from fossil fuels, but biomass can also be used as feedstock. The production chain for the most common artificial and natural polymers is illustrated in Figure 3.2. The figure includes some examples of common applications, including the manufacture of microplastics for particular industrial or commercial applications.

[8] Resin – a semi-viscous liquid capable of hardening permanently http://en.wikipedia.org/wiki/Synthetic_resin

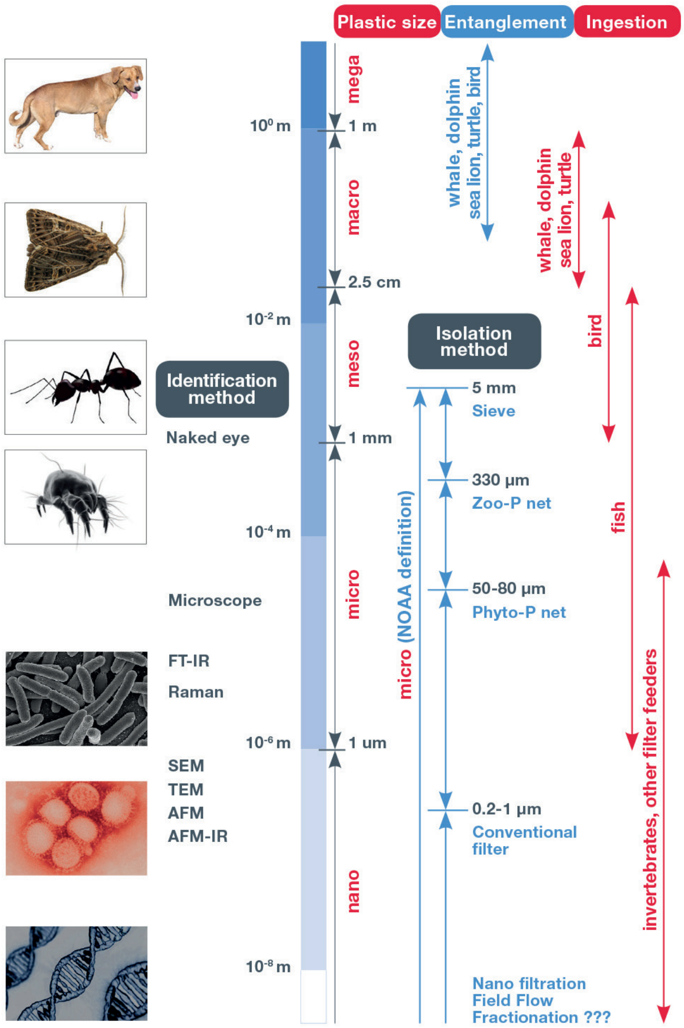

Figure 3.1 *Size range of plastic objects observed in the marine environment and some comparisons with living material. These size distinctions could form the basis of a more rigorous description.*

The availability of bio-based raw materials (feedstock) is expected to increase in the near future, providing alternative feedstock to fossil fuel raw materials. Being bio-based, however, does not necessarily make the plastic biodegradable; in fact, bio-based resins such as bio-PE or bio-PET are developed to mirror the properties of their conventional counterparts to allow same lifetime, applications and recycling capabilities. They are drop-in substitutes for the conventional plastic resin with the same structure. For instance a very small fraction of bio-based PET resin or bio-PET is presently used in soda bottles.

The bulk of common thermoplastics manufactured (PE, PP) are used in packaging products that have a relatively short useful lifetime that end up in the waste and litter streams rapidly. Plastics used in building construction (e.g. PVC) constitute about a third of the production but have much longer service lives. Figure 3.3 provides a summary of the major application areas for the commodity thermoplastics used in high volume.

Table 3.1 Frequency of occurrence of different polymer types in 42 studies of microplastic debris sampled at sea or in marine sediments (from Hidalgo-Ruz et al. 2012)

Polymer type	% studies (n)
Polyethylene (PE)	79 (33)
Polypropylene (PP)	64 (27)
Polystyrene (PS)	40 (17)
Polyamide (nylon) (PA)	17 (7)
Polyester (PES)	10 (4)
Acrylic (AC)	10 (4)
Polyoximethylene (POM)	10 (4)
Polyvinyl alcohol (PVA)	7 (3)
Polyvinyl chloride (PVC)	5 (2)
Poly methylacrylate (PMA)	5 (2)
Polyethylene terephthalate (PET)	2 (1)
Alkyd (AKD)	2 (1)
Polyurethane (PU)	2 (1)

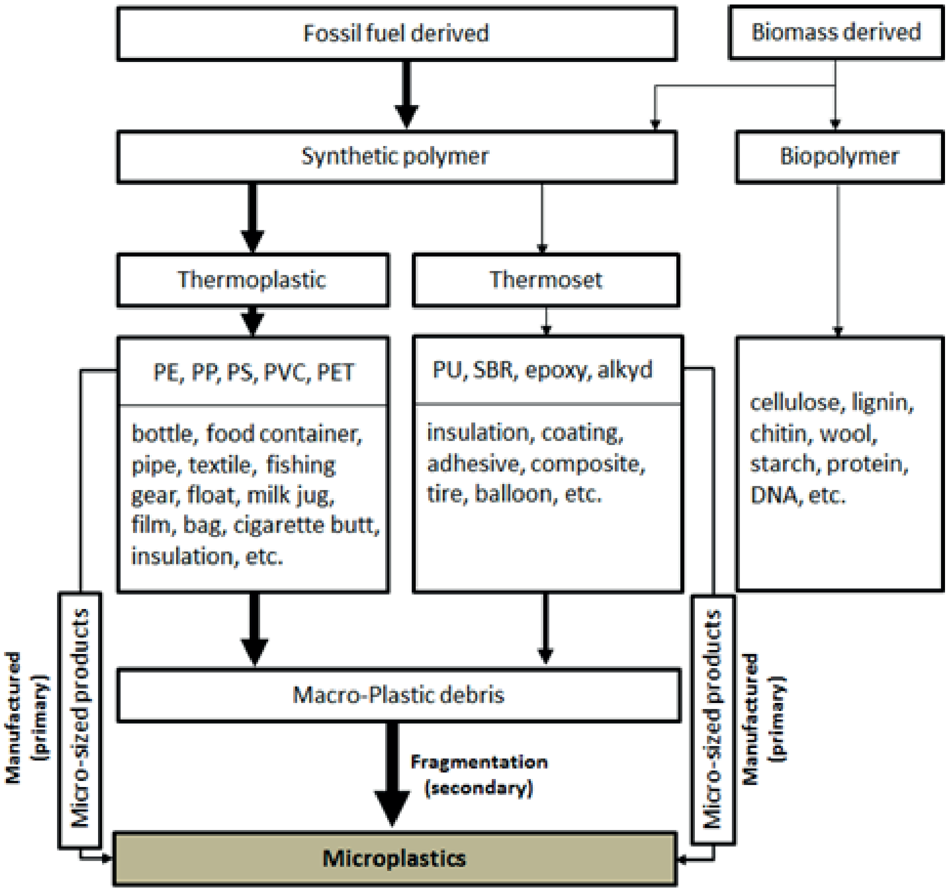

Figure 3.2. *Production of the most common artificial (plastic) and natural polymers, including some typical applications. Microplastics are manufactured for particular applications, such as industrial scrubbers or in personal cleaning products such as toothpaste. All plastics can be subject to fragmentation on environmental exposure and degradation into (secondary) microplastics. The proportion of plastic reaching the ocean to become plastic litter depends on the effectiveness of the re-use, recycle and waste management chain.*

Table 3.2 Selection of reported polymer compositions in a variety of media (see Table 3.1 for abbreviations)

Matrix	Size	Polymer composition	Reference
sediment/ shoreline	<1 mm	PES (56%), AC (23%), PP (7%), PE (6%), PA (3%)	Browne et al. (2011)
sediment/ sewage disposal site	<1 mm	PES (78%), AC (22%)	Browne et al. (2011)
sediment/ beach	<1 mm	PES (35%), PVC (26%), PA (18%), AC, PP, PE, EPS	Browne et al. (2008)
Sediment/ Inter- and sub-tidal	0.03–0.5 mm	PE (48.4%), PP (34.1%), PP+PE (5.2%), PES (3.6%), PAN[a] (2.6%), PS (3.5%), AKD (1.4%), PVC (0.5%), PVA[b] (0.4%), PA (0.3%)	Vianello et al. (2013)
sediment/ beach	1–5 mm (pellet)	PE (54, 87, 90, 78%), PP (32, 13, 10, 22%)	Karapanagioti et al. (2011)
water/ coastal surface microlayer	<1 mm	AKD (75%), PSA[c] (20%), PP+PE (2%), PE, PET, EPS	Song et al. (2014)
water/ sewage effluent	<1 mm	PES (67%), AC (17%), PA (16%)	Browne et al. (2011)
fish	0.13–14.3 mm	PA (35.6%), PES (5.1%), PS (0.9%), LDPE (0.3%) AC (0.3%), rayon[d] (57.8%)	Lusher et al. (2013)
bird	-	PE (50.5%), PP (22.8%), PC and ABS[e] (3.4%), PS (0.6%), not-identified (22.8%)	Yamashita et al. (2011)

[a] PAN: polyacrylonitrile, [b] PVA: polyvinyl alcohol, [c] PSA: poly(styrene:acrylate), [d] rayon – a semi-synthetic compound produced from pure cellulose, [e] ABS: acrylonitrile butadiene sytyrene

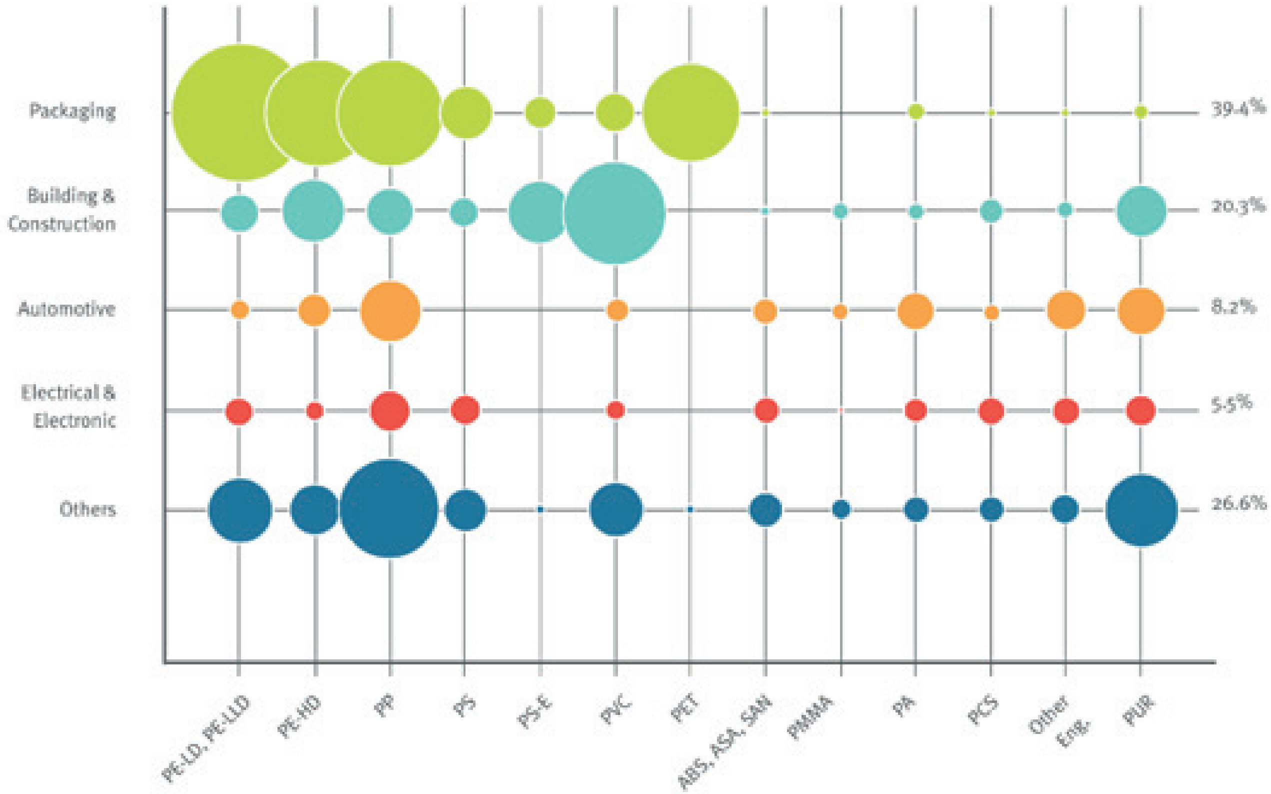

Figure 3.3. *European plastics demand (EU27 + Norway & Switzerland) by resin type and industrial sector in 2012. Nylons (mainly Nylon 6 and Nylon 66) in fishing gear applications and polystyrene, polyurethane foams used in vessel insulation and floats, are employed extensively in the marine environment. Figure courtesy of PlasticsEurope (PEMRG)/ Consultic/ECEBD.*

Table 3.3 Densities and common applications of plastics found in the marine environment (adapted from Andrady 2011)

Resin type	Common applications	Specific gravity
Polyethylene	Plastic bags, storage containers	0.91–0.95
Polypropylene	Rope, bottle caps, gear, strapping	0.90–0.92
Polystyrene (expanded)	Cool boxes, floats, cups	0.01–1.05
Polystyrene	Utensils, containers	1.04–1.09
Polyvinyl chloride	Film, pipe, containers	1.16–1.30
Polyamide or Nylon	Fishing nets, rope	1.13–1.15
Poly(ethylene terephthalate)	Bottles, strapping	1.34–1.39
Polyester resin + glass fibre	Textiles, boats	>1.35
Cellulose Acetate	Cigarette filters	1.22–1.24

It would be mistaken to assume that the volume or production trend of particular polymer types or applications inevitably corresponds with the pattern of plastic litter observed. The variety of resin types produced is reflected in the composition of plastic debris recovered from the marine environment (Tables 3.1, 3.2), but there are many societal, economic, technical and environmental factors at play in determining the distribution and composition of plastic litter.

One key property that influences the behaviour of plastics in the marine environment is the density with respect to the density of seawater. Objects containing a void, such as a bottle, will tend to float initially but once objects lose their integrity it is the density of the plastic that will determine whether objects float and sink. The rate at which this occurs will influence the distance the object will be transported from its source. The densities of common plastic resins are shown in Table 3.3. In addition, the development of biofilms on the surface of the particle may alter the density sufficiently to cause it to float, even if the 'clean' polymer is less dense than seawater.

3.2 'Primary' and 'Secondary' microplastics

The distinction between primary and secondary microplastics is based on whether the particles were originally manufactured to be that size (primary) or whether they have resulted from the breakdown of larger items (secondary). It is a useful distinction because it can help to indicate potential sources and identify mitigation measures to reduce their input to the environment. Primary microplastics include industrial 'scrubbers' used to blast clean surfaces, plastic powders used in moulding, micro-beads in cosmetic formulation, and plastic nanoparticles used in a variety of industrial processes. In addition, spherical or cylindrical virgin resin pellets, typically around 5 mm in diameter, are widely used during plastics manufacture and transport of the basic resin 'feedstock' prior to production of plastic products. Secondary microplastics result from the fragmentation and weathering of larger plastic items. This can happen during the use phase of products such as textiles, paint and tyres, or once the items have been released into the environment. The rate of fragmentation is controlled by a number of factors (Section 3.2.2).

In addition to synthetic microplastics, naturally occurring biopolymers (Figure 3.2) may be present in the oceans. However, regardless of their particle size these are less of a concern because they are generally biodegradable and are less hydrophobic compared to synthetic plastics. Most natural polymers readily biodegrade into CO_2 and H_2O in the oceans (Poulicek et al. 1991). Biopolymers have been always present in the oceans unlike the microplastics whose origins are recent.

Although microplastics greatly outnumber large plastic items in marine systems, they still make up only a small proportion of the total mass of plastics in the ocean (Browne et al. 2010). This means that even if we were able to stop the discharge of macroplastic litter into the sea today, on-going degradation of the larger litter items already at sea and on beaches would likely result in a sustained increase in microplastics for many years to come.

3.2.1 *Generation of microplastics*

As plastic marine debris on beaches and floating in water is exposed to solar UV radiation it undergoes weathering degradation and gradually loses its mechanical integrity (Pegram and Andrady 1989). With extensive weathering plastics generally develop surface cracks (Cooper and Corcoran 2010) and fragment into progressively smaller particles (Qayyum and White 1993; Yakimets et al. 2004). This is the most likely process for the generation of secondary microplastics in the marine environment. Weathering degradation would occur particularly rapidly on beaches and at relatively low rates in floating debris. In the aphotic and low-oxygen environments in mid-water or sediment, the degradation and fragmentation are particularly slow. Knowledge of the fragmentation rates and mechanisms for common plastics in debris are needed to reliably infer the rates of microplastics generation, their particle size distribution (PSD) and their impact on different biota. Such crucial information, especially the fragmentation mechanics, are not known reliably even for common plastics materials.

3.2.2 *Weathering degradation of plastics in the ocean*

The dominant cause of degradation of plastics outdoors is solar UV radiation, which facilitates oxidative degradation of polymers (Andrady et al. 1996). Photodegradation of common plastics such as polyethylenes, polypropylenes and polystyrene are free-radical mediated oxidation reactions (Celina 2013). The basic mechanism of this autocatalytic oxidation of common plastics is well established (Cruz-Pinto et al. 1994). During advanced stages of degradation, the plastic debris typically discolours, develops surface features, becoming weak and brittle (embrittle) in consequence over time. Any mechanical force (e.g. wind, wave, animal bite and human activity) can break the highly degraded, embrittled plastics into fragments.

Unlike virgin resin pellets, plastic products can incorporate a range of additives selected to modify the properties of the resin to meet the intended product application. These additives typically change the rate of oxidative degradation (and therefore weathering rates) of plastics. For example, UV and heat stabilizers and antioxidants used as additives often markedly retard light-induced degradation of the plastic material.

While the weathering of common plastics and their various formulations has been extensively studied in different environments, these studies have historically focused on the early stages of degradation that impact the useful lifetime of the product. Therefore, only very limited information is available on extensive oxidation and fragmentation of highly weathered plastics in the environment. Furthermore, there is virtually no information on weathering of plastics stranded on shorelines, floating in seawater (Andrady 2011; Muthukumar et al. 2011) and especially submerged in seawater or sediment. The effects of variables such as mechanical impact, salinity, temperature, hydrostatic pressure, presence of pollutants such as oil in seawater and bio-fouling (reducing UV exposure) on the rates of weathering according to various types of plastic items are virtually unknown.

Presently, there are no reliable methodologies to determine the age (or duration of outdoor exposure) of microplastics collected from the field, making it very difficult to investigate the degradation dynamics of microplastics in marine systems from collected field samples. While it is possible to quantify their extent of weathering by chemical analysis (FTIR[9] or Raman spectroscopy) the duration of their exposure in the marine environment cannot be deduced from such information. The highly variable rates of weathering of large plastic items due to differences in polymer type, additive composition and environmental factors complicate the assessment of age. Without an accurate assessment of age, developing three-dimensional models of microplastic abundance is somewhat unconstrained. For example, a particular plastic can move great distances either because it is in a fast current or because it simply has been in the ocean for a long time.

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[9] Fourier transform infrared spectroscopy

3.2.3 *Fragmentation of plastics*

As plastic debris photo-degrades, especially on land, objects begin to show characteristic surface cracks and pits (Cooper and Corcoran 2010). Localization of cracks to the surface layer (of a couple of 100 microns) is a consequence of the rapid attenuation of the damaging solar UV radiation as it transmits in the bulk of the plastic. The microplastics enter the environment from this embrittled weak surface layer of oxidizing plastic debris. These reactions continue on in the microplastic particles generated (Gregory and Andrady 2003), possibly progressing to yield particles at the nano-scale. However, the existence of nano-scale plastic in the ocean has not been reported as yet.

Both weathering and fragmentation rates are relatively rapid on beaches but generally several orders of magnitude slower, decreasing in the following order; plastics floating in water, in the mid-water column or in the marine sediments. The degradation on beaches may be enhanced by the higher UV radiation, higher sample temperatures and mechanical abrasion attained by the beach litter, although some interaction between those factors is expected. The relative rates of degradation of plastic in different compartments of the marine environments have not been quantified but in any event depends on the plastic. However, the degradation of floating plastic is well known to be impeded by low water temperatures. Biofouling of floating plastics in the ocean is ubiquitous, and often leads to a rich growth of surface fauna. This shields the plastic from solar UV and invariably increase its density and hence sinking out of the photic zone, preventing further UV-mediated degradation (Gregory and Andrady 2003; Ye and Andrady 1991). In the aphotic (dark) and cold sediment environment no appreciable degradation is expected. In cases where the surface foulants are foraged or otherwise removed, the plastic may subsequently resurface into the floating debris. However, virtually no information is available on the fate of plastics in aphotic marine sediment.

> Formation of microplastics in the ocean is influenced by a combination of environmental factors and the properties of the polymer

The general lack of research information on weathering and fragmentation of plastics in the marine environment is a very significant gap in relevant scientific knowledge. Lack of data on how the combined effects of photo-oxidation, fragmentation, mechanical abrasion and additive chemicals affect the formation of microplastics is a significant barrier to the production of reliable quantitative models to describe the behaviour of plastics and microplastics in the ocean.

3.2.4 *Biodegradation and Mineralization*

An understanding of terminology is important when describing the fate of plastics in the ocean. Complete degradation refers to the destruction of the polymer chain and its complete conversion into small molecules such as carbon dioxide or methane (also called mineralization). This is distinct from degradation which refers to an alteration in the plastic's properties (e.g. embrittlement, discolouring; Section 3.2.2) or its chemistry. Few plastics undergo complete degradation or mineralization in the marine environment. Plastics such as aliphatic polyesters, bacterial biopolymers and some bio-derived polymers are readily biodegradable in the environment. But often, these are more expensive to produce than commodity plastics. Ideally, biodegradability is desirable only after the useful service life when the product is in litter or marine debris. But, for most applications it is the durability of plastics that is the most sought after property; it is not clear if the existing biodegradable plastics deliver the requisite mechanical integrity and durability needed for most applications during their useful life.

3.3 Sampling methods for microplastics in the marine environment

3.3.1 *Introduction*

Sampling and analysis form our link to gaining knowledge about the natural world and are necessary for studying and assessing the environmental impacts of microplastics. Choices made in the design and selection of sampling and analytical methods determine what types of microplastics are sampled and what types of microplastics are detected; methods have limitations in particle size ranges and types of plastic materials targeted for measurement. Methods all have a given degree of specificity in what is targeted which depends on how the microplastics are extracted from the environmental matrix, such as seawater, sediment and biota.

Sampling and analysis is the first step in recording the presence or absence of microplastics in the ocean. Astute researchers in the early 1970s first realized the existence of microplastics in the open ocean (Carpenter et al. 1972) and there followed a steady trickle of confirmatory records until an explosion of interest and publication from about 2005 onwards (Figure 1.1). The ecological risk posed by microplastics (see Section 4) is calculated by combining the potential hazard with the probability of encountering that hazard. In order to assess probability it is important to gain an adequate understanding of the distribution of microplastics in the various environmental compartments.

Whether sampling at the sea surface, on the seabed or in the intertidal it is important to recognize that a variety of methods are available (Nuelle et al. 2014; Hidalgo Ruz et al. 2012). Currently there are no universally accepted methods for any of these matrices and the methods available all have potential biases. For example, the mesh size of the net or sieve used to extract microplastics from the bulk medium will influence the shape and size of particle captured. Separation of microplastics from a bulk medium becomes increasingly more challenging as the particle size decreases. For particles less than 100 μm visual separation is typically followed by forensic analysis, for example by spectroscopy. However, whether or not a particle is selected for subsequent forensic determination will be influenced by the degree to which it stands out against the background of other particulates in the sample. For example brightly coloured plastic fibres are conspicuous compared to more spherical natural sediment and are likely to be more completely sampled than plastic particles which have similar size and shape to that of natural sediment. Plastic particles of this latter type are hence likely to be under-sampled (Woodall et al. 2014). In addition the distribution of microplastics within a particular matrix is variable in time and space; for example particles can become redistributed vertically in the water column as a consequence of surface turbulence (Kukulka et al. 2012). Similarly particles can become buried or exposed on sandy beaches according to the prevailing sediment depositional regime (Turra et al. 2014).

Methods development for sampling and analysis of microplastics is an important, emerging area of research and development in marine litter science (e.g. Galgani et al. 2011). Many decisions are made in the process of designing and implementing sampling plans that can affect the end result of a study, and reliability and representativeness of the results. Ancillary parameters such as the sample volume, collection technique and sea state (Kukulka et al. 2012) are important to consider. This section provides a brief overview of sampling approaches.

3.3.2 *Sampling seawater*

Sampling for microplastics in the water column requires decisions about the size ranges to be targeted for sampling and analysis, then selecting the appropriate equipment. Concentrations of microplastics are usually too low to allow sampling by standard water samples, used for routine chemical analysis (e.g. 1–100 l). Some form of filtration is usually required to allow much larger volumes of water (many m-3) to be analysed. Some studies have employed bulk water sampling followed by vacuum filtration to capture microplastic particles (Ng and Obbard 2006; Desforges et al. 2014). More commonly, towed nets are utilized to filter large volumes of water in situ. A variety of surface-towing nets have been employed over time, designed primarily for sampling biological specimens (e.g. manta net, neuston net, ring net), with variable net mesh, net aperture and net length dimensions (Figure 3.4).

Towing protocols also vary in terms of the depth of water sampled (ranging from microns to tens of cm) and length of tow. Below the sea surface, obliquely towed nets have been employed to sample from the sea surface to a particular depth (e.g. Doyle et al. 2011), while multiple opening–closing nets sample discrete depth layers (Kukulka et al. 2012). Continuous plankton recorders (CPR)[10] collect plankton at a depth of 10 m and CPR samples have been analysed for microplastics (Thompson et al. 2004). Archived samples, both from towed nets and CPR tows, can provide a valuable resource for microplastic research.

When nets, sieves or filtration systems are used, the mesh size selected determines the minimum size that is targeted for sampling, although smaller particles will be captured (Goldstein et al. 2013). The majority of nets used currently have a nominal mesh size of 333 μm, with the CPR membrane being 285 μm. A number of factors such as net clogging influence the actual volume of water filtered and the sampling efficiency. This problem tends to increase in inverse proportion to the mesh size, and finer mesh nets are more liable to damage.

Figure 3.4 *Manta net being used to collect microplastics from surface waters in the Pacific, operated from S/V Kaisei, 2009. Image courtesy of Doug Woodring, Project Kaisei; http://projectkaisei.wordpress.com/the-science-team/.*

Results may be reported in terms of the abundance of microplastics (number km^{-2} or number m^{-3} seawater) or the mass of microplastics (total mass km^{-2} or mass m^{-3} seawater). Both metrics can be useful. However, surface nets can only be used to quantify abundance in a two dimensional area of sea surface; this is because surface nets are only partially submerged and can move vertically relative to the sea surface and so, unlike sub-surface nets, it is not possible to obtain reliable estimates of volume since the amount of water passing through the net will vary according to its vertical position in relation to the sea surface. Macroplastics, such as fishing debris, are far fewer in number but have a much greater mass, whereas microplastics are far more numerous but have a correspondingly lower mass. It is helpful if both mass and abundance are reported (Browne et al. 2010; Morét-Ferguson et al. 2012; Eriksen et al. 2013b). Mass is useful from an overall waste management perspective whereas number is likely to be of greater ecological significance. The mass of plastics is reported on a dry weight basis, as is the mass of natural inorganic particles. If comparisons are made with the abundance of living biota, such as zooplankton, it is essential to report the latter on the basis of wet weight, to avoid misleading interpretations on the relative quantities in the environment.

Improved techniques for bulk sampling and quantification of sub-millimetre sized particles in seawater are under development. Sampling of nanoparticles using towed nets is impractical (it would have to be a nano-membrane technology). The volumes required for detection of particles in the nano-size range is unknown, but likely to be in the same order as the volume needed for sampling microplastics that are >333 μm. Man-made nanoparticles in the nanotechnology size range (approximately 10–100 nm) are expected to be present in the environment as aggregates due to surface interactions (Quik et al. 2012),

[10] http://www.sahfos.ac.uk

and may not be homogenously distributed throughout the water column. Man-made nanoparticles are also likely to aggregate with any naturally occurring particles including those in the nano-size range. Particles in the 100 nm to 1 μm size range may not aggregate as strongly because surface interactions diminish with increasing particle size.

3.3.3 *Sampling sediments*

Sampling shoreline sediments is generally more straightforward than sampling seawater. However, sampling seabed sediments can require significantly more effort and resources. Sampling shoreline sediments for microplastics will vary according to the purpose of the study. Aspects to consider include the sampling depth (surface or vertical profile), the sample size, and the location in relation to the strandline (an accumulation zone). Sediment samples may undergo some form of separation in the field, such as a hand-held sieve (Figure 3.5), before further processing in the laboratory. Sampling finer-grained sediments will usually require more elaborate, laboratory-based separation techniques. Protocols are being developed for sampling shoreline sediments for marine debris, including some with particular regard to microplastics (e.g. Galgani et al. 2011).

Significant heterogeneity has been observed in the distribution of microplastics on beaches, both from surface transects and vertical profiles, emphasizing the need to include these considerations when designing an effective sampling strategy (Browne et al. 2010; Turra et al. 2014).

Figure 3.5 *Collecting microplastics from surface sediments by dry sieving, prior to carrying out compositional analysis; Busan, Republic of Korea.*

3.3.4 *Sampling biota*

Microplastics have been observed in several species of fish, bivalves, crustaceans and birds, with greatest focus on stomach content analysis (see Section 4). The stomach content of birds may contain plastic objects covering a wide size spectrum, whereas tissues tend to contain much smaller size ranges because smaller particles are more likely to be translocated from the GI tract (see Section 4). Sampling of birds relies on the recovery of dead specimens, usually from shorelines or coastal nesting sites, for example from mid-ocean islands. Objects observed may be several cm in diameter (e.g. cigarette lighter) but much smaller objects have also been found (Figure 3.6). The longest running monitoring programme operates in the North Sea, based on the analysis of recovered carcasses of the northern fulmar (*Fulmarus glacialis*) (van Franeker et al. 2011). This has been incorporated into a wider programme for environmental management, providing the basis for establishing an Ecological Quality Objective, based on the average mass of plastic in the stomach.

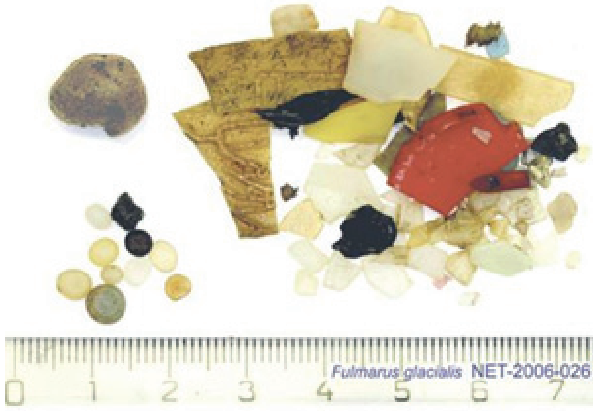

Figure 3.6 *Fragments of plastic, including microplastics, in the stomach contents of a northern fulmar (Fulmarus glacialis) from the North Sea. Image courtesy of OSPAR/KIMO, photograph Jan van Franeker.*

3.4 Determining the composition of microplastics

The analysis of environmental samples is a multi-step process that may include: sample preparation (such as sample homogenization or pre-concentration steps); extraction of microplastics; further purification ('clean-up') of the microplastic extract to remove additional non-microplastic matrix; and, detection and quantification of particles and identification of polymer types.

The specific composition of the microplastics in the sea is potentially very broad, reflecting the innovations in materials science over the past century that have brought a multitude of different polymers, copolymers and blends, combined with a variety of fillers and additives, giving each new material and each new product its characteristic physical–chemical properties. These innovations and the diversity of plastic material composition that results, has created challenges especially for laboratory technicians carrying out analytical work for targeted, quantitative analyses of microplastics in environmental matrices.

Besides targeting the plastic materials, the other major challenge is analysing the broad range of particle sizes of microplastics, which is important for understanding microplastic distribution, dispersal and dynamics but also the size-dependent biological effects (Section 4). Our ability to identify polymers of microplastics varies with particle size. Many studies to date have focused on large microplastics (1–5 mm), including pre-production resin pellets, which are visible to the naked eye and can be picked out of nets, beach sand or biota samples with tweezers. However, when smaller particles are targeted for analysis, they are harder to identify with the techniques presented below.

Separation

Microplastics need to be separated from other organic and inorganic particles materials in the sample prior to being counted, weighed and the polymer type identified. Initial separation can be achieved by density separation using solutions of varying density (e.g. $ZnCl_2$, NaI and sodium polytungstate). Co-extracted small organic particles, which may interfere with microscopic as well as spectroscopic identification, can be removed using hydrogen peroxide and sulphuric acid. It becomes increasingly difficult to distinguish plastic from non-plastic particles with decreasing size, using microscopic examination alone (Figure 3.7). Spectroscopy can confirm the presence of plastics and provide the polymer composition. In addition there have been recent advances in separation of microplastic from natural organic material. Such separation has been achieved in surface water samples using an enzymatic digest to remove planktonic organisms (Cole et al. 2014).

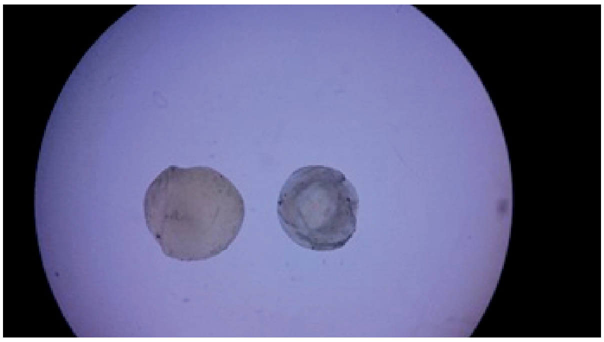

Figure 3.7 *Microscope image of a plastic pellet (left) and squid eye (right), both are approximately 1 mm in diameter.*

Raman and FTIR spectroscopy

Spectroscopy is required to confirm the identification of plastics, and their synthetic polymer for particles <1 mm in size. Microscopic FTIR (Fourier transformed infra-red) and Raman spectroscopy are the most promising methodologies in this regard. Current methods of analysis of field-collected microplastics make it possible to identify polymer types in particles as small as approximately 10 μm. These particles are visible under the light microscope and are still large enough to be identified as plastic using FTIR or Raman microscopy. These techniques rely on light transmission and wavelengths of light, and if the particle is smaller than these wavelengths, no reliable polymer IR spectrum can be achieved. This results in a major challenge to the identification of plastic particles in the 20 nm to 10 μm (10,000 nm) size range.

Fluorescently labelled nano- and micro-sized plastic particles can be utilized in laboratory experiments examining microplastic behaviour, allowing measurement through fluorescence detection. This approach is suitable to laboratory studies but does not solve the problem of measuring unknown and unlabelled plastic particles in environmental matrices. Development of new analytical techniques is required to extract, isolate and identify micro- and nano-sized plastic particles in the marine environment but to date no validated methods yet exist for field samples.

Method validation

The pioneering microplastic field surveys to date have taken place in the research and development (R&D) sphere and have been largely semi-quantitative. When a new chemical contaminant begins to be measured in environmental matrices, much effort is required to evaluate and improve existing methods and develop new products and initiatives, such as reference materials, proficiency testing schemes, ring tests, intercalibration exercises and standard operating protocols (SOPs). This helps to ensure that the quality of the data produced meets predefined performance criteria, which may lead to some form of accreditation. The field of microplastics research is at a less mature stage by comparison. In addition, the extremely varied nature of microplastics in the field, in terms of composition and distribution, makes it unlikely that such stringent procedures are either possible to achieve in a meaningful way or strictly necessary. The resulting data can still be of use for determining the relative state of the environment, and informing decisions on possible management measure.

3.5 Distribution of microplastics in the marine environment

3.5.1 *Influence of the source*

The distribution of microplastics in the ocean is influenced by the nature and location of the source of entry, as well as the subsequent complex interaction of physical, chemical and biological processes. There is growing information about all these aspects, but there remain major uncertainties about the spatial and temporal distribution of microplastics, and likely trends. Identification of the sources is important to gain an accurate assessment of the quantities of plastics and microplastics entering the ocean, to provide an indication of regional or local 'hot spots' of occurrence, and to determine the feasibility of introducing management measures to reduce these inputs.

Primary microplastics are manufactured particles designed for particular applications (Section 3.2.1). A proportion of these particles is released from discrete point sources such as factories and sewage discharges. In addition, there is evidence of virgin resin pellets being lost during transport at sea[11] or during transshipment. There is also evidence of point source inputs

[11] Loss of PP pellets from the container vessel Yong Xin Jie near Hong Kong during Typhoon Vicente, August 2012; http://e-info.org.tw/node/79464

near to plastic processing plants where the abundance of plastic pellets or powders can be considerable (e.g. Norén and Ekendahl 2009). However, there is a lack of quantitative data on diffuse inputs via small, but regular and persistent, losses from multiple sources such as loss of plastics pellets from processing plants or of micro-beads discharged through domestic wastewater systems. One study estimated that 200 tons of micro-beads were used in the USA annually, in personal care products, and that approximately 50% of these would pass through sewage treatment to the ocean (Gouin et al. 2011).

Estimating the distribution of microplastic based on secondary inputs is particularly difficult since it relies on accurate assessment of the distribution of macro-plastics and the degradation process (which is also not well known). There is a lack of data comparing the abundance of macroplastics and microplastics at local scales. However, it is unlikely that the abundance of microplastic and macroplastics will be closely correlated as large and small objects will be influenced by environmental processes to differing degrees. For example, larger floating objects will be more prone to transport by winds than microplastics (Browne et al. 2010), and this is reflected in circulation models used to simulate the transport of micro- and macro-debris (Eriksen et al. 2014; Lebreton et al. 2012).

In some cases it is possible to link the presence of microplastics to particular industrial sectors. For example, data from shorelines in southern Korea indicate that the great majority of microplastic fragments are composed of EPS (Heo et al. 2013). The prevalence in this region is explained by the wide scale use of EPS in buoys for aquaculture installations. Similar high occurrences of EPS have been reported from Japan and Chile, also linked to coastal aquaculture. In most other regions the composition of microplastics will be much more varied and less dominated by a single component, presenting great difficulties in attributing occurrence to a particular source.

3.5.2 *Distribution of microplastics based on direct observations*

Understanding how microplastics are distributed both horizontally and vertically in the oceans is a prerequisite to assessing potential impacts. In short, there can be no direct impacts where there are no, or very few, microplastics. However, there is likely to be a greater potential for impacts if microplastics accumulate in specific locations. Before we can properly assess risks it is therefore essential to understand how microplastics are distributed in space, for example between broad geographic regions (temperate, tropical, polar); between open and relatively enclosed seas (e.g. the Mediterranean versus the Pacific Ocean); between compartments including sea surface, water column and benthic sediments; and between coastal habitats (e.g. salt marsh, mangrove, coral reef, mussel bed). It is also important to quantify the distribution across international boundaries as differences in production, consumption, usage and waste management practices have the potential to influence inputs to the ocean and are essential when considering measures aimed at reducing such inputs.

Surface ocean

The geographical coverage of microplastics sampling is growing each year. The bulk of microplastics surveys have so far been conducted in the northern hemisphere, and the majority of surveys are of the sea surface using plankton nets and on shorelines. Microplastics at the sea surface have been reported in the coastal ocean (Carpenter et al. 1972; Doyle et al. 2011; Reisser et al. 2013), the open ocean (Carpenter and Smith 1972; Law et al. 2010; Goldstein et al. 2012; Eriksen et al. 2013b), and in enclosed or semi-enclosed seas such as the Mediterranean Sea (Collignon et al. 2012; Law et al. 2014), North Sea (Dubaish and Liebezeit 2013) and South China Sea (Zhou et al. 2011). Three studies have reported microplastics in the near-surface water column (typically upper tens of metres; Lattin et al. 2004; Doyle et al. 2011; Kukulka et al. 2012) but not in the deeper water column beyond ~200 m depth, possibly because there have been no dedicated sampling efforts in this regime. The North Atlantic and North Pacific Oceans and Mediterranean Sea are the best-sampled regions of the ocean for floating microplastics (Figure 3.8). Microplastics are widespread in the oceans across temperate and tropical waters, and have been reported near to population centres and also in considerable concentrations in more remote locations, as a result of long-distance transport in the surface ocean. While there is considerable spatial variability in reported abundances, studies have reported at least the presence of microplastics at all of the locations they examined. A key challenge is to scale up from regional seas and ocean systems in order to assess the quantities of plastic and microplastic contamination at a global scale. Such work is essential in order to better estimate the scale of the problem and to facilitate monitoring efforts that will be essential to evaluate the success of measures to reduce inputs of debris to the ocean. Considerable progress has been made recently in estimating quantities of surface plastic on a global scale (Cózar et al. 2014; Eriksen et al. 2014). There is also evidence of substantial accumulations of plastic and microplastics on the sea bed including areas of the deep sea down to 5766 m in the Kuril-Kamchatka Trench in the NW Pacific (Fischer et al. 2015), but estimating total quantities of plastic debris in the deep sea will be much more challenging than at the sea surface (Pham et al. 2014; Woodall et al. 2014).

Shorelines and seabed

The majority of studies on beaches have focused on larger items of debris. However, microplastics have also been reported on beaches at numerous locations worldwide (e.g. Gregory 1978; Wilber 1987; Browne et al. 2011; do Sul et al. 2009; Hidalgo-Ruz et al. 2012). Industrial resin pellets have frequently been reported as they are easily identifiable by eye and have been targeted for study of absorbed contaminants by the International Pellet Watch programme (Takada 2006). Most studies survey only the surface sediments, although some have collected samples below the surface (e.g. Claessens et al. 2011). Turra et al. (2014) found plastic pellets were distributed in beach sediments in Brazil to depths of at least 2 metres, with greater concentrations consistently being observed in sub-surface layers relative to the current beach surface.

There are several studies indicating that the abundance of microplastics in subtidal sediments can be greater than on shorelines (Thompson et al. 2004; Browne et al. 2011; Claessens et al. 2011). There have been very few reports of microplastics in deep sea sediments, but one study recorded their occurrence on the seabed at a water depth of 5000 m (Van Cauwenberghe et al. 2013c).

Spatial and temporal trends

Only a small number of data sets have sufficient sampling to begin to tease apart spatial and temporal trends in microplastic concentration. This is exacerbated by inherent space–time variability in environmental drivers, together with microplastic sources and transport between the various compartments (surface ocean, intertidal, seabed). Thompson et al. (2004) published the first assessment of microplastic abundance over time, and found that while the amount of microplastics measured between the British Isles and Iceland increased from the 1960s and 1970s to the 1980s and 1990s, no significant increase was observed between the later decades. Similarly, Law et al. (2010) found no significant increase in annual mean concentrations of floating microplastics in the western North Atlantic subtropical gyre between 1986 and 2008, or in the eastern North Pacific subtropical gyre between 2001 and 2012 (Law et al. 2014). Goldstein et al. (2012) reported a significant two-order-of-magnitude increase in floating microplastic in the eastern North Pacific from 41 measurements collected from 1972 to 1987 and 1999 to 2010; however, data in the later time period were deliberately collected in the predicted region of highest plastic concentration, while earlier microplastic data were incidentally collected in more broadly dispersed samples. While it is possible, and even likely, that concentrations of floating microplastic in the ocean are increasing over time (based on increased plastic production, use and disposal since the 1950s), it is a challenging task to isolate such a trend given the large variability in the data and the size of the ocean that would need to be regularly and randomly sampled to properly account for this variability.

The concentration of microplastics recorded is directly influenced by the sampling approach used, which can vary significantly between studies. There is a need for greater harmonization to facilitate comparability (Galgani et al. 2011). Comparing concentrations between matrices is fraught with difficulty because the methods used are quite different, for example to sample sediment and bulk seawater.

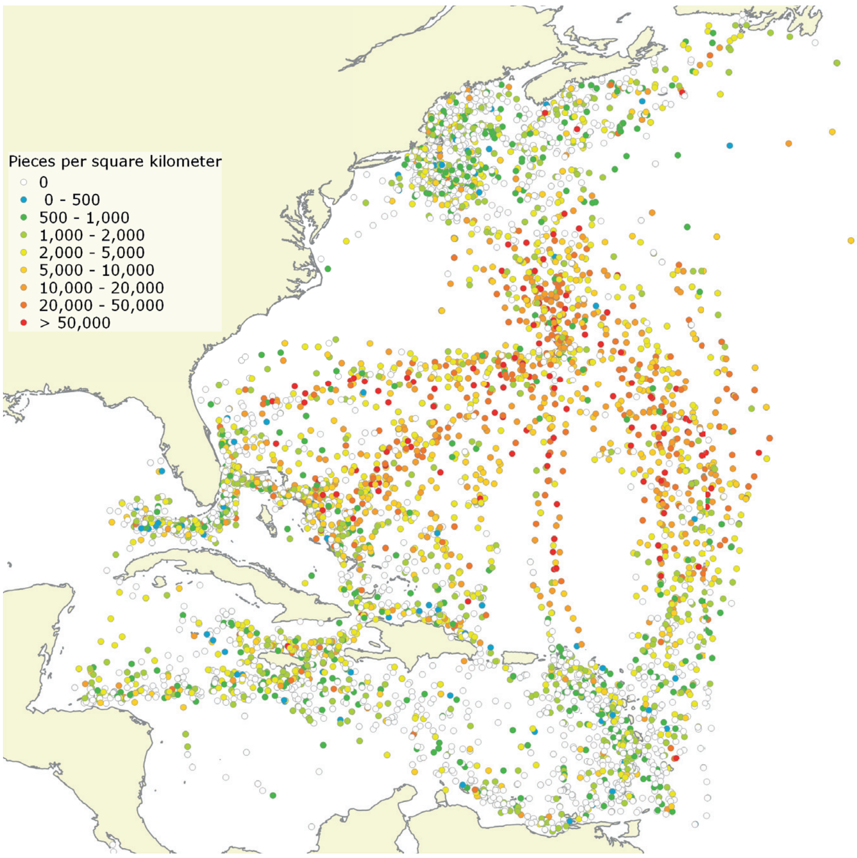

Figure 3.8 *(a) Distribution of microplastics in the western North Atlantic, 1986-2008. Sea Education Centre, Woods Hole, MA (downloaded from: http://onesharedocean.org/open_ocean/pollution/floating_plastics)*

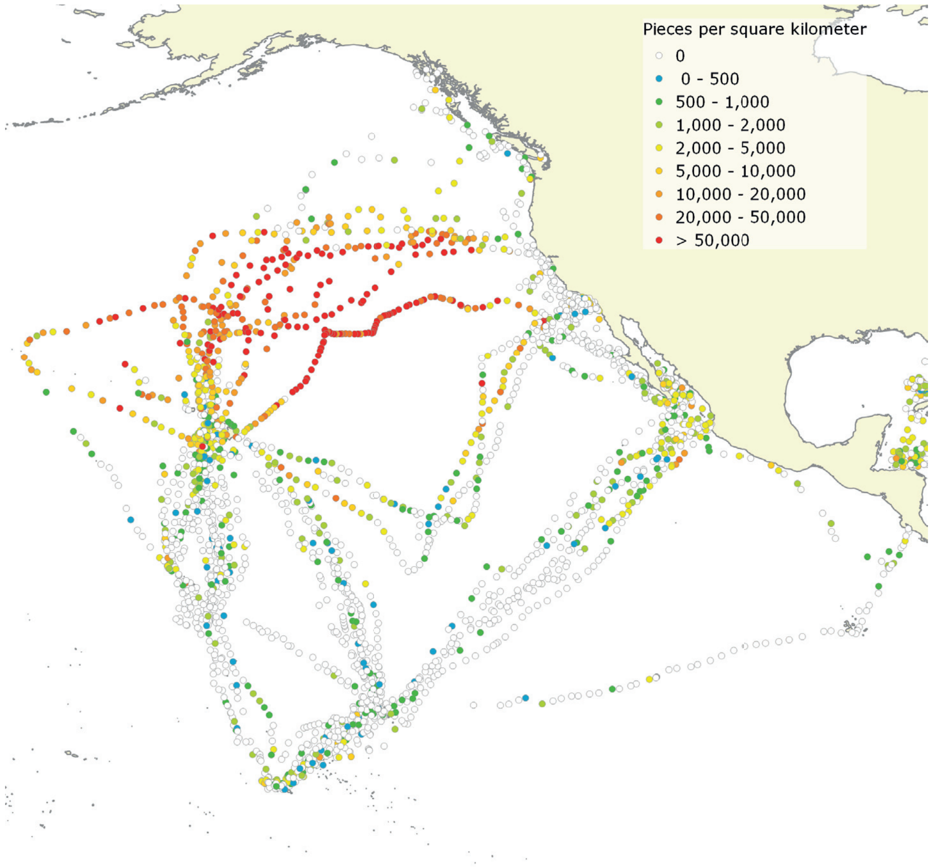

Figure 3.8 *(b) Distribution of microplastics in the western North Pacific, 2001-2012. Sea Education Centre, Woods Hole, MA (downloaded from: http://onesharedocean.org/open_ocean/pollution/floating_plastics)*

Table 3.4. Observations of microplastics in seawater

Location	Sampling method	Reported concentration	Reference
Seawater measurements			
North Sea - open water - sea surface	Continuous plankton recorder; 280 µm mesh silkscreen	Maximum concentration 0.04 – 0.05 fibres/m^3	Thompson et al. 2004
Western North Atlantic - coastal - sea surface	Plankton net, 333 µm mesh	0.01 – 14.1 particles/m^3	Carpenter et al. 1972
Western North Atlantic - open ocean - sea surface	Plankton net, 0.33 mm mesh	47 – 12,080 particles/km^2	Carpenter and Smith 1972
Western North Atlantic - coastal and open ocean - sea surface	Plankton net, 0.947 mm mesh	60.6 – 5465.7 particles/km^2 (mean values)	Colton et al. 1974
Western North Atlantic - open ocean - sea surface	Plankton net, 335 µm mesh	20,328 particles/km^2 (mean near 30°N)	Law et al. 2010
Eastern North Atlantic - coastal - sea surface	Plankton nets, 180 µm and 280 µm mesh; continuous plankton recorder, 335 µm	0.01 – 0.32 cm^3/m^3	Frias et al. 2014
Mediterranean Sea - sea surface	Plankton net, 333 µm mesh	Mean concentrations: 0.116 particles/m^2, 0.202 mg/m^2	Collignon et al. 2012

Table 3.4. Observations of microplastics in seawater *(cont.)*

Location	Sampling method	Reported concentration	Reference
Mediterranean Sea - sea surface	Plankton net, 200 μm mesh	Mean concentrations: 0.94 particles/m^3 (Ligurian Sea) 0.13 particles/m^3 (Sardinian Sea)	Fossi et al. 2012c
North Pacific - open ocean - surface	Plankton net, 150 μm mesh	Maximum concentrations: 34,000 pieces/km^2, 3.5 mg/m^2	Wong et al. 1974
North Pacific - open ocean - sea surface	Plankton net, 333 μm mesh	Mean concentrations: 80 particles/km^2 (Bering Sea) 3370 particles/km^2 (subarctic) 96,100 particles/km^2 (subtropical)	Day and Shaw 1987
Eastern North Pacific - open ocean - sea surface	Plankton net, 330 μm mesh	31,982 – 969,777 pieces/km^2 64 – 30,169 g/km^2	Moore et al. 2001
Eastern North Pacific - open ocean - sea surface	Plankton net, 335 μm mesh	In accumulation zone: 156,800 pieces/km^2 (mean) 33,909 pieces/km^2 (median)	Law et al. 2014
Western North Pacific - Kuroshio Current - sea surface	Plankton net, 330 μm mesh	Mean concentrations: 174,000 pieces/km^2, 3600 g/km^2	Yamashita and Tanimura 2007
Australia - coastal and open ocean - sea surface	Plankton nets, 333 and 335 μm mesh	4256 pieces/km^2 (mean) 1932 pieces/km^2 (median)	Reisser et al. 2014

Table 3.5. Observations of microplastics in seawater and sea ice

Location	Sampling method	Reported concentration	Reference
Seawater measurements			
UK estuarine beach - surface to 3 cm deep	0.25 m^2 quadrats, NaCl flotation	1 – 8 particles per 50 ml sediment	Browne et al. 2011
Belgian marine sediments - beach and subtidal	Van Veen grab for subtidal sampling; sediment cores; flotation in saline solution, 38 µm mesh sieve	Mean concentrations: 166.7 particles/kg dry sediment (harbours) 97.2 particles/kg dry sediment (sublittoral) 92.8 particles/kg dry sediment (beaches)	Claessens et al. 2011
Portugal beaches - surface to 2 cm deep	0.5 m^2 and 2 m^2 quadrats, flotation in NaCl solution, 1 µm filter	Mean concentrations: 185.1 items/m^2 36.4 g/m^2	Martins and Sobral 2011
Lagoon of Venice - surface to 5 cm deep	Box corer, flotation in NaCl solution, 32 µm mesh sieve	672 – 2175 particles/kg dry weight	Vianello et al. 2013
Equatorial western Atlantic island beaches - surface to 2 cm deep	900 cm^2 quadrats, 1 mm mesh sieve	4.6 x 10^{-3} g marine debris per gram of sand (mean)	Ivar do Sul et al. 2009
Brazil beaches - surface to 2 m deep	1 m^2 trenches, sampling plastic pellets at 0.1 m intervals from 0.2 to 2 m depth, flotation in seawater, 1 mm mesh sieve	0.10 – 163.31 pellets/m^3	Turra et al. 2014
Singapore mangroves - surface to 4 cm deep	1.5 m^2 quadrats, flotation in saline solution, 1.6 µm filter	3.0 – 15.7 particles per 250 g dry sediment	Nor and Obbard 2014
Kuril-Kamchatka Trench (NW Pacific) - surface to 20 cm deep	Box corer (0.25 m^2 sampling area), 300 – 1000 µm mesh sieves	60 – 2020 particles/m^2	Fischer et al. 2015
Sea Ice			
Arctic Ocean sea ice	Sea ice cores, melted and filtered with 0.22 µm filters	38 – 234 particles per m^3 of ice	Obbard et al. 2014

3.5.3 *Transport pathways*

Surface transport

The most extensive spatial pattern in sea surface microplastics is their accumulation in large-scale subtropical ocean gyres, where convergent ocean surface currents concentrate and retain debris over long time periods (e.g. Wilber, 1987; Law et al. 2010; Goldstein et al. 2012; Law et al. 2014), and in enclosed seas such as the Mediterranean (Collignon et al. 2012) where surface water is retained for long periods of time because of limited exchange with the North Atlantic. These retention mechanisms are further supported by results of numerical models that predict where floating debris will accumulate in the surface ocean based on ocean physics (Section 3.4.4). While the highest concentrations of floating debris have been observed in subtropical gyres and in the Mediterranean Sea, there is significant small-scale variability within these regions, with order of magnitude variations in concentration observed on scales of 10s of km (Law et al. 2014).

Floating microplastic acts as a passive tracer and is therefore transported in the direction of net flow, which results from a combination of large-scale (1000s km) wind-driven currents as in the subtropical gyre down to centimetre-scale turbulent motion, and including all scales in between from eddies and surface and internal waves, for example. In addition, while the gyres are relatively steady circulation features in time, smaller scale water movements are highly time-dependent because they are locally driven in response to often quickly changing wind and sea conditions. Thus, while it is easy to predict that floating microplastic will be encountered near the centre of subtropical gyres at any given time, one cannot predict the concentration of debris at a particular time and location within the gyre. Similarly, one is unlikely to encounter large amounts of floating microplastic in boundary currents at the edges of gyres, or at equatorial or sub-polar latitudes; however, microplastic might still be found in these places at any particular time, especially if located near a debris source.

There are additional considerations, for example estimates of the rates of transfer between reservoirs in marine habitats, organisms or compartments. For example if, in what is probably an unrealistically simplistic scenario, the ultimate fate for most microplastics was the sea bed then understanding the amount of time spent at the sea surface or in the water column, while en route to the sea bed, would be critical to our understanding of rates of accumulation, relative abundance in each of these compartments and how long it might take for any changes in the quantity of microplastics entering the ocean to be apparent. Therefore, in undertaking these assessments it is important to know not only the abundance of microplastics, but also the size distribution, shape and polymer type; all of these have the potential to influence the type and magnitude of any associated impacts.

Vertical transport in seawater

It is important to note that oceanic currents are reasonably well known, but vary with depth. To further complicate matters, if particles change buoyancy, their pathways will depend on time in a specific vertical layer in the ocean. Because of their likely slow sink rates microplastic dispersal might be influenced by varying circulations at different depths. A study by McDonnell and Buesseler (2010) found sinking rates of marine particles to vary between 10 to 150 metres per day. In the deep ocean this means particles would take about one month to a year to reach the sea floor from the surface. Typical horizontal currents are on the order 1 metre per second, but decay quite rapidly to just a few centimetres a second at 1000 metres. Thus, a sinking particle may transit from 1 kilometre (fast sinking rate) to 35 kilometres (slow sinking rate) horizontally from its point of origin. This assumes the particle is continuously sinking, however, it is also possible particles spend a long time in the surface layer before sinking, in which case the horizontal displacements would be much greater.

The role of biofouling on density changes in microplastics is poorly known. Some larger items of microplastics such as pre-production pellets support colonization by macrobiotic fouling organisms (Gregory 2009) and items are likely to develop a microscopic biofilm (Lobelle and Cunliffe 2011; Zettler et al. 2013). Experiments indicate that biofouling of large plastic items can cause sinking through increased density (Ye and Andrady 1991).

Retention in biota and sediment

Microplastics can be taken up and retained for varying periods by marine organisms, which can potentially transport them significant distances. In the case of seabirds and seals, microplastics can even be carried back onto land. Microplastics may be trapped in sediments for long periods, although wave action and beach erosion can release particles from at least shallow water sediments. Microplastics might be more readily re-suspended from bottom sediments than larger plastic items simply because they are small and of low density compared to natural sediment and hence more easily disturbed by wave action, currents or bioturbation. Hence it is important to consider temporary and permanent sinks of microplastic.

3.5.4 *Modelling the transport and distribution of microplastics*

Given the challenges and limitations in assessing microplastic distributions by direct observations, various techniques have been employed to *estimate* where microplastics might be found and in what numbers. These include both theoretical and numerical modelling. Both approaches involve deriving an estimate based on known factors that include sources, sinks and forcing. Ideally two of these are known and the model is used to estimate the third. In the specific case of marine microplastic either the source or sink may be known, and the transport mechanism is presumed to be ocean currents. Thus the model would utilize known input/output and transport to estimate output/input. The transport mechanisms include ocean (and in the case of aerosols, atmospheric) currents and translocation by marine organisms. The former can be estimated with reasonable accuracy using numerical ocean modelling; the latter is much more challenging. An example of these approaches comes from modelling of the track taken by macroscopic items of tsunami debris across the Pacific Ocean from Japan to the western seaboard of the USA (Lebreton et al. 2012. There are several examples of the application of numerical models to study a subset of these, including tracking individual large items (debris, boats, etc.), subsurface items (Wilcox et al. 2013), dispersal of smaller particles (e.g. oil spills, planktonic larvae), formation and distribution of water masses, etc.

Using numerical models to track marine debris has thus far focused mainly on surface floating debris (Lebreton et al. 2012; Maximenko et al. 2012; van Sebille et al. 2012). Due to the nature of this particular problem, models start with an initial condition, for example a point source of known amount. Relevant forcing is then primarily wind and wind-driven near-surface currents. The model integration then gives an estimate of the pathways and landing points for the particles.

Extending this to examining pathways of marine microplastic is not straightforward for many reasons. Firstly, the initial conditions (sources) are not well known. Lebreton et al. (2012) experimented using different source points for debris, including the area of urbanized watershed, coastal population density, and shipping density, and their study also included estimates of landing locations (deposition on shore). Maximenko et al. (2012), in contrast, assumed a continuous distribution of particles. In both studies the particles aggregated in discrete regions of the open ocean, but in the latter case the simulation failed to reproduce the observed higher concentrations in the Mediterranean. The output from the Lebreton model was used to estimate the relative abundance of microplastics in Large Marine Ecosystems (Figure 3.9), as a contribution to the GEF Transboundary Waters Assessment Programme (http://geftwap.org). The approach cannot provide an accurate estimate of actual abundances, but can provide useful insights to help inform management decisions on future funding decisions.

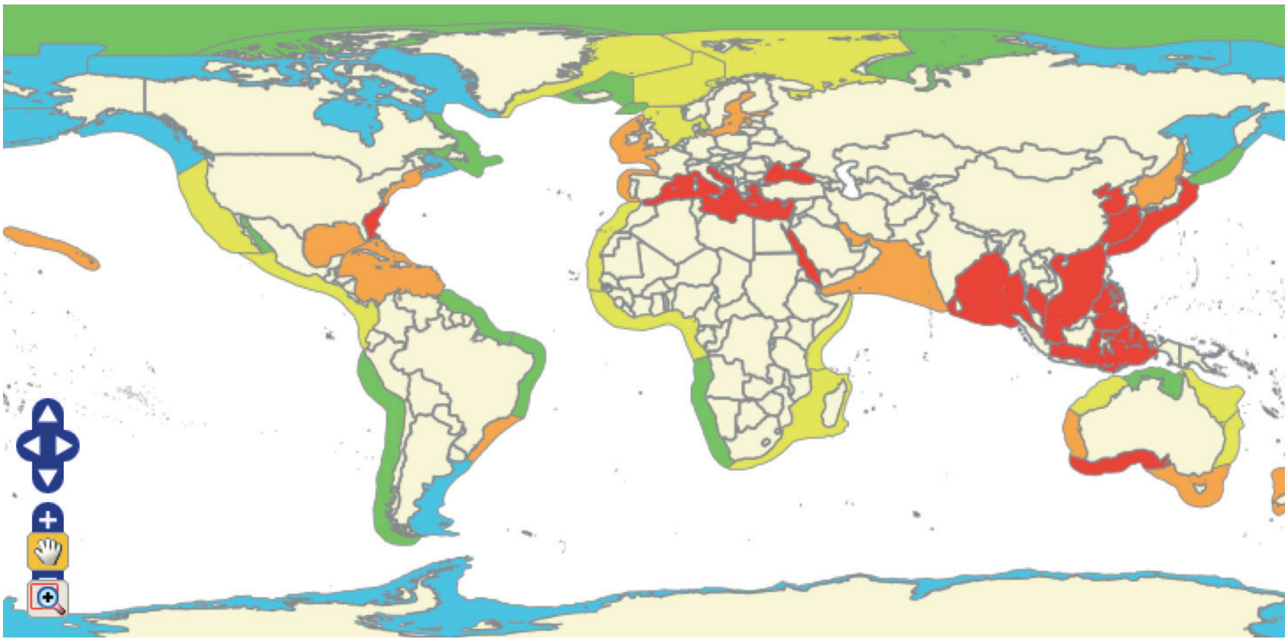

Figure 3.9. *Estimated relative distribution of microplastic abundance in Large Marine Ecosystems, based on Lebreton et al. 2012. Screen shot from www.oneshared.ocean.org*

Secondly, particles may change density over time adding an additional (vertical) dimension. Most studies have assumed a constant density, assuming that surface currents are the sole drivers. Thirdly, the ultimate fate of these particles is not well known, but it likely includes vastly different geophysical regimes, including open-ocean, benthic, near-shore and on-shore. Finally, these particles become integrated into marine ecosystems by biological uptakes and discharges (redistribution). Thus, particle pathways cannot be treated as "passive" tracers in ocean currents. Nonetheless, numerical modelling may provide important insights into estimating pathways and thus locations of marine microplastic. One way to do this would be an extension of modelling work used to study floating debris, and to add a vertical component based on known rates of density changes.

Regional modelling studies have attempted to identify local accumulation areas at-sea (Pichel et al. 2007; Martinez et al. 2009; Eriksen et al. 2013b) and on-shore (Kako et al. 2007). Pichel et al. (2007) investigated the accumulation of debris in the North Pacific Subtropical Convergence Zone (STCZ) and were able to relate various forcing (e.g. winds) and indicators of convergence (e.g. sea surface temperature gradients) to derive a Debris Estimated Likelihood Index (DELI).

In summary, numerical models represent a tool for estimating pathways, sources and sinks of marine microplastics. In order to be effective however, the models need to have accurate descriptions of the initial conditions (sources for forward trajectories or sinks for backward trajectories) and changes in particle density. Finally, it should be pointed out that the particular issue of microplastic pathways in the ocean, and the application of numerical models of circulation, is in some sense a matter of statistics. Ocean models could therefore be used to estimate or predict areas of accumulation in a broad sense (percentages, likelihood, etc.) but it would be extremely difficult to apply these techniques to individual particles.

3.6 Recommendations for further research

- Generate data on weathering-induced fragmentation of at least the PE, PP and EPS plastics in the marine environment.
- Examine the influence of weathering on particle sorption characteristics.
- Establish improved and validated methods for sampling at the sea surface in sediments and in biota.
- Organize inter-calibration exercises and harmonize reporting units to make future data comparable around the world.
- Design sampling strategies to establish time trends and spatial trends in selected marine areas.
- Conduct additional sampling of sub-tidal and in particular deep sea sediment.
- Investigate nano-sized plastic particles in marine organisms as a critical input for future risk assessments.
- Develop more realistic transport models, to incorporate variable particle properties, 3D circulation and sources of plastics and microplastics.

4 EFFECTS OF MICROPLASTICS ON MARINE BIOTA

4.1 Introduction

The potential ecological and human health risks of microplastics are relatively new areas of research, and there is currently a large degree of uncertainty surrounding this issue.

Risk is a function of hazard and exposure (dose), and evaluating the risks from microplastics requires knowledge of hazard (i.e. the potential of microplastics to cause adverse effects through plausible mechanisms), exposure levels (i.e. the quantities of microplastics detected in the environment, including in living organisms) and their effects (identification of dose-response relationships and threshold levels). The risk assessment of microplastics in the marine environment is still in the hazard characterization phase due to limited information on exposure levels and established effect levels. Rational policy measures are difficult to develop given the current incomplete and uncertain risk analysis, and it is important that priority should be given to systematically improving assessment of the risk of microplastics in the world's oceans.

The definitions of hazard, exposure and risk used in this document follow the International Union of Pure and Applied Chemistry (http://www.iupac.org). Hazard is a set of inherent properties of a substance, mixture of substances or a process involving substances that, under production, usage or disposal conditions, make it capable of causing adverse effects to organisms or the environment, depending on the degree of exposure; in other words, it is a source of danger. Consider the hazards posed by plastics in the environment that differ based on size of the plastic debris and size of the organism. Exposure is the concentration, amount or intensity of a particular physical or chemical agent or environmental agent that reaches the target population, organism, organ, tissue or cell, usually expressed in numerical terms of concentration, duration and frequency (for chemical agents and microorganisms) or intensity (for physical agents). Risk expresses either the probability of adverse effects caused under specified circumstances by an agent in an organism, a population or an ecological system; or the expected frequency of occurrence of a harmful event arising from such an exposure.

Particles have their effect as a consequence of several potential factors, relating either to physical or chemical effects. For physical effects particle size and shape will be important. For chemical effects two key factors act together to determine their potential to cause harm: their large surface area and reactivity, and the intrinsic toxicity of the polymer and absorbed contaminants. Smaller particles have more surface area per unit mass and therefore will likely exhibit more intrinsic toxicity. From this perspective, smaller microplastic particles less than 100 micrometres may be considered to be more likely to cause chemical effects in marine organisms, but this hypothesis has not been robustly tested. Shapes of microplastic range from fibres to spheres with varying surface roughness and sizes include fine particles (~200 nm) down to ultrafine particles (<200 nm) and it is likely that far smaller sizes in the size range of nanoparticles occur in the environment as well. It is important to note that the toxicities of engineered nanoparticles (ENP) are themselves diverse, and the toxicity of a given ENP may not be directly extrapolated to secondary nanoplastics (Andrady 2011).

4.2 Exposure

4.2.1 *Exposure through the gills*

External exposure results when microplastics contact the outer surfaces of the organism, including gills. Subsequently they may be translocated from the outside into the organism. The magnitude of external exposure depends on the concentration and size distribution of the microplastic particles and upon the specific nature of the organism. For most or all organisms that actively feed, external exposure of microplastics is small relative to exposure through ingestion (see below). The possible exception to this is very small (less than 40 μm) particles which may pass across gills. In non-filter feeding marine organisms such as the shore crab (Carcinus maenas), Watts et al. (2014) tested uptake of fluorescently labelled polystyrene microspheres (8–10 μm) through inspiration across the gills as well as ingestion of pre-exposed food. Ingested microspheres were retained within the body tissues of the crabs for up to 14 days following ingestion and up to 21 days following inspiration across the gill, with uptake significantly higher into the posterior versus anterior gills. These results identify ventilation as a possible route of uptake of microplastics into a common marine non-filter feeding species. Results were used to construct a simple conceptual model of particle flow for the gills and the gut.

4.2.2 *Ingestion*

Field studies have demonstrated that microplastics are ingested by a large variety of marine taxa representing various trophic levels, including fish-eating birds, marine mammals, fish and invertebrates, e.g. lugworms, amphipods and barnacles, mussels, sea cucumbers, zooplankton. The occurrence of plastic particle ingestion is reported from all oceanic regions (Table 4.1 (a–g)) in numerous species, for example in pelagic planktivorous fish from the North Pacific Central Gyre (Boerger et al. 2010), pelagic piscivorius fish from the North Pacific Ocean (Jantz et al. 2013) and pelagic and benthic (bottom dwelling) fish from the English channel (Lusher et al. 2013) and the North Sea (Foekema et al. 2013), in nephrops in Clyde sea (Murray and Cowie 2011), marine mussels from Belgian breakwaters (Van Cauwenberghe et al. 2012a), stranded whales (de Stephanis 2013), harbour seals from the North Sea (Rebolledo 2013), Franscicana dolphins from the coast of Argentina (Denuncio et al. 2011), Northern Fulmars from the North Sea (van Franeker et al. 2011), wedge-tailed shearwaters from the Great Barrier Reef, Australia (Verlis et al. 2013) and Magellanic penguins from the Brazilian coast (Brandao et al. 2011).

Invertebrates that ingest microplastics include deposit feeding lugworms Arenicola marina (Thompson et al., 2004) and sea cucumbers (Graham and Thompson, 2009), filter feeding salps Thetys vagina (sponges, polychaetes, echinoderms, bryozoans, bivalves, barnacles Semibalanus balanoides (Thompson et al. 2004; Ward and Shumway, 2004; Van Cauwenberghe et al. 2013a, and detritivores, such as amphipods Orchestia gammarellus (Thompson et al. 2004). There is also evidence of planktonic organisms other than salps consuming microplastics, namely arrow worms and larval fish (Carpenter et al. 1972 cited in Fendall et al. 2009), copepods in laboratory feeding trials (Wilson 1973 cited in Fendall et al. 2009), invertebrate larvae such as trochophores (Bolton and Havenhand, 1998 cited in Fendall et al. 2009), the echinoderms echinoplutei, ophioplutei, bipinnaria and auricularia (Hart 1991 cited in Fendall et al. 2009) and freshwater zooplankton (Bern 1990). Results are from both laboratory and field studies.

A number of studies have focused on the exposure of marine microplastics under controlled conditions (Browne et al. 2013; Rochman et al. 2013a; Wright et al. 2013a, Cole et al. 2014; Chua et al. 2014). In addition, there is a body of literature on the particle size selection or preferences by many animals, using artificial fluorescent plastic beads or industrial primary plastic powder. A selection of the work is presented in Table 4.2. Two review articles that appeared in 2011 (Andrady 2011; Cole et al. 2011), and one in 2013 (Wright et al. 2013b) listed some of the laboratory studies that have been conducted.

Table 4.1 (a) Field observations of the occurrence of plastic particles in biota in the North Sea

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
North Sea						
Mytilus edulis, Blue mussel	Belgium	March 2013	Comparison of consumption mussels and wild type mussels	Microscopic fibres ranging from 200 – 1500 μm identified in mussel tissues	Not investigated	De Witte et al. 2014
Mytilus galloprovincialis, Mediterranean mussel	Belgium	March 2013	Comparison of consumption mussels and wild type mussels	Microscopic fibres ranging from 200 – 1500 μm identified in mussel tissues	Not investigated	De Witte et al. 2014
Mytilus edulis/ galloprovincialis hybrid	Belgium	March 2013	Comparison of consumption mussels and wild type mussels	Microscopic fibres ranging from 200 – 1500 μm identified in mussel tissues	Not investigated	De Witte et al. 2014
Mytilus edulis, Blue mussel	Germany	2013	Quantification of microplastic level in bivalve species reared for human consumption	Average of 0.36 ± 0.07 particles per gram tissue (ww) identified	Not investigated	Van Cauwenberghe & Janssen 2014
Clupea harengus, Herring	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	8/566 individuals contained plastic particles	No significant difference in condition factor between individuals that contained plastic and those without	Foekema et al. 2013
Gadus morhua, Cod	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	10/80 individuals contained plastic particles	No significant difference in condition factor between individuals that contained plastic and those without	Foekema et al. 2013
Merlangius merlangus, Whiting	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	6/105 individuals contained plastic particles	No significant difference in condition factor between individuals that contained plastic and those without	Foekema et al. 2013
Melanogrammus aeglefinus, Haddock	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	6/97 individuals contained plastic particles	Condition factor significantly lower in individuals that contained plastic than those without plastic. Data deemed insufficient to confirm the hypothesis	Foekema et al. 2013
Trachurus trachurus, Horse mackerel	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	1/100 individuals contained plastic particles	No significant difference in condition factor between individuals that contained plastic and those without	Foekema et al. 2013

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
Eutrigla gurnardus, Grey gurnard	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	1/171 individuals contained plastic particles	No significant difference in condition factor between individuals that contained plastic and those without	Foekema et al. 2013
Scomber scombrus, Atlantic mackerel	North Sea	July – October 2010	Quantify the occurrence, number and size of plastic particles and test the hypothesis that ingested plastic adversely affects the condition of fish	1/84 individuals contained plastic particles	No signficant difference in condition factor between individuals that contained plastic and those without	Foekema et al. 2013
Fulmarus glacialis, Northern fulmar	North Sea	2003–2007	Disseminate concept of the Fulmar-Plastic-EcoQO. Long term beached bird study.	95% of sampled birds had plastic in their stomachs. Critical level of 0.1 g of plastic exceeded in 58% of individuals and 60% of Dutch birds	Not investigated	van Franeker et al. 2011
Prionace glauca, Blue shark	North Sea, Channel, Irish Sea, Spitzbergen	1955–2011	CEFAS fish stomach contents records	4.7% contained plastic in gut contents	Not investigated	Pinnegar 2014
Gadus morhua, Cod	North Sea, Channel, Irish Sea, Spitzbergen	1955–2011	CEFAS fish stomach contents records	28.57% contained plastic in gut contents	Not investigated	Pinnegar 2014
Eutrigla gurnardus, Grey gurnard	North Sea, Channel, Irish Sea, Spitzbergen	1955–2011	CEFAS fish stomach contents records	14.29% contained plastic in gut contents	Not investigated	Pinnegar 2014
Scyliorhinus canicula, Lesser spotted dogfish	North Sea, Channel, Irish Sea, Spitzbergen	1955–2011	CEFAS fish stomach contents records	4.76% contained plastic in gut contents	Not investigated	Pinnegar 2014
Pollachius virens, Saithe	North Sea, Channel, Irish Sea, Spitzbergen	1955–2011	CEFAS fish stomach contents records	23.81% contained plastic in gut contents	Not investigated	Pinnegar 2014
Merlangius merlangus, Whiting	North Sea, Channel, Irish Sea, Spitzbergen	1955–2011	CEFAS fish stomach contents records	23.81% contained plastic in gut contents	Not investigated	Pinnegar 2014

Table 4.1 (b) Field observations of the occurrence of plastic particles in biota in the Mediterranean Sea

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
Mediterranean Sea						
Calonectris diomedea, Cory's shearwater	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	47/49 individuals contained plastic particles. Average of 14.6 ± 24.0 particles per bird and 22.4 ± 48.8 mg in weight	No signficant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Puffinus mauretanicus, Balearic shearwater	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	32/46 individuals contained plastic particles. Average of 2.5 ± 2.9 particles per bird and 3.8 ± 8.4 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Puffinus yelkouan, Yelkouan shearwater	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	22/71 individuals contained plastic particles. Average of 4.9 ± 7.3 particles per bird and 29.8 ± 86.6 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Ichthyaetus audouinii, Audouin's gull	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	2/15 individuals contained plastic particles. Average of 9.8 ± 35.7 particles per bird and 22.7 ± 67.6 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Larus michahellis, Yellow-legged gull	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	4/12 individuals contained plastic particles. Average of 0.9 ± 1.98 particles per bird and 1.4 ± 2.3 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Ichthyaetus melanocephalus, Mediterranean gull	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	1/4 individuals contained plastic particles. Average of 3.7 ± 7.5 particles per bird and 12.6 ± 25.3 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Rissa tridactyla, Blacked-legged kittiwake	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	2/4 individuals contained plastic particles. Average of 1.2 ± 1.9 particles per bird and 4.9 ± 6.7 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Morus bassanus, Gannet	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	1/8 individuals contained plastic particles. Average of 0.1 ± 0.3 particles per bird and 0.3 ± 0.8 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013
Catharacta skua, Great skua	Catalan Coast, Spain	2003–2010	Opportunistic study to quantify and characterize plastics in seabirds caught as bycatch by longliner fishing vessels	1/2 individuals contained plastic particles. Average of 0.5 ± 0.7 particles per bird and 0.4 ± 0.5 mg in weight	No significant correlation identified between mean body mass and the number or mass of ingested plastic	Codina-Garcia et al. 2013

Table 4.1 (c) Field observations of the occurrence of plastic particles in biota in the North Atlantic Ocean

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
North Atlantic Ocean						
Nephrops norvegicus, Norway lobster	Clyde Sea, UK	May – June 2009	To determine whether N. norvegicus ingests small plastic fragments in the Clyde Sea	100/120 animals contained plastic in their stomach. Predominantly monofilament	Not investigated	Murray & Cowie 2011
Crassostrea gigas, Pacific oyster	Brittany, France	2013	Quantification of microplastic level in bivalve species reared for human consumption	Average of 0.47 ± 0.16 particles per gram tissue (ww) identified	Not investigated	Van Cauwenberghe & Janssen 2014
Myoxocephalus aenus, Grubby	Long Island Sound, USA	February – May 1972	Opportunistic sampling of fish caught for analysis of power plant impacts	White, opaque polystyrene spherules ingested and found in the gut	Not investigated	Carpenter et al. 1972
Pseudopleuronectes americanus, Winter flounder	Long Island Sound, USA	February – May 1972	Opportunistic sampling of fish caught for analysis of power plant impacts	White, opaque polystyrene spherules ingested and found in the gut	Not investigated	Carpenter et al. 1972
Roccus americanus, White perch	Long Island Sound, USA	February – May 1972	Opportunistic sampling of fish caught for analysis of power plant impacts	White, opaque polystyrene spherules ingested and found in the gut	Not investigated	Carpenter et al. 1972
Menidia menidia, Silversides	Long Island Sound, USA	February – May 1972	Opportunistic sampling of fish caught for analysis of power plant impacts	White, opaque polystyrene spherules ingested and found in the gut	Not investigated	Carpenter et al. 1972
Merlangius merlangus, Whiting	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	16/50 contained plastic particles	Not investigated	Lusher at al. 2013
Micromesistius poutassou, Blue whiting	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	14/27 contained plastic particles	Not investigated	Lusher at al. 2013
Trachurus trachurus, Atlantic horse mackerel	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	16/56 contained plastic particles	Not investigated	Lusher at al. 2013
Trisopterus minutus, Poor cod	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	20/50 contained plastic particles	Not investigated	Lusher at al. 2013
Zeus faber, John dory	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	20/42 contained plastic particles	Not investigated	Lusher at al. 2013
Aspitrigla cuculus, Red gurnard	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	34/66 contained plastic particles	Not investigated	Lusher at al. 2013

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
Callionymus lyra, Dragonet	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	19/50 contained plastic particles	Not investigated	Lusher at al. 2013
Cepola macrophthalma, Red band fish	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	20/62 contained plastic particles	Not investigated	Lusher at al. 2013
Buglossisium luteum, Solenette	Plymouth, UK	June 2010 –July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	13/50 contained plastic particles	Not investigated	Lusher at al. 2013
Microchirus variegates, Thickback sole	Plymouth, UK	June 2010 – July 2011	Part of routine long term trawl sampling. 70–75 mm cod end mesh size	12/51 contained plastic particles	Not investigated	Lusher at al. 2013
Uria aalge, Common murre	Newfoundland & Labrador, northwest Atlantic	1980s, 1990s, 2010s	Evaluate change over time in the ingestion of plastic by murres	4/374 contained plastic particles	Not investigated	Bond et al. 2013
Uria lomvia, Thick-billed murre	Newfoundland & Labrador, northwest Atlantic	1980s, 1990s, 2010s	Evaluate change over time in the ingestion of plastic by murres	114/1662 contained plastic particles	Not investigated	Bond et al. 2013

Table 4.1 (d) Field observations of the occurrence of plastic particles in biota in the South Atlantic Ocean

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
South Atlantic Ocean						
Pachyptila vittata, Broad-billed prion	Gough Island, Central South Atlantic Ocean	October & November 1979	Opportunistic sampling after observing plastic pellets in regurgitated skua pellets	Thirty-three plastic pellets observed with prion bones and feathers in regurgitated predatory Great skua Catharacta skua pellets	Not investigated	Bourne & Imber 1980
Puffinus gravis, Great shearwater	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	11/13 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Pelagodroma marina, White faced storm petrel	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	16/19 birds contained plastic particles in their gizzards	Statistically weak correlation identified between mass of ingested plastic and body mass	Furness 1985a
Pachyptila vittata, Broad-billed prion	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	12/31 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Fregetta grallaria, White-bellied storm petrel	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	5/13 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Garrodia nereis, Grey-backed storm petrel	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	3/11 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Stercorarius antarcticus, Tristan skua	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	1/11 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Puffinus assimilis, Little shearwater	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	1/13 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Lugensa brevirostris, Kerguelen petrel	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	1/13 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Pterodroma incerta, Atlantic petrel	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	1/13 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a
Pterodroma mollis, Soft-plumaged petrel	Gough Island, Central South Atlantic Ocean	September – October 1983	Dead birds collected for analysis and others harvested as necessary for sampling	1/18 birds contained plastic particles in their gizzards	No negative impacts identified	Furness 1985a

Table 4.1 (e) Field observations of the occurrence of plastic particles in biota in the North Pacific Ocean

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
North Pacific						
Fulmarus glacialis, Northern fulmar	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	16/19 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Puffinus tenuirostris, Short-tailed shearwater	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	4/5 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Oceanodroma furcata, Fork-tailed storm petrel	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	18/19 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Oceanodroma leucorhoa, Leach's storm petrel	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	31/64 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Phalacrocorax pelagicus, Pelagic cormorant	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	2/10 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Larus canus, Mew gull	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	1/4 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Rissa tridactyla, Black-legged kittiwake	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	20/256 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Rissa brevirostris, Red-legged kittiwake	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	4/15 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Uria aalge, Common guillemot	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	1/134 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Ptychoramphus aleuticus, Cassin's auklet	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	4/35 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Aethia psittacula, Parakeet auklet	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	195/208 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Aethia cristatella, Crested auklet	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	1/40 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Cepphus columba, Pigeon guillemot	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	1/43 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Fratercula corniculata, Horned puffin	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	44/120 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995
Fratercula cirrhata, Tufted puffin	Alaska	1988–1990	Targetted sampling of seabirds for feeding ecology studies	120/489 birds had ingested plastic particles (mainly pellets)	Not investigated	Robards et al. 1995

Table 4.1 (f) Field observations of the occurrence of plastic particles in biota in the Central Pacific Ocean

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
Central Pacific						
Phalaropus fulicarius, Red phalarope	California	May 1980	Opportunistic sampling of 7 dead migratory birds	6 birds contained plastic particles in their stomach. Most were 'nibs' and some was styrofoam	Not investigated	Connors & Smith 1982
Pterodroma rostrata, Tahiti petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/121 birds had ingested plastic	Not investigated	Spear et al. 1995
Puffinus nativitatus, Christmas shearwater	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	2/5 birds had ingested plastic	Not investigated	Spear et al. 1995
Puffinus pacificus, Wedge-tailed shearwater	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	17/85 birds had ingested plastic	Negative relationship identified between plastic ingestion and physical condition (body weight)	Spear et al. 1995
Fregatta grallaria, White-bellied storm petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/18 birds had ingested plastic	Not investigated	Spear et al. 1995
Oceanodroma tethys, Wedge-rumped storm petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/296 birds had ingested plastic	Not investigated	Spear et al. 1995
Sterna fuscata, Sooty tern	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/64 birds had ingested plastic	Not investigated	Spear et al. 1995
Gygis alba, White tern	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/8 birds had ingested plastic	Not investigated	Spear et al. 1995
Pterodroma externa, Juan Fernandez petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/183 birds had ingested plastic	Not investigated	Spear et al. 1995
Pterodroma cervicalis, White-necked petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/12 birds had ingested plastic	Not investigated	Spear et al. 1995
Pterodroma pycrofti, Pycroft's petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	2/5 birds had ingested plastic	Not investigated	Spear et al. 1995
Pterodroma leucoptera, White-winged petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	13/110 birds had ingested plastic	Negative relationship identified between plastic ingestion and physical condition (body weight)	Spear et al. 1995
Pterodroma brevipes, Collared petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	2/3 birds had ingested plastic	Not investigated	Spear et al. 1995

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
Pterodroma nigripennis, Black-winged petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	3/66 birds had ingested plastic	Not investigated	Spear et al. 1995
Pelagrodroma marina, White-faced storm petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	11/15 birds had ingested plastic	Not investigated	Spear et al. 1995
Oceanodroma leucorhoa, Leach's storm petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	70/354 birds had ingested plastic	Negative relationship identified between plastic ingestion and physical condition (body weight)	Spear et al. 1995
Stercorarius longicaudus, Long-tailed jaeger	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/2 birds had ingested plastic	Not investigated	Spear et al. 1995
Pterodroma ultima, Murphy's petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	1/7 birds had ingested plastic	Not investigated	Spear et al. 1995
Pterodroma longirostris, Stejneger's petrel	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	34/46 birds had ingested plastic	Negative relationship identified between plastic ingestion and physical condition (body weight)	Spear et al. 1995
Puffinus griseus, Sooty shearwater	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	27/36 birds had ingested plastic	Negative relationship identified between plastic ingestion and physical condition (body weight)	Spear et al. 1995
Puffinus bulleri, Buller's shearwater	Tropical Pacific	1989–1991	Targetted sampling of seabirds to quantify incidence of plastic ingestion	3/3 birds had ingested plastic	Not investigated	Spear et al. 1995
Lepas anatifera, a gooseneck barnacle	North Pacific Subtropical Gyre	2009–2012	Opportunistic sampling of floating debris items with barnacles attached to assess microplastic ingestion	90/243 barnacles had ingested plastic	No evidence found of accute harm but negative long term effects could not be ruled out	Goldstein & Goodwin 2013
Lepas pacifica, a gooseneck barnacle	North Pacific Subtropical Gyre	2009–2012	Opportunistic sampling of floating debris items with barnacles attached to assess microplastic ingestion	34/85 barnacles had ingested plastic	No evidence found of accute harm but negative long term effects could not be ruled out	Goldstein & Goodwin 2013
Astronesthes indopacifica	North Pacific Central Gyre	February 2008	To determine if small mesopelagic planktivorous fish were ingesting plastic fragments	Mean of 1.0 plastic particles and 0.03 mg plastic per fish gut	Not investigated	Boerger et al. 2010

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
Cololabis saira	North Pacific Central Gyre	February 2008	To determine if small mesopelagic planktivorous fish were ingesting plastic fragments	Mean of 3.2 plastic particles and 1.97 mg plastic per fish gut	Not investigated	Boerger et al. 2010
Hygophum reinhardtii	North Pacific Central Gyre	February 2008	To determine if small mesopelagic planktivorous fish were ingesting plastic fragments	Mean of 1.3 plastic particles and 1.82 mg plastic per fish gut	Not investigated	Boerger et al. 2010
Loweina interrupta	North Pacific Central Gyre	February 2008	To determine if small mesopelagic planktivorous fish were ingesting plastic fragments	Mean of 1.0 plastic particles and 0.64 mg plastic per fish gut	Not investigated	Boerger et al. 2010
Myctophum aurolanternatum	North Pacific Central Gyre	February 2008	To determine if small mesopelagic planktivorous fish were ingesting plastic fragments	Mean of 6.0 plastic particles and 4.66 mg plastic per fish gut	Not investigated	Boerger et al. 2010
Symbolophorus californiensis	North Pacific Central Gyre	February 2008	To determine if small mesopelagic planktivorous fish were ingesting plastic fragments	Mean of 7.2 plastic particles and 5.21 mg plastic per fish gut	Not investigated	Boerger et al. 2010

Table 4.1 (g) Field observations of the occurrence of plastic particles in biota in the South Pacific and Indian Oceans

Marine species	Location	Date of study	Purpose of study	Details of ingestion	Reported impact of ingestion	Reference
South Pacific Ocean						
Ardenna tenuirostris[12], Short-tailed shear-water	Phillip Island, Victoria, Australia	April – May 2010	Opportunistic sampling of 67 dead, beach cast chicks analysed for stomach content and body condition	Mean mass of plastic per bird was 113 $\pm$8.2 mg (not certain that all was microplastic). No relationship identified between plastic mass or number of particles found and fat scores	None identified	Carey 2011
Arctocephalus spp., Antarctic fur seals	Macquarie Island, Australia		Opportunistic sampling of scats for plastic particles	All 145 scats contained at least 1 plastic particle. Majority 3–5 mm length. Hypothesized that they were ingested via predation of Electrona subaspera by the fur seals	Not investigated	Eriksson & Burton 2003
Indian Ocean						
Stolephorus commersonii, Commerson's anchovy	Kerala, India	August 2013	Targetted sampling as part of a larger study into mud banks	6/16 individuals had microplastic particles in their gut	Not investigated	Kripa et al. 2014

[12] Ardenna tenuirostris – formerly known as Puffinus tenuirostris

Table 4.2. Selected laboratory studies of microplastics exposure in marine organisms

Marine species	Plastic particle exposure and effect	Reference
Blue mussel *M. edulis* to crab *C. maenas*	Transition 0.5 μm PS from mussel to crab by trophic transfer	Farrell & Nelson 2013
Blue mussel *M. edulis*	Translocation to hemolymph of mussel after ingestion; 3–9.6 μm, into blood cells including macrophages 0–80 μm. Transfer into cells	Browne et al. 2008; von Moos et al. 2012; Höher et al. 2012; von Moos et al. 2012
Blue mussel *M. edulis*	Exposure to 10, 30 90 μm MPs Indications for selective uptake of 10 μm MPs Reduced clearance rate	Van Cauwenberghe et al. 2012b, 2013a
Zooplankton & mysid shrimp	Neomysis integer Ingestion, trophic transfer of fluorescent 10 μm PS from zooplankton to mesozooplankton Trophic transfer	Setälä et al. 2014
Shore crab *Carcinus maenas*	Uptake via gills of 8–10 μm PS and ingestion. Retention in foregut Watts et al. 2014 Echinoderm larvae Active capture and ingestion, 20 μm	Hart 1991
Lancet fish	Polystyrene beads 0.05–25 μm Unrestricted intake of polystyrene beads, max 100 μm	Ruppert et al. 2000
copepod		
Centropages typicus	Microbeads 10-70 μm, selective ingestion of 59–65 μm	Wilson 1973

4.2.3 *Uptake and transition into tissues, cells and organelles*

Up until now only a very few studies have examined the presence of microplastics in tissues or body fluid of field-collected organisms. Evidence for such internal microplastic exposure relates mainly to filter feeding mussels and sediment deposit feeding polychaetes (see Table 4.2) and is described below.

In experimental studies, marine mussels – a species also used for human consumption – were exposed to seawater containing microplastics accumulated plastic particles in the hemolymph and once the particles were ingested they were able to move from the gut to the circulatory system and be retained in the tissues (Browne et al. 2008). Van Cauwenberghe et al. (2012b, 2013a) exposed Mytilus edulis (filter feeder) and Arenicola marina (deposit feeder) to different sizes of microplastics at a total concentration of 110 particles per mL. After exposure, lugworms had on average 19.9 $\pm$ 4.1 particles in their tissue and coelomic fluid, while mussels had on average 4.5 $\pm$ 0.9 particles in their tissue and 5.1 $\pm$ 1.1 per 100 μL of extracted hemolymph (Van Cauwenberghe et al. 2012b, 2013a). Experimental studies by Browne et al. (2008) have shown that microscopic polystyrene particles 3 and 9.6 microm of size are ingested and accumulated in the gut of the mussel Mytilus edulis and translocate to the circulatory system within 3 days and were taken up by hemocytes. Studies with HDPE powder in a size range of $>$0 to 80 μm by von Moos et al. (2012) demonstrated intracellular uptake of microplastic particles into the cells of digestive tubules and transition into cell organelles of the lysosomal system.

Accumulation of plastic inside of lysosomes coincides with breakdown of the lysosomal membrane and release of degrading enzymes into the cytoplasm causing cell death (von Moos et al. 2012). A strong immune response towards those HDPE particles expelled from the digestive tubules into the surrounding storage tissue and fibrous encapsulation of the plastic engulfing macrophages. In the same exposure study Höher et al. (2012) evidenced uptake into hemolymph from the digestive system, with specific uptake of HDPE into proliferating granulocytes and basophilic hemocytes.

Ecotoxicological experiments on sea urchin embryos showed that plastic pellets that have not entered the marine environment have a stronger effect on embryo development than beach collected ones (Nobre et al. 2015), suggesting that leaching of additives would have a higher toxicity than organic pollutants absorbed into the stranded pellets. Toxicity of beach collected pellets depended on the ecotoxicological method and varied among trials, suggesting variability in toxicity among samples of pellets at the beach.

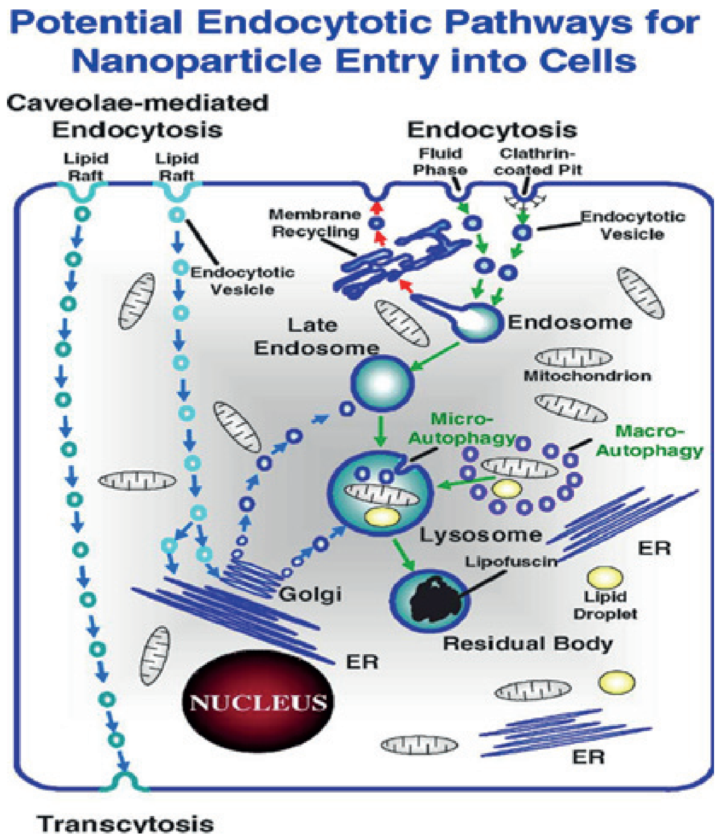

Figure 4.1. *Pathways for endocytosis in the cell which could be exploited by manufactured and defragmented microplastic. Endocytosis via clathrin-coated pits (receptor mediated) or uncoated pits (fluid phase) transfers materials to the lysosomal degradative compartment, while caveolar endocytosis can result in translocation to the endoplasmic reticulum (ER), Golgi or through the cell by trancytosis (Shin and Abraham 2001; van der Goot and Gruenberg 2002) modified by Moore 2006.*

Uptake routes into (eucaryotic) cells are evolutionary conserved and particles traverse by diffusion selectively by the size of pores in cell membranes, of which only 2% are large sized pores (400 nm pore radius); 30% of medium size (40 nm); and 68% of small size (1.3 nm). Specialized coated vesicles transport particles smaller than 200 nm. In contrast, larger particles up to 40 micrometres are taken up by engulfment through endocytosis and phagocytosis.

In general, in vivo exposure to small sized microplastic indicates that, due to the physiological mechanisms involved in the feeding process, nanoparticle agglomerates taken up by the gills are directed to the digestive gland where intra-cellular uptake of nano-sized materials induces lysosomal perturbations (Canesi et al. 2012) (Figure 4.1).

4.2.4 *Excretion*

In the field, the occurrence of microplastics in organisms represents recent exposures to these materials. Our current knowledge of the excretion of microplastics from marine organisms is based solely on laboratory studies. After microplastics are assimilated into the organism (hemolymph or tissues) they either accumulate or are excreted depending on the size, shape and composition of the particles used in the studies. If accumulated, the chemical and/or physical effects are expected to develop and to be maintained through time. If excreted, these effects are expected to be reversed in a healing and regeneration process.

Microplastic concentrations in the hemolymph peak at a certain time after a single discrete exposure (which depends on species, plastic type and exposure time) and then reduce in abundance (Browne et al. 2008; Farrell & Nelson 2013;). It is not known how much is eliminated or transferred to other organ compartments or tissues. Recent studies in mussels after acute exposure to HDPE (0–80 μm size range) for 12 h followed by regeneration in plastic-free seawater indicate elimination of microplastic from the digestive tubules after a period of 12 to 48 hours, and a shift of HDPE particles into newly formed connective tissue (fibrosis) around the tubules, indicating a repair mechanism of injured tissue. Similar experiments with PVC microplastics revealed particle retention in the gut for up to 12 days and that small size particles had a higher retention time than larger ones.

4.2.5 Transfer of microplastics in the food web

Microplastic particles may be passed through the food web as predators consume prey. Farrell and Nelson (2013) fed mussels (Mytilus edulus) which had been exposed to 0.5 μm polystyrene microspheres to the crab Carcinus maenas. Microplastics were found in the stomach, hepatopancreas, ovary and gills of the crabs, and the maximum amount of microplastics were detected 24 hours post feeding. Nearly all of the ingested microplastics were cleared from the crabs after 21 days. In a laboratory feeding study, all ten zooplankton taxa tested from the Baltic Sea ingested 10 μm polystyrene microspheres (Setälä et al. 2014). Microspheres contained within copepods were transferred after mysid shrimps ingested them, again demonstrating trophic transfer of microplastics. Lusher et al. (2013) documented microplastic particles in the gastrointestinal tracts of 36% of 504 individual fish collected from the English Channel, representing 10 species of teleost fish, confirming ingestion of microplastics in prey items in the field. Similarly, Murray and Cowie (2013) found microplastics (mostly plastic strands) in the gut contents of 62% of Norway lobsters (Nephrops norvegicus) collected from the Clyde Sea, and confirmed in companion laboratory studies that ingested plastic fibres were effectively retained with the GI tract.

4.3 Microplastics as a vector of chemical transport into marine organisms

4.3.1 *Introduction*

Microplastics in marine environments carry chemicals that can be considered as contaminants from an ecotoxicological risk perspective, from two principal sources (Teuten et al. 2009). The first includes the additives, monomers and by-products contained in plastic particles. The size, condition and residence time of microplastic particles and the hydrophobicity of the chemicals controls how much of these chemicals are retained by microplastics in marine environments. The second type of contaminants are hydrophobic compounds and metals sorbed from surrounding seawater. This includes most POPs and PBTs, including polycyclic aromatic hydrocarbons (PAHs) and the other petroleum hydrocarbons. Sorption will tend towards equilibrium between the plastic and seawater, phases with the direction of absorption/desorption depending on the absorption kinetics and the relative concentrations in the two media. The size of microplastics, polymer type and hydrophobicity of the contaminant will all exert an influence.

This characteristic has been employed in sampling methods to isolate and concentrate dissolved POPs from natural waters (e.g. Adams et al. 2007; Cornelissen et al. 2008), and to assess POP/PBT bioavailability in water and sediments (e.g. Leslie et al. 2013). Indeed, the International Pellet Watch Programme (IPW) deliberately uses marine microplastic particles as passive samplers of organic contaminants in waters throughout the world (Ogata et al. 2009; IPW website: http://www.pelletwatch.org/). The magnitude of the POP-plastic interaction depends on the nature of the plastic as well as the hydrophobicity of the chemical, as quantified by several studies (Teuten et al. 2009; et al. 2012; Endo et al. 2005).

The rate of uptake and release of POPs from plastics largely depend on size of plastics. With increase in the size (thickness) of plastics, sorption and desorption becomes slower. To thin polyethylene film with thickness of 50 μm PCBs (CB52) sorbed in 50 days to reach equilibrium (Adams et al. 2007), whereas sorption of PCBs to PE pellets with diameter of 3 mm is slower (Mato et al. 2001) and takes approximately one year to reach equilibrium (Rochman et al. 2012, 2013b, 2014a). The slow sorption and desorption was explained by slow diffusion in aqueous boundary layer (Endo et al. 2013) and/or in intra-particle (matrix) diffusion (Karapanagioti and Klontza 2008). In addition, the slow desorption may transport POPs to remote ecosystems. Plastic pieces that contain higher concentrations of POPs than the other plastics are often found on the beaches of remote islands (e.g. Hirai et al. 2011; Heskett et al. 2012).

However, recent laboratory experiments demonstrated that stomach oil acts as organic solvent, facilitates the elution of PBDEs from the plastic matrix and enhances bioavailability of the additive chemicals (Tanaka et al. 2013). Because stomach oil is common among many species of seabirds and plastic ingestion is observed for various species of seabirds, wider species of seabirds in various regions should be investigated in future efforts. However, only limited species of seabirds and the other animals have been examined. Magnitude and expansion of the chemical transfer by microplastics in the biosphere should be studied.

4.3.2 *Contaminant transfer from μm-size plastics to lower-trophic-level organisms*

Well-established pharmacokinetic-based models have established that dietary uptake is often the majority mechanism of POPs exposure for fish and shellfish (e.g. Thomann et al. 1992; Arnot and Gobas 2004). While diffusive uptake of dissolved POPs across the surfaces of skin, gills and other respiratory surfaces should not be ignored, it is the ingestion of contaminated prey items and subsequent transfer of POPs from food to organism that supplies most of the contaminant burden. As reviewed in this chapter, a growing number of studies demonstrate that, under the right conditions, many species of marine organisms will ingest microplastic particles. As organisms consume a mixed diet consisting of a variety of particles (including perhaps microplastics), the total dietary exposure equals the weighted average POPs concentration of the mixture weighted for selective assimilation. Assimilation efficiency is defined as the fraction of the POP concentration in a prey item or food particle that is transferred into the organism, and is a function of the diffusional gradient between food and organism and the gut residence time. Species-specific features, including especially digestive enzymes and active transport mechanisms, also influence the POP assimilation efficiency. It is important to note that net POPs transfer from food to organism is thought to only occur when the POPs concentration in the partially digested food exceeds that in the organism, driving the diffusional gradient across the digestive walls (Kelly et al. 2004). Therefore, the magnitude of dietary exposure to POPs depends explicitly on over- or under-enrichment of POPs in the food relative to the organism, regardless of how enriched the food is relative to the surrounding water or sediment.

Partitioning, bioavailability and assimilation

Several studies document that marine microplastics are covered with biofilm communities (Zettler et al. 2013 and references therein). This organic layer likely acts as a reservoir for POPs, although studies demonstrating persistent differences in POPs affinities among plastic types deployed in marine waters suggest that the biofilms modify rather than control POPs associations with aged marine microparticles. When these particles are ingested, it is likely that the nutritionally rich biofilm organic matter is stripped from the particles, with coincident release of the co-adsorbed POPs. Emerging studies have suggested that contaminant transfer does take place (e.g. Chua et al. 2014; Rochman et al. 2014b; Browne et al. 2013; Gaylor et al. 2011). However, whether biofilms facilitate the transfer of contaminants into the organism has not been investigated.

As described earlier, many organisms are able to translocate assimilated microplastic particles within their tissues, storing the foreign body within intracellular structures. It is possible that this defence mechanism would deliver microplastic-associated POPs and additive chemicals to different tissue types and locations than those resulting from uptake from food and water. Given the long residence time of such sequestered particles relative to the lifetime of the organism, even slow chemical release may cause low but chronic delivery within the animal. This mechanism has not been studied in marine organism and is not included in current pharmacokinetic models. The relatively low frequency of occurrence and density of tissue-encapsulated microplastics in field collected marine specimens suggests this mechanism is likely not an important vector in overall chemical delivery to marine species. However, it is possible that this unstudied mechanism may provide a unique process to deliver chemicals to specific organs, especially for very small plastic particles that can cross membranes. Further quantitative investigations, especially heuristic application of existing models to explore the potential importance, are required to confirm this. Considerable literature exists examining the release of chemicals from polymers and other macromolecules in human systems, where these solid materials are used as drug delivery vehicles.

As noted above, transfer of POPs and additive chemicals from food to organism depends on the relative concentration of chemicals in the food compared to what already exists in the animal. Due to the influence of growth dilution (i.e. the increase in organism weight due to growth reduces the POPs concentration in the tissue even though the total POPs mass in the organism remains the same), the diffusional gradient in the gut is often positive (i.e. the food is enriched in POPs relative to the organism). However, the opposite situation may occur, where relatively contaminated organisms ingest cleaner food. In this case, partitioning of POPs from the organism back into the food during digestion, with subsequent excretion, is possible. This process is analogous to those used to depurate commercial shellfish prior to harvest and limit the effects of ingested poisons by administration of activated carbon.

Model approaches to assess the role of μm-size plastics on contaminant accumulation in lower-trophic-level organisms

In a recently published series of papers, the issue of the net effect of microplastics on the transfer of PCBs to the deposit feeding lugworm was measured (Besseling et al. 2012) and modelled (Koelmans et al. 2013). By enhancing an established pharmacokinetic model to include the microplastic-influenced processes discussed above, the authors were able to quantitatively address the impact of microplastics as a delivery vehicle for PCBs to marine organism. As their experimental design included extremely high microplastic concentrations (up to 7.4% by weight) in sediment, the work represents a 'worse case', skewing the experiment in favour of finding any possible influences. The laboratory experiment exposed lugworms to three levels of polystyrene and constant total levels of PCBs and measured feeding activity, growth rates, and PCB congener accumulation over time. The model included partitioning of PCB congeners to the added microplastic, the ingestion of microplastic particles, and the dynamics of POPs transfer within the worms.

When simulating a closed system where there is a finite amount of POPs, Koelmans et al. (2013) determined that partitioning competition between the added plastic, sediment and pore-water and the transfer of PCB congeners from the organism to relatively clean plastic during gut transport dominated the overall net POPs exposure. At the end of 30 days, lugworms living in highly altered sediments (7.4% polyethylene) are predicted to accumulate 25 times less PCBs than those living in plastic-free sediments, a difference that was not attributed to changes in exposure moderated by the plastic rather than the minor alterations observed in behaviour, feeding rates, or growth rates. Modelled dissolved PCB exposure from pore-water decreased as PCBs partitioned onto the added plastic.

To explore a more realistic scenario, Koelmans et al. (2013) also model behaviour in an open system, where there is a very large pool of available POPs (i.e. adding plastic to the system does not deplete the dissolved or sediment bound POPs concentrations). In this scenario, addition of even high concentrations (10% by weight) of polystyrene did not affect PCB bioaccumulation (<1% decrease). Because polyethylene has a higher affinity for PCBs, however, the simulation suggests a 2–5 fold decrease in PCB bioaccumulation for polyethylene concentrations in the sediment ranging from 0.1% to 10% by weight. This results from the compensating mechanism of plastic ingestion offsetting PCB uptake by dermal exchange and diet. Although partitioning among pore-water, sediment and plastic begins at equilibrium, feeding and digestion increases the organism PCB concentrations following the standard bioaccumulation paradigm. Since the plastic remains in equilibrium with the surrounding pore-water and sediment, it is now 'clean' relative to the POPs level in biota, resulting in net POPs elimination by back partitioning to ingested plastic particles.

The two important implications of this recent work are (1) when considering all POPs exposure mechanisms simultaneously, addition of POPs-free microplastics if anything decreases bioaccumulation of POPs in deposit feeding organisms, and (2) the magnitude of the calculated impacts on bioaccumulation are quite small relative to typical variation observed in the field.

Laboratory experiments on transfer of POPs from µm-size plastic to lower-trophic-level organisms

In recent years, there have been several studies based on laboratory experiments to evaluate plastic-mediated transfer of POPs to lower-trophic-level organisms. Browne et al. (2013) studied transfer of four kinds of organic contaminants (nonylphenol, phenanthrene, BDE47, and triclosan) from PVC to benthic organisms (lugworm). PVC particles of 230 µm were pre-sorbed with these contaminants at environmentally relevant concentrations and added to clean sands where lugworm was incubated for 10 days and concentrations of the contaminants in the tissue were measured. Concentration of the PVC was 5% of sand. All the contaminants were significantly detected in gut of the lugworm following 10-day incubation, clearly indicating the transfer of the organic chemicals from microplastic to the biological tissue. They also incubated the lugworm in sand presorbed with nonylphenol and phenanthrene without microplastics and found higher concentrations of the pollutants than those on the incubation with microplastics. This could be explained by retention (partitioning) of the hydrophobic pollutants by PVC in sands as predicted by above model approach. Because Browne et al. (2013) utilized clean sands, importance of plastic-mediated transfer relative to natural path (i.e. pollutant uptake through contaminated sediment) was not evaluated. Besseling et al. (2012) studied the relative importance of the transfer of PCBs from natively PCBs-contaminated sediments to similar species of the benthic organisms (lugworm). They added three levels (0.074 %, 0.74 % and 7.4 % dry weight) of polystyrene (PS) particles (400 – 1300 µm) to the sediment to examine the enhancement or depression of bioaccumulation of 19 congeners of PCBs in the lugworm tissue. Microplastic concentration (740 mg/kg or more) on this experiment was one to three order of magnitude higher than those observed in actual environments (up to 81 mg/kg, Reddy et al. 2006). Increased PCB accumulation was observed for several congeners at the lowest PS dose of 0.074 %. Though the increase was statistically significant, the increment was small (i.e. 1.1 – 1.5 times than control (no addition of PS)) and was observed for limited congeners (i.e. CB31, 52, and 105) and no increase was observed for many congeners. These results are basically consistent with the estimation by above model approach. The laboratory experiments and the model approach can conclude that transfer of organic pollutants from µm-sized plastic to tissue of benthic organism occurs but its role to pollutant transfer could be less important relative to natural path at the present condition (i.e. lower concentration of microplastics than natural sedimentary organic matter). However, more studies are necessary to improve the model approach so that it can represent the increase in bioaccumulation of some congeners observed by Besseling et al. (2012). Also field observation to examine the conclusion is necessary. Furthermore, it is concerned that the concentrations of microplastic in sediment and relative importance of microplastics would be increasing in future. Even now, we may underestimate the concentrations of µm-sized or nm-sized plastics in sediment due to less development of the methods for the collection, identification, and counting of the tiny plastic particles in bottom sediments.

Regarding µm-sized plastics in water column, there have been several laboratory experiments to examine the transfer of pollutants to organisms. Chua et al. (2014) exposed amphipod to µm-sized (11 – 700 mm) polyethylene particles which were pre-sorbed with a range of PBDEs (BDE28, 47, 100, 99, 154, 153, and 183). They measured PBDEs concentrations in tissue of the amphipod after 72-h exposure and detected all the BDE congeners in the tissue, indicating the occurrence of transfer of the chemicals from microplastic to the tissue of amphipod. In addition, they observed higher PBDEs uptake by amphipod in control, i.e. system without microplastics, than those with microplastic, again suggesting the retention of hydrophobic pollutants in microplastics which is consistent with above model approach. They fed only microplastics to the amphipod and, therefore, their role of PBDE transfer relative to natural path was not assessed. Rochman et al. (2013a) conducted laboratory experiments where Japanese Medaka was exposed to polyethylene pieces less than 500 µm. The PE pieces were pre-sorbed with variety of POPs through deployment in polluted waters for 3 months and mixed with natural food stuff including cod liver oil and fed to the fish. Statistically significant enhancement of PBDE bioaccumulation was observed for fish fed with contaminated microplastic, suggesting the transfer of PBDEs from microplastic to the organisms. However, no significant increase was observed for PCBs and PAHs mainly due to higher concentrations of POPs in fish fed with natural food stuff only. This may indirectly suggest microplastic play only minor role to bring POPs to biota in comparison to natural path.

A feeding experiment using chicks of Streaked shearwater (Calonectris leucomelas) supported this idea. Chicks were fed plastic resin pellets collected from Tokyo containing PCBs together with their natural food (Japanese sand lance) and periodically monitored for PCBs in the preen gland oil excreted from gland at the tail of the bird (Teuten et al. 2009; Yamashita et al. 2007). Significant increases in concentrations of lower-chlorinated biphenyls were observed one week after the feeding of the plastics, suggesting the transfer of the PCBs from the plastics to the tissue of seabird. However, they did not see any significant difference in the PCB concentrations after two weeks. This was also explained by the "natural" exposure of the seabirds through their food (prey) because the plastic was fed only at the beginning of the experiments and PCB amounts exposed through natural food overwhelm the exposure from the ingested plastic in the later stage of the experiment. This is also consistent with the studies that correlated plastic ingestion and PCB concentrations in the fatty tissue of seabirds, Short-tailed shearwater (Yamashita et al. 2011). Their approach is similar to Ryan et al. (1988) and found significant but weak correlation between mass of ingested plastics and tissue concentration of lower-chlorinated congeners.

Field evidence of transfer of contaminants from μm-size plastic to lower-trophic-level organisms

There has been very limited number of field studies to examine the POPs transfer from microplastic to lower-trophic-level organisms. Rochman et al. (2014b) measured various organic pollutants in fish tissue collected in South Atlantic gyre where accumulation of microplastic was observed. They observed higher concentrations of PBDEs in the tissue of lanternfish collected at areas with higher plastic accumulation in water column. This correlation suggests the important role of plastic-mediated transfer of POPs. The correlation was obtained probably because concentrations of plastic were higher relative to natural food items, e.g. zooplankton. Similarly to the benthic system, the relative contribution of microplastic-mediated POPs transfer depends on the concentration of microplastics relative to natural food items. In some locations, such as the Central Pacific gyre, concentrations of plastic were higher than those of plankton. Similar areas may be observed in coastal zones in proximity to intensive anthropogenic activity, such as Tokyo Bay (Hideshige Takada, unpublished results). Furthermore, there is concern that there will be an increase in the extent of such areas unless there are substantial reductions in the input of plastics to the ocean.

The Koelmans et al. (2013) work applies to the test organism (lugworm) and POPs (PCB congeners) studied in sediments. As several studies have now demonstrated microplastic ingestion in field-caught fish and shellfish (Lusher et al. 2013; Murray and Cowie 2011), the question remains as to the potential role of microplastics in POPs accumulation in the water column. However, the relatively low number of microplastics in marine waters relative to food items coupled with potential selective feeding suggests that microplastics play a minor role among the large variety of natural particles in delivering POPs to higher trophic levels.

Metals

The microplastics collected from the ocean contain metals, although in very small concentrations (Ashton et al. 2010; Holmes et al. 2012). Weathered particles have a higher potential to accumulate metals from the environment compared to new plastic (Ashton et al. 2010; Fotopoulou & Karapanagioti 2012), although in both cases the magnitude of metals accumulation is quite low relative to natural particles. Nakashima et al. (2012) showed that metals in stranded macroplastics may be leached to the surrounding water and release of metals should be enhanced in acid conditions like in the gut of many organisms. The relative importance of microplastic-facilitated transport of metals into aquatic organisms has not been directly measured.

4.3.3 *Field evidence of contaminant transfer from mm-size plastics to higher-trophic-level organisms*

There have been several field studies to examine the transfer of POPs from ingested plastics to marine organisms with a focus on seabirds. Ryan et al. (1988) measured amounts of plastics in the digestive tracts of Great shearwaters (Puffinus gravis) and concentrations of PCBs in the fat tissue of the bird and examined the correlation between amounts of plastics and PCB concentrations. A positive correlation was observed between the mass of ingested plastic and the PCB concentration in the fat tissue of birds, suggesting the transfer of PCBs in plastics to the organisms. However, correlation was weak because marine organisms, especially higher-trophic animals, are exposed to PCBs through natural prey in addition to ingested plastics.

Tanaka et al. (2013) examined the transfer of PBDEs (an additive used as a flame retardant for certain applications) from the ingested plastics to the tissue of the seabirds with focus on higher brominated congeners, not found in prey items of the seabirds. PBDEs in abdominal adipose of oceanic seabirds (short-tailed shearwaters, Puffinus tenuirostris) collected in northern North Pacific Ocean were analysed. In 3 of 12 birds, higher-brominated congeners (viz., BDE209 and BDE183) which were not present in the natural prey (pelagic fish) of the birds were detected. The same compounds were present in plastic found in the stomachs of the 3 birds. These data and their follow-up observations of the same species of seabirds indicated the transfer of plastic-derived chemicals from ingested plastics to the tissues of marine-based organisms. However, the mechanism of the transfer of the chemicals from the plastics to the biological tissue was not revealed. Because the ingested plastics were relatively large (mm to cm-size) and BDE209 and BDE183 are highly hydrophobic, slow release and low bioavailability of the chemicals have been suggested.

4.4 Biological impacts

Section 3 of this report makes apparent that microplastics have become both widespread and ubiquitous in the marine environment. The biological impact of microplastics on organisms in the marine environment is only just emerging (Gregory 1996; Barnes et al. 2009; Ryan et al. 2009; Cole et al. 2011). Adverse effects of microplastics on marine organisms can potentially arise from physical effects (physical obstruction or damage of feeding appendages or digestive tract or other physical harm). In addition, microplastics can act as vectors for chemical transport into marine organisms causing chemical toxicity (additives, monomers, sorbed chemicals). Translocation of microplastics from the gut to other tissues may result in 'internal' exposure of microplastics causing particle toxicity and particle dependent chemical toxicity of leached chemicals. In addition to impaired health, the ingestion of microplastics could potentially cause population, community level effects and affect ecosystem wide processes. Microplastics could also serve as carrier for the dispersal of chemicals and biota (invasive species, pathogens), thus greatly increasing dispersal opportunities in the marine environment, potentially endangering marine biodiversity. The wide range of potential effects of microplastics on marine organisms and ecosystems is further explored below.

4.4.1 *Physical effects*

The small sizes of microplastics make them available to a wide range of marine organisms posing a potential threat to biota (Derraik 2002; Barnes et al. 2009; Fendall and Sewell 2009; Thompson et al. 2004; Cole et al. 2011). This may be particularly the case for small-sized deposit and suspension feeders, such as zooplankton, polychaetes, crustaceans and bivalves. Microplastics may present a mechanical hazard to small animals once ingested, similar to the effects observed for microplastics and larger animals (Barnes et al. 2009; Cole et al. 2011). The physical effect may be related to entanglement (no records, expected for larger particles), obstruction of feeding organs, e.g. salps (Chan & Witting 2012) and zooplankton (Cole et al. 2013), reduction in the feeding activity/rate/capacity (Besseling et al. 2012; Cole et al. 2013), or adsorption of microplastics on the organism surface, e.g. algae (Bhattacharya et al. 2010) and zooplankton (Cole et al. 2013). Direct effects may occur after ingestion and translocation into tissues, cells and body fluids causing particle toxicity. These studies are summarized in Table 4.2.

So far, only few field studies have attempted to investigate the impacts of microplastics on marine organisms and these refer to larger sizes of microplastics in birds and fish. For example, sub-lethal or lethal effects were difficult to relate to plastic ingestion in fulmars (van Franeker et al. 2011) and plastic characterization seemed unrelated to physical condition in the shearwater species (Codina-García et al. 2013). Foekema et al. (2013) found no clear relation between the condition factor of North Sea fish and the presence of ingested microplastics. However, the authors noted that the particles were probably too small to expect they can cause feelings of satiation and intestinal blockage potentially resulting in a decreased condition factor in the relatively large specimens examined.

In contrast to the field situation, effects of microplastics have been reported in numerous laboratory studies with a wide variety of fish and invertebrate species exposed to relatively high concentrations of virgin/unpolluted microplastics (Table 4.2). Bhattacharya et al. (2010) worked with nano-sized plastic beads and two species of algae (one freshwater and one marine/freshwater species) and found that sorption of nanoplastics to algae hindered algal photosynthesis and appeared to induce oxidative stress. Microplastic adhered to the external carapace and appendages of exposed zooplankton which can significantly decrease function and algal feeding (Cole et al. 2013). A recent study showed that ingestion of microplastics by lugworms leads to decreased feeding activity in sediments that contain 7.4% polystyrene (Besseling et al. 2012). In the same species Wright et al. (2013b) found statistically significant effects on the organisms' fitness and bioaccumulation, but the magnitude of the effects was not high.

Many marine organisms have the ability to remove unwanted natural materials including sediment, natural detritus and particulates from their body without causing harm. However, once ingested there is the potential for microplastics to be absorbed into the body upon passage through the digestive system via translocation and causing particle toxicity with associated inflammation and fibrosis. These studies are summarized in Table 4.3 and a number of studies are highlighted below.

It is known that xenobiotic microplastic particles accumulating in organs and tissues may evoke an immune response, foreign body reaction and granuloma formation (Tang & Eaton 1995). A few studies of marine organisms have clearly demonstrated such direct particle toxicity effects of microplastics translocated from gut to body fluids into organs, cells, and even organelles. Mussels were exposed to primary HDPE plastic powder >0-80 μm, which was absorbed by digestive gland vacuoles (von Moos et al. 2012). Accumulation of plastic inside of lysosomes coincided with breakdown of the lysosomal membrane and release of degrading enzymes into the cytoplasm causing cell death. A strong immune response towards those HDPE particles which were expelled from the digestive tubules into the surrounding storage tissue was diagnosed. The plastic engulfing macrophages were encapsulated by fibrous tissue, resulting in granulocytoma formation during the exposure time of 96 h. In the same exposure study Höher et al (2012) evidenced uptake into hemolymph from the digestive system as Browne et al. (2008) with specific uptake of HDPE into proliferating granulocytes and basophilic hemocytes reflecting the strong immune response also seen in the digestive gland.

4.4.2 *Comparison with observed effects in mammalian systems*

A large body of evidence in the peer-reviewed literature reveals that microparticles of plastic in the human body or mammals are unhealthy. In the absence of studies for marine biota, the effects of particles observed in human cells and tissues or in animal models give an insight into the possible risks of particle exposure in other organisms and in humans. Humans occupy a high trophic level in the marine food chain, and can potentially be exposed to micro- and nano-plastics (especially primary micro- and nano-plastics) while using products that contain them.

Mobility of tiny plastic particles of various size ranges in the human body has been demonstrated in studies of uptake in the gastrointestinal and lymph (Hussain et al. 2001), crossing the human placenta (Wick et al. 2011). The many studies of fine solid particles in air have taught us what particulates can do in human and mammalian tissues and how they negatively impact health through causing allergic reactions, asthma, cancer and heart disease. In the human system much has been learned from PE and PMMA exposures when implants made of these materials degrade and particles are released into the human body causing particle-induced osteolysis (e.g. Martinez et al. 1998; Petit et al. 2002; Nich et al. 2011).

Table 4.3 Selected laboratory studies of biological effects of microplastics exposure in marine organisms

Marine species	Plastic particle exposure and effect	Reference
Phytoplankton *Scenedesmus*	Adsorption of 20 nm PS Hindered algal photosynthesis and promotion of algal ROS indicative of oxidative stress	Bhattacharya et al. 2010
Zooplankton, various species	Uptake of 1.7–30.6 μm PS beads varying by taxa, life-stage and bead-size. Microplastics adhered to the external carapace and appendages of exposed zooplankton. 7.3 μm microplastics (>4000 mL–1) significantly decreased algal feeding.	Cole et al. 2013
Blue mussel *Mytilus edulis*	Uptake of 0–80 μm MPs into digestive system, into digestive tubules with translocation into cells and cell organells (lysosomes). Granulocytoma formation (inflammation). Increase in SB haemocytes; decrease in lysosome stability. Exposure to 10, 30 90 μm MP (incl PS) Indications for selective uptake of 10 μm MPs. Reduced clearance rate 30-nm PS. Reduced filtering/feeding activity	von Moos et al. 2012 Van Cauwenberghe et al. 2013a Wegner et al. 2012
Lugworm (*Arenicola marina*)	PS microplastic. Statistically significant effects on the organisms' fitness and bioaccumulation, but the magnitude of the effects was not high. Exposure to 130 μm (mean size) PVC conc. 1% of sediment (w/w) reduced total energy reserves by approximately 30%, mainly linked to a reduction in lipid reserves.	Besseling et al. 2012 Wright et al. 2013b
copepod *Tigriopus japonicus*	Exposure to 0.05, 0.5 and 6 μm PS .100% survival in 96h tox test. Chronic mortality for 0.05 μm PS >12.5 μg/mL. Reduced fecundity for 0.5 and 6 μm PS.	Lee et al. 2013b
Carp species *Carassius carassius*	Absorption of 24 nm NPs. Food chain transport of NPs affects behaviour and fat metabolism.	Cedervall et al. 2012
Brown mussel *Perna perna*	Leached and virgin microplastics (PVC and PE microbeads), in different concentrations (0.5 and 2.5 g/L) and periods of exposure (6, 12, 24, 48, 96 and 144h) indicated physical (and not chemical) impacts. Altered expression levels of AIF and HSP70 proteins and lysosomal stability in the cells in mussels exposed to microbeads during 144h and in mussels exposed to microbeads during 144h, irrespective to concentration.	Preliminary results of master's thesis of Liv Ascer and Marina Santana
Sea urchin *Lytechinus variegatus*	Plastic pellets (virgins and beach-collected) affect embryonic development, but virgin ones have a stronger effect.	Nobre et al. 2015
copepod *Centropages typicus*	Exposure to ≥4000 particles/mL of 7.3 μm PS significantly decreased copepod feeding on algae.	Cole et al. 2013
copepod *Calanus helgolandicus*	Exposure to 75 particles/mL of 20 μm PS for 24 hrs significantly decreased copepod feeding capacity. Prolonged exposure significantly decreased reproductive output (egg hatching success and survival)	Cole et al. 2013
Japanese medaka *Oryzias latipes*	Fish fed a diet containing virgin PE pellets and pellets with sorbed PAHs PCBs and PBDE cogeners, having been exposed in a contaminated marine environment, show evidence of hepatic stress	Rochman et al. 2013a

In a study of exposure to ultrafine polystyrene particles in rats, lung inflammation and enzyme activity were impacted, in a dose-dependent way, the greater the surface area to volume ratio of the particle. Toxicity increased in direct proportion to a decrease in particle size from 535 nm to 202 nm to 64 nm polystyrene (Brown et al. 2001). Many other effects of ultrafine plastic were measured in vitro in the same study, including induction of increases in IL-8 gene expression in epithelial cells and an increase in cytosolic calcium ion concentration. The authors suggest that these particle-induced calcium changes may be significant in causing pro-inflammatory gene expression, such as chemokines. A large body of literature has been published on the human toxicity of particles, mainly via the inhalation exposure route (e.g. Hesterberg et al. 2010).

More knowledge of the transfer of microparticles, including microplastics and nanoplastics, through biological membranes can also be mined from the drug delivery research literature. There are ongoing investigations of how the bioavailability and uptake of medicines can be improved by way of micro- or nano-particulate carriers (e.g. Hussain et al. 2001 for microplastics and De Jong & Borm 2008; Wesselinova 2011 for some reviews of the emerging field of nanomedicinal applications, including attention to toxicity).

When humans or rodents ingest microplastics (<150 μm) they have been shown to translocate from the gut to the lymph and circulatory systems (Hussain et al. 2001). Wick et al. (2011) recently demonstrated how nano-sized polystyrene particles up to 240 nm in diameter cross the human placenta in perfusion experiments. Synthetic polymers may in some cases be less harmful than the classic engineered nano-plastics. In a recent study, coating toxic carbon nano-tubules with a polystyrene-based polymer was tested with the aim of reducing the cytotoxicity, oxidative stress, and inflammation in an in vivo mice lung test and an in vitro murine macrophage test (Tabet et al. 2011).

These studies from mammalians and the medical field issue a warning that when the size of the microparticle approaches the range below approximately a quarter of an mm, adverse effects may start to emerge due to particle interactions with cells and tissues, particle uptake in endosomes, lysosomes, the lymph and circulatory systems and the lungs. These include deleterious effects at cellular level (Berntsen et al. 2010; Fröhlich et al. 2009) or uptake into placental tissue (1et al. 2010) or lymph and circulatory systems (Hussain et al. 2001;). Human exposure is also a concern if seafood containing microplastics is consumed.

4.4.3 *Chemical effects*

Section 4.3 demonstrated that microplastics serve as a vector of hazardous chemicals including POPs to marine organisms. In many cases, they are also exposed to chemicals through prey and a dominant contribution from microplastic over natural food has been reported for limited species of animals so far. Conclusive evidence of adverse effects caused by chemicals associated with microplastics is difficult to obtain, but progress has been made. Rochman et al. (2013a) demonstrated the transfer of POPs from plastic to fish and adverse effects from environmentally relevant concentrations. Lavers et al. (2014) showed negative correlation of plastic ingestion with some body conditions of a species of seabird (Flesh-footed shearwaters) whose population decrease is of concern. However, contribution of plastic-derived chemicals has not been clearly evidenced to cause declined body conditions and population-level effects.

A laboratory experiment utilizing lugworms (Arenicola marina) demonstrated chemicals associated with microplastic cause adverse effects (Browne et al. 2013). The lugworms were exposed to nonylphenol, phenanthrene, BDE-47, and triclosan with PVC and/or Sand. Transfer of the chemicals from microplastics to gut was observed. Reduction of some biological functions was observed. The results indicated that survivorship and feeding were diminished by triclosan associated with PVC. Contribution of plastic-derived nonylphenol to phagocytic activity and lower oxidative status likely induced by nonylphenol and phenanthrene were suggested.

4.4.4 *Potential effects on populations, communities and ecosystems*

Our knowledge indicating population or higher-level effects caused by micro- and nano-plastics in the marine environment is poor. Microplastic may not only affect species at the organism level; they may also have the capacity to modify population structure with potential impacts on ecosystem dynamics (Wright et al. 2013a,b), including bacteria and viruses. Negative effects on the photosynthesis of primary producers and on the growth of secondary producers, potentially result in a reduced productivity of the whole ecosystem and represent a primary concern.

The bacteria that colonize plastic particles were shown to differ from surrounding water (Zettler et al. 2013) and sediment (Harrison 2012). Biofilm formation on plastic can be temporally variable and is linked to the productivity of the surrounding seawater (Artham et al. 2009). Biofilm is able to be recorded at least one week after exposure, increasing through time, and may influence plastic buoyancy (Lobelle & Cunliffe 2011) and, indeed, microplastics distribution and availability. The increase in biofilm is supposed to increase the food availability to zooplankton (Kirchman and Mitchell 1982), which may have a bottom up effect on plankton communities.

Plastics in the marine environment, floating in the surface or in the water column or in the bottom, may act as new habitats or new food source for marine organisms, the 'plastisphere' sensu (Zettler et al. 2013). In this context, plastics may have an additive effect on floating patches of seaweeds or create new ones in areas were natural floating patches do not occur.

Table 4.3. Selected studies showing translocation of microplastics from the gut to the circulatory system and various tissues and cells in humans and other mammals and mammalian systems

Species	MP exposure and effect	Reference
Human lymph and circulatory system	Absorption of PE particles taken up in lymph and circulatory system from gastro-intestinal tract	Hussain et al. 2001
Human placenta (*ex vivo*)	Fluorescent 50, 80, 240 and 500 nm PS particles. Particles up to 240 nm were taken up by the placenta	Wick et al. 2011
Rat	535, 202 and 64 nm PS Lung inflammation and enzyme activities were affected, with increasing severity as particle size decreased	Brown et al. 2001
Human airway smooth muscle cell	Fluorescent 40 nm PS particles decreased cell contractility	Berntsen et al. 2010
Human endothelial cells (blood vessels)	Carboxyl PS latex beads in sizes of 20-500 nm were tested. 20 nm PS particles induced cellular damage through apoptosis and necrosis	Fröhlich et al. 2010
Human macrophages	Fluorescent PS microspheres (1, 0.2, and 0.078 μm). Particle uptake of all sizes: on average, 77 $\pm$ 15% (mean $\pm$ SD) of the macrophages contained 0.078 μm, 21 $\pm$ 11% contained 0.2 μm particles, and 56 $\pm$ 30% contained 1 μm particles. Particle uptake steered by non-endocytic processes (diffusion or adhesive interactions).	Geiser et al. 2005
Dog	PVC particles (5–110 μm) appeared in the portal vein and will reach the liver	Volkheimer 1975

Independently from the size of the particle, fouling organisms may find in plastics an additional mean to disperse (Gregory 2009). Individual plastic particles or plastic patches may be considered as stepping-stones (sensu MacArthur & Wilson 1967), such as they create new hard bottoms and increase their availability in the ocean. This allows organisms, in a single or multiple generations, to enhance the probability to occur in certain areas in comparison to the situation considering only natural floating debris. A study on the colonization of stranded plastic debris in Arctic and Antarctic islands estimated that human litter more than doubles the rafting opportunities for biota (Barnes 2002).

According to Barnes (2002), Barnes & Milner (2005) and Gregory (2009), this situation may increase the risk of dispersal of aggressive alien and invasive species and thus endanger sensitive coastal habitats. Hypothetically, marine debris (Majer et al. 2012), as also supposed for floating seaweeds (Rothäusler et al. 2012), may also increase gene flow, thus allowing genetic mixing among populations and decreasing genetic variability within populations.

Similarly to floating seaweeds (Vandendriessche et al. 2007), relatively more dense aggregations of floating plastic particles may possibly act as refuges or feeding grounds for fishes. An increase in abundance of microplastics through time was positively correlated to abundance of *Halobates sericeus* and its egg densities (Goldstein et al. 2012). Increasing population densities may have different outcomes at the community and ecosystem level, as discussed for *Halobates* micans (Majer et al. 2012). Depending on the species being favoured by microplastics, one may expect an increase in predatory pressure by Halobates, a top-down effect, or in the food supply to *Halobates* consumers, a bottom-up effect.

Depending on the amount and size of the particles, different functional groups may be directly affected by microplastics, compromising ecological process and ecosystem function. As exposed above, adsorption of microplastics in the organism surface, e.g. algae (Bhattacharya et al. 2010) and zooplankton (Cole et al. 2013), was demonstrated to reduce the photosynthetic and feeding rate, respectively. However, what this effect at the base of the food chain could mean for the productivity and resilience of ecosystems in the long term is unknown. Considering that amount of plastics entering the ocean is increasing, plastic degradation produces smaller particle sizes, smaller particles are supposed to be more toxic, and the effect of microplastics at higher levels of organization is supposed to increase, it is possible to suppose an increasing impact of microplastics on marine systems. However, due to their complexity, with species-specific and generalized response from the biota to the presence of microplastics, with external and internal exposures and with physical and chemical effects, which are not well understood, the direction of this effect is hard to be predicted.

Indirect effects may occur due to the presence of small plastic particles in sediments, which were reported to increase permeability, warm more slowly, and reach lower maximum temperatures (Carson et al. 2011).

4.4.5 *Potential effects on humans*

The potential accumulation of microplastics in the food chain, especially in fish and shellfish (species of molluscs, crustaceans and echinoderms) could have consequences for the health of human consumers. This seems particularly the case for filter-feeding bivalves such as mussels and oysters in Europe but could equally be applicable for deposit-feeding sea cucumber which is more popular in the Asian cuisine.

Microplastics have been shown to be ingested by several commercial species such as mussel, oyster, crab, sea cucumber and fish (Tables 4.1, 4.2). Relatively high concentrations of microplastics were detected in Belgian commercial grown mussels (*Mytilus edulis*) and oysters (*C. gigas*), respectively on average 0.36 $\pm$ 0.07 particles g^{-1} wet weight (w.w.), and 0.47 $\pm$ 0.16 particles g^{-1} w.w. (Van Cauwenberghe and Janssen 2014). As a result, the annual dietary exposure for European shellfish consumers can amount to 11,000 microplastics per year. Another Belgian study analysed microplastic contamination between consumption mussels and wild type mussels (mainly *M. edulis*), collected at Belgian department stores and Belgian groins and quaysides, respectively (De Witte et al. 2014). The number of total microplastics varied from 2.6 to 5.1 fibres/10 g w.w. of mussel, which compared well with the former study, despite the fact that both Belgian studies used different methods of analysis and size detection limits. A maximum concentration of 105 particles g^{-1} dry weight (d.w.) (d.l. $>$ 10 mm) was reported in wild mussel (*M. edulis*) from the Dutch coast (Leslie et al. 2013); these levels are one order of magnitude higher (13.2 particles g^{-1} ww; using a conversion factor from d.w. to w.w. of 8 assuming a lyophilization rate of 0.12).

Although it is evident that humans are exposed to microplastics through their diet and the presence of microplastics in seafood could pose a threat to food safety (Van Cauwenberghe and Janssen 2014), our understanding of the fate and toxicity of microplastics in humans constitutes a major knowledge gap that deserves special attention. Therefore, an analysis and assessment of the potential health risk of microplastics for humans should comprise dietary exposure from a range of foods across the total diet in order to assess the contributing risk of contaminated marine food items.

4.5 Recommendations for further research

- Examine the extent to which nano-sized plastic particles may cross cell membranes and cause cell damage, under natural conditions, including knowledge and expertise from the medical and pharmaceutical industry (drug delivery).
- Examine the extent to which additive chemicals may cross the gut wall and assess the risk of harm at an individual and population level.
- Examine the extent to which adsorbed organic contaminants may cross the gut wall and assess the risk of harm at an individual and population level.
- Assess the potential health risk of microplastics for humans, including dietary exposure from a range of foods across the total diet in order to assess the contributing risk of contaminated marine food items.
- Examine the potential of microplastics to translocate non-indigenous species, including pathogenic organisms, relative to other transport vectors.
- Examine the potential for accumulations of plastics and microplastics to form additional floating ecosystems.
- Examine species-specific gut conditions that may influence chemical availability and transfer.
- Consider using stable or radioactive labelled compounds (polymers, additive chemicals and absorbed contaminants) to establish the degree of transfer under different conditions.

5 SOCIAL ASPECTS OF MICROPLASTICS IN THE MARINE ENVIRONMENT

5.1 Introduction

The use of plastics has proliferated in recent decades, due to a complex mix of perceived societal and economic benefits. Unfortunately, the rate of increase in use has not been matched by the adoption of suitable systems to control unwanted plastic items. The working group was asked to consider some of the social aspects around the issue of microplastics in the ocean. The scope of this ToR was quite restricted, to explore the potential role of social science approaches for addressing the issue of microplastics, based on the realization that people's perceptions and behaviours contribute to the problem but are also crucial in any solutions suggested. This scoping exercise for the social scientists was rather different from the rest of the report because no established field of research exists in the social sciences that specifically addresses microplastics. Thus, the social scientists were asked to selectively review relevant approaches rather than producing a quantitative analysis of perceptions and behaviours. The data for a more quantitative analysis are largely lacking, even considering the impact of macro debris, which is a much more recognizable problem.

Perceptions influence the behaviour of:

a) the general public;

b) the complex web of industries involved in design, materials science, engineering, manufacturing, advertising and retail;

c) users of products such as the aquaculture, fisheries, catering, health-care and tourism sectors;

d) legislators and environmental managers responsible for many different aspects of plastic use and disposal.

Using predominantly the lens of risk perception, this chapter explores the current state of understanding about public perceptions regarding: i) the composition and extent of marine debris and microplastics; and, ii) the welfare impacts of microplastics on society. These two aspects are key to understanding the very disparate roles of humans in the system as decision-makers and agents, who can play an active role in working towards solutions, and as individuals experiencing the consequences of microplastics. This relationship is summarized in Figure 2.2 where people can act in cleaning up the problem (e.g. by taking part in beach cleans) and they may be affected by the presence of litter (e.g. as coastal tourists). National, regional and individual differences in these social aspects will also be explored briefly. However, it was anticipated that the literature on microplastics per se would be very limited. Consequently this section draws mainly from published and forthcoming research on macro marine debris and the general risk perception literature (rather than more behavioural social science) and applies these insights to microplastics.

5.2 Perceptions of marine litter and microplastics

5.2.1 *Perceptions of marine litter in general*

There is evidence that at least some sections of the public are aware of our dependency on the marine environment. For instance, as early as 1999, 75% of people in a US survey believed that the health of the ocean is important for human survival (Ocean Project 1999). When focusing on environmental matters related to the marine environment specifically, several environmental topics are of particular interest to the public, such as climate change, chemical pollution and ocean acidification (e.g. Vignola et al. 2013; Peterlin et al. 2005; Fleming et al. 2006). Similarly, marine debris is commonly noted as one of the most important issues when people are asked whilst visiting the coast (e.g. Santos et al. 2005; Widmer & Reis 2010). In general, microplastics are not mentioned spontaneously in such surveys. This could indicate either a lack of perceived importance, or simply a lack of knowledge and recognition of this particular environmental issue.

One of the largest scientifically based assessments of public perceptions was conducted in Europe, in a survey of 10,000 citizens from ten European countries, where respondents were asked to identify the three most important environment matters regarding the coastline or sea (Buckley and Pinnegar 2011). The survey was conducted in the context of assessing perceptions about climate, but allowed the respondents to express their concerns freely. When stating levels of concern for a number of environmental issues, including overfishing, coastal flooding and ocean acidification, the term 'pollution', particularly water and oil pollution, was mentioned frequently. Marine debris-related terms, such as 'litter', 'rubbish' and 'beach cleanliness' were also reported, but much less frequently (Figure 5.1).

Figure 5.1. *Main responses from a multinational sample from 10 countries (n = 10,106) to a qualitative question that asked individuals to state the three main marine environmental matters. Frequency of responses is illustrated by the size of the text, with pollution noted most often (reproduced from Buckley and Pinnegar 2011).*

In addition to research examining the level of importance individuals place on the marine environment and the various perceived threats to it, some studies have started to explore the public's current understanding about macro marine debris more specifically. One multinational survey (MARLISCO; www.marlisco.eu) explicitly examined perceptions in different societal groups about macro marine debris. A number of sectors were chosen, including: design and manufacturing, maritime industries, policy makers, media organizations, education and environmental organizations. This was not intended to be representative of society in general, but that portion of society that might be considered as being more connected to the issue of marine litter and microplastics. With a sample of just under 4,000 respondents from over 16 mostly European countries, the MARLISCO survey found that the majority of respondents were concerned about marine litter and perceived the marine environment as being highly valuable to society. There was a belief that the situation regarding marine litter was worsening, and that most of marine litter was derived from the sea[12] (B. Hartley unpublished data). This survey also found that all groups significantly underestimated the proportion of marine litter items composed of plastic by about 30% (B. Hartley unpublished data). A separate survey on UK commercial fishers found similar patterns in perception, whereby fishers underestimated the proportion of litter that is plastic, and on average, were unsure whether marine litter was increasing or decreasing (Defra report, forthcoming).

In a Chilean beach visitor survey, most visitors reported that they did not dispose of litter on beaches despite a large proportion of marine debris being left by visitors in general (Eastman et al. 2013; Santos et al. 2005). Even though respondents generally claimed not to be individually responsible, they did identify the overall public to be the main source of debris (Santos et al. 2005, Slavin et al. 2012; Eastman et al. 2013). In terms of the effects and impacts of marine debris, the main problems that beach users identified were related to the impact on marine biota, human health and safety, and attractiveness (B. Hartley unpublished data; Santos et al. 2005; Wyles et al. 2014; Wyles et al. under review). Thus, these findings suggest that beach-users and commercial fishers have a basic understanding of marine litter in general.

5.2.2 *Perceptions about microplastics*

Individuals' perceptions about macro marine debris are relevant for understanding the overall issue of microplastics, as macro plastic can break down to form secondary microplastics. For the purpose of this report, the extent of individuals' knowledge specifically relating to microplastics is more relevant. Unfortunately, very little has been published in this area. To our knowledge there are only two studies that included any questions specifically related to microplastics. Firstly, a citizen science programme, involving 1,000 school students in Chile, found that the majority of children (aged 10 to 17) had never heard of microplastics before (Hidalgo-Ruz and Thiel 2013). Secondly, in a multinational survey, using a web-based flash survey method (http://ec.europa.eu/public_opinion/flash/fl_388_en.pdf) of over 26,000 Europeans, 78% agreed to the statement that *"the use of micro plastic particles in consumer cosmetic and similar products should be forbidden"* (European Commission 2014).

There has been no published in-depth investigation of individuals' understanding of this issue. Consequently, a pilot study was carried out in 2013, specifically for this report, to begin to explore this area (for the purpose of this report, it will be termed the GESAMP pilot survey; (S. Pahl unpublished data). A sample of 68 adults in a city on the coast of Southwest of England (31 men, 36 females, 1 not stated; average age 43; *SD* = 13 years; age range = 19-71), were questioned about their perceptions of microplastics. Roughly half (53%) had heard of the term 'microplastics'. When asked to define the term, most people described it as *"very small, tiny particles of, miniature pieces of plastic"*. Some people were not able to answer this question, with others giving other answers that were either vague (e.g. *"man-made material"*) or very detailed (e.g. *"carrier bags, lids, toothbrushes"*), or focusing on the degradability (e.g. *"something that never goes away"*). When asked to estimate the size of these particles, the most common responses were that they were microscopic or not visible (25% of responses), less than 1 mm (37%) or less than 5 mm (21%). Of the remaining responses, 12% thought they were larger than 5 mm, with 6% unable to provide an answer. In terms of distribution and abundance, 74% of the respondents believed the quantity of microplastics in the marine environment was increasing, and the majority believed microplastics could be found in the deep sea, surface seawater, on beaches, in marine animals and in polar seas. As illustrated in Figure 5.2, the overall consensus was that a lot can be found on beaches, with less in the deep sea and in polar seas. Consequently, this preliminary research suggests that although about half the participants had heard of the term, the 'public', on the basis of this small rather unrepresentative sub-set, have a limited understanding of the existence and concept of microplastics. Clearly, further research is needed to substantiate this finding.

To explore concern for microplastics specifically, the GESAMP pilot survey also included a question on concern. On a scale from 1 (not at all concerned) to 10 (extremely concerned), respondents were, on average, quite concerned (M = 6.91; SD = 2.63).[13] However, respondents were more concerned about other issues such as the health of the natural and marine environment in general, the cost of living and climate change. These findings were consistent with those reported by Potts and colleagues (2011).

[12] The working group considered that there are no reliable estimates of the quantities of plastic entering the ocean. It is conceivable that more than half comes from land but the available evidence suggests that significant regional and local variations in the proportion of sea- and land-derived plastic occur. http://www.marlisco.eu

[13] Not surprisingly, this was lower than the concern expressed by 29 experts in a special workshop on microplastics using the same scale (expert M = 8.16, SD = 1.69; t(98) = 2.45, p = .02, d = .48 (medium effect).

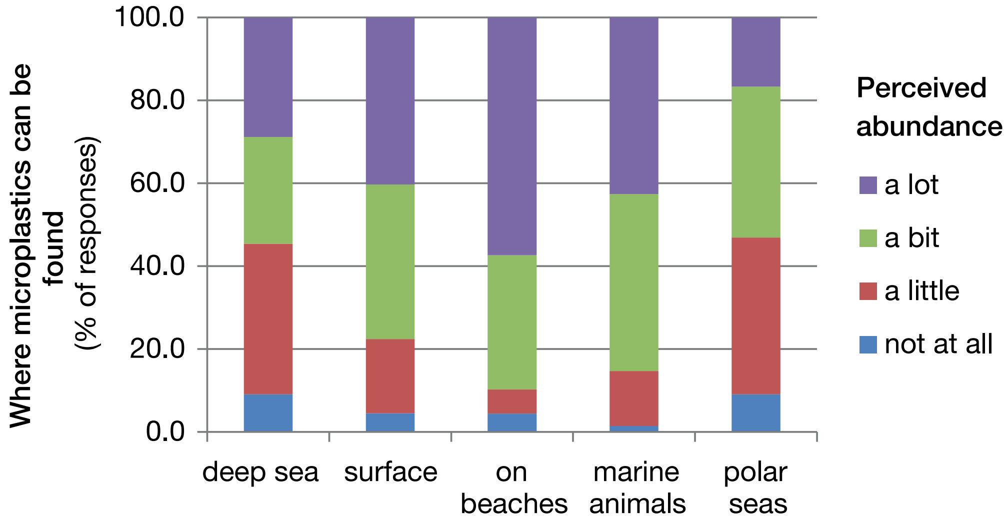

Figure 5.2. *The frequency of responses to the question about perceived abundance in different areas of the marine environment (perceived distribution) from the GESAMP pilot survey (n = 68, S. Pahl unpublished data).*

It is worth listing a number of limiting factors that can influence the outcome of a perception survey, and therefore the apparent level of knowledge of or concern over a particular issue. The circumstances of the request may affect the willingness to cooperate, e.g. between educational and organizational settings versus 'cold-calling' or a street survey. Younger people with more exposure to social media may be more responsive to using this medium than other members of society. Age, gender, educational attainment and cultural or religious background may influence responses (see below) so larger, ideally representative surveys are desirable. If the respondent has prior knowledge of the topic they may be more willing to express their views. If individuals are active in 'environmental affairs' and campaigning then their advocacy may encourage others in their sphere of influence to volunteer their views. As a result, the outcome of any survey of people's opinions needs to be viewed in the particular context and circumstances of the survey, and conclusions about the wider population cannot necessarily be drawn. When investigating concern specifically, it is important to acknowledge the effect of simply asking questions. For instance, if a general public sample is asked about microplastics, this could suggest that the researcher believes it is something to be concerned about. During data collection for the GESAMP pilot survey, one respondent reported that they had not heard of the term prior to this survey, but as they were being asked about it, they assumed it should be something to be concerned about. Thus, in a field of research in its infancy, a perception survey may at the same time establish opinions as well as trying to measure them.

5.2.3 *Public perceptions and coverage in the printed and digital media*

An analysis of the reporting of issues in the printed and digital media, or the frequency with which certain words or search terms are used on the internet or in social media, can provide an indication of the level of interest either by the public in general or a particular sub-set of individuals (e.g. a group of 'activists'). Of course, it would be imprudent to draw exact conclusions as there are many confounding factors that may interfere with extracting reliable information of perceptions of a specific topic. However, usage statistics regarding media resources can indirectly indicate the public's concern and interest surrounding an issue. For instance, Google Trends can "reflect how many searches have been done for a particular term, relative to the total number of searches done on Google over time" (Google Trends, 2014a). For the purpose of this report, a very basic exploration of the trends relating to marine debris and microplastics was undertaken although some questions remain about how exactly these scores are calculated (see Note in Fig. 5.3 and the results of including slightly different research terms in the subpanels). First, Figure 5.3 (a) shows how searches for 'marine debris' and 'marine litter' have fluctuated over the past ten years (2004–2014). Second, when 'Great Pacific Garbage Patch' was included in the search (Figure 5.3 (b)), the patterns for the former two phrases change drastically, as this new term was evidently more commonly searched and thus had a strong effect (Gaudet 2012; Google Trends 2014b). Third, in terms of 'microplastics' and 'microbeads', the recent peaks in searches for the terms could potentially suggest an increase in interest and concern in the topic (Figure 5.3 (c)).

Google Trends can offer information on search trends, has good geographical spread (depending on internet access and use of that particular search engine) and is a free source; however, limitations still need to be acknowledged. For instance, the search terms are language dependent, searches cannot combine two terms (e.g. 'micro' and 'plastics'), and results may include unrelated topics (e.g. for hair extensions and as ingredients in products such as pillows and cosmetics). Consequently, this analysis needs to be considered a basic insight in the public's interest in microplastics. Ideally, results obtained using Google Trends should be validated by correlating them with survey data to see if the same patterns emerge in the more direct approaches (Mellon 2013).

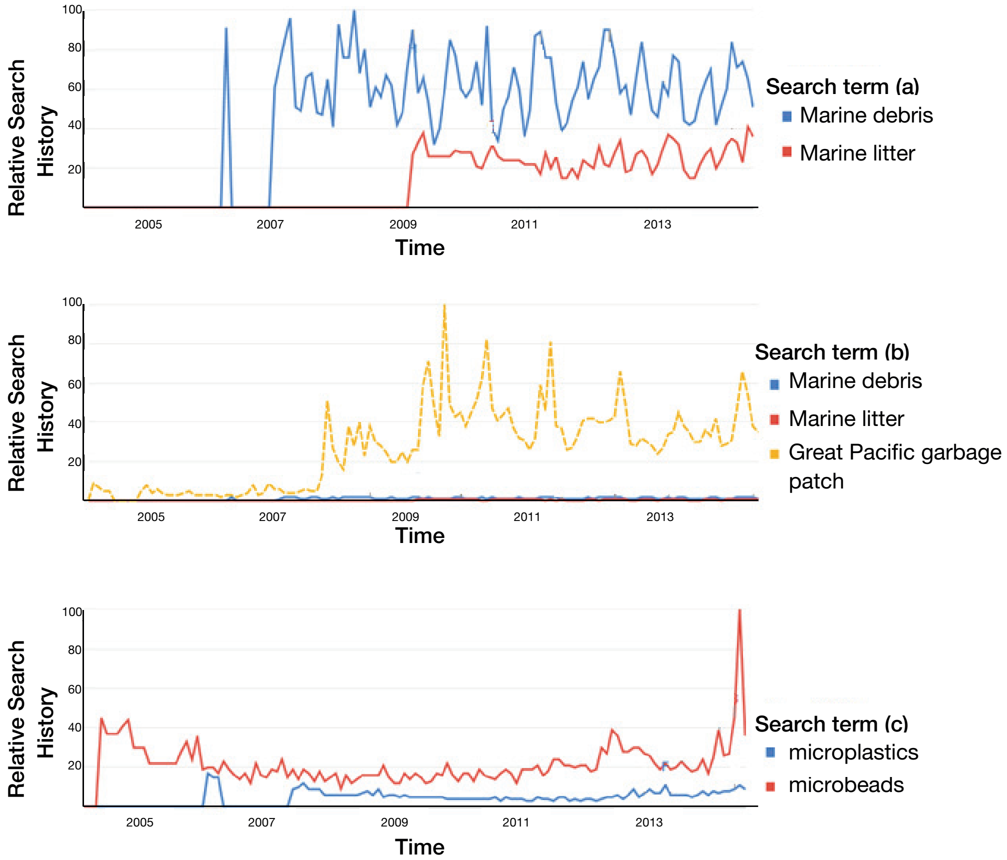

Figure 5.3. *The use of the terms (a) marine debris and marine litter; (b) marine debris, marine litter, and the Great Pacific Garbage Patch; and (c) microplastics and microbeads via internet search trends (Google Trends 2014b).*

Note. According to Google Trends, "the numbers on the graph reflect how many searches have been done for a particular term, relative to the total number of searches done on Google over time. They don't represent absolute search volume numbers, because the data is normalized and presented on a scale from 0-100. Each point on the graph is divided by the highest point and multiplied by 100. When we don't have enough data, 0 is shown" (https://support.google.com/trends/answer/4355164?hl=en-GB&rd=1).

In addition to Google Trends, examining newspaper articles offers another perspective, although similar caveats apply in terms of the danger of over-simplifying the relationship between printed media reports and public perceptions. The first scientific publication dedicated to microplastics appeared in Science in May 2004 (Thompson et al. 2004). Within a year of this publication, it received regional to international media coverage, with over 50 stories addressing this specific article (see Table 5.1).

Similar to Google Trends, it is possible to review the trends over time in media stories by searching newspaper archives. For the purpose of this report, the terms surrounding 'micro plastics' and 'micro beads' (with and without spaces and hyphens) were searched within the LexisNexis newspaper archive; however, unlike Google Trends, the results were validated by only including those that made reference to marine pollution and excluded duplicate articles. In total, 29 items were found within the UK national newspapers between 3 July 2004 and 3 July 2014.[14] Most articles were published in national broadsheet/mid-market newspapers, with a striking increase in interest in the most recent years; however, very few articles appeared in the popular mass newspapers over this time period ('tabloid' newspapers, see Figure 5.4).

In addition to these descriptive trends in Google searches and national press articles, other media attention suggests a potential growing interest and concern. For instance, there have been a number of TV documentaries including the Austrian movie "Plastic Planet" (2009) by Werner Boote, the documentary "Midway, Message from the Gyre" (2013) by Chris Jordan and a feature length film "Plastic Seas" by Jeneene Chatowsky (2013). A growing number of websites are dedicated to marine debris and microplastics, such as the NOAA Marine Debris Program (http://marinedebris.noaa.gov/); the 5 Gyres Foundation (http://5gyres.org/); MARLISCO, Europe (http://www.marlisco.eu/), PlasticTides, Bermuda (http://www.plastictides.org/), and International Pellet Watch (http://www.pelletwatch.org/).

[14] The daily newspapers sampled were: The Times, The Guardian, The Daily Telegraph, The Independent, The Daily Mail, The Express, The Mirror, The Sun, and The Daily Star. The Sunday newspapers sampled were: The Sunday Times, The Observer, The Sunday Telegraph, The Independent on Sunday, The Mail on Sunday, The Sunday Express, The Sunday Mirror and The People.

Finally, dedicated social media campaigns have the potential to bring about change to society. The campaign "Beat the Micro Bead" (www.beatthemicrobead.org) originated in the Netherlands and illustrates public concern regarding microplastics (or microbeads) entering the marine environment from personal care products such as shampoos, toothpaste and lip balm. Up until July 2014, this particular campaign had over 2,000 Twitter followers, 3,200 Facebook 'likes' and 17,000 views of YouTube. More recently the campaign has been extended to an international scale and a number of producers have announced their plans to reconsider and potentially phase out the use of microplastics in their products (e.g. Beiersdorf 2014; L'Oréal 2014; Unilever 2014).

Nevertheless, whilst media coverage can influence and indicate the public's interest and concern, and can lead to changes in the commercial sector, there is a risk that messages may be misinterpreted and perceptions and opinions presented as 'facts'. A good example is how the observation that plastic accumulated in the North Pacific sub-tropical gyre led to the phrase the "Great Pacific Garbage Patch", conjuring visions, amongst some, of a huge island of solid garbage floating in the Pacific.[15] This example is a representation of the media impact on society, by choosing a metaphor concept, as well as an illustration of a dramatic image of certain environmental issue, which can be used as a way to enhance a perceived importance of the issue. In this case, the metaphor succeeded in catching public attention, but fails to carry the accuracy and the complexity of the situation. As O'Neill and Smith (2014) emphasize, images are subject to interpretation by the viewer. Scientific data indicate that there are, in fact, areas of accumulation zones, but these are mainly composed by microplastics floating over an extensive area without an exact size (Goldstein et al. 2013). Some organizations have specifically designed websites to try to clarify some common misconceptions and to give accurate information about it (e.g. NOAA Marine Debris Program).[16] Thus, as well as indicating public interest, the media can be a source of correct (and incorrect) information about a topic, which in turn can influence the general public's risk perception and understanding of the topic.

[15] http://www.abc.es/20120416/ciencia/abci-septimo-continente-basurero-flotante201204161033.html
[16] http://marinedebris.noaa.gov/marinedebris101

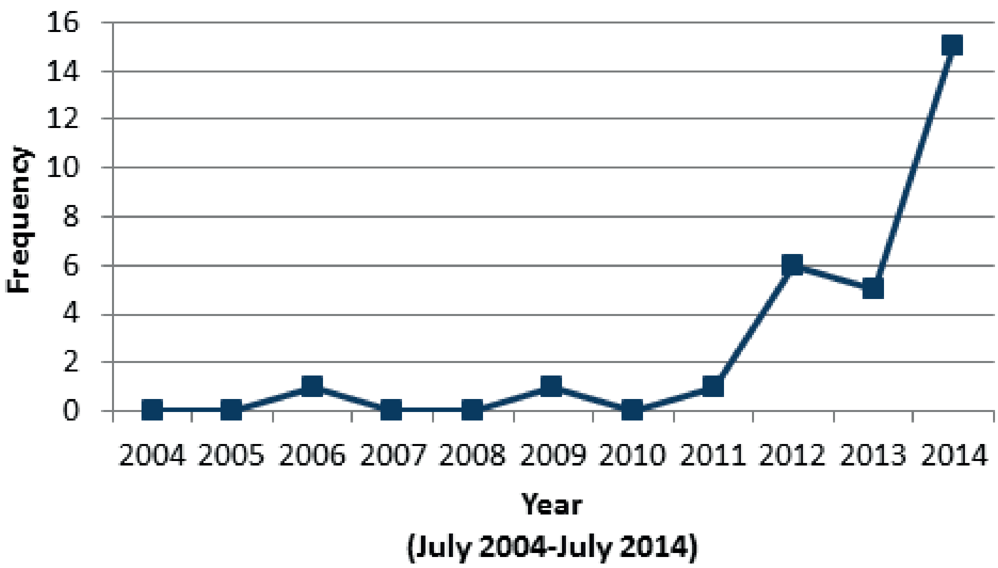

Figure 5.4. *Frequency of newspaper articles with the terms 'micro plastics' and 'micro bead' within the UK newspapers.*

5.2.4 *Perceived Risks*

Discrepancies in perceived level of risk between experts and the public have been observed in the general risk perception literature. For instance, the public has been found to perceive much greater health risks associated with biotechnology in food than experts have (Savadori et al. 2010; Slovic 1987; 1999). While experts may focus on probabilities or annual fatalities, the public evaluate risks in terms of a number of psychological factors. The two most prominent factors derived from large-scale empirical studies are commonly referred to as 'dread risk' and 'unknown risk' (Slovic 1987). 'Dread risk' is composed of the following perceptions: strong emotional feelings of dread, lack of control over the issue, catastrophic potential and fatal consequences, more risks than benefits, involuntariness and difficulty reducing the risk. 'Unknown risk' is higher when issues are unknown to those exposed and unobservable, with unknown and delayed consequences, and when the issue is seen as new and also relatively unknown to science. From these psychological factors, it is possible to produce quantitative representations of risk perceptions for a range of issues (also known as cognitive maps, see Figure 5.5).

Table 5.1. Examples of media coverage of the article Lost at sea: where is all the plastic? (Thompson et al. 2004)

National Coverage	European Coverage	International Coverage	Commercial Coverage
BBC 1 TV National News	France 2, National TV Documentary feature for Complement d'enquete	BBC World Service	Plastics and Rubber Weekly
BBC 1 TV Newsround	German Republic Radio SWR2	Canadian Broadcasting Corporation	Chemical and Engineering News, Washington
BBC TV News 24	German Public Radio AR1	Canadian West Radio News	Chemistry and Industry Magazine
BBC Radio 4: Today Programme	Liberation, France	Discovery Channel, Canada	Materials Today, UK
BBC Radio 4: You and yours	Science et Avenir, France	National Peoples Radio, USA (2 million)	
BBC Radio 1,2, 3, 4: News	Basler Zeitung, Switzerland	BBC Radio Falklands	
BBC Radio Scotland	Frankfurter Allergemine, Germany	New York Times	
BBC Radio Devon	Berliner Zeitung, Germany	Washington Post	
Radio Manchester	Der Spiegel, Germany	Washington Times	
The Guardian	Gazeta Wyborcza, Poland	Wtop Radio, Washington (1 million)	
Evening Herald, Plymouth	Svenska, Sweden	Wall St Journal	
Western Morning News	CORDIS News web site	Bloomberg News	
The Scotsman		Boston Globe	
New Scientist web site		Omaha World Herald	
CBBC web site		Houston Chronicle	
BBC Wildlife Web site		Lexington Herald, Kentucky	
		La Hora, Chile	
		Honolulu Advertiser	
		Taipei Times, Taiwan	
		Straits Times, Singapore	
		Pravda, Russia	
		ABC National Network Australia	
		National Radio, New Zealand (250 K)	
		Business Week Magazine	
		National Geographic web site	
		Nature web site	

Moreover, discrepancies in perceived risk between experts and public may also be due to societal processes when dealing with new information, e.g. reported in the media. These have been described as either risk amplification (the public think risks are higher than experts do) or risk attenuation (the public think risks are smaller than experts do). These processes take place in a network of social groups and institutions, including scientists, reporters, the mass media and politicians (Kasperson et al. 2003). Related to this, the level of trust in a source has been shown to influence an individual's risk perception. For example, if individuals distrust the science or management of a hazard, they are likely to perceive a greater risk, which has been found with the use of pesticides and pathogens (Williams & Hammitt 2000). This is especially important to consider in the case of microplastics as the general public cannot assess the abundance and risks of microplastics for themselves (see Anderson & Petersen 2013 for a related observation on nanotechnologies). Consequently, the role of the communicator gains more weight, and factors such as trust in experts become important. From the literature, we know that independent academics are the most highly trusted group of communicators (as opposed to the media or government bodies, for example). Moreover, it is not just expertise that is linked to trust. Trust is highest if a decision-maker is perceived to have both high perceived expertise and warmth (White & Eiser 2006; White & Johnson 2010). 'Warmth' in this context refers to a perception of genuine care and shared values.

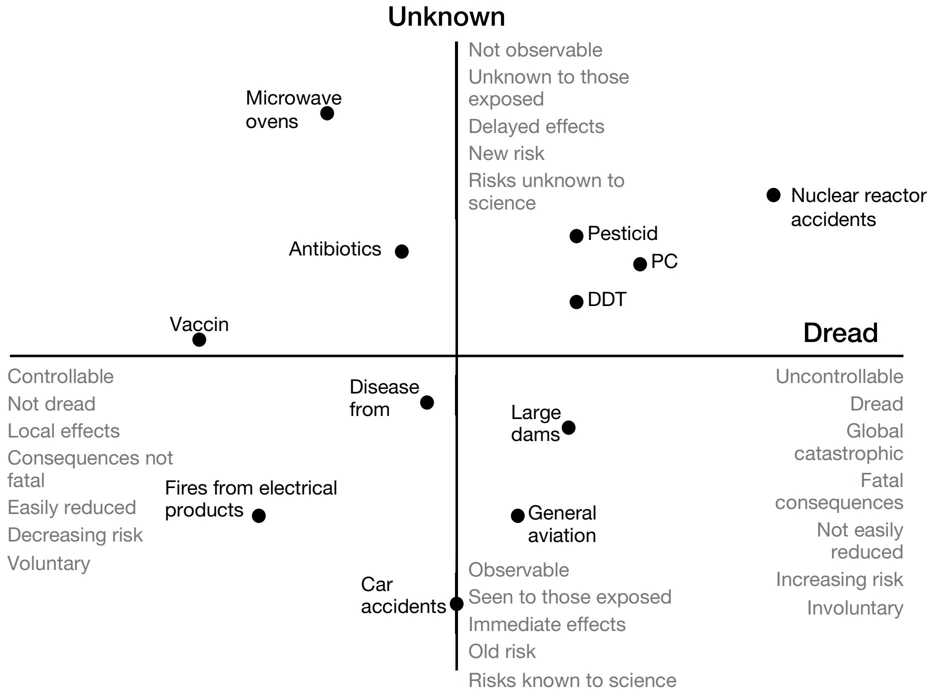

Figure 5.5. *A cognitive map of perceptions of risks for a number of technological and environmental issues according to dread risk and unknown risk (adapted from Slovic 1987).*

In addition to the magnitude of perceived risk of microplastics in general, specific behavioural issues may affect people directly, such as consumption of seafood. As outlined in Section 4, there is a possibility that microplastics may be transferred to humans via seafood. What do we know about the perceived risk and benefits of seafood consumption? Using a cross-sectional survey on 429 Belgium consumers, Verbeke and colleagues (2005) found that respondents believed there were harmful contaminants in fish, explicitly referring to PCBs and heavy metals. We can speculate that microplastics could be seen as another type of contaminant. However, the risks associated with harmful contaminants were rated less important than the beneficial nutrients fish was seen to provide. Overall, fish was seen to offer greater benefits than risks. In other work, risk does not feature highly when considering seafood consumption. Instead, taste and quality of the fish have been found to be the most important predictors in seafood consumption, with price and convenience as the main barriers (Olsen 2004; Weatherell et al. 2003). From this limited literature on seafood consumption, it seems that people who consume seafood are not highly concerned about the contaminants in seafood, or that people who are very concerned do not consume seafood. In any case, no research has explicitly examined the perceived risks of microplastics in seafood, thus research is required that investigates risk perceptions regarding microplastics in seafood.

5.3 Social and socio-economical impacts

Marine environments offer a range of benefits and services to human society, including recreational uses, food resources, waste management and water quality (Peterson & Lubchenco 1997; UK National Ecosystem Assessment 2011). As a recreational resource alone, visiting the coast or simply viewing images of marine environments can improve a person's mood and cognitive attention, as well as improving physical health indicators such as reducing blood pressure (Felsten 2009; Hipp & Ogunseitan 2011; White et al. 2010; White et al.

2013; Wyles et al. under review). Marine debris is one of the factors that has the potential to undermine the benefits of marine ecosystem services. This immediate, common form of visual pollution has been explicitly rated as unattractive by observers (Tudor & Williams 2006; WHO 2003) and can even be considered as a key reason not to visit particular marine sites (Ballance et al. 2000; McKenna et al. 2011; Moore & Polley 2007; Tudor & Williams 2006; Wilson et al. 1995). As well as being disliked, environments with debris can reduce people's positive mood (Pretty et al. 2005; Roehl & Ditton 1993; Wilson et al. 1995; Wyles et al. under review). While there are these insights about macro marine debris, so far no research has examined the social impacts of microplastics directly. This could be because it is a recent research topic (Depledge et al. 2013) or because microplastics cannot be easily seen with the naked eye (Wilkinson et al. 2007). The smaller the plastic debris gets, the harder it is to recognize.

Cost impacts related to marine debris have already been demonstrated. For instance, it is considered as a problematic and an expensive issue for the coastal tourist industry, which is important revenue for many countries (World Tourism Organization 2013). For the 20,000 km of UK coastline alone, it has been estimated to cost roughly €18 million ($24 million) each year to remove beach debris to help maintain the tourism revenue (Mouat et al. 2010). The fishing industry also experiences large economic losses due to the time and expense of getting caught in marine debris, clearing nets of rubbish and repairing equipment (Mouat et al. 2010). On the other hand, the ingestion of microplastics by commercially valuable marine species, which has been already reported in fish from the North Pacific Ocean (Choy & Drazen 2013), can also have potential future impact on the fishing industry. Research noted above implies generic contamination of seafood is currently not an influential factor in consumer choice, however, if the general public are later found to be concerned about this issue, the idea of consuming plastics within fish may affect the consumption of seafood, potentially leading to economic losses in the seafood industry.

5.4 The role of individual, group and regional differences

So far, we have described general insights into the perception and social impacts of micro (and macro) plastic and focused on those processes that are common among people. This type of research is similar to marine sciences research describing general, averaged trends, as opposed to comparing different geographical regions or comparing regions that vary in wind or tidal conditions. However, the latter comparative research is also undertaken and complements the picture. In the social sciences this typically focuses on differences in the respondents. It is not within the scope of this assessment to review this comprehensively but we will briefly summarize a few insights into individual, group and geographical differences. First, demographics can play a role in people's understanding, concern and perceived risk. For instance, when examining consumer perceptions of the risks and benefits of fish, younger male respondents with a higher education and without children believed more strongly that seafood contained harmful contaminants (Verbeke et al. 2005), and women were more aware of the potential health benefits. Individuals with a lower socio-economic status have been found to be less aware of general marine issues and have been reported to leave more litter at the beach (Eastman et al. 2013; Fletcher & Potts 2007; Ocean Project 1999; Santos et al. 2005). A common phenomenon found in the risk perception literature is the "white-male effect" that describes that white men have lower risk perceptions for a broad range of hazards than white females, and than non-white males and females (Finucane et al. 2000; Flynn et al. 1994, see also discussion in Slovic 1999). Various reasons for this difference have been discussed including lower status and power in society and different worldviews. White males were characterized more by hierarchical and individualistic worldviews than the other groups, and reported more trust in technology and less trust in government in a US sample. Finucance et al. (2000) showed that worldview remained important even when age, income, education and political orientation were controlled for statistically, highlighting the importance of general perceptions about the world. The importance of marine litter generally can differ with demographics; for instance, mothers state a high importance of marine litter present on the coast when choosing to visit the coastal environment (Phillips & House 2009).

In addition to these socio-demographic factors, psychological differences in perceptions, worldviews and values are also important. Concern, and also sustainable behaviours, have been found to differ according to value systems. For instance individuals with a greater sense of connectedness to nature state a greater concern regarding environmental issues and perform more pro-environmental behaviours (Davis et al. 2009; Hinds & Spark 2008; Mayer & Frantz 2004; Nisbet et al. 2008. Political orientation has been shown to play a big role for risk perception. For example, Dunlap and MacCright (2008) have shown for the USA that Democrats are more likely to say global warming is happening compared to Republicans, and this gap is widening. Dunlap and MacCright report that 48% of Republican as opposed to 52% of Democrat supporters said global warming was happening in 1997, but this discrepancy had increased to 42% vs. 76% in 2008.

Risk perceptions and knowledge about marine issues can also differ according to stakeholder group. When examining perceptions about marine debris in general, Hartley and colleagues (in preparation) compared different stakeholders including manufacturers, retailers, educators, policy makers and domestic users of the marine environment. Overall, the different stakeholders were similar in their knowledge and concern for marine litter, but there were some subtle differences. For instance, unsurprisingly the environmental groups were more concerned about the issue. All groups also underestimated how much of the marine litter is composed of plastic materials; however, the environmental organizations and coastal/marine industries were closer to the scientific estimate of 75% (OSPAR 2007). Marine litter in coastal habitats was found to be more important among a general public sample, but less so among coastal experts who focused on physical disturbance from recreational activities (Wyles et al. 2014). Other stakeholder differences have also been found in the GESAMP pilot study on microplastics described above. When compared to the audience poll of scientists and NGO representatives at a symposium dedicated to microplastics, the general public was less concerned than the latter experts (see above).

Finally, in addition to these individual and stakeholder differences, geographical location has also been found to play a role. For instance, within the same country, people who live closer to the coast have been reported to be more aware of marine issues (Buckley and Pinnegar 2011; Fletcher & Potts 2007; Steel et al. 2005a, 2005b). A large-scale survey undertaken by Steel and colleagues in 2003 found generally low levels of ocean literacy (knoweldge and understanding) in US adults (Steel et al. 2005a, 2005b). While education, socio-economic status, age and gender were shown to be associated with respondents' levels of ocean literacy, those respondents who lived in coastal states and who visited the coast frequently were found to be more knowledgeable than those who rarely spent time at the coast. This suggests an association between direct experience and familiarity with the issues (Fletcher et al. 2009). Indeed, personal attachment to the marine environment has been shown to be a key factor in generating a sense of marine citizenship among UK citizens (see McKinley & Fletcher 2010).

Differences have also emerged between countries. For instance, a survey that gathered responses from 7,000 individuals from seven European countries found that Germany placed great importance on ocean health, whereas the UK, Poland, Spain and Portugal rated ocean health relatively low compared to other issues (Potts et al. 2011). When deciding to visit a particular coastal site, another cross-national study found differences between countries. For people in Ireland and Wales, cleanliness was seen as the most important factor, whilst Turkish and US samples noted cleanliness to be the second most influential factor, with distance to the coast being more important (McKenna et al. 2011). Whilst stakeholder differences were quite small, numerous national differences were also found in the survey reviewing individuals' understanding of marine litter, with countries expressing differences in perception of distribution of marine litter, source, experience of marine litter and composition of the rubbish (Hartley et al. in preparation). Some variations in concern was also reported, with Portugal, Slovenia and the UK reporting a greater concern about marine litter, and Romania, Cyprus, Denmark and the Netherlands the least. For the one question examining microplastics in a cross-national European sample, similar differences were found whereby respondents agreeing with the statement that microplastics should be forbidden from cosmetic products varied between countries 53% (Estonia) to 85% (France and Croatia) (European Commission 2014). The GESAMP pilot survey did not find reliable effects of age and gender (S. Pahl unpublished data). However, little research has been dedicated to microplastics specifically, and this gap needs to be filled.

5.5 Overcoming barriers and towards solutions

Selected insights from the psychological and more generic social science literature have been described above, and, where possible, applied to microplastics specifically. Although only a snapshot of some relevant themes, this body of work highlights how we can integrate social aspects when working towards solutions. It is advisable to integrate science and social science efforts early on in order to make sure the public is informed of the issue and potential solutions. Certainly, many initiatives can contribute to the goal of increasing the awareness on the impacts of microplastics. There is no one perfect solution to the issue, but there are numerous approaches, such as changing the legislation, improving plastic waste facilities and management, changing plastic use and consumption, and education and public engagement should be part of these. A combination of these factors will help address the issue of microplastics in the oceans. Overall, understanding risk (and benefit) perception is important, as these have been found to influence behaviour and acceptability of regulatory approaches (see Zlatev et al. 2010 for an example in the domain of health). For instance, Klöckner (2013) recently reviewed the influence of a number of factors contributing to a range of environmental behaviours. He highlighted that psychological factors play a fundamental role in people's behaviour. Specifically, the lower people's perceived responsibility and capability of addressing the issue, the less likely they were to take action. This could be relevant for driving solutions towards reducing microplastics. In terms of marine debris in general, the MARLISCO survey found that Governments and policy makers were seen as the agents most responsible for tackling the issue, whilst those who were the most capable were seen to be the environmental groups rather than the Governments and policy makers (Hartley et al. in preparation). People may also ascribe responsibility and capability to technological innovations. Rather than focus on personal solutions (e.g. reduce litter), there is often a fondness for technological solutions that can fix problems (Slovic 1999). This could include microplastics, as there has been recent interest in a potential technological solution of mechanical cleaning of the open ocean. Unfortunately, ascribing responsibility and capabilities to technological solutions could encourage a negative spill-over effect, promoting an unintended behaviour of people not managing their waste responsibly. Such a spill-over effect would be particularly concerning if the technological fix was actually ineffective. Worryingly, this has already been indicated in marine debris in general. In the US, it was found that people litter more when they perceive the item to be biodegradable (Keep Los Angeles Beautiful 2009).

Consequently, any solution to this global multidimensional environmental issue would need to consider people's current perceptions and apply multiple approaches that complement one another, addressing both the microplastics entering the environment (e.g. management of waste) and those already in the environment (e.g. mass clean ups). Additional social research is required in order to understand people's current perceptions of the issue of microplastics. In addition to reviewing the limited research on microplastics and making inferences from related research, this chapter has highlighted where work dedicated to microplastics explicitly is missing. For instance, very little is known about individuals' knowledge and understanding, perceived risks, and the associated consequences of microplastics specifically on humans.

Future research needs to consider methodological aspects. For instance, studies on individuals' knowledge and understanding of microplastics should consider regional, demographic, and individual differences. Also, surveys should include a wider geographical coverage, since to date only a select number of countries is represented (e.g. US and Europe). Finally, new studies should address the economic consequences of microplastics. At the same time, attention should be focused on potential solutions and their acceptability, including social 'solutions' such as education, public engagement and behaviour change campaigns.

5.5.1 *Education and Public Engagement*

Education and public engagement are often referred to as ways of improving public understanding and working towards social solutions for environmental problems such as microplastic accumulation. In terms of education, there are two main ways to increase the public understanding of environmental issues: formal and informal education (Dori & Tal 2000). Formal education refers to the inclusion of scientific topics in centralized curricula in a country's educational systems. Informal education refers, amongst other contexts, to volunteering projects where self-directed, voluntary learning is guided by individual interests and needs. For instance, beach clean-ups occur across the world, organized by several environmental organizations (e.g. Ocean Conservancy, Project AWARE). An example is the annual international beach clean-up day, where in 2013 approximately 650,000 participants from 92 different countries were involved (Ocean Conservancy 2014). These activities represent educational opportunities that have been useful for enhancing local engagement of the issue (Storrier & McGlashan 2006), and increases in marine awareness have recently been demonstrated (Wyles et al. under review; Hartley et al. in press). It can also encourage other pro-environmental behaviour, for instance fishers engaged in the Fishing for Litter scheme run by KIMO (where KIMO pays for the waste disposal of the rubbish caught by the registered fishers during their working day; KIMO 2014) reported reducing waste entering the marine environment, both at work and during their leisure time, than fishers not involved in this scheme (Defra report, forthcoming). Thus, engaging stakeholder groups with marine debris through informal education and engagement can have numerous benefits.

On the other hand, volunteer participation can also be useful for scientific research, a field referred to as citizen science (Cohn 2008; Bonney et al. 2009). Working with volunteers is beneficial in many respects: it allows for more information to be collected when resources are limited, it can be used as an educational tool, and it can promote environmental concern and stewardship in participants (Anderson & Alford 2013). Certain projects have already been looking at marine debris, predominantly focusing on determining the distribution and composition of the debris and their impact on marine biota. Some examples are the Marine Conservation Society from the UK, Our Sea of East Asia (OSEAN) from South Korea (see Hong et al. 2013; 2014) and the National Marine Debris Monitoring Program from US (see Ribic et al. 2011; 2012). The only programme that has been working specifically with the topic of microplastics, is the programme Científicos de la Basura (Litter Scientist) from Chile (Bravo et al. 2009; Eastman et al. 2013; Hidalgo-Ruz & Thiel 2013). This programme is an outreach citizen science project with school children throughout Chile and Easter Island. The information provided by these volunteers has contributed to a better knowledge about large-scale patterns of marine debris and microplastics in the SE-Pacific and also to raising environmental awareness in the region (Hidalgo-Ruz & Thiel 2013). Four main steps have been applied: (a) Contact and commitment of the participants, (b) Development and explanation of sampling protocols and motivational materials, (c) Application of activities and recovery of the obtained data, and (d) Writing of the report and release of the information to local and national press. The experience of these projects suggests that involving the public in studies of marine debris and therefore microplastics can support the enhancement of scientific literacy about microplastics, but can also bring about awareness and an attitude change of this ecological issue in society. Nevertheless, more research is needed specifically evaluating the long term effect and influence of these activities on public understanding of science and environmental awareness (Hidalgo-Ruz & Thiel 2013).

Although these education and public engagement activities are necessary and important parts of engaging society, it is important to allow for proper interactions between scientists, experts and the public rather than the one-way notion that scientists ought to feed the right information to the public. People's perceptions, views and behaviours are influenced by a complex set of factors (as noted above) that can appear to be irrational to someone outside of that group. It is important, therefore, to recognize these differences and take them into account when seeking explanations for the status quo and mechanisms for delivering change (Slovic 1999). Consequently, if we want to engage people, we need to meet them on their terms and acknowledge their construction of the risk issue. Only by building on people's perceptions and using their strengths will we achieve lasting change and consensual solutions (e.g. Pahl et al. 2014).

5.6 Recommendations for further research

To conduct empirical social research on microplastics to address: a) individuals' knowledge and understanding; b) perceived risks; and, c) the associated consequences on humans. Social perceptions are linked to behaviour and support of measures addressing the issue.

To improve the geographical representativeness of this work – outside North and South America and Europe – to identify needs and tailor information to account for social, economic and other cultural differences, and promote effective mitigation strategies.

To analyse the economic impacts of microplastics, in terms of cost-benefit to forecast future effects in response to any changes in microplastic use/input.

Promote the collection and evaluation of examples of public engagement programmes (e.g. citizen science; beach cleans) in terms of their effects on perceptions and actions, including longitudinal follow-ups.

6 KEY OBSERVATIONS AND CONCLUSIONS

The following represent some of the key observations and conclusions that emerged during the assessment process. They are intended to be understandable by a non-technical audience. Readers are encouraged to refer to the preceding Sections 3, 4 and 5 for further explanation, discussion and a summary of the evidence. A confidence level of ‘high’, ‘medium’ and ‘low’ has been given to each statement, based on a consensus within the working group.

6.1 Sources, distribution and fate of microplastics

High confidence

1. The term ‘microplastics’ has been adopted to describe small plastic particles, generally <5 mm in diameter, sampled in the environment.

2. Commonly available techniques restrict the minimum particle size sampled, currently 10s to 100s microns in diameter. However, it is likely that plastic particles a few nanometres in diameter are present in the environment; hence microplastic fragments span a size range of over 5 orders of magnitude.

3. Microplastics may be manufactured for particular applications or result from fragmentation of larger items. They can be released as a result of many different human activities, but there are no reliable estimates of the quantities entering the marine environment, at a regional or global scale.

4. Most microplastic particles are composed of the six major polymer types. Those composed of polyethylene, polypropylene and expanded polystyrene are more likely to float, and those composed of polyvinyl chloride, polyamide (nylon) and polyethylene terephthalate (PET) are more likely to sink.

5. The surface of any solid object rapidly becomes coated with inorganic and organic compounds and biofilms when immersed in seawater. This may cause floating plastic particles to sink.

6. Plastics will tend to absorb and concentrate hydrophobic contaminants from the surrounding seawater. In addition, additive chemicals incorporated during manufacture may represent a significant proportion of the particle composition.

7. After entry into the ocean microplastics can become globally distributed and have been found on beaches, in surface waters, seabed sediments and in a wide variety of biota (invertebrates, fish, birds, mammals), from the Arctic to Antarctic. They become concentrated in some locations such as ocean gyres, following long-distance transport, but also close to population centres, shipping routes and other major sources.

8. A very high degree of spatial and temporal variability in particle distribution has been observed, partly linked to small-scale circulation and mixing processes in the upper ocean.

9. It seems unlikely that a cost-effective technical solution can be developed and maintained to allow the large-scale removal of significant quantities of floating microplastics from the ocean. Any proposed scheme would be ineffective as long as plastics and microplastics continue to enter the ocean.

10. Better control of the sources of plastic waste, through applying the principles of the 3 Rs (Reduce, Re-use, Recycle), and improving the overall management of plastics via the circular economy, represents the most efficient and cost-effective way of reducing the quantity of plastic objects and microplastic particles accumulating in the ocean. The working group agreed the urgency of implementing effective measures to reduce all inputs of plastic to the ocean.

11. Even if all releases of plastic to the environment were to cease immediately, the number of microplastics in the ocean would be expected to continue to increase as a result of continuing fragmentation, on the basis of current evidence.

Medium confidence

12. Although it appears likely that the quantities of microplastics in the ocean are increasing, due to the continuing fragmentation of existing plastic objects, there is very limited reliable evidence about variations in the abundance of microplastics in space time, despite the availability of some long-term datasets.

13. Dissolved metals will become adsorbed to the surface of plastic particles, in a similar manner as metals adsorb to inorganic sediment particles.

6.2 Effects

High confidence

1. Microplastics are ingested by a wide range of marine organisms including invertebrates, fish and birds and in some organisms the incidence of ingestion is widespread across populations.

2. The movement, storage and elimination of microplastics by marine organisms will depend on the size of the particle. Particles at the smaller end of the size spectrum (nano scales) have been shown to cross membranes into cells, in controlled laboratory experiments.

3. When microplastics cross cell membranes, some tissues have been shown, in vitro, to exhibit a response to the presence of particles; i.e. causing inflammation and cell damage, followed by healing responses and fibrous encapsulation of particles.

4. The risk of associated effects following exposure to microplastics will depend on: i) the number of particles; ii) the size distribution, shape, surface properties, polymer composition and density of the particles; iii) the duration of exposure; iv) the kinetics of absorption and desorption of contaminants, with respect to the plastic and the organism; and, v) the biology of the organism.

Medium confidence

5. Marine organisms are exposed to microplastics via the same pathways used to food, including filtration, active grazing and deposit feeding, and via transport across the gills.

6. Emerging evidence suggests that some additive chemicals, which can be present in relatively high concentrations in some particles, transfer across the gut and concentrate in tissue, under natural conditions. Absorbed contaminants have been shown to exhibit similar behaviour in the laboratory, but there is not yet published, unequivocal evidence to demonstrate that this occurs under natural conditions. The relative importance of contaminant exposure mediated by microplastics compared to other exposure pathways remains unknown.

7. Microplastics may be transferred from prey to predator, but the process will be species-specific. Currently there is no evidence to support or refute potential bio-magnification of particles or associated chemicals.

8. Among the various types of seafood, consumption of filter feeding invertebrates, such as mussels or oysters, appears the most likely route of human exposure to microplastics. However, there is no evidence to confirm this is occurring.

9. The ingestion of microplastics may have an effect on the feeding, movement, growth and breeding success of the host organism.

Low confidence

10. If there are effects on individuals, there is a potential to have impacts at a population level for some species, but this is very uncertain.

6.3 Social aspects

High confidence

1. The presence of macro debris has been recorded to have negative social and economic impacts, reducing the ecosystem services and compromising perceived benefits.

2. Public engagement and education is a useful tool to help raise awareness and promote positive behaviour change, whilst we further develop our scientific knowledge.

Medium confidence

3. Even though there appears to be little awareness in terms of microplastics specifically, there is a general awareness of marine litter and marine threats as a broader concept.

4. Based on the risk assessment literature, perceptions of risk and impacts are influenced by individual, stakeholder group and cultural and other factors. There is no reason to think reactions to the risk of microplastics will be any different.

5. Understanding individuals' perceptions (knowledge, concern, perceived risk) and the impact of microplastics on individuals are important as these have influential consequences. For instance, they influence political pressure, personal behaviour change, acceptance of new products and influence commercial impacts (e.g. to stop using products that contain microplastics).

Low confidence

6. Based on limited survey reports, there appears to be little awareness of the specific issue of microplastics amongst the general public. However, according to on-line media trends, there appears to be increasing attention being paid to this topic. There is evidence of the increasing use of smartphone applications and social media in relation to plastic issues, but it is not clear what proportion of the public is engaged, and the global significance of such initiatives.

7. Based on inferences from similar environmental issues and the generic risk perception literature, it is likely that the perception of risk will increase if public knowledge of microplastics increases.

8. Microplastics are thought to have the potential to have negative socio-economic impacts. For example, if people perceive a high risk e.g. of transfer through seafood (influencing the fishing industry).

7 KEY POLICY-RELATED RECOMMENDATIONS

7.1 Rationale

This assessment represents the first attempt, at a global scale, to identify the main sources, fate and effects of microplastics in the ocean. As a result we have an improved understanding of the scale of the problem posed by the presence of microplastics, and of the link between larger plastic items (macro- and mega-plastics) and the generation of 'secondary' microplastics. It has been possible to state, with more confidence, what is known (Section 6), although there remain considerable areas of uncertainty that will require further investigation.

Policy-makers, and other decision-makers in the public (e.g. municipalities) and private sectors (e.g. manufacturing, retail, tourism, fisheries), need guidance now on how best to target the microplastics issue. This was considered at some length, recognizing that there is a need for decisions to be made before all possible evidence has been collected. In addition, it was recognized that a number of outstanding issues remain which would benefit from more detailed assessment. For these reasons two sets of policy-related recommendations have been proposed:

1. Action-orientated recommendations addressing marine microplastics

2. Recommendations to improve a future assessment(s)

These policy-related recommendations are based on the detailed analysis described in the main sections of the report. Each is preceded by a specific challenge to be addressed, and is followed by a series of potential solutions considered to be the most cost-effective. They are in addition to a number of technical recommendations included in the main body of the report, which are largely concerned with identifying research needs. They are also linked to the key conclusions (Section 6) that summarize what is known with reasonable certainty.

Any litter reduction measures that are proposed need to be targeted, effective, equitable and cost-efficient. It is critical that measures are designed to minimize unintended, adverse consequences. For example, replacement of plastic by glass bottles on tourist beaches may increase the incidence of injury, if littering behaviour persists. Inadequate separation of waste streams during plastics recycling may result in the contamination of consumer goods, such as children's toys, with unnecessary additives.

Reducing the input of marine debris to the marine environment is a complex 'wicked' problem (Brown et al. 2010), with many possible part-solutions requiring input, commitment, acceptance and resources from a wide range of individuals, institutions,

industries and socio-economic sectors, such as manufacturing, retail, tourism, fisheries, aquaculture and shipping, as well as society at large. These recommendations are designed to support this process.

7.2 Action-orientated recommendations addressing marine microplastics

7.2.1 *Challenge 1*

Comprehensive improvement to waste generation and management practices is essential in order to reduce the entry of plastics and microplastics into the marine environment. This requires an adequate understanding of the relative importance of different types of materials and sources at global, regional and sub-regional scales, and the socio-economic sectors involved. The input of macro-plastics and microplastics is highly variable and poorly quantified on a regional basis, presenting great difficulties in designing and implementing cost-effective mitigation strategies. Reducing the input of macro-plastics represents the most effective way of minimizing the increase in the abundance of microplastics in the ocean.

> Recommendation 1: identify the main sources and categories of plastics and microplastics entering the ocean

Suggested solution/response:

Identify probable 'hotspots' of land- and sea-based sources for plastic and microplastics, using a combination of targeted modelling, knowledge of actual and potential sources (e.g. coastal tourism, aquaculture, fisheries, riverine inputs, urban inputs), environmental and societal data. This will allow mitigation measures to be better targeted, and used to predict and verify their effectiveness. Examples of 'hot spots', from available evidence, include: the Bay of Bengal, Mediterranean Sea, Gulf of Mexico, Japan Sea and other far eastern seas.[17] This can help to inform the development of effective measures in other regions.

Risk of not addressing this challenge:

Efforts to reduce plastics entering the ocean may be poorly targeted, and fail to yield tangible results. Scarce resources may be wasted which could have been better directed.

7.2.2 *Challenge 2*

There is growing acceptance, especially at an institutional level, that land- or sea-based inputs of plastic waste to the ocean should be reduced. A lack of capacity, technical or financial resources is often cited as a barrier to the implementation of effective waste reduction strategies. In addition, decision-makers are faced with many other demands, affecting the local environment, economy, society and political process, which may be given higher priority in allocating effort and funding.

> Recommendation 2: utilize end-of-life plastic as a valuable resource rather than a waste product

Suggested solution/response:

There is great potential in promoting the 3 Rs (Reduction, Re-use and Recycling) as a key contribution to reducing plastic waste generation and reducing the input of plastic to the oceans. This will be aided by the development of innovative and effective solutions as an intrinsic part of the circular economy.18 In this way 'unwanted' plastic can be seen as a useful resource, with commercial value, rather than a waste problem requiring the allocation of scarce public and private sector resources. Such action reduces our reliance on non-renewable reserves of oil and gas to produce plastics and reduces the need for waste management, for example via landfill. This is a rapidly

[17] Ocean gyres represent accumulation zones but, in general, are too remote to directly link debris with a particular source.
[18] http://www.ellenmacarthurfoundation.org/business/reports

developing field that is being embraced by business and institutions, and it needs to be encouraged at a global level. However, adequate controls have to be in place to ensure that plastic waste streams are separated appropriately, to reduce the potential for unnecessary and unwanted cross-contamination, especially of consumer products made with recycled plastic. Commercially available 'biodegradable'19 plastics do not offer a viable alternative, and in most cases will not lead to a reduction in microplastic formation.

With this change in philosophy, other approaches from the business and commercial sectors may be useful, such as the use of value-chain models. This can help to guide the optimum use of resources, identify intervention points and provide opportunities for economic incentives throughout society,20 with an end-point being the reduction of inputs of marine debris.

Risk of not addressing this challenge:

It will be more difficult to bring about a significant reduction in plastics entering the ocean, and this may come to be seen as an inevitable consequence of economic growth. When faced with hard choices about allocating public and private sector resources, it may be difficult to justify expenditure on 'ocean pollution', which is avoidable, compared with more immediate societal needs (e.g. health service, education and other economic investment).

7.2.3 *Challenge 3*

Legislation alone will be insufficient to substantially reduce the input of plastic waste into the ocean. It will require a change in perceptions in the public and private sectors, as well as society more widely, as these play a key role in influencing decisions and behaviour. This applies in many areas of risk perception and management. For example, emerging evidence suggests that perceptions influence waste generation and management in general and, more specifically, littering behaviour. It will also influence whether society will be willing to support better waste management practices, such as recycling schemes.

> Recommendation 3: promote greater awareness of the impacts of plastics and microplastics in the marine environment

Suggested solution/response:

Utilize expertise from the social sciences, including psychological studies, to better understand perceptions of risk, social responsibilities and the drivers of behaviours in the public and private sectors. Facilitate the transfer of complex and uncertain scientific findings into a language that can be understood by target stakeholder groups (e.g. industrial production, manufacturing, retail, fisheries, aquaculture, coastal tourism, shipping). Take proper account of regional, cultural, gender, economic, educational and other demographic differences, in assessing perceptions and behaviours. This can embrace the outputs from the assessments of social resilience and governance, conducted as part of the GEF Transboundary Waters Assessment.[21]

Risk of not addressing this challenge:

It will be more difficult to gain political agreement, public and private sector commitment, and public acceptance, to pursue direct mitigation measures for litter reduction, as well as encouraging the introduction of the circular economy and the benefits of treating unwanted plastics as a resource. It will be more difficult to encourage particular key socio-economic sectors, and the public in general, to adapt their behaviours and contribute to the overall goal of reducing marine plastics.

7.3 Recommendations to improve a future assessment

7.3.1 *Challenge 4*

The word 'microplastics' has tended to be used as an 'umbrella' term covering particles ranging in size over several orders of magnitude, from particles several mm in diameter to those in the nano size range (<1 μm). Particles in these size ranges may be introduced directly or may gradually form by fragmentation. The sampling methods normally used to collect microplastics tend to exclude material <330 μm. This means there is very limited information about the occurrence of finer plastic particles, including nano-plastics, in the ocean and particularly the degree to which nano-plastics interact with biota internally.

The available evidence from the medical, pharmaceutical and toxicology literature suggests that nano-sized particles are much more likely to cross cell membranes and induce a response that may adversely affect marine life. Therefore they have the potential to pose a greater risk to the organism than micro-sized plastics. Unfortunately, at present it is not possible to provide a credible assessment of the extent to which nano-plastics do present a risk.

> Recommendation 4: include particles in the nano-size range in future assessments of the impact of plastics in the ocean

Suggested solution/response:

Encourage the inclusion of expertise on pharmacology, mammalian toxicology, nano-polymer sciences and nano-engineering in future assessments. Critically review laboratory-based experiments examining the behaviour and potential effects of nano-plastics and assess their relevance to the natural environment. Assess current sampling and detection methods for nano-sized plastic particles, particularly in biota.

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[19] see Section 3.2.4 for an explanation of 'biodegradable' plastics

[20] for example: plastic bottle deposits, fishing net return schemes

[21] Transboundary Waters Assessment Programme, a full-size GEF project, 2012–2014; http://geftwap.org

Risk of not addressing this challenge:

The extent to which nano-size plastics pose a significant risk to the marine environment and human health will remain unknown. Meanwhile, there is a very high probability that the quantities of nano-plastics in the marine environment will increase substantially, due to the fragmentation of larger plastic particles and, potentially, due to the direct introduction of particle in the nano-size range.

7.3.2 *Challenge 5*

The surface of any object exposed to seawater rapidly becomes coated with a variety of inorganic and biological coatings. This mechanism, utilizing natural materials such as timber as a vector for the transfer of organisms, has been taking place for millions of years. However, the rapid increase in floating plastics, which do not disintegrate in transit, has the potential to bring about a rapid increase in the importance of this vector. Colonization of plastic objects by larger sessile organisms is observed frequently. There is emerging concern that microplastics may also act as a vector for microorganisms, including pathogenic species of bacteria, resulting in an increase in the occurrence of non-indigenous species (NIS).[22]

> Recommendation 5: evaluate the potential significance of plastics and microplastics as a vector for organisms in future assessments

Suggested solution/response:

Review the published evidence on NIS introductions and potential vectors (e.g. ship hull transfer, ballast water transfer), to estimate the relative importance of plastics and microplastics as a transport vector for macro- and micro-organisms. Assess potential consequences in terms of biodiversity and ecosystem functioning. Undertake a targeted risk assessment based on existing data on NIS introductions, and utilize existing circulation models to identify key transport routes, and the conditions favourable for growth, including for pathogenic and invasive organisms.

Risk of not addressing this challenge:

We will be unsure whether plastics and microplastics do represent a significant risk for the introduction of NIS, including pathogenic microorganisms. This may have serious consequences for both ecosystem and potentially human health.

7.3.3 *Challenge 6*

There is emerging evidence that some organic compounds present as additives, in relatively high concentrations in some categories of plastic, are capable of transferring into the body tissue of fish-eating sea birds. This has been demonstrated for PBDE[23] flame-retardants using a chemical fingerprinting technique, which can distinguish the composition of PBDEs in the plastic particles and the tissue of prey species (Tanaka et al. 2013). The extent to which other chemicals are bioavailable to species of interest is unknown. The role of digestive fluids in influencing transfer rates (e.g. utilizing fish oil for digestion in birds) is also unclear. The extent to which this poses a risk to individual organisms, or to the population as a whole, and to predators of the affected species, including humans, remains untested.

> Recommendation 6: future assessments should address the chemical risk posed by ingested microplastics in greater depth

Suggested solution/response:

Compare information from laboratory-based experiments of the bioavailability of the target chemicals with field-based observations of their distribution in the tissue of marine organisms. Include expertise on animal behaviour and physiology for target species, including important commercial species. Take account of gut retention times and the gut environment when assessing risk. Include a consideration of particle size and shape when assessing risk of damage.

Risk of not addressing this challenge:

We will remain unsure as to whether microplastics do pose a significant additional risk to organisms in terms of chemical composition, particle shape and size.

[22] Non-indigenous species are sometimes referred to as 'alien' species. Where NIS become established and out compete native species they may be referred to as 'invasive' species.

[23] PBDE – Polybrominated diphenyl ethers, chemicals classified according to the number of bromine rings, can act as endocrine disruptors, affecting fertility.

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ANNEX I – MEMBERSHIP OF THE WORKING GROUP

Member	Affiliation
Peter Kershaw, chair	Independent consultant
Heather Leslie, co-chair	VU University, Amsterdam, Netherlands
Anthony Andrady	Independent consultant
Courtney Arthur	NOAA, United States
Joel Baker	University of Washington, United States
Henk Bouwman	North West University, South Africa
Sarah Gall	Plymouth University, United Kingdom
Valeria Hidalgo-Ruz	Universidad Catolica del Norte, Chile
Angela Koehler	Alfred Wegener Institute, Germany
Kara Lavender Law	Sea Education Association, United States
Sabine Pahl	Plymouth University, United Kingdom
Jim Potemra	University of Hawaii, Hawaii
Peter Ryan	University of Cape Town, South Africa
Won Joon Shim	Korea Institute of Ocean Science & Technology, Republic of Korea
Hideshige Takada	Tokyo University of Agriculture & Technology, Japan
Richard Thompson	Plymouth University, United Kingdom
Alexander Turra	University of Sao Paulo, Brazil
Dick Vethaak	Deltares and VU University Amsterdam, Netherlands
Kayleigh Wyles	Plymouth Marine Laboratory, United Kingdom

Industry observers

Keith Christman, American Chemistry Council

Roberto Gomez, Plastics Europe

Ralph Schneider, Plastics Europe

Secretariat

Luis Valdes, IOC-UNESCO

Edward Kleverlaan, IMO

Fredrik Haag, IMO

Jennifer Rate, IMO

ANNEX II – LIST OF REPORTS AND STUDIES

The following reports and studies have been published so far. They are available from the GESAMP website: http://gesamp.org

1. Report of the seventh session, London, 24-30 April 1975. (1975). Rep. Stud. GESAMP, (1):pag.var. Available also in French, Spanish and Russian

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9. Report of the tenth session, Paris, 29 May - 2 June 1978. (1978). Rep. Stud. GESAMP, (9):pag.var. Available also in French, Spanish and Russian

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11. Marine Pollution implications of coastal area development. (1980). Rep. Stud. GESAMP, (11):114 p.

12. Monitoring biological variables related to marine pollution. (1980). Rep. Stud. GESAMP, (12):22 p. Available also in Russian

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21. Report of the fourteenth session, Vienna, 26-30 March 1984. (1984). Rep. Stud. GESAMP, (21):42 p. Available also in French, Spanish and Russian

22. Review of potentially harmful substances. Cadmium, lead and tin. (1985). Rep. Stud. GESAMP, (22):114 p.

23. Interchange of pollutants between the atmosphere and the oceans (part II). (1985). Rep. Stud. GESAMP, (23):55 p.

24. Thermal discharges in the marine environment. (1984). Rep. Stud. GESAMP, (24):44 p.

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26. Atmospheric transport of contaminants into the Mediterranean region. (1985). Rep. Stud. GESAMP, (26):53 p.

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28. Review of potentially harmful substances. Arsenic, mercury and selenium. (1986). Rep. Stud. GESAMP, (28):172 p.

29. Review of potentially harmful substances. Organosilicon compounds (silanes and siloxanes). (1986). Published as UNEP Reg. Seas Rep. Stud., (78):24 p.

30. Environmental capacity. An approach to marine pollution prevention. (1986). Rep. Stud. GESAMP, (30):49 p.

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55. Biological indicators and their use in the measurement of the condition of the marine environment. (1995). Rep. Stud. GESAMP, (55):56 p. Available also in Russian

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58. The invasion of the ctenophore Mnemiopsis leidyi in the Black Sea. (1997). Rep. Stud. GESAMP, (58):84 p.

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72. Report of the thirty-first session, New York, 13-17 August 2001. (2002). Rep. Stud. GESAMP, (72):41 p.

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75. Estimations of oil entering the marine environment from sea-based activities (2007), Rep. Stud. GESAMP, (75):96 p.

76. Assessment and communication of risks in coastal aquaculture (2008). Rep. Stud. GESAMP, (76):198 p.

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80. Report of the thirty-sixth session, Geneva, 28 April - 1 May 2009 (2011), Rep. Stud. GESAMP, (80):83 p.

81. Report of the thirty-seventh session, Bangkok, 15 - 19 February 2010 (2010), Rep. Stud. GESAMP, (81):74 p.

82. Proceedings of the GESAMP International Workshop on Micro-plastic Particles as a Vector in Transporting Persistent, Bio-accumulating and Toxic Substances in the Oceans (2010). Rep. Stud. GESAMP, (82):36 p.

83. Establishing Equivalency in the Performance Testing and Compliance Monitoring of Emerging Alternative Ballast Water Management Systems (EABWMS). A Technical Review. Rep. Stud. GESAMP, (83):63 p, GloBallast Monographs No. 20.

84. The Atmospheric Input of Chemicals to the Ocean (2012). Rep. Stud. GESAMP, (84) GAW Report No. 203.

85. Report of the 38th Session, Monaco, 9 to 13 May 2011 (pre-publication copy), Rep. Stud. GESAMP, (85): 118 p.

86. Report of Working Group 37: Mercury in the Marine Environment (in prep.). Rep. Stud. GESAMP, (86).

87. Report of the 39th Session, New York, 15 to 20 April 2012 (pre-publication copy), Rep. Stud. GESAMP, (87):92 p.

88. Report of the 40th Session, Vienna, 9 to 13 September 2013, Rep. Stud. GESAMP, (88):86 p.

89. Report of the 41st Session, Malmö, 1 to 4 September 2014, Rep. Stud. GESAMP, (89): in prep.

90. Report of Working Group 40: Sources, fate and effects of microplastics in the marine environment: a global assessment. Rep. Stud. GESAMP, (90):96 p.