99

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

REPORTS AND STUDIES

GUIDELINES FOR THE MONITORING AND ASSESSMENT OF PLASTIC LITTER IN THE OCEAN

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PREFACE

The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has been involved in the issue of marine plastic litter and microplastics for over a decade. Initially interest was focussed on microplastics, which were considered as an emerging issue, and resulted in the preparation of a scoping paper. This was followed by an international workshop in 2010, organised by GESAMP, on the subject of: *Microplastic particles as a vector in transporting persistent, bio-accumulating and toxic substances in the ocean*. This was one of the first workshops that brought together representatives of the chemicals industry, academia, policy makers, intergovernmental organisations and NGOs. It was hosted by IOC-UNESCO in Paris, with additional financial support from the European Commission. One of the conclusions of the workshop was that further assessment of the potential impacts of microplastics was warranted. This led to the formation of GESAMP Working Group 40 (WG40) in 2012: *Sources, fate and effects of microplastics in the marine environment*. The first WG40 report was published in 2015: *Sources, fate and effects of microplastics in the marine environment – a global assessment*. The second was published in 2016: *Sources, fate and effects of microplastics in the marine environment – Part two of a global assessment.*

It became apparent during the assessment, and preparation of the reports, that there were relatively few data available from monitoring programmes. Most data that had been published were from individual surveys or research projects, and there was a lack of harmonisation of sampling methods and attention to natural environmental variability. This made the collation and comparison of data problematic. At the same time, it was decided that the artificial cut-off imposed by only focussing on microplastics was inappropriate. Marine plastic litter covers a wide spectrum of sizes, and larger items tend to fragment to smaller particles. The title and remit of WG40 was modified to reflect this more inclusive approach.

An increasing number of administrations and individual organisations have started to develop routine monitoring programmes for marine litter and microplastics, in response to greater political and social awareness. Reliable monitoring allows the setting of indicators and targets and supports decision-making. The need for greater harmonisation of methods has become more critical with the adoption of the UN Sustainable Development Goals (SDGs), in particular SDG14.1.1: floating plastic litter as a global indicator of marine pollution. This need has been recognised in resolutions passed by the UN Environment Assembly (UNEA), with GESAMP being considered an appropriate mechanism to develop appropriate recommendations.

These Guidelines are the output of the third phase of WG40. It is the product of a group of dedicated independent scientists, supported by a number of national and international bodies. They are intended to provide practical guidelines and recommendations, in particular to organisations that are less experienced in marine environmental monitoring. As technologies advance, and experience is gained, the Guidelines may need to be revised. But for the moment we hope the content of this report provides a helpful contribution.

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1. BACKGROUND

1.1 Purpose and objectives

The principle purpose of this report is to provide recommendations, advice and practical guidance, for establishing programmes to monitor and assess the distribution and abundance of plastic[1] litter, also referred to as plastic debris, in the ocean. It is a product of the GESAMP Working Group (WG40) on 'Sources, fate and effects of plastics and microplastics in the marine *environment*'[2], co-led by the Intergovernmental Commission on Oceanography (IOC-UNESCO) and the United Nations Environment Programme (UNEP). The report was prepared by 19 independent experts from 14 countries, with financial support from a number of agencies and national governments (Annex I). The term 'plastic litter' is used throughout, but is synonymous with 'plastic debris'. In some cases the report refers to monitoring strategies and sampling protocols that have been designed for the monitoring of all forms of marine litter (i.e. processed wood, metal, textiles, glass, munitions, and plastics).

The main audience of the report is intended to be national, inter-governmental and international organisations with responsibilities for managing the social, economic and ecological consequences of land- and sea-based human-activities on the marine environment. The decision to produce these Guidelines reflects the lack of an internationally agreed methodology to report on the distribution and abundance of marine plastic litter and microplastics, a topic that is attracting increasing concern. Use of a harmonised system will benefit the development of monitoring programmes, as envisaged under UN Sustainable Development Goal indicator 14.1.1[3] (marine litter), and help to raise the category of this indicator from Tier 3 ('*No internationally established methodology or standards are yet available*') to Tier 2 *('Indicator is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries')* (section 3.2.2). For practical purposes the number of references provided has been kept relatively small, citing a limited number of key sources of information that, where possible, are publicly accessible and provide an entry point to more in-depth literature.

The intention is to promote a more harmonised approach to the design of sampling programmes, the selection of appropriate indicators (i.e. type of sample), the collection of samples or observations, the characterisation of sampled material, dealing with uncertainties, data analysis and reporting the results. The Guidelines cover all size ranges of plastic litter encountered in the marine environment, on shorelines, floating on the sea surface, suspended in the water column, deposited on the seabed or associated with biota (ingested/encrusted/entangled). They may be used for the monitoring of items originating from specific sources (e.g. Abandoned Lost or otherwise Discarded Fishing Gear, ALDFG) or specific items to evaluate the efficiency of dedicated reduction measure (e.g. single-use consumer plastics, sanitary-related items).

This document is intended to inform the establishment of national and regional field monitoring programmes. It provides links to protocols and data recording sheets that are intended be used in the field. The scope is restricted to monitoring plastic litter in the marine environment. However, many of the techniques described can be used in freshwater environments, specifically for monitoring rivers and lakes, with appropriate modification.

GESAMP recognises the benefits of sharing information and good practice, the need for capacity building, making links, access to training and collaboration among partners. The Global Partnership on Marine Litter (GPML) was set up to fulfil these functions and those interested in this topic are encouraged to take part in this initiative, which can be accessed through the Marine Litter Network[4].

1.2 Plastic litter as a global ocean concern

Humanity has long used the ocean to dispose of goods and materials regarded as waste, either directly or indirectly (e.g. via run-off). Since the 1950s, when large-scale production of plastics began, an increasing proportion of solid waste in the ocean has consisted of this material, representing up to 80% of marine litter found in surveys (UNEP, 2016). This is a result of both land-based and sea-based human activities. Plastic litter is most obvious on shorelines, where litter accumulates due to current, wave and wind action, river outflows and by direct littering at the coast. However, plastic litter occurs on the ocean surface, suspended in the water column, on the seabed and in association with biota, due to entanglement or ingestion (Figure 1.1).

We know the total global production of plastics with reasonable confidence (8.3 Gt from 1950 to 2015, Geyer *et al.* 2017) but not the proportion that has entered the ocean. Major sources or 'leakage' points include poorly managed solid and liquid waste on land, through either direct entry or via rivers, activities on the shoreline, shipping and fisheries.

The term 'plastic litter' covers an extremely wide variety of materials, ranging in size from ocean-going boat hulls many metres in length to particles a few nano-metres in diameter. 'Plastic' covers a very wide range of compositions and properties. Size, shape and composition all influence the distribution,

1 The definition of plastic adopted in this report includes: synthetic polymers with thermo-plastic or thermo-set properties (synthesized from hydrocarbon or biomass raw materials), elastomers (e.g. butyl rubber), material fibres, monofilament lines and coatings.
2 http://www.gesamp.org/work/groups/40
3 https://sustainabledevelopment.un.org/sdg14
4 http://marinelitternetwork.com/the-partnership/

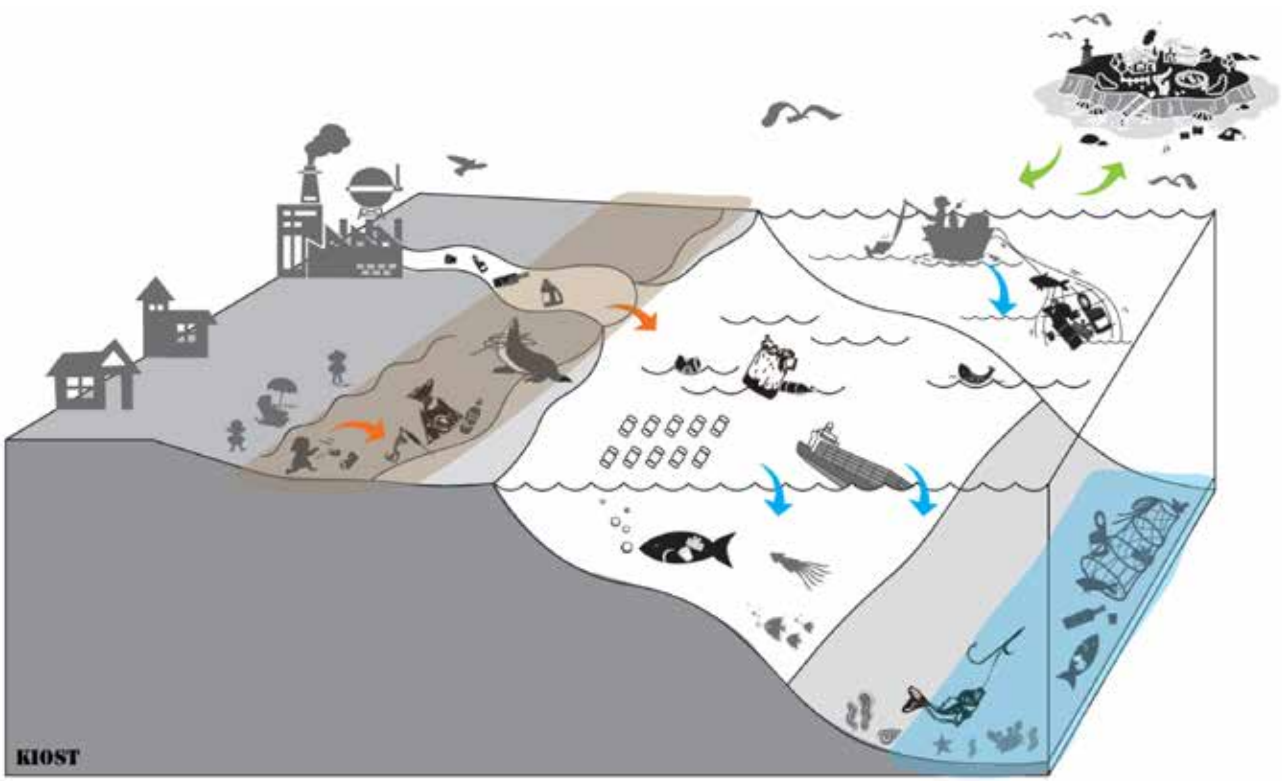


Figure 1.1 Schematic representation of sources of marine plastic litter and microplastics (adapted from GESAMP 2015).

fate and effects in the environment and need to be accounted for where possible. These factors are discussed further in Chapter 2.

1.3 The role of monitoring and assessment

Monitoring the marine environment for the presence of plastic litter is a necessary part of assessing the extent and possible impact of marine litter, devising possible mitigation methods to reduce inputs, and evaluating the effectiveness of such measures. However, it is important to use consistent and reliable methods of sampling and sample characterisation (e.g. number, size, shape, mass and type of material; Chapter 2) to gain greatest benefit.

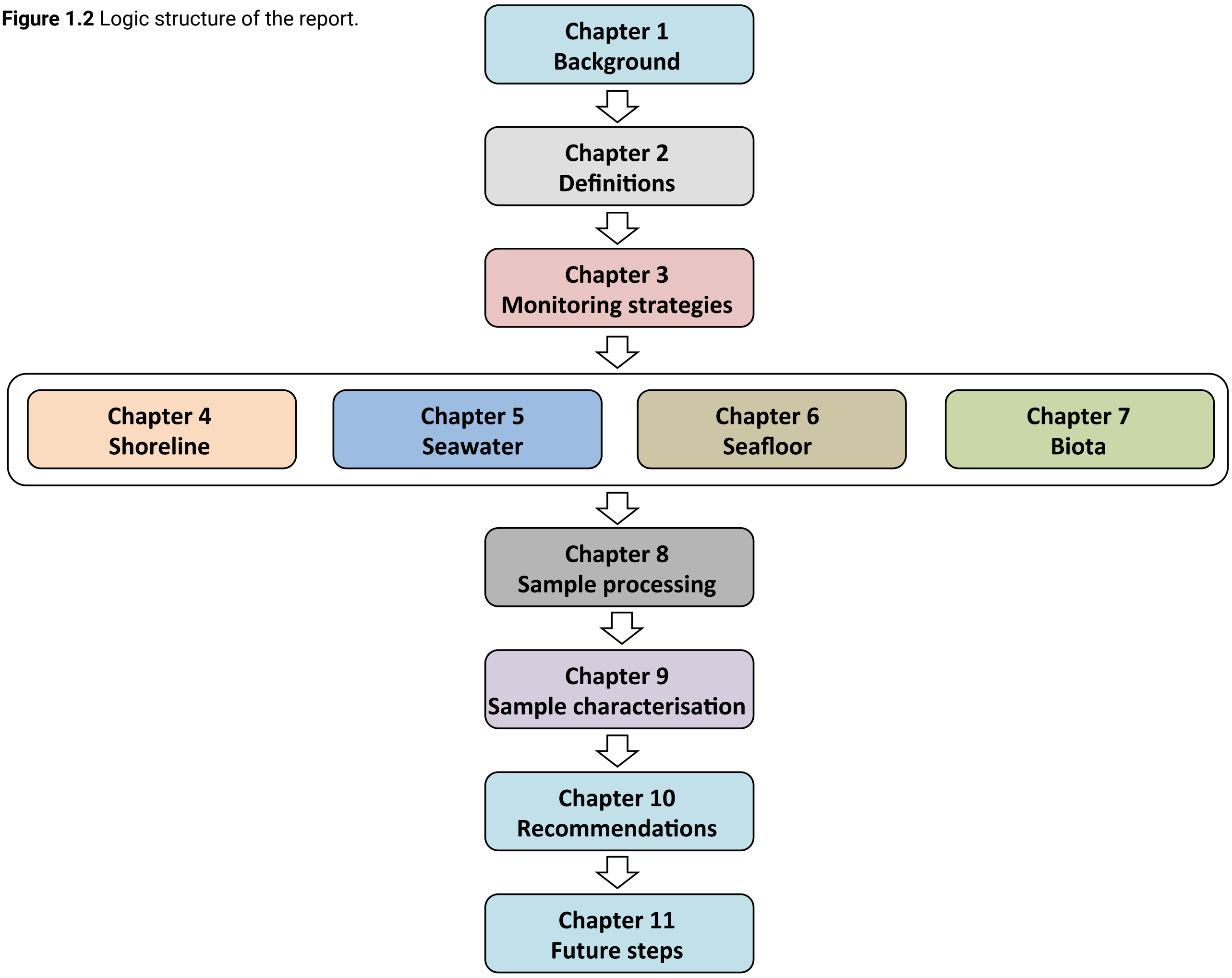
The magnitude of the change to be detected determines the sampling effort required to reliably detect spatial and temporal trends, taking account of the inherent variability in the property being measured

When setting up a sampling programme the design needs to take into account the management objectives (e.g. compliance, efficacy of reduction measures), the environmental setting and the most appropriate indicators to be targeted (Chapter 3). Indicators are selected to describe the 'state' of the environment, such as the quantity of litter per unit of measurement (i.e. area, length, number of organisms). It is common to compare the measured 'state' against a baseline or reference state. But, as plastic litter is ubiquitous in the ocean, it is unlikely that the baseline will be zero. There needs to be a degree of consistency in the techniques used and in the frequency and location of sampling, to allow reliable estimates of changes in space and time. The magnitude of the change to be detected, coupled with the inherent variability in the measured parameter, determines the sampling effort required to reliably detect spatial and temporal trends. This is discussed further in Chapter 3.

1.4 How to use the report - structure

The report is intended to provide a step-by-step approach to designing and implementing a programme for monitoring marine plastic litter, assuming no prior knowledge (Figure 1.2). Using definitions and terminology that are widely accepted and understood by the user group is key to creating a harmonised approach and increasing the potential for sharing data and information. Chapter 2 provides definitions of common terminology used in existing marine litter monitoring. It is followed by a description of some basic principles of monitoring and assessment that are applicable in most cases (Chapter 3). This is intended to maximise the utility of the data gathered, recognising that in many cases resource constraints will limit the scale of any monitoring programme. Chapters 4 – 7 describe the environmental settings, selection of monitoring strategies and special considerations for each of the environmental compartments: shoreline, sea-surface and water column, seafloor and biota. Some degree of sample preparation in the laboratory is usually required, whichever sampling methods are used in the field. A selection of common procedures is included in Chapter 8. Chapter 9 presents a range of more sophisticated laboratory-based techniques for recording the biological, chemical or physical characteristics of the sample, if this information is required. Links are provided throughout the

Figure 1.2 Logic structure of the report.



report to sources of supplementary information, including existing monitoring programmes, more detailed descriptions of methods and case studies. The report concludes (Chapter 10) with a series of recommendations, including selection criteria dependent on both resource/capacity limitations and policy questions being addressed.

The recommendations are directed, primarily, to assist national authorities and regional bodies in setting up programmes to establish the current status and trends of contamination by marine plastic litter (indicator selection, method harmonisation, establishing baselines) in waters under their jurisdiction. They are intended to complement established monitoring and assessment programmes, such as those developed in the framework of the Regional Seas[5], the European Union[6] and the United States[7]. These existing initiatives, together with the IOC/UNEP guidelines published in 2009[8], provided a key input to the development of these updated guidelines and are listed in Annex II. Deciding on what constitutes the target or preferred state is beyond the scope of the report. This decision is part of the governance process, informed by scientific evidence, taking account of other social, economic and political factors. The report ends presenting future steps towards more effective monitoring programmes, as the improvement of the SDG 14.1.1 indicators and new developments regarding data management.

5 http://cearac.nowpap.org/activities/marine-litter/
6 http://mcc.jrc.ec.europa.eu/dev.py?N=41&O=434&titre_chap=TG%20Marine%20Litter
7 https://marinedebris.noaa.gov/reports-and-technical-memos
8 http://wedocs.unep.org/bitstream/handle/20.500.11822/10739/MarineLitterSurveyandMonitoringGuidelines.pdf?sequence=1&isAllowed=y

2. DEFINITIONS AND TERMINOLOGY

2.1 The need for clarity

Effective communication depends on a common understanding of the meaning of language. In the field of environmental management this means that the terminology we use to describe the state of the environment is clearly defined. The use of common definitions aids the process of harmonising methods used to measure contamination of the ocean and the interpretation of data. In this way, any organisation with an interest in monitoring the state of the ocean can use similar methods, descriptors and data handling, encouraging the pooling of resources and integration of datasets. In turn it becomes easier for regional bodies to implement harmonised monitoring and assessment programmes amongst their member organisations.

Scientific interest in the fate and effects of plastic litter began in the 1960s, following the beginning of increased industrial manufacture of plastics in the 1950s. However, investigations remained relatively limited until about 15 years ago (GESAMP 2015). The methods used to sample and describe plastic litter have been developed and modified since then, by individuals or organisations, leading to a diversity of approaches. This can have advantages for scientific research but presents a disadvantage when establishing a monitoring programme.

These Guidelines provide a set of recommended definitions, based largely on common usage, and may differ from those used in specialised technical fields, in which more formal definitions are required (e.g. ISO standards)

Terms such as 'litter, 'debris' and 'plastic' may have particular meanings to different groups of people, sometimes depending on the scientific or technical context, or simply cultural preference. Definitions of 'monitoring' and 'assessment' are included (section 2.2), and the issues around describing the ***size*** of items of litter are explored (section 2.3.1), as this has been a point of contention. These Guidelines provide a set of recommended definitions, based largely on common usage, in a global context. In some cases, these may differ from those used in specialised technical fields, in which more precise definitions are required (e.g. ISO standards).

The different types and especially sizes of plastic litter result in different distribution patterns in the marine environment. Due to their contrasting abundances and distribution patterns, the sampling, identification and quantification of different sizes and types of plastics require different methodological approaches – the following sections offer detailed descriptions of some commonly used methods

2.2 Monitoring and assessment

Monitoring can be strictly defined as the repeated measurement of a characteristic of the environment, or of a process, in order to detect a trend in space or time. Certain conditions need to be fulfilled to make sure the measurements are representative, such as using the same sampling methods, taking account of variations over time and any local environmental factors that may influence the results. Sampling does not always have to take place at a constant location. Random sampling can also be used.

Monitoring data are usually reported in terms of number of items or the mass (kg) of items per unit area, volume or length. Both types of data can be useful, but they provide different information, so it is preferable to record both number and mass. For example, while the number of items on a shoreline, residing on the seafloor or floating on the sea surface (Eriksen *et al.* 2014) may be dominated by smaller objects, the mass of marine litter tends be dominated by fewer larger items, such as fishing gear, depending on the location. A preoccupation with numbers may detract from dealing with a more important category, from a policy perspective.

Assessment can have two definitions in the present context. An initial assessment may be carried out to provide a 'snap shot' of environmental conditions in order to design and direct a monitoring programme more effectively. In the context of monitoring, an assessment usually is considered to be part of the process whereby the results of a monitoring programme are analysed and used to inform the decision-making process, for example as to whether some reduction measure has been effective.

Advice on the selection of monitoring and assessment approaches is provided in Chapter 3. The different types and especially sizes of plastic litter result in different distribution patterns in the marine environment. Due to their contrasting abundances and distribution patterns, the sampling, identification and quantification of different sizes and types of plastics require different methodological approaches. These area described in detail in Chapters 4-7

2.3 Composition of plastic marine litter

2.3.1 Definition of plastic litter

We use the definition of marine litter proposed by UNEP in 1995, as: 'any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment'[9]. In reality 'persistent' is a relative term; for example, the relative persistency of common litter categories can be summarised as: food waste < paper < wood < iron < plastic. We define plastic here as a synthetic

9 Global Programme of Action for the Protection of the Marine Environment from Land-based Activities, adopted in Washington DC, 1995

organic polymer. Polymers are formed from individual monomers linked together to form long chains, rather like a train formed of many individual carriages linked together. Most plastics are synthesised from fossil fuels but biomass can be used (UNEP 2018). Although the Guidelines have been developed specifically for plastic litter, the same principles will apply for other types of material.

Marine litter:
"… any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment"
UNEP (1995)

In this report plastic is defined as: synthetic polymers with thermo-plastic or thermo-set properties (synthesized from hydrocarbon or biomass raw materials), elastomers (e.g. butyl rubber), material fibres, monofilament lines, coatings and ropes. Most plastics can be divided into two main categories: thermoplastics (capable of being deformed by heating), which include polyethylene, polypropylene and polystyrene; and, thermoset (non-deformable), which include polyurethane, paints and epoxy resins. About 15% of total synthetic polymer production consists of fibres, such as polyester and acrylic. Many plastics are produced as a mixture of different polymers and various plasticizers, colorants, stabilizers and other additives. Another significant component of plastic marine litter is semi-synthetic material, such as cellulose nitrate and rayon, made from biomass. Further details about the production and formulation of plastic from fossil fuels and biomass are presented in UNEP (2018).

The history of plastics development dates back to the end of the 19th century, though the infrastructure for its mass production arose during World War II. As a result of this increased production capacity, together with a growing understanding of its versatility especially in regard to basic consumer products, there has been an exponential increase in the manufacture of these materials since the 1950s. Nearly half of all plastics created have been manufactured since the year 2000[10] (Geyer *et al.*

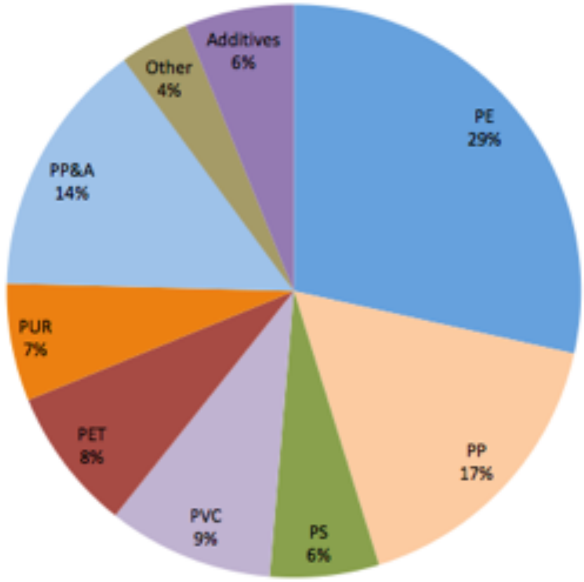


Figure 2.1. Global market share of common polymers, PE = polyethylene (as HDPE, high density, or LDPE, low density); PP = polypropylene; PVC = polyvinyl chloride; PUR = polyurethane; PS = polystyrene; PET = polyethylene terephthalate; Others include Teflon, polycarbonate, acrylonitrile butadiene styrene, etc. (Adapted from Geyer *et al.* 2017).

Table 2.1 Common polymers and applications, together with their tendency to float or sink in the aquatic environment, based on density difference (without additional floatation, such as a fishing float) (modified from GESAMP 2016).

Polymer	Common applications	Specific gravity	Behaviour
Polystyrene (expanded)	Cool boxes, floats, cups	0.02-0.64	Float
Polypropylene	Rope, bottle caps, gear, strapping	0.90–0.92	
Polyethylene	Plastic bags, storage containers,	0.91–0.95	
Styrene-butadiene (SBR)	Car tyres	0.94	
Average seawater		***1.03***	
Polystyrene	Utensils, containers	1.04–1.09	Sink
Polyamide or Nylon	Fishing nets, rope	1.13–1.15	
Polyacrylonitrile (acrylic)	Textiles	1.18	
Polyvinyl chloride	Thin films, drainage pipes, containers	1.16–1.30	
Polymethylacrylate	Windows (acrylic glass)	1.17-1.20	
Polyurethane	Rigid and flexible foams for insulation and furnishings	1.20	
Cellulose Acetate	Cigarette filters	1.22–1.24	
Poly(ethylene terephthalate) (PET)	Bottles, strapping	1.34–1.39	
Polyester resin + glass fibre	Textiles, boats	>1.35	
Rayon	Textiles, sanitary products	1.50	
Polytetrafluoroethylene (PTFE)	Teflon, insulating plastics	2.2	

10 https://news.nationalgeographic.com/2018/05/plastics-facts-infographics-ocean-pollution/

2017). While intentional releases (e.g. littering by public, illegal dumping on land or at sea) may occur, most estimates suggest the majority of plastic litter entering the ocean originates from inadequate waste management on land, combined with certain maritime sectors such as fisheries (UNEP 2016).

2.3.2 Types and uses of plastics

There are many hundreds of different types of polymer and mixtures of polymers in commercial production, but the market is dominated by: polyethylene (as both high-density, HDPE, and low-density, LDPE), polypropylene (PP), polyvinyl chloride (PVC), polyurethane (PUR), polystyrene (PS), and polyethylene terephthalate (PET) (Figure 2.1). These six polymers make up about 80% of plastics production and are likely to form a large proportion of most marine litter. Table 2.1 provides examples of common products and their associated polymer resin, as well as their density as a virgin material.

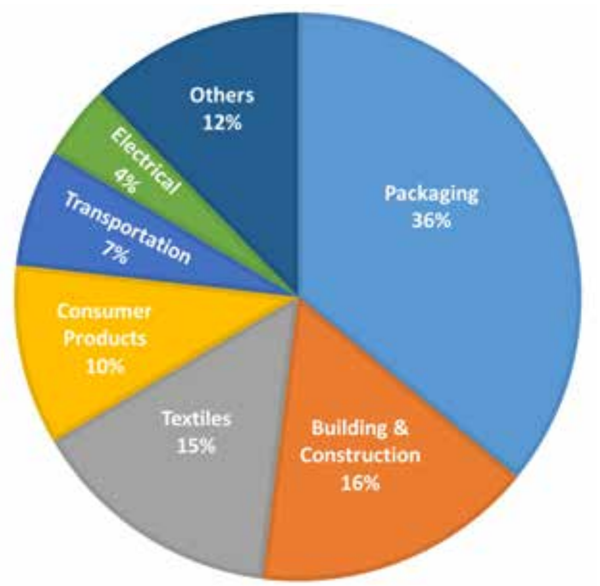


Figure 2.2. Global plastics demand by market sector. Others include appliances, medical, mechanical engineering etc. (adapted from Geyer *et al.* 2017).

In addition to understanding the most common polymers used within plastic materials, understanding their main uses within the global market can provide insight into the ultimate sources of plastic litter. As detailed in Figure 2.2, packaging represents the dominant market sector for plastics (36%), followed by building and construction (16%) and textiles (15%).

2.3.3 Chemicals associated with plastics

Plastics litter can contain a wide variety of chemicals. These can include those that originated during manufacture, such as monomers and chemicals added to fulfil a function, and chemicals that are absorbed from the environment, if the plastic is in contact with seawater or sediments. Additive chemicals include flame-retardants, UV stabilisers, antioxidants, plasticisers, stabilisers, fillers, pigments and lubricants. Typical additives found in some common polymers are provided in Table 2.2. They can be present in relatively high concentrations in some durable plastics (e.g. used in electronic goods manufacture) can present a potential health risk as several have endocrine disrupting properties (UNEP 2018).

The composition of plastics has evolved over time, with new polymers, co-polymers and additive chemicals emerging. This means that plastic objects manufactured in the 1950s, 1960s and 1970s may differ in composition from those manufactured more recently. For example, pigments used initially were often based on heavy metals (e.g. cadmium, arsenic, lead, chromium and mercury), leading to high concentrations in 'old' plastic litter measured today (Filella and Turner 2018). Recommended methods for characterising the chemical composition of plastics are provided in Chapter 9.

Table 2.2 Additives in five common polymers indicating their function and relative proportion (taken from Hermabessiere *et al.* (2017).

Polymer	Additive type	Quantity in polymer (%w/w)	Hazardous substances
PP	Antioxidant	0.05-3	Bisphenol A; Octylphenol; Nonylphenol
	Flame retardant (cable insulation and electronic applications)	12-18	Brominated flame retardant; Boric acid; Tris (2-chloroethyl) phosphate
HDPE	Antioxidant	0.05-3	Bisphenol A; Octylphenol; Nonylphenol
	Flame retardant (cable insulation application	12-18	Brominated flame retardant; Boric acid; Tris (2-chloroethyl) phosphate
LDPE	Antioxidant	0.05-3	Bisphenol A; Octylphenol; Nonylphenol
	Flame retardant (cable insulation application	12-18	Brominated flame retardant; Boric acid; Tris (2-chloroethyl) phosphate
PVC	Plasticiser	10-70	Phthalate
	Stabiliser	0.5-3	Bisphenol A; Nonylphenol
PUR	Flame retardant	12-18	Brominated flame retardant; Boric acid; Tris (2-chloroethyl) phosphate

2.4 Types of plastic marine litter

2.4.1 Common categories of macro-litter

In the case of macro-litter it is useful to provide a description of the items (Figure 2.3). This is usually achieved by assigning each item to an agreed list of categories. There is a need for robust, quantitative data to identify the types and sources of litter and support and justify management decisions, such as introducing bans or restrictions on certain items, and to help in negotiating a reduction in trans-boundary sources. In some circumstances there may a need to balance the benefits of having a comprehensive list, with perhaps 100+ categories, with pragmatic and operational considerations. But, if details are ignored in the field the information cannot be retrieved in retrospect. In addition, there are likely to be regional variations in the types and quantities of different litter items, so there needs to be scope for flexibility to allow local managers to decide the most appropriate number of categories and the descriptors used, while allowing comparability of assessments at larger scales in order to support management decisions.

Figure 2.3 Litter on a beach in Senegal, showing a wide variety of different categories of litter, including plastic sheets, shoes, rubber sheets, plastic cups, straps, plastic bags, cigarette packets, fabric and building material (© IFREMER).

It is common to adopt a hierarchical approach that describes: (i) the composition (e.g. plastic, glass, metal), (ii) the overall form (e.g. bottle, film, rope, net, bag), and (iii) the size. The category lists used by Regional Seas[11], the EU-MSFD[12] and the NOAA MDMAP[13] monitoring programmes, tend to have a common root based on the UNEP/IOC guidelines (Cheshire *et al.* 2009), but with some modifications to meet the specific regional requirements. There is an on-going initiative within the European Union (Marine Strategy Framework Directive) to create a common category list, covering the four European Regional Seas, that provides comparability and flexibility. The UNEP/IOC guidelines define 77 categories of marine litter (Annex III). Each item may be identified further by construction, colour, length or weight. The category type lists may be further refined to suit the requirements of monitoring different environmental compartments, different size categories or different sampling methods. This is described in more detail in section 3.3.2, and additional examples of category lists for different environmental compartments are provided in Annex III.

We can also define primary-use and secondary-use items. For example, vehicle tyres are often used as fenders on vessels, bait boxes and crab pots can be made from modified plastic boxes, and disused plastic liquid containers are used as floats in small-scale fisheries.

2.4.2 Marine litter associated with fisheries and aquaculture

Litter associated with fishing industries may include the fishing gear itself such as nets, pots, floats, ropes fish aggregating devices (FADs) and associated material, referred to collectively as abandoned lost or otherwise discarded fishing gear (ALDFG), or associated items like bait boxes, polystyrene ice chests, plastic crates, foul weather gear, and the like (Figure 2.4). For litter associated with fisheries and aquaculture, it will be important to have separate identification categories that allow for different types or characteristics of fishing gear, that will vary by region and with the target species (Annex IV). This may include any gear marking tags (FAO 2016). Such information can provide useful information about which fishery, or aquaculture facility, the gear originated from.

Figure 2.4 Examples of fishing gear – clockwise from top left: Fisheries Aggregation Device in Western Indian Ocean (FAD, image courtesy of Ministry of Ocean Economy, Marine Resources, Fisheries and Shipping', Government of Mauritius); beam trawl showing green 'dolly' rope, North Sea (©Kimo International, courtesy of Mike Mannaart) ; derelict crab pots after recovery operation (©NOAA); Hawaiian long-line fishery (©NOAA).

It is estimated that in some regions, up to 20% of gear is lost at sea because accidents, adverse weather conditions, gear conflicts and entanglement (e.g. on wrecks) and intentional abandonment. In European Seas it is estimated that over 11,000 tons of ALDFG enter the marine environment each year[14].

11 https://www.unenvironment.org/explore-topics/oceans-seas/what-we-do/working-regional-seas
12 http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/index_en.htm
13 https://mdmap.orr.noaa.gov/login

14 https://ec.europa.eu/fisheries/new-proposal-will-tackle-marine-litter-and-%E2%80%9Cghost-fishing%E2%80%9D_en

The material is designed to be durable in the marine environment and takes many years to degrade, often continuing to attract and trap commercial and non-commercial fish and shellfish (i.e. ghost fishing).

2.4.3 Primary and secondary microplastics

Microplastics can be categorised as being of primary or secondary origin. GESAMP recommends the following definition, as first published by GESAMP in 2015 (GESAMP 2015):

- primary microplastics are purposefully manufactured to carry out a specific function (e.g. abrasive particles, powders for injection moulding, resin pellets for bulk transportation of polymers between manufacturing sites); and
- secondary microplastics represent the results of wear and tear or fragmentation of larger objects, both during use and following loss to the environment (e.g. textile and rope fibres, weathering and fragmentation of larger litter items, vehicle tyre wear, paint flakes).

Both types of particles will be subject to similar processes in the ocean. Plastics will tend to fragment if subject to UV radiation and mechanical abrasion. It follows that there will be a tendency for the proportion of smaller fragments to increase relative to the number of larger litter items.

Categories of microplastics:
Primary – purposely manufactured to fulfil a function
Secondary – resulting from wear and tear or fragmentation of larger objects

---

2.5 Physical descriptors of plastic marine litter

2.5.1 Size

The size and shape of a litter item are crucial measures to be included in marine litter monitoring. Both properties can affect the behaviour of litter in the environment, including the further degradation, transport and the extent and nature of any impacts. Marine litter forms a continuum of sizes, from microscopic particles to objects many metres across, such as a boat hull. For such a simple concept the definition of particle size has been the subject of much discussion. As mentioned above, the methods used to sample and quantify plastic litter have developed over several decades, and the terminology used to describe physical attributes has changed accordingly. In these Guidelines we have attempted to take account of both scientific convention and common usage in established monitoring programmes. The intention is to produce a set of definitions that will be useful for investigators new to the field as well as being compatible with existing practice. Plastic particles in the nano size range (< 1 μm) undoubtedly exist in the ocean, but science and technology will have to develop considerably before nano-particles can be included in routine monitoring. For that reason they are not discussed further.

Size definition of microplastic particles

In most fields of science we can rely on the SI (Systèm International) to provide an agreed set of measurement units. This is not the case in the field of marine litter. Several of the terms commonly used to describe relative size, such as meso, macro and mega, are not part of the SI system, but are simply useful descriptors, understandable by many (Table 2.2, Figure 2.5).

The two global assessment reports published by GESAMP in 2015 and 2016 (GESAMP 2015, 2016) mentioned the lack of an internationally-agreed definition. It was decided to include all particles <5mm within the assessment of sources, fate and effects of microplastics, for pragmatic reasons to avoid excluding any relevant published studies. At that time, GESAMP did not make a formal recommendation. 'Micro' is an SI descriptor and some scientists have argued that microplastics should be defined as being < 1,000 μm (<1mm). Which size definition is most appropriate has remained a contentious topic, with advocates of both < 1 mm and < 5 mm (Frias and Nash 2019).

Defining the size of microplastic particles:
GESAMP recommends < 5mm diameter as the 'common definition' of the upper size boundary for microplastic particles for monitoring purposes.

As this report concerns the harmonisation of monitoring approaches, GESAMP has decided to recommend a 'common definition' of < 5mm in recognition that several national and regional monitoring programmes are using this definition routinely, to encourage a harmonised approach and reduce ambiguity. It is also recognised that researchers may wish to use alternative or additional size categories (e.g. < 1mm, 1-2mm, 1-5mm) to address specific scientific questions. Monitoring agencies may wish to include additional size categories in response to a particular policy need, but for routine monitoring we recommend the use of < 5mm. It is important to note that this definition will include flakes and fibres, with the longest dimension < 5mm.

In the field of marine litter monitoring often it is necessary to introduce additional descriptors, for very practical reasons related to working under field conditions. In addition, there is an advantage in using categories that aid decision-making or support a particular investigation. For example, plastic resin pellets make up one important type of primary microplastic. These, typically, are in the size range 1 - 5 mm and have been referred to as 'microplastics' in the scientific literature for at least a decade (GESAMP 2016). It makes little sense to insist on placing these into a 'milli-plastic' size category, ranging from 1 to 1000 mm. While litter appears in a continuous size spectrum, ranging from shipwrecks to almost molecular level, there is need for conventions that allow harmonised measurement and reporting of the different size fractions. The use of differing size ranges leads to a non-comparability of measurements. There is a clearly defined societal need to quantify marine litter in order to provide for the most (cost) effective measures. Therefore we need harmonised data acquisition and reporting.

What is key is to record what is being measured and the methods used for attaining said measurement, to avoid ambiguity and promote a more harmonised approach. In addition, the investigators need to be aware of the limitations of whatever methods they are using. For example, many studies of floating plastics, using towed nets, report the quantity of micro- or meso-sized material per unit area of sea surface. However, the sampling effectiveness is influenced by several factors, most importantly the mesh size of

Table 2.2 Size categories of plastic marine litter, assuming a near-spherical form, showing common definitions and alternative options that may be appropriate for operational reasons.

Field descriptor	Relative size	Common size divisions	Measurement units	References	Alternative options	Remarks
Mega	Very large	> 1 m	Metres	GESAMP		
Macro	Large	25 – 1000 mm	Metres Centimetres Millimetres	MSFD	25 – 50 mm	
Meso	Medium	5 – 25 mm	Centimetres Millimetres	MSFD	< 25 mm 1 – 25 mm	MARPOL Annex V (pre revision)
Micro	Small	< 5 mm	Millimetres Microns	NOWPAP MSFD	1 – 5 mm < 1 mm > 330 μm*	 Eriksen *et al.* (2014)
Nano§	Extremely small	< 1 μm	Nanometres		< 100 nm	Not considered for monitoring

*operationally-defined, referring to the typical mesh size of 330 μm of towed plankton nets; §nano-sized particles can only be identified under carefully controlled laboratory conditions and may form a monolayer on one (plates) or two (fibres) dimensions

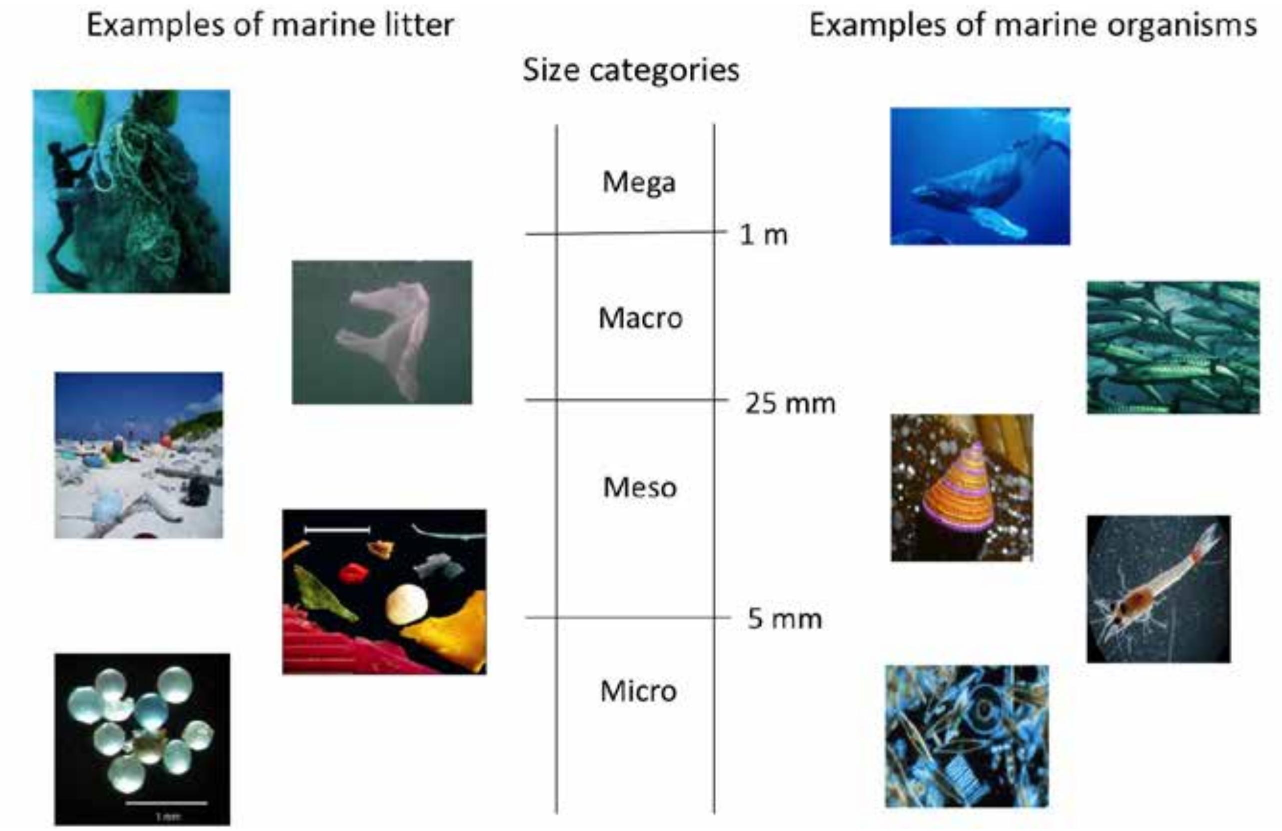


Figure 2.5 Schematic showing field descriptors, typical aquatic organisms in that size category, examples of marine litter and common size divisions.

the sampling net which is most frequently 330 µm. This means that any particles of < 330 µm will be greatly under-sampled.

Plastic fragmentation
Most conventional plastics will persist in the marine environment for a considerable time. Fragmentation will occur if plastics are subject to UV radiation, causing the surface to become brittle, and physical abrasion, such as on exposed shorelines or at the sea surface (GESAMP 2015). If plastics are deposited on the seafloor or buried in sediments then they are likely to remain intact indefinitely. Plastic fragments will have similar structural properties as larger items of the same polymer. It is only with the intervention of microorganisms that the polymer will start to break down into its component elements. This is an extremely slow process in the ocean, even for polymers that may be marketed as 'biodegradable'. A fuller discussion on biodegradable and compostable materials can be found in (UNEP 2015).

2.5.2 Shape of microplastics

Microplastics are heterogeneous, exhibiting a range of shapes or morphologies from spherical beads to angular fragments and long fibres. Identifying these morphologies can provide some indication of potential sources, such as textiles or ropes for fibres, as well as their behaviour within an environmental compartment (e.g. beaching vs. sinking, ingestion by biota).

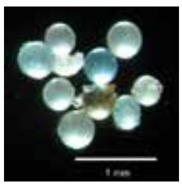
There is currently no standardized scheme for morphological characterization of plastic litter, but five general categories are used, as we recommend here, and are briefly described in Table 2.3. Similar to size, there may be cases (i.e. a particular scientific question) in which these 5 general categories may be subdivided. For example, in areas with known fishing activities a research group may wish to separate the "Line" category into "Filaments" (from fishing) and "Fibres" (from textiles) in order to gain insight into particular source apportionments. We encourage reporting the original data in these finer subdivisions with the recognition that subdivisions can be combined for ease of harmonizing and comparing data.

In practice these morphological descriptions can be subjective. A flowchart is provided in Chapter 9 to assist in harmonizing morphological classifications, helping to create a common descriptive scheme.

2.5.3 Colour

Colour may provide useful information about the source of marine litter. It may fulfil other purposes such as identifying preferential feeding strategies by organisms, or the conditions that objects have been exposed to (e.g. weathering, biofilm development).

Table 2.3 Morphological descriptors for marine plastic particles and some larger plastic objects (images: fragment ©Richard Thompson, all other images ©Sam Mason).

Field description	Alternative descriptor	Characteristics	Example
Fragment	Granule, flake	Irregular shaped hard particles having appearance of being broken down from a larger piece of litter	
Foam	EPS, PUR	Near-spherical or granular particle, which deforms readily under pressure and can be partly elastic, depending on weathering state	
Film	Sheet	Flat, flexible particle with smooth or angular edges	
Line	Fibre, filament, strand	Long fibrous material that has a length substantially longer than its width	
Pellet	Resin bead, Mermaids' tears	Hard particle with spherical, smooth or granular shape	

However, identification of colour by people is very subjective, and may be hindered by visual deficiencies such as colour blindness.

Like morphology, there is currently no standard scheme for colour designation for plastic litter. While broad colour classifications are not sufficient to indicate particle similarity given the range of shades available within a single category (e.g. navy, turquoise, sky blue, and cyan all as "blue"), given the infinite spectra of colour, being too particular would be unreasonably time-consuming, if not impossible on a large scale. There is a need for a balance between these two extremes. We recommend either the 12 basic colour terms of the ISCC-NBS (Inter-Society Colour Council National Bureau of Standards) System of Colour Designation or the 8-colour classification scheme being proposed by the European Marine Observation and Data Network (EMODnet[15], Galgani *et al.* 2017). This is explored further in Chapter 9.

15 http://www.emodnet.eu

3. DESIGNING MONITORING AND ASSESSMENT PROGRAMMES

3.1 The role of monitoring and assessment

Monitoring and assessment are essential steps towards addressing specific questions about marine litter, including microplastics. They are needed to assess the state or level of pollution and provide objective information to design mitigation measures as well as to assess their effectiveness and promote adaptive management. But, it is critical to understand the underlying policy concerns as this will help to determine the nature and extent of the approach (Box 3.1). In this chapter we present general criteria that need to be considered when designing a monitoring scheme. Specific aspects for each of the four compartments addressed in this report are presented in Chapters 4 to 7.

Monitoring should be set as an on-going long-term process based on a series of repeated measurements made to detect a baseline condition (e.g. number and types of items) and temporal changes in marine litter. Assessments use such information in a critical and contextualised way to design and evaluate public policies and mitigation measures.

Since monitoring is goal dependent, the sampling strategies, protocols and indicators used must be tailored to the specific questions being asked, which are often driven by policy considerations. The rationale for recommending particular monitoring strategies is explored further in Chapter 10. These may include risks to human health, compliance with national or international environmental regulation, impacts on biodiversity, the influence of the tourism sector and maritime safety. In addition, recommendations also consider the capacity of government agencies or other organisations, which may limit the scope of any monitoring activities.

Box 3.1: Examples of policy concerns:

- ❑ Abundance of marine litter in seas under national jurisdiction
- ❑ Type and origin of marine litter
- ❑ Identification of hotspots
- ❑ Setting targets for reduction measures
- ❑ Impacts on:
  - biodiversity and animal welfare
  - human health issues and injuries
  - seafood safety
  - food security – ghost fishing
  - tourism and recreation
  - maritime safety (navigation)

The provision of reliable data on marine litter occurrence depends on following accepted standards and practices. This report provides recommendations on methods for developing monitoring strategies in the four main environmental compartments (i.e. shoreline, sea surface/water column, seafloor and biota), from sample collection

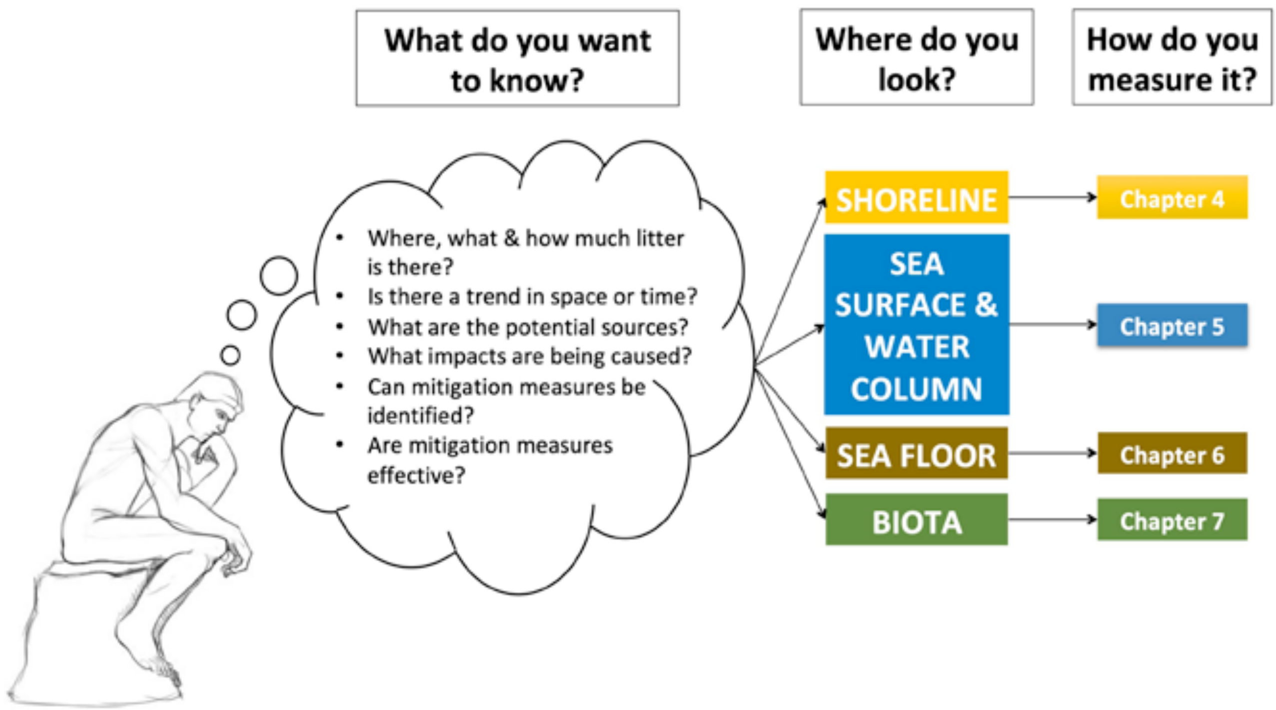


Figure 3.1. Examples of key questions, the marine compartments where monitoring may be conducted and the chapters where the methods are described.

and processing (including detailed protocols and metadata requirements) to characterisation of items and data reporting.

Questions of interest may also focus on specific human activities that generate marine litter, such as navigation (e.g. cargo, garbage), fisheries (e.g. ALDFG) and aquaculture (e.g. ropes, buoys). Similarly, monitoring may also target specific products, brands or items of interest for mitigation measures. Figure 3.1 provides examples of key policy questions, the marine compartments where monitoring may be conducted and the chapters where the methods are described.

The policy questions can be grouped into four categories (Hutto and Belote 2013):

1. Surveillance monitoring: is there a change in condition that needs to be addressed through management?
2. Implementation monitoring: were management treatments implemented as prescribed?
3. Effectiveness monitoring: was the management activity effective in reaching the stated goal?
4. Ecological effects monitoring: where there unintended consequences of the management activity?

Irrespective of the question, a robust monitoring strategy should incorporate four key aspects adapted from (Hanke *et al.* 2013); it should:

1. Define spatial and temporal scales and areas for sampling;
2. Use rigorous and repeatable sampling and analytical procedure protocols;
3. Develop suitable mapping and dissemination tools to show the environmental status of the different indicators (section 3.2); and
4. Link the sampling scales and indicators to management issues (mitigation measures, for example), as well as resource considerations.

The design of a monitoring programme at a given spatial scale or political level (local, sub-national national, regional or global) should consider a match between the questions and principles above and practical aspects related to methodological, environmental/ecological, institutional (resource availability, technical capacity and institutional arrangements), communication, sustainability and ethical considerations.

Monitoring and assessment carried out at local or sub-national scales can be utilised for wider scale assessments using harmonised approaches. Some form of governance framework is recommended to collate, store, share and analyse data, and communicate the results.

New monitoring and assessment programmes will benefit by following a more harmonised approach to allow greater consistency in reporting and facilitate the exchange of data between different organisations.

3.2 Indicators and targets

3.2.1 Some definitions

An indicator provides a measure of the 'state' of the environment, such as the abundance of plastic litter in the ocean, using data gathered by monitoring the shoreline, sea surface, seafloor or biotic compartments. As above, the selection of indicators and the monitoring methods used will also depend on the policy questions being addressed as well as local environmental, social and economic considerations. Indicators, in conjunction with other measures and proxies (e.g. oceanographic currents, socioeconomic data), can be used to detect the presence of marine litter in a given habitat (exposure) and the spatial and temporal trends of accumulation (sinks), as well as to provide information on its potential sources or on its subsequent impacts on biodiversity and benefits

Table 3.1. Definitions and examples of marine litter indicators, baseline and targets (based on UNEP 2016).

Term	Definition	Examples
Indicator	A measure of the state of the environment subject to a pressure (i.e. littering)	Number of litter items per unit length of shoreline Mass of ingested plastic in seabird
Baseline	A reference state, usually based on data obtained by monitoring an indicator in the environment	Number of litter items per unit length of a reference shoreline Mass of ingested plastic in reference seabird
Target	A defined state, usually set up by a national administration or regional body, with the expectation that effective management measures can be implemented to achieve it	< 'y' litter items per unit length of shoreline < 'x' grams of ingested plastic in seabird
Aspirational target	A desired (or ideal) state to be achieved in the future, which cannot be achieved in the short- to medium-term	< 'z' items of litter items per unit length of shoreline (where z << y) < 'w' grams of ingested plastic (where w << x)

provided by nature to society. An additional function of indicators is to evaluate the effectiveness of mitigation measures.

Environmental indicators should have the following characteristics (UNEP 2016):

- Scientifically valid;
- Simple to understand by the public and policy makers;
- Sensitive and responsive to change;
- Cost-effective; and
- Policy relevant.

The quantity and profile of litter is often compared with a baseline, or reference state, to give a measure of the extent of contamination. A target may be set for the preferred or desired state (aspirational target) to be achieved. It may be linked to specific mitigation measures and operate at a range of spatial and temporal scales. Table 3.1 provides definitions and examples of marine litter indicators, baseline and targets, related both to the preferred (target) and desired (aspirational target) states, according to (UNEP 2016).

3.2.2 UN Sustainable Development Goals - Indicator 14.1.1

The United Nations Agenda 2030 and the Sustainable Development Goals (SDGs)[16] include the density of floating plastic litter as one of the key indicators of ocean 'pollution' under SDG 14.1 (Table 3.2). Currently this indicator is categorised as Tier 3, under a process created under the United Nations Environment Assembly (UNEA), meaning that: *'no internationally established methodology or standards are yet available for the indicator, but methodology/ standards are being (or will be) developed or tested'*. The guidelines presented in this report will contribute towards raising this indicator to Tier 2 *('Indicator is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries')*.

At present there is only a single indicator of marine plastic litter, but other sub-indicators are under development to include other compartments (Table 3.3). These will be considered under the SDG and UNEA processes. Additional marine litter indicators, together with associated baselines and targets, have been adopted by the Global Partnership on Marine Litter (GPML[17]) and may give a broader and more detailed view on the accomplishment of target 14.1. The choice of indicators will be guided by what is practical, as well as fulfilling the policy aims, especially for countries with limited monitoring experience or capacity. A range of partners will be needed to fulfil the aims of this global initiative, at national, regional and global scales. This includes the potential role of citizen science, a described in more detail in section 3.4.

16 https://www.un.org/sustainabledevelopment/

3.3 Data requirements for monitoring

3.3.1 Measurement units and data management

Indicators may be expressed in different measurement units depending on the sampling method used, the compartment evaluated (shoreline, sea surface, seafloor or biota) and the question addressed. Estimates of marine litter abundance may be expressed as number or mass (g or kg), per unit of distance (m, km), area (m^{-2}, km^{-2}), volume (l^{-1}, m^{-3}), depending on the environmental compartment and sampling method. Accumulation rates must incorporate a temporal unit, which may vary with the magnitude of the process governing litter dynamics, such as stranding on the shoreline during tidal cycles or seasonal accumulation (e.g. d^{-1}, a^{-1}).

The rationale for selecting number or mass depends on both the policy question(s) being addressed and pragmatic concerns in producing reproducible and reliable data. Ideally both units would be used. For example, while the number of items on a shoreline, residing on the seafloor or floating on the sea surface, may be dominated by smaller objects, the mass of marine litter tends be dominated by fewer larger items, such as fishing gear, depending on the location (Eriksen *et al.* 2014, Lebreton *et al.* 2018), although regional variations in the relative proportions are likely. The number of items may be important from a policy perspective if the concern is about assessing the overall abundance of marine litter. In the case of seafood safety then numbers of microplastics may be more useful than total mass. From the perspective of assessing navigation hazards then mass may be more appropriate (e.g. the mass of a floating rope in relation to probability of fouling the propeller). Generally mass is more difficult to assess:

17 https://www.unenvironment.org/explore-topics/oceans-seas/what-we-do/addressing-land-based-pollution/global-partnership-marine

Table 3.2. United Nations Sustainable Development (UNSD) Goal 14 target and indicator of plastic debris.

Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development				
Target	Indicator*	UNSD Indicator Code	Tier	Marine debris sub-indicator
14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including plastic debris and nutrient pollution	14.1.1 Index of coastal eutrophication and floating plastic debris density	C140101	3**	Under development

* Custodian Agency: UNEP; Partner Agencies: IOC-UNESCO, IMO and FAO.
** No internationally established methodology or standards are available for the indicator.

Table 3.3 Examples of potential sub-indicators for indicator 14.1.1 of the United Nations Sustainable Development Goal 14, related to i) the source (or attribution) of marine litter, ii) the state of marine litter or a proxy for the state (distribution and quantities), and iii) the impacts of marine litter; as defined by an expert workshop hosted by IOC-UNESCO in September 2018.

Type of Sub-Indicator	Core 14.1.1*	Data source for monitoring+	Other data sources+	Level of reporting	Partners
i) Sub-Indicators related to the source (or attribution) of marine litter					
Plastic pollution potential (based on the use and landfilling of plastics)	G	M	N	River basin	Waste statistics partners for SDG 12
River litter	C	I		River basin	GEMS
Modelling of litter movement through oceans	C	M		Global	NASA and ESA, GESAMP Working Group 40
Other parameters related to plastic consumption and recycling	N		I		
ii) Sub-Indicators related to the state of marine litter or a proxy for the state (distribution and quantities)					
Beach litter	G	I, N		National	Regional Seas, GESAMP WG 40, Citizen Science organisations
Floating plastics (concentration and large items over 10m)	G	S		TBD	NASA and ESA
Water column plastics	C	I		National	GESAMP WG 40
Microplastics (floating, water column and sea floor)	C	I		National	GESAMP WG 40
Plastic ingestion	N		I	National	GESAMP WG 40, Citizen Science organisations
Sea floor plastic litter	N		I	National	GESAMP WG 40
iii) Sub-Indicators related to the impacts of marine litter					
Entanglement	N		I, N		Citizen Science organisations
Health indicators (human health and ecosystem health)	N		I, S, N		

* G = Global monitoring core parameter, C = Collected globally, but will not be reported as part of the official SDG reporting framework, N = National monitoring parameter.
+ S = Satellite based global data product, M= globally modelled data, I = In situ data collected from countries, N = Nationally derived data, which is based on national modelling, citizen science or other national data products.

(i) very large items may be difficult to weigh;

(ii) sand or over debris may be entangled with the litter item;

(iii) items that are wet or dry will have different masses; and,

(iv) items that are sealed may hold contents. Some of these difficulties can be overcome if the items are easily recovered, but this will not be possible for camera surveys for example.

For marine litter in the meso- size range and above it is possible to sample the complete size range within each category. For microplastics this is rarely the case. The most common method of sampling floating microplastics is to use a towed net, such as a manta trawl (section 5.3), with a fixed mesh size, usually 330 µm. The means that any particle < 330 µm in diameter will be under-sampled. One way of over-coming this problem would be to pump a water sample through a 1 µm filter, to provide a measure of all the particles in the microplastic size range (1 µm – 5 mm). However, this is not feasible for routine monitoring. This is an operational constraint but it should not detract from the utility of using towed nets for monitoring purposes, to detect trends in space and time.

Metadata

Monitoring data need to be collected in a structured and formal manner to allow reliable assessments to be made. Part of this process is the recording of ancillary data to describe the monitoring activity (i.e. metadata). This will include basic information such as: survey identifier, location, date, equipment used and general environmental variables. Specific metadata requirements, as well as examples of data sheets, are presented as Annexes for each environmental compartment.

Data management
A monitoring and assessment programme should have a very clear data management policy, including data capture standards, quality control, storage, sharing, analysis, reporting and communication, as well as periodic assessment of the programme to determine whether it is achieving its goals.

The quality of the data collected is one important aspect that should be guaranteed, especially when sampling relies on citizen scientists (see below). Samples are normally taken by different people/observers, including non-specialized ones, and comparability between them should be secured. This also applies for the processing (Chapter 8) and characterization (Chapter 9) of samples.

Once data are collected they should be stored securely with provision for regular back-ups to prevent data losses. This includes field data sheets and/or digital information and metadata. Data sharing should be faciliated to allow access by different interested users, especially when supported by public funding agencies.

Currently there is no international data governance on marine litter but regional centres have been established in several areas. Examples of projects and data repositories on marine litter are listed in Annex II. A more co-ordinated solution for data management is envisaged to comply with the reporting requirements for SDG 14.1.1.

3.3.2 Marine litter categories

Recording the type of litter according to an agreed list of categories (e.g. EU-MSFD[18]) can be very useful, especially for proving information about the relative importance and potential sources of litter, or other specific policy concern, including the effectiveness of targeted reduction measures, such as restrictions on the use of certain products (e.g. straws, plastic bags) or improved waste management measures (e.g. port reception facilities) (UNEP 2016). Usually macro-litter items will offer more clues as to their origins, since they can be more easily associated with their original use.

Category lists tend to be hierarchical, allowing flexibility on the number of major categories, sub-categories and additional descriptors. Depending on the policy question, the categorisation of items in terms of type of material (glass, metal, wood, type of plastic), function (packaging, disposable items, fishing equipment, 'user' items which are designed to

18 http://mcc.jrc.ec.europa.eu/documents/201702074014.pdf

Table 3.4 An example of a hierarchical category list, for sea floor litter, based on OSPAR (2010). A Photo Guide has been published by ICES[19] to aid the identification of litter items collected during OSPAR surveys.

Main category	Sub-category - examples	Main category	Sub-category - examples
Plastic	Bottle < 2 litre	Wood - machined	Crates
	Bottle, drum > 2 litre		Fish boxes
	Cigarette lighter		Wood < 0.5 m
	Fishing net		
	Buoy	Metal	Bottle cap
	Foamed plastic buoy		Aerosol can
	Foamed plastic packaging		Drink can
			Food can
Rubber	Boots		Electrical appliance
	Balloon		
	Tyre	Glass	Light bulb
			Bottle
Cloth	Clothing		
	Sacking	Ceramics	Tile
	Furnishing		Pot
Paper/cardboard	Bags	Sanitary	Condom
	Cardboard sheet		Cotton bud stick
	Cigarette packet		Tampon and applicator
	Newspaper and magazines		
		Medical waste	Syringe
			Medicine container

19 http://ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/HAPISG/2018/01%20WGML%20-%20Report%20of%20the%20Working%20Group%20on%20Marine%20Litter.pdf

have a long lifespan), brand and any other distinguishing features may be highly useful. Manufacturer's marks and addresses on labels indicate the place of manufacture, but not necessarily where an item entered an environmental compartment. For example, litter from ships may originate far from where it is discarded, and may be transported before reaching the sampling location. The advantage of recording this type of data is that items can be combined into categories based on multiple criteria to better inform on potential sources.

In practice, it is seldom possible to record all descriptive categories for each litter item. The policy question needs to drive the methods and the choice of what level of detail the information on items should have. Established macro-litter monitoring programmes and protocols usually provide discrete classification lists (Annex III). Often, these have a common foundation based on the IOC/UNEP category list (Cheshire *et al.* 2009)[20], with additional descriptors based on organisational and policy needs. There is an initiative to produce a list of compatible categories by collaboration of the four European Regional Seas (OSPAR, HELCOM, UNEP-MAP and BSC) with the EU-MSFD Technical Group. It is anticipated that this will be published in early 2019.

3.4 Basics of survey design

3.4.1 General considerations

A marine litter monitoring programme should be designed using a logical and adaptive framework, guided by key policy-relevant questions, as exemplified above. Monitoring and assessment both require a consistency of approach, in terms of sampling location, as well as sample frequency, processing and characterisation. This is essential in order to reliably detect spatial and temporal trends. Well-established programmes may continue to use existing methods for this reason. A harmonised approach may recommend the use of 'standards' (e.g. ISO, EN, ASTM), for example, covering a specific analysis. However, this report does not advocate the use of standardised monitoring methods. There must be flexibility to design programmes that are appropriate for the policy questions being addressed and the environmental, social and economic constraints that apply in each situation. Marine litter monitoring strategies cannot thus be based on the logic of "one size fits all". They are a result of a combination of compromises (e.g. resources, capacity, conflicting priorities, geography) that define their magnitude and complexity. A guide to selecting the most appropriate and cost-effective approach is provided in Chapter 10.

This report does not advocate the use of *standardised* monitoring methods. There must be flexibility to design programmes that are appropriate for the policy questions being addressed and the environmental, social and economic constraints that apply in each situation.

An initial or continued evaluation of marine litter demands the design of an appropriate and representative sampling strategy; for example, as developed under the European Union's MSFD marine litter descriptor[21]. Litter abundance and composition may vary considerably in space (mm to 100s km) and time (seconds to years) The strategy should be informed by the socio-ecological processes that influence litter abundance in the ocean, having appropriate spatial and temporal components. The spatial component will determine the number and location of monitoring sites and the temporal component will determine the sampling frequency or number of sampling events.

Selection of sampling sites

The quality and utility of a monitoring and assessment programme is strongly dependent on its design, including sampling site selection. One key consideration is to ensure that the sites are representative of the state of litter in a defined area, which could be a length of coastline or a whole region. This might be obtained by the randomised selection of sampling plots. In other cases sampling location may be constrained by an existing sampling protocol (e.g. utilising annual fisheries stock assessment cruises).

The following levels of resolution can be defined:

- Spatial resolution – the size of individual sampling units (e.g. length of beach transect in metres)
- Temporal resolution – the frequency of sampling of individual units (e.g. monthly, quarterly, annual)
- Sample/ecological resolution – defined collection criteria (e.g. on the basis of size or type of litter item)

Examples of varying spatial and temporal scales on monitoring surveys are given in Table 3.5.

A degree of sampling replication is necessary to evaluate the degree of inherent variability of the system. Having multiple sample units that are adjacent in time or space can be used to estimate sample variability (i.e., sample mean and standard error). Statistical tools, such as power analysis, can help to determine the minimum sample size, but a complete discussion of power analysis, effect size and statistical power is beyond the scope of the Guidelines (see Quinn and Keough 2002). Compromise may be needed between the desire to obtain a truly representative sample of the abundance of litter and the level of resources available.

The choice of which area to monitor will depend on a number of considerations, which may include: the presence of vulnerable or sensitive habitats (e.g. Marine Protected Areas, MPAs); the distribution of activities representing potential sea-based sources of marine litter such as fisheries, aquaculture, shipping and offshore extractive industries (Figure 3.2); and, the occurrence of potential land-based

20 http://wedocs.unep.org/xmlui/handle/20.500.11822/13604

21 http://mcc.jrc.ec.europa.eu/documents/201702074014.pdf

Table 3.5. Considerations of extent and resolution when describing the scale of inference for a marine litter monitoring programme.

Scale of inference		
Spatial	**Temporal**	**Ecological**
Target population (extent)		
Global	Decadal	Entire assemblage of items meeting the collection criteria
National	Annual	
Regional	Monthly	
Local	Weekly	
Sampling unit (resolution)		
Shoreline	Monthly	Individual items meeting the collection criterion
Transect	Weekly	
Quadrat	Daily	

sources of litter such as coastal tourism, high coastal population density and major river outfalls. In addition, monitoring areas may be selected due to their tendency to accumulate litter, irrespective of the socio-economic impact. Such sinks or hotspots may occur close to a source or at a considerable distance.

Key consideration in survey design is the magnitude of change one wishes or is able to detect. The smaller the magnitude of detection, the more comprehensive the monitoring programme needs to be. If the intention is to detect a specific percentage reduction, then monitoring programmes must be designed to enable statistical evaluations that are accurate and reliable. Limitations in sampling effort (i.e. reduced number of samples or spatial and temporal replication) may not produce sufficiently precise estimates to detect modest changes in abundance. Opportunistic sampling can provide a cost-effective approach, where litter monitoring is integrated into an existing monitoring programme (e.g. assessment of biodiversity, fish stocks evaluation by trawling), also analysing the sampling strategy to assess if this is suitable for litter monitoring too.

Replicate sampling provides a measure of the variability in litter abundance at each site. Replication may be in space (e.g. three closely spaced samples taken contemporaneously) or in time (e.g. daily sampling over one week at the same location). If temporal variation is significant it may be more appropriate to record a rolling-mean, for example a moving average over a five-year period to detect a trend over a decadal time scale. Knowledge of the dynamics of the compartment being investigated will help to account for, and minimise, spatial and temporal variations in marine litter abundance. The expected frequency of occurrence will determine the sampling design: volume, distance or area to be sampled to establish a reliable estimate of the abundance. In general, fewer larger items will need greater sampling effort than relatively numerous smaller particles.

Ocean circulation modelling can help to predict 'hotspots' and trends in marine litter abundance, and can be used in the sampling design. The reliability of model outputs will depend on a number of factors including the amount and quality of information on

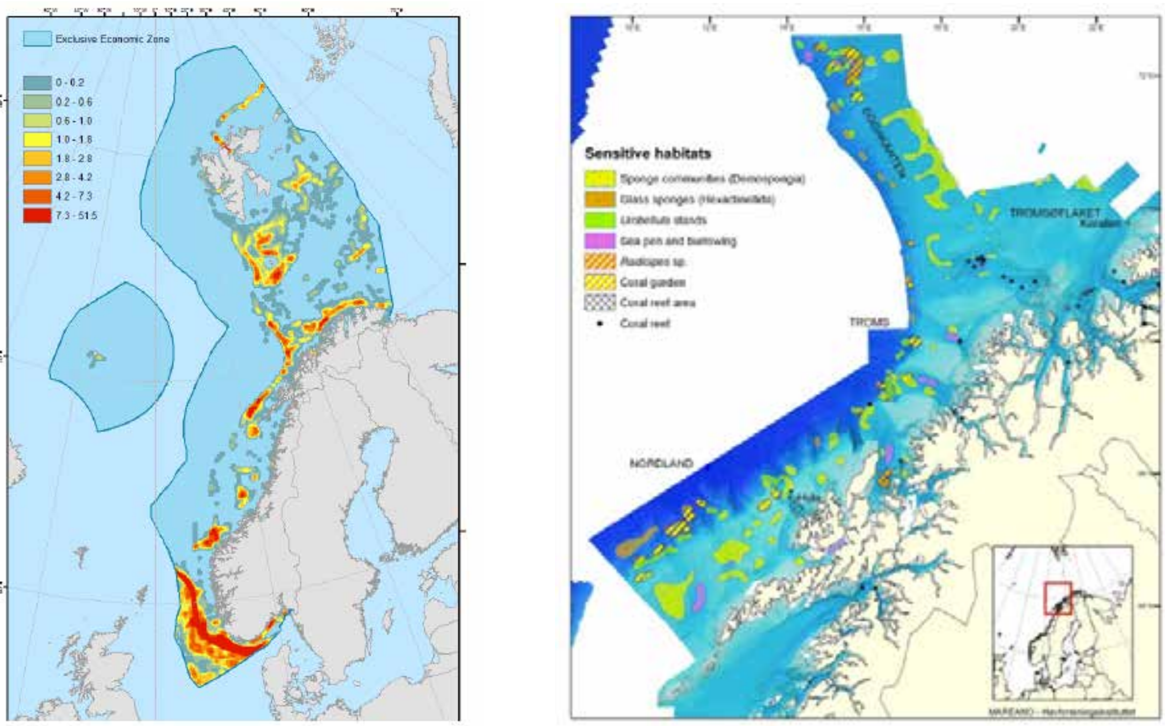


Figure 3.2 Distribution of fishing intensity and sensitive habits off the Norwegian coast - potential factors influencing the monitoring strategy (reproduced with permission from Institute Marine Research, Bergen).

sources, litter characteristics and oceanographic processes (Hardesty *et al*. 2016, 2017, NOAA 2016).

Microplastic contamination
Experience has shown that contamination is likely to occur at each stage of sampling, processing and characterising microplastics samples. Examples have been documented of finding paint chips from the towing vessel, fibres from the clothing of those carrying out the procedures and general contamination from airborne microplastics in the laboratory. It is important to recognise that this, if likely to occur, demands measures to minimise and make use of 'blank' samples to quantify any contamination that does occur. This topic is covered in more detail in section 8.2.

3.4.2 Rapid assessment surveys

Rapid assessment surveys may be used to provide an initial 'snap-shot' of the distribution and abundance of marine litter. They have been used to assess the impact of catastrophic natural events, such as the aftermath of tsunamis and typhoons, and to provide a basis for the development of a monitoring programme. Such surveys can produce a, qualitative or semi-quantitative estimate of litter abundance and composition, sufficient to direct further recovery operations or monitoring design. One relatively quick and low-cost method is based on the Biodiversity Rapid Assessment Programme, RAP[22]. Other examples include the Coastal Scenic Quality (Ergin *et al*. 2004), grading of surface litter based on their characteristics and abundances (EA/NALG 2000), Beach Scenery Index (Williams and Micallef 2009), Visual Scoring Indicator (Korea Marine Litter Institute[23]), the clean-coast index (Alkalay *et al*. 2007) and the Marine Litter Pollution Index (Scott Wilson, 6IMDC[24]). (Rangel-Buitrago *et al*. 2018) trialled the first three of these on a set of beaches in Colombia and derived composite scores for each site, but there is a need to assess consistency among approaches, and repeatability among observers. Rapid assessments may also make use of information provided by citizen science initiatives, such as the *Monitoring Toolbox* provided by NOAA as part of their Marine Debris Monitoring and Assessment Project (MDMAP)[25].

The development of image capture using satellite (Mace 2012, Moy *et al*. 2018, Lebreton *et al*. 2018) and aerial photography (Lebreton *et al*. 2018) has proved to be very useful for rapid assessments of larger litter items, allowing coverage across large spatial scales. Innovative approaches here include using coupled balloon-assisted photos with *in situ* mass measurements (Nakashima *et al*. 2011), ortho-photographs from planes (Moy *et al*. 2018), and several initiatives using drones (Deidun *et al*. 2018). There are several projects working to develop machine-learning algorithms to identify plastic items remote imagery (Acuña-Ruz *et al*. 2018). Aerial approaches are particularly useful for detecting litter in dense vegetation (e.g. reed beds), for non-destructive observations in sensitive habitats (e.g. salt marshes) and for remote or inaccessible coastlines.

Several examples of rapid assessment surveys are provided as case studies in Chapter 4.

3.4.3 Monitoring litter from fisheries and aquaculture (ALDFG)

The term ALDFG covers a wide range of fisheries-related materials, including fragments of nets and lines, floats, ropes, pots, fish boxes and nets. Some of these items will be accounted for in routine monitoring operations of the shoreline. In other cases different methods may be required, especially if the intention is to locate and recover ALDFG that is ghost fishing. Simultaneous location and removal operations can be successful if managers have a precise knowledge of where the gear is located or confidence that concentrations of lost gear occur in a general area. Some advanced methods, such as side-scan and sector-scanning sonar, are under development and may assist in initial assessments of locations and concentrations of lost gear to inform and guide subsequent monitoring and removal operations (Morrison and Murphy 2009, Sullivan *et al*. 2018). Seafloor litter protocols based on imagery (diving and remote imagery) appear more efficient than trawling or grapnels in the collection of more detailed information on interactions between fishing gear and marine organisms, such as ghost fishing and entanglement (Galgani *et al*. 2018, Buhl-Mortensen and Buhl-Mortensen 2017).

The mandate of some institutions /organizations already includes monitoring and/or controlling ALDFG and ghost fishing (FAO 2016), but there is a need to harmonize dedicated data collection protocols where they are in place, and to fill gaps for those lacking procedures to collect this information. Standardizing data fields and database formats will facilitate comparisons between regions, enabling the pooling of data necessary to support large spatial scale analyses within and across regions. Obtaining accurate and regular information on ALDFG can support estimates of ghost fishing mortality and the efficiency of reduction measures. Reporting systems on ALDFG can contribute to reducing the amount of ALDFG in the water and thus reduce ghost fishing if implemented in combination with a derelict gear retrieval programme (Gilman 2015), where retrieval responses ideally are conducted as close to the time of loss as possible to maximize the likelihood of finding and then removing the lost gear (FAO 2016). For all approaches, the logs/reporting sheets generally include the categorization of fishing related items to enable a better identification of items, their sources and their impacts. The Global Ghost Gear Initiative (GGGI) was launched in 2015 as a global

22 https://www.conservation.org/publications/Documents/CI_Biodiversity-Handbook.pdf
23 http://internationalmarinedebrisconference.org/index.php/opportunities-considerations-and-challenges-in-debris-monitoring-within-coastal-environments/
24 http://internationalmarinedebrisconference.org/index.php/towards-a-global-monitoring-plan-for-the-world-oceans/
25 https://marinedebris.noaa.gov/research/monitoring-toolbox

collective alliance, with the overall objective of reducing the occurrence and impact of ALDFG. The website is an excellent source of information about the occurrence of ALDFG and efforts to mitigate its impact[26].

3.4.4 Biological and ethical considerations

Biological indicators can provide information regarding the overall state of the environment and the interaction of litter with biota, which has the potential to cause harm. The selection of a suitable indicator depends on the distribution, sensitivity and movements (if relevant) of the species, knowledge of its biology and mechanisms of impact. Selection criteria are described in more detail in Chapter 7. Biological indicators may be region-specific, due to a limited distribution range, although different species in other areas may have similar biological traits, enabling a comparison between sites on a larger scale. Migratory species or species with a broad range and high mobility will provide information on larger spatial scales (depending on the retention period of the litter in the gut). The inclusion of ancillary data, such as age, size or development stage, can provide a clearer indication of the vulnerability of the species. Thus, categorizing litter and the choice of an indicator species will differ according to the size of the litter in which one is interested.

Opportunistic analysis of dead animals can provide useful data for monitoring population trends over time, representative of a specific sub-region. In these conditions, the monitoring modes must be adapted (duration, assessment of trends) and considered for long term monitoring (e.g. decades). Moreover, the conservation status of a species must be considered before inclusion in any monitoring programme that would require destructive sampling. Interventions on living or dead specimens, such as autopsies of stranded animals, must conform to national regulatory provisions. More details on the challenges of using biological indicators are presented at Chapter 7.

3.4.5 Programme set up and sustainability

Monitoring and assessment programmes ideally should have a formal structure and mandate. If monitoring programmes are established as a matter of public policy it is more likely that they will be supported in the longer term, with appropriate institutional and financial arrangements. Monitoring may be conducted by government officials, NGOs, universities and even individuals. It is important to acknowledge the role of non-governmental organisations and individuals in providing information about the distribution and impact of marine litter, and helping to generate public awareness. This can help to gain political support as well as provide useful input into the design of the formal programme.

The institutional arrangements will define the lead organisation as well as the collaborating institutions. The creation of a coordinating committee may be helpful to aid collaboration among the various levels of governance (e.g. regional, national, state/province and municipal) and other partners (e.g. NGOs, citizens' group, academic institutions). These arrangements can cover the provision of monitoring guidelines, examples of best practice, shared facilities (e.g. boats, field equipment, laboratories, analytical equipment), data collection, data sharing and storage, communication and outreach.

One approach to make best use of limited resources is to take advantage of other studies and programmes where litter monitoring can be integrated. For example, regular marine litter monitoring of the seafloor has been incorporated in the International Bottom Trawl Surveys, undertaken for fish stock assessment purposes in the Northeast Atlantic, under the coordination of ICES[27]. The surveys use an agreed protocol to ensure consistency (Chapter 6). Another example is the regular collection of marine debris data by fishery observers on board vessels of the Hawai'i-based pelagic long-line fishery in the North Pacific. This is fishery-dependent sampling. Nine years of data have been analysed to date. The engagement of citizens can be a useful strategy both to assist in data collection (e.g. reporting of stranded or entangled animals, taking part in shoreline clean ups), to raise awareness and take action (e.g. cleaning up the shoreline – section 3.4).

3.5 The role of Citizen science

3.5.1 Basic principles

There is a growing recognition that members of the public represent a very important resource for finding out more about the environment, in their role as citizen scientists. This was acknowledged in the identification of potential partners for developing the SDG 14.1.1 sub-indicators (Table 3.3). The potential of citizen scientists is well summed up in a statement attributed to to The EU-funded programme Doing It Together Science (DITOs)[28]. The programme, involving nine European countries, was initiated in recognition that:

> ***'Citizen science empowers citizens in exploring, measuring and experimenting with the world around them can play a valuable role Citizens have a major role to play in addressing the challenges to a sustainable future. It is by 'doing science together' that we combine our resources and expertise to raise awareness, build capacity, and innovative lasting solutions grounded in society.'***

There is a long tradition of citizen science volunteers in marine litter research (Hidalgo-Ruz and Thiel 2015, Zettler *et al.* 2017). Most citizen science studies have been conducted on sandy beaches given their accessibility and interest to the general public. Citizen scientists participate in a wide range

26 https://www.ghostgear.org/about-us

27 https://ocean.ices.dk/Project/IBTS/

28 http://www.togetherscience.eu/about

of activities, ranging from the reporting of incidental findings to collection of specific samples with some active participation in analysis/identification, data evaluation and publication of results (Figure 3.4).

Many of the common sampling protocols can benefit from the participation of motivated and well-trained citizen scientists. The use of mobile phone applications can improve the output, as it provides a harmonised approach and a ready data framework. Furthermore, the use of the collected data is facilitated when being submitted to a dedicated project/initiative. A good example of this approach is the 'Ghost Gear Reporter App' developed under the Global Ghost Gear Initiative[29]. Depending on the complexity of sampling programmes, volunteers may autonomously conduct surveys, or they can support professional scientists in their sampling efforts. However, quality control and assurance is important for comparability between observers. Interested volunteers should participate in existing programmes within their regions where possible, or extend existing citizen science protocols to their local beaches (section 4.6). Given the complex habitats and inherent difficulties with marine litter sampling in some habitats, there is an advantage if volunteers operate under the supervision of professional scientists.

3.5.2 Types of project

Samples or data gathered by citizen science projects can include:

(i) observational data of litter impacts,

(ii) collection of specific litter items,

(iii) bulk estimates of gross amounts of litter,

(iv) frequency data on litter types, and

(v) quantitative data on litter densities (Figure 3.5).

For example, volunteers can report on incidental observations of stranded organisms, observations that would be prohibitively expensive if carried out as an institutional programme e.g. (van Franeker *et al.* 2017). Participants in the International Pellet Watch Program[30] carefully sample plastic pellets on the beach, place these in aluminium foil envelopes, and send them for analysis at the Laboratory of Organic Geochemistry in the Tokyo University of Agriculture and Technology, where they are analysed by environmental chemists. In other projects citizen scientists may become more involved, helping in the analysis of samples; for example, recording bite-marks of fishes on plastics or the occurrence of plastics in a seabird diet. Some projects initiatives help to identify litter hotspots, and direct clean-up

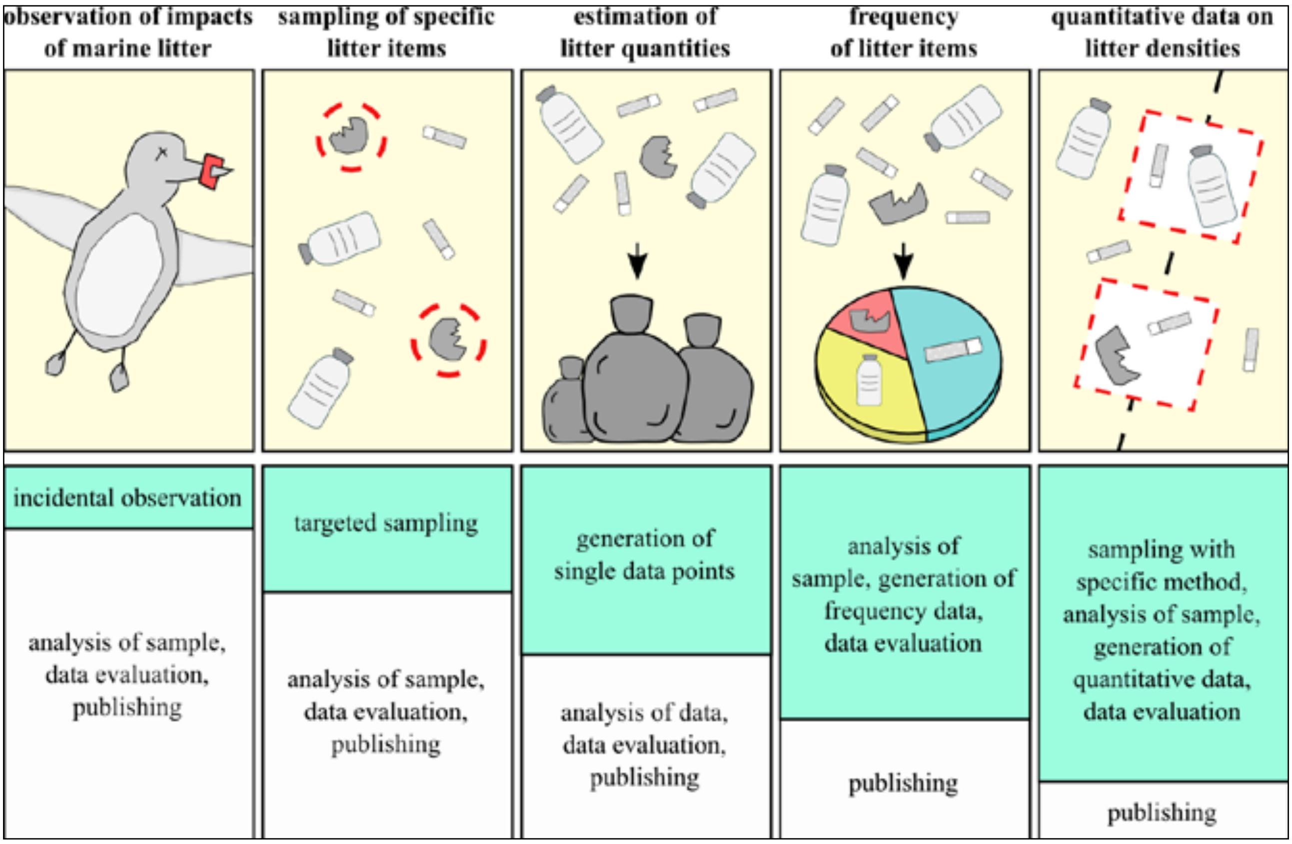


Figure 3.4 Levels of participation of citizen scientists in marine litter research. Top panels illustrate methods and type of data gathered by citizen scientists. Bottom panels show the degree of involvement by citizen scientists (turquoise area) in the scientific process (entire box). Figure authors: Tim Kiessling and Martin Thiel (Creative Commons BY-NC 4.0 licence).

29 https://globalghostgearportal.net/dp/gra.php

30 http://www.pelletwatch.org/

activities (e.g. Global Alert Platform[31]). Many litter projects generate frequency data, typical for clean-up activities where volunteers clean all marine litter from the beach and then categorize the different litter items (e.g. NOAA Marine Debris Program[32]). Clean-up projects may also generate bulk estimates of litter amounts at a particular site (e.g. Ocean Conservancy International Coastal Cleanup[33]). Some citizen science projects produce quantitative data on litter (total litter items per unit area (m^{-2}) or per unit length (m^{-1}) of a shoreline transect). In these projects, professional scientists typically accompany the volunteer participants to ensure data quality and comparability. Additional examples of projects are given for each compartment at specific chapters.

Goals of citizen science projects

Many citizen science projects have a strong component of public engagement in the scientific and policy-making process. Within the context of marine litter monitoring it is fundamental to identify the scientific objective of a study that utilizes volunteer participation, as this will help to determine whether the use of citizen volunteers is advantageous or could complicate the achievement of the scientific goals of the project. In terms of a monitoring programme, the objectives may be related to a policy relevant goal and thus increase the stimulus to citizens.

3.5.3 Overall recommendations and cost-benefits

The cost-effectiveness of citizen science programs depends on a number of factors. Although potentially less costly than other approaches, citizen science still requires financing. A recent study has explored different models for financing citizen science actions (DITOs Consortium 2018). A rigorous citizen science programme requires intensive coordination and communication with the volunteer participants. The resulting data must be controlled, reviewed and validated by experts in order to remove mistakes and spot unlikely results from mistakes or misunderstandings in data acquisition.

Regular contact and training are likely to be required. Materials that provide background information and the rationale for any sampling need to be provided. Costs will increase if these have to be produced in hard copy and sent to volunteers, especially when communities lack reliable digital communication and availability of printing facilities. These and other costs must be balanced with the potential benefits. Examples of training material available for digital download by citizens can be found at NOAA Marine Debris Program[34], the Ocean Conservancy International Coastal Cleanup[35] and the Global Ghost Gear Initiative[36]. Citizen scientists can fulfil certain basic tasks but complex samples or data collection may require substantial expertise and training and/or expensive equipment (van der Velde *et al.* 2017).

Box 3.2: Guidelines for successful citizen science programmes

- ❑ Recruit actively
  - Presentation
  - Social media
- ❑ Prepare simple step-by-step instructions with images and video
  - Test them yourself
  - Ask several friends (who are not experts) to test them
  - Modify instructions accordingly
- ❑ Make it as easy as possible for the volunteers
  - Laminated and electronic versions of instructions
  - Complete sampling kits with pre-paid shipping
  - Confirm understanding BEFORE the sampling event
  - Easy to use data sheets and/or electronic data uploads
- ❑ Provide feedback to maintain motivation!
- ❑ Explanation of results
- ❑ Visual aids to show volunteer their contributions

(from Zettler et al. 2017)

31 http://www.globalalert.org/
32 https://marinedebris.noaa.gov/research/monitoring-toolbox
33 https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/start-a-cleanup/
34 https://marinedebris.noaa.gov/research/monitoring-toolbox
35 https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/start-a-cleanup/
36 https://globalghostgearportal.net/dp/index.php

Under those circumstances, it may be more cost-efficient to have small and well-trained research teams that collect and/or process samples and data. However, where citizen scientists frequently visit areas that are difficult or expensive to visit by professional scientists, active participation of volunteers can benefit marine litter monitoring programmes (Hidalgo-Ruz and Thiel 2015).

It is important to keep several essential requirements in mind when working with citizen scientists, which can be summarised (Box 3.2). This can ensure that the data produced by the citizens are reliable and useful, and will encourage the citizen scientist to remain committed. The focus here is on the participation of citizen scientists in marine litter monitoring for the purpose of generation of scientific information. However, the involvement of the wider general public in research can generate additional outcomes, including awareness raising and increasing social consciousness, custodianship of local environment and pressure on policy makers to take action (Figure 3.5) (Thiel *et al.* 2018). The potential of citizen scientists to contribute to monitoring of marine litter in the four main environmental compartments is explored further in the appropriate sections.

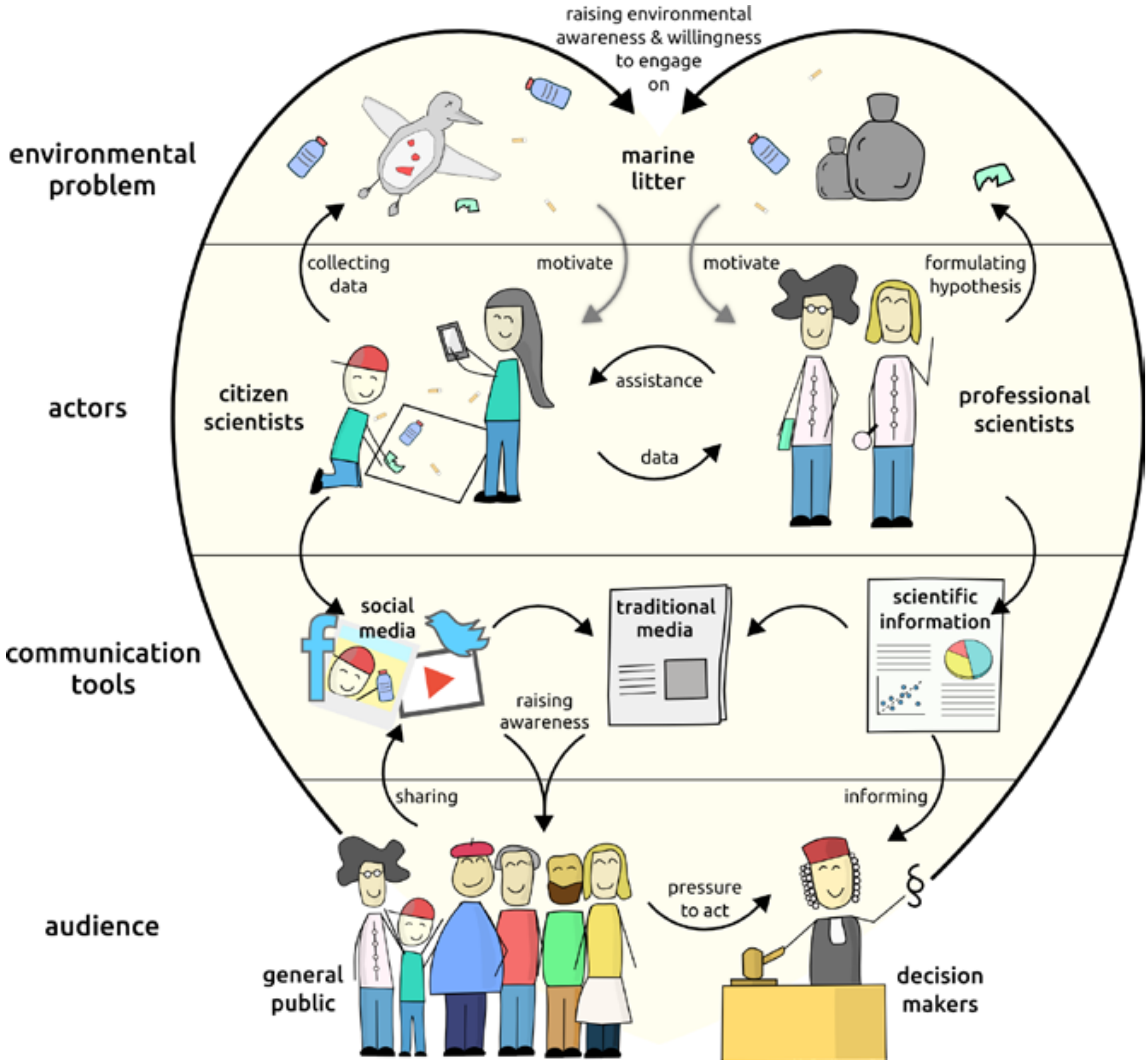


Figure 3.5 The important role of citizen scientists in raising awareness and advancing active engagement on the marine litter problem: Citizen scientists contribute valuable scientific data to professional scientists and may influence the general public by reporting about their experience, for example in the form of social media. This, in turn, encourages the general public and eventually decision makers to act on the environmental problem in question. Figure authors: Tim Kiessling and Martin Thiel (Creative Commons BY-NC 4.0 licence).

4 MONITORING METHODS FOR SHORELINES

4.1 Description and relevance of shoreline compartment

The shoreline is the interface between land and sea, and is an important compartment for monitoring because it is:

(i) where marine litter is present in high quantities;

(ii) closer to land-based sources; and,

(iii) most accessible. As a result, shorelines typically are the first environmental compartment considered for quantifying marine litter.

This chapter describes the tools to survey and monitor marine litter in the intertidal and associated zones (e.g. backshore, saltmarsh, dunes). The seafloor, or sub-littoral zone, is considered in Chapter 6.

Several approaches can be used to survey and monitor shoreline litter; this chapter summarises the methods that should best deliver the key information needed from a policy perspective, with a view to guiding the use of scarce resources to track amounts and types of marine litter, and assess the efficacy of mitigation measures. Sampling strategies also need to take account of the wide variety of shoreline environments (Figure 4.1). This chapter recommends strategies and methods to support a multi-level survey and monitoring programme on shoreline litter. However, not all plastic size categories are feasible or recommended to be sampled on all shoreline types.

Shorelines tend to be highly dynamic due to a combination of oceanographic (tides, waves and currents) and meteorological (winds and rainfall) processes. In addition to the underlying geology, this influences the overall nature of the shoreline (e.g. mud flats, sand, cobbles, boulders, wave-cut platform, width, slope) and time-dependent changes in composition. This will influence the distribution, abundance and types of marine litter that occur, and its variability in space and time. The zone immediately inland of the intertidal zone is called the backshore. This may be rocky, consist of mobile dunes or engineered structures, be colonised by stabilising vegetation or be backed by terrestrial ecosystems. Onshore and offshore winds will tend to blow floating litter onto and away from the shoreline, while alongshore winds can produce pronounced onshore or offshore currents by a process known as Ekman transport (Figure 4.2).

Figure 4.1. Examples of different types of shoreline, with evidence of marine litter: **(a)** coral boulders, Indian Ocean, Seychelles UNESCO World Heritage Marine Site, ©Seychelles Islands Foundation, **(b)** cobble beach, North Sea coast Suffolk UK, ©Peter Kershaw, **(c)** sandy beach, North Sea coast Netherlands ©Peter Kershaw, **(d)** high-energy wave-cut platform, East Pacific coast Vancouver Island British Columbia, ©Peter Kershaw, **(e)** dynamic sandy beach with remains of protective sea defences, North Sea coast Happisbergh Norfolk UK, ©Peter Kershaw, **(f)** lower-energy rocky shore in sea loch (fjord), Northeast Atlantic coast, Ireland, ©IFREMER.

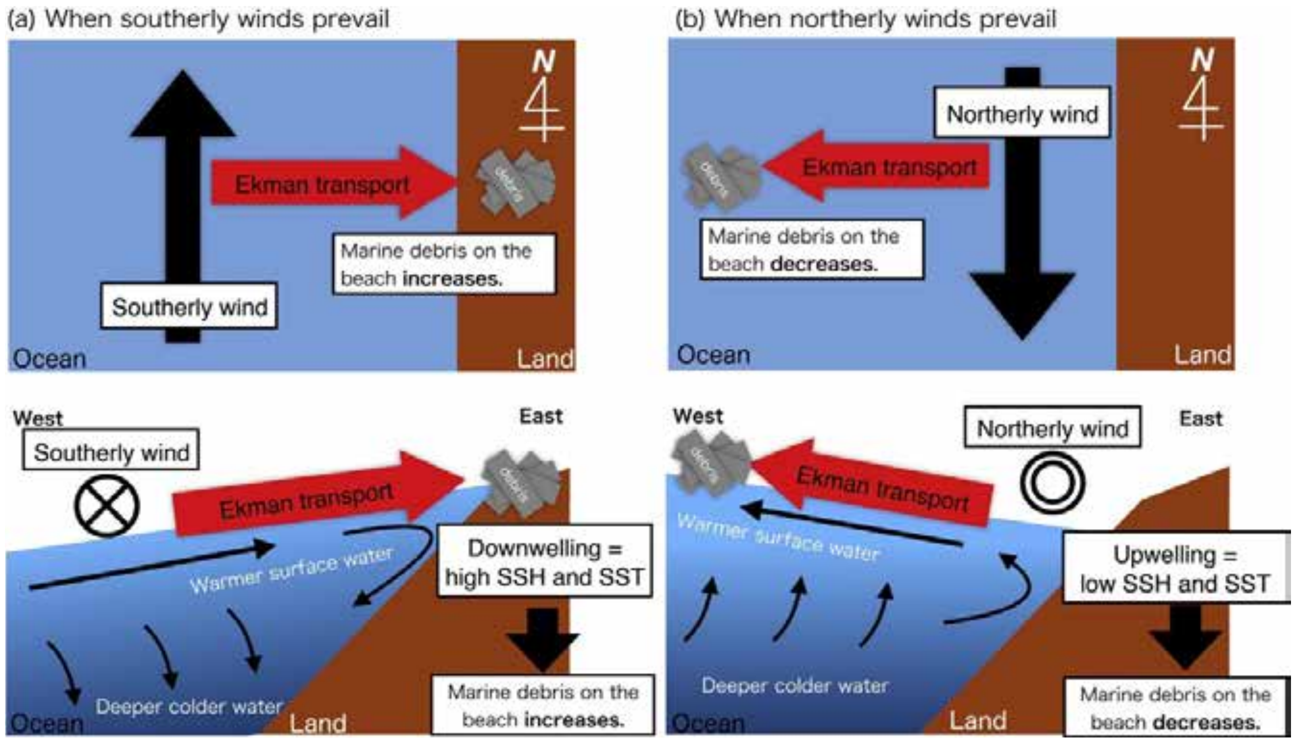


Figure 4.2 Movement of marine litter onshore or offshore is influenced by Ekman transport, generated by winds running parallel to the coast due to the Coriolis effect; SSH = sea surface height, SST = sea surface temperature. The example displayed is for a north-south trending coastline in the northern hemisphere, such as the western seaboard in North America from California to British Columbia, with the Ekman transport in a clockwise direction. In the southern hemisphere the transport is counter-clockwise. Image reproduced under a Creative Commons Licence (© Kako *et al.* 2018).

Figure 4.3 Short-term changes in beach morphology captured by a fixed-point webcam, following a storm event. Image reproduced under a Creative Commons Licence © Kako *et al.* (2018).

The slope of the shoreline will affect the retention of litter, with more gently sloping shorelines expected to favour accumulation. Beach profiles can be altered dramatically by storms, potentially burying or uncovering litter (Figure 4.3). This combination of physical processes means that the abundance of litter may be expected to vary on time scales of hours, days, weeks, months and years. In addition, a combination of exposure to UV irradiation and physical abrasion will result in the weathering and fragmentation of plastics exposed on the shoreline, resulting in an overall decrease in particle size over time. However, shorelines offer a cost-effective approach to monitoring trends, despite their dynamic nature, provided the system variability is taken into account during the programme design.

Human activities also influence shoreline litter dynamics. Proximity to sources affects the amount of litter washing ashore. Visitors to the shoreline contribute directly to litter loads, and this may be difficult to separate from litter washing ashore. Seasonal variation in visitor numbers can thus influence temporal patterns in shoreline litter. People also modify the amounts and types of litter by individual beach-combing and taking part in organised clean-ups (Figure. 4.4). In some regions there has been a gradual increase in beach cleaning efforts. (Ryan and Swanepoel 1996). These efforts are to be applauded but they will add an additional level of uncertainty in establishing longer-term trends in the overall abundance of marine litter (Ryan *et al.* 2009, Opfer *et al.* 2012). A schematic of the morphology and dynamics of a typical sandy

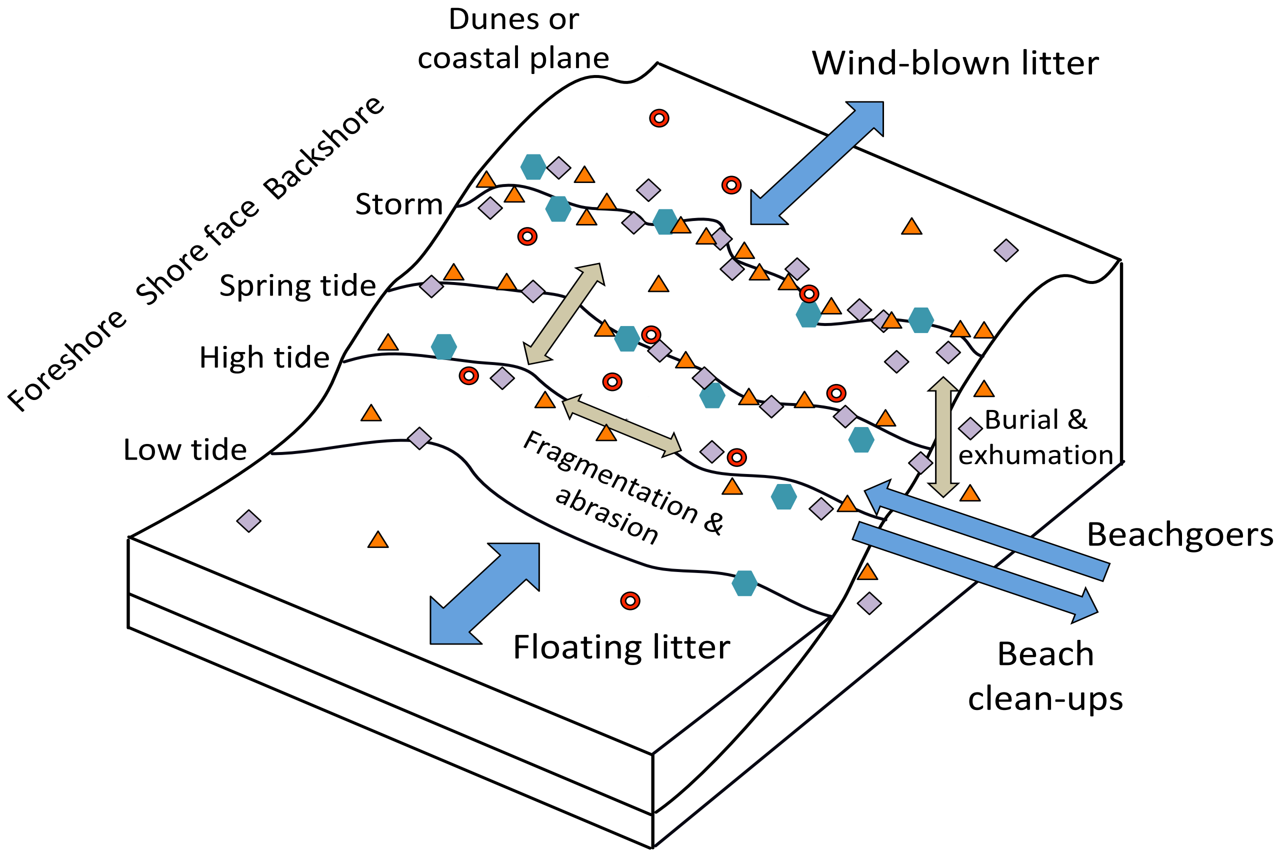


Figure 4.4 Examples of factors affecting the dynamics of litter on a sandy beach.

beach is presented in Figure 4.4, showing the likely distribution of marine litter.

Most litter typically washes ashore, but beach visitors and wind-blown litter from the land also contribute litter inputs (blue arrows in Figure 4.4). Beach litter (green circles) tends to accumulate in a series of strand-lines linked to wave, tidal and storm cycles. Within the beach, litter is moved by the wind, tides and waves (grey arrows), which may carry litter back into the sea, onto the backshore, dune or coastal plain where it may become trapped by vegetation. Litter can be transported along the shore by wind, wave and current action. In addition it can be periodically buried (darker circles) and re-exposed, especially by wind events. Over the long term, items exposed to UV radiation become brittle and break down into smaller fragments, aided by mechanical abrasion. Beach cleaning (red arrows) selectively removes larger litter items from beaches.

When designing marine litter surveys it is necessary to differentiate between standing-stock surveys, where the total load of litter is assessed during a one-off count, and the assessment of accumulation and loading rates, during regularly repeated surveys of the same stretch of beach with initial and subsequent removal of litter (JRC 2013). Beach cleaning, by individual members of the public or organised groups, has become more popular, with growing public awareness of the marine litter problem. This action is to be applauded, while recognising that it may affect the apparent stranding rates in monitoring surveys.

Much of what we know about marine litter and its dynamics on shorelines comes from studies of sandy beaches. Other shoreline types (cobble and boulder beaches, rocky shores, salt marshes and mangroves) have different litter dynamics linked to their structural characteristics and environmental setting. We first describe how to sample litter on sandy beaches, then discuss how these approaches need to be modified for other shoreline types.

4.2 Rapid assessment surveys

4.2.1 Assessing the impact of natural disasters

Rapid assessment surveys can be very useful in two circumstances:

(i) in the event of a major natural disaster, such as a tsunami or typhoon;

(ii) to provide a baseline to inform the development of a routine monitoring programme; and,

(iii) to identify accumulation 'hot-spots' for possible intervention. The approaches available vary in sophistication and cost.

Aerial surveys can be very helpful for carrying out rapid assessments of litter distribution following major natural events, such as major storms (typhoons, hurricanes) and tsunamis, or following accidents (e.g. ship capsize or major loss of shipping containers). Once images are captured they can be analysed visually using image processing and spatial analysis to enhance the litter component (Kataoka *et al.* 2018) (Figure 4.5). Some form of ground-truthing may be required to verify the nature of the material captured in the image, particularly when information about the origin is required. Aerial surveys using conventional aircraft are of limited use for routine monitoring due the logistical and resource constraints. However, developments in drone technology and artificial machine learning (AI) offer a possible alternative approach (see section 4.6 on citizen science).

Case Study: The Tōhoku Earthquake and ADRIFT project

The most comprehensive use of aerial surveys to assess the distribution of marine litter was implemented following the devastating tsunami caused by the Great Japan Earthquake (Tōhoku Earthquake) in 2011. Over 15,000 people lost their lives in the disaster. An incidental consequence was the rapid introduction of approximately 5 million tonnes of debris into the coastal waters of eastern Japan. Tsunami debris started washing ashore on the western seaboard of North America within one year of the earthquake. This led to the development of a major three-nation study (Japan, Canada and USA), overseen by the Ministry of Environment of Japan and carried out in conjunction with the North Pacific Marine Science Organization (PICES). It was called ADRIFT (Assessing the Debris-Related Impact of Tsunami). The final scientific report of the study was completed in 2017[37], and there have been a series of individual peer-reviewed publications and journal special issues, accessible though the PICES ADRIFT webpage[38]. Additional products include on-line libraries of aerial surveys of tsunami debris washed ashore along the shoreline of British Columbia[39] and the Hawaiian Islands[40] (Figures 4.5, 4.6 and 4.7).

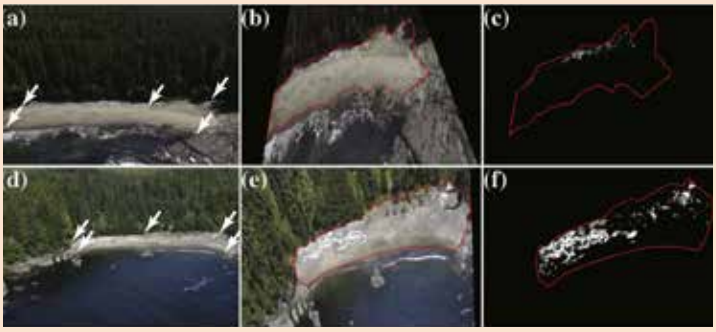


Figure 4.5 Vancouver Island. Transformation of oblique aerial photographs from two sites on Vancouver Island, British Columbia (a-c and d-f) by georeferencing, followed by extraction of pixels representing marine debris (white pixels), images from Kataoka *et al.* (2018).

Figure 4.6 Aerial survey of tsunami debris from the 2011 Tōhoku Earthquake along the Hawaiian coast; top – distribution map, middle- boat hulls identified from the air and subject to ground-truthing to confirm whether associated with the tsunami, bottom - object identified from careful visual analysis of the image; Creative Commons License, (Moy *et al.* 2018).

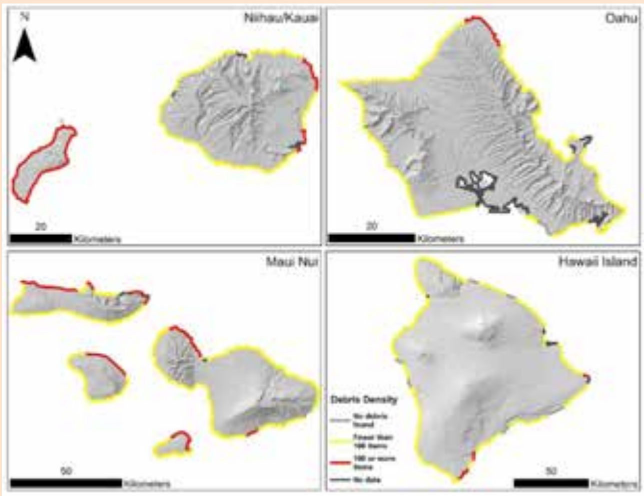


Figure 4.7 Overview of marine litter density from aerial surveys of the Hawaiian archipelago

37 https://meetings.pices.int/publications/projects/ADRIFT/funded-projects/08_Hansen_Year3_report_rr.pdf
38 https://meetings.pices.int/projects/ADRIFT
39 https://www.arcgis.com/home/webmap/viewer.html?webmap=3c5fb88b7f3f4d97974615acad67af3e
40 https://doi.org/10.1016/j.marpolbul.2017.11.045

4.2.2 Application for designing a monitoring programme

The rapid identification of accumulation areas, to better inform the design of a monitoring programme, has not been systematically considered until recently. Knowledge about where litter accumulates not only aids in identifying representative sites but also where cleaning effort should be concentrated to support reduction measures. This approach is feasible for relatively small areas (e.g. small – medium sized islands, areas on conservation concern), mapping the distribution of sites where litter tends to accumulate.

Case study: mapping of accumulation areas on the coastline of Corsica

Within the project AMARE[41], this strategy was adopted for some Mediterranean Marine Protected Areas (MPAs) using a simple protocol to locate hotspots. This provided a scientific basis for further detailed monitoring using more sophisticated protocols or for better location of coastal section to clean, a point not always considered when implementing monitoring protocols.

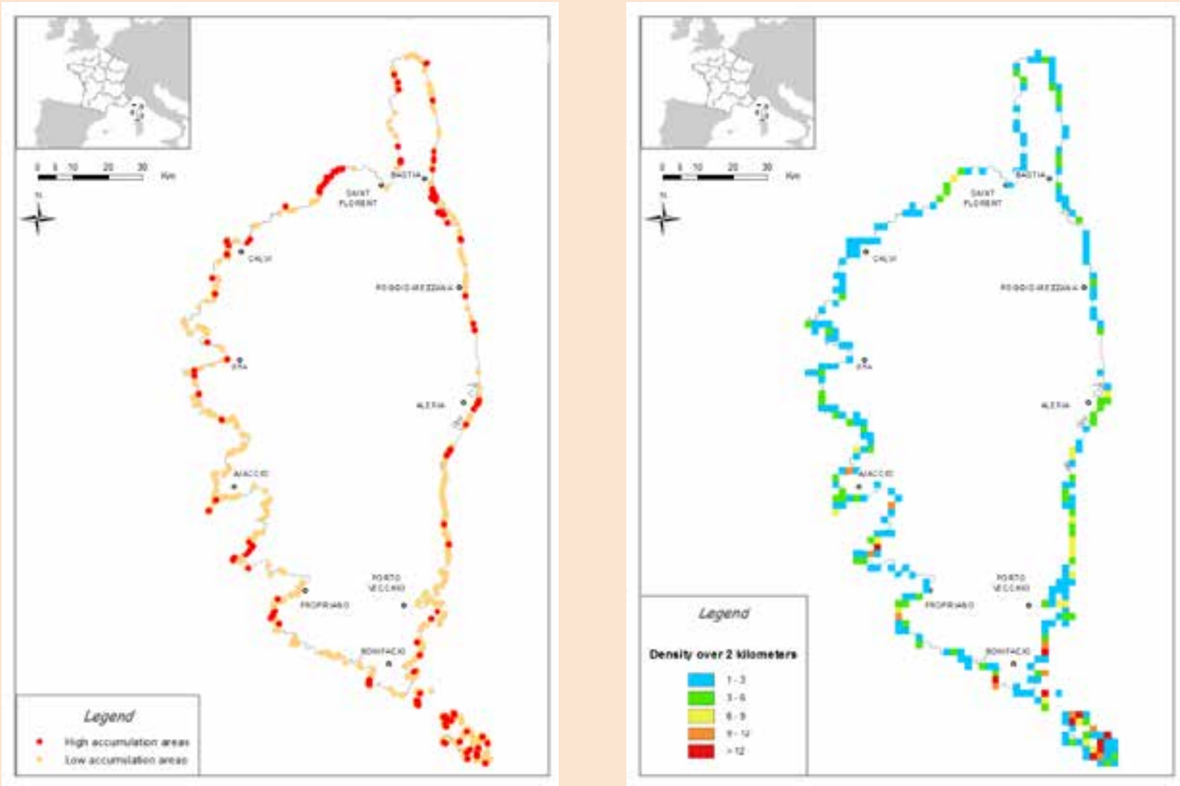


Figure 4.8 Accumulation areas of stranded litter along the coastline of Corsica, France, and the northern Sardinian islands, Italy. Data were obtained from small boats (5-6 m) operating at low speed (1-12 knots) from 20-100m from shore. Positions of accumulation areas were recorded using GPS. The number of accumulation areas per 2 km of coastline was reported to provide consistent results to support both the location of monitoring sites and associated modelling predictions. **(A)** Low (2-10 litter items/site yellow dots) or High (> 10 litter items/site, red dots) accumulation zones. **(B)** GIS (*.shp) files mapping the number of areas of beached high debris load on 2 km stretches of coastline.

As an example, surveys performed in 2016/2017 along the coast of Corsica, a large French island with > 1,000 km of coastline, mapped 'hotspots' of stranded litter (Figure 4.8). The presence of litter was recorded for low accumulation zones (2-10 litter items/site, usually a 5-30 m distance) and high accumulation zones (> than 10 litter items/site). Areas with evidence of regular cleaning procedures based on visual evidence, questionnaires and information taken from MPA managers, were indicated as such.

The approach is not based on a detailed assessment of debris type, but rather provides initial information on sites of interest. The fate of most items is unknown and accumulations occur at some locations as determined by several factors. These include currents and circulation patterns, coastline structure, weather conditions, associated beach morphodynamics, local land-based sources, abundance of litter in adjacent coastal waters and, in some cases, clean-up efforts. The amounts observed thus reflect the long-term balance between inputs (both local, land-based sources and stranding) and removal (through export, burial, degradation and clean-ups). Apart from episodic storms events that may affect the number of items rather than the location of stranding, most of the factors affecting litter inputs and removal are fairly constant and then define the sites where the litter ends up.

41 AMARE – Actions for Marine Protected Areas https://amare.interreg-med.eu

4.3 Routine monitoring of the shoreline

4.3.1 Establishing a baseline

At the start of any monitoring operations it is important to establish a baseline. The results of subsequent surveys can be compared with the baseline to see whether there has been a change in quantities of litter on the shoreline, perhaps as the result of policy interventions. The baseline can be established from a single survey. However, there is inherent variability in the distribution and abundance of litter on shorelines, due to the dynamic nature of the environment. It can be more helpful to combine the results of a number of repeated surveys (monthly, quarterly or annually) to provide a mean value and range (over a specified time period) that takes account of shorter-term fluctuations, if resources allow.

The initial survey of the distribution and abundance of litter on the shoreline provides an estimate of the 'standing stock' of litter. It is an efficient way to assess large-scale spatial patterns in the distribution and composition of marine litter. Such surveys measure the amount and composition of marine litter at a shoreline within a predetermined length or area of shoreline (Ryan *et al.* 2009, Lippiatt *et al.* 2013). This initial survey, assuming the litter encountered is collected and removed, is likely to produce much higher litter abundances than any subsequent surveys.

4.3.2 Accumulation surveys

Regular repeated surveys of the same stretch of shoreline, with initial and subsequent removal of litter, provide an estimate of the accumulation and loading rates (JRC 2013). They will reflect the balance between inputs (from land and sea) and removal (through export, burial, degradation, beach cleaning), depending on how frequently the surveys are carried out. For example, OSPAR carry out shorelines four times a year, to assess the long-term balance. More frequent surveys will provide information on what is arriving over that shorter time frame.

The basic aim of shoreline monitoring is record changes in the amount and/or composition of litter washing ashore over time can be used to infer changes in at-sea litter loads in adjacent coastal waters, as well as changes in littering by beach visitors. A common goal for marine litter monitoring surveys is to address specific policy-related questions, as described in Chapter 3. Typical questions might include:

- *'Is the total amount of marine litter on the shoreline increasing or decreasing?'*
- *'Has banning straws by local businesses made a difference to the number of straws found on beaches?'*
- *'Has there been a decrease in ALDFG as a result of improved waste reception facilities in local fishing ports?'*

The best way to answer such questions is to conduct accumulation surveys, which estimate the flux of litter onto the shoreline. Changes in the amount and/or composition of litter washing ashore over time can be used to infer changes in at-sea litter loads in adjacent coastal waters, as well as changes in littering by beach visitors.

Accumulation surveys require more effort and resources than a single baseline survey. There must be an initial clean-up that removes litter from the study site. It is effectively impossible to clean all meso- and micro-debris from a section of beach, and so accumulation studies are largely restricted to macro- and mega-litter. Even for macro-litter, the initial clean-up is a significant challenge. This is followed by a series of replicated surveys that collect all litter for counting and (ideally) weighing (see constraints on weighing above), giving the quantity of litter that has accumulated in the intervening period (e.g. month, quarter, year). The figure will reflect the balance between litter being deposited on the beach (stranded or littering by beach goers) and removed (washed or blown off, removed by beach cleaning). It should not be assumed that the accumulation rate will be constant between surveys. Unless a shoreline is closed to the public, or is very remote, it is best to assume that some form of beach cleaning may be taking place. Larger items such as bottles and bags may be removed preferentially during unsupervised clean-ups, leaving behind smaller items such as bottle caps, straws, cotton-bud sticks and cigarette butts (Ryan *et al.* 2009).

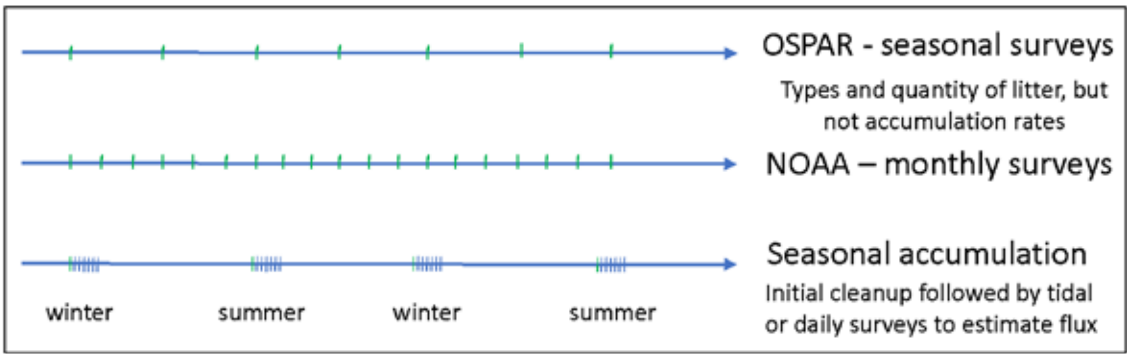


Figure 4.9 Examples of sampling intervals for repeated surveys to show the suggested regime of short bursts of daily or tidal-cycle litter accumulation measurements, repeated seasonally, in relation to other on-going monitoring regimes which are impacted by changes in beach cleaning effort.

Table 4.1 Advantages and disadvantages of different shoreline sampling strategies.

Purpose	Strategy	Advantages	Disadvantages
Baseline (macro- and mega-litter)	Single survey of standing stock of all macro- and mega-litter, with removal of litter	• Provides initial assessment of litter distribution and abundance • Relatively straightforward	• Cannot quantify temporal variability in standing stock
Baseline (meso-litter)	Single survey of standing stock of sub-sample of meso-litter	• Provides initial assessment of meso-litter distribution and abundance	• Cannot quantify temporal variability in standing stock • More time-consuming
Baseline (micro-litter)	Single survey of standing stock of sub-sample of micro-litter	• Provides initial assessment of micro-litter distribution and abundance	• Cannot quantify temporal variability in standing stock • More time-consuming
Accumulation survey	Repeated surveys over defined time period e.g. monthly, quarterly or annually	• Provides information on temporal trends, balanced over a defined period (inputs and outputs) • Takes account of inherent variability in litter abundance	• Depends on regular sampling and commitment of resources • Does not give the arrival rate
Accumulation survey	Rapid repeated surveys over defined time period e.g. daily for 5-10 days; repeated several times during the year (to account for seasonal factors)	• Provides information on the arrival rate per day per unit length of shoreline • Provides information on seasonal changes	• Requires significant commitment of personnel • Requires initial removal of large quantities of litter • Requires large number of replicates (e.g. to account for wind blown litter)

Accumulation studies provide information on the balance of litter on the shoreline (arrival – removal rates). If the arrival or deposition rate is required then much more frequent sampling is required, requiring a much greater input of resources. This is unlikely to be justified for routine purposes, rather to address a specific issue. For this purpose the approach is to carry out short bursts of daily accumulation sampling to assess changes in accumulation rate over time (Figure 4.9). These can be run for 5-10 days (the longer the better), preferably at least twice a year, to sample seasonal variation (e.g. linked to rainy and dry seasons). Ideally, litter should be divided into items in the intertidal and backshore zones, to try to differentiate marine inputs from littering by beach visitors (although littering can occur throughout, and stranded litter can blow onto the backshore within hours or even minutes of stranding). Of course, even sampling once a day does not preclude informal beach cleaning by beach goers. Some form of signage instructing beach goers that a study is taking place can be considered. The advantages and disadvantages of different sampling strategies are summarised in Table 4.1.

4.3.3 Monitoring macro- and macro-litter

The methods for monitoring macro- and mega-litter are relatively straightforward on most shorelines. Two challenges arise: estimating the total number of litter items and defining the upper limit of the shoreline. Most established programmes advocate recording all 'visible' litter items between the waterline and the backshore within a defined length of shoreline. The OSPAR protocol (OSPAR 2010) defines the sampling unit as a fixed section of beach covering the whole of the area between the water edge to the back of the beach (Figure 4.10), with a beach length of 100 m (for identifying all litter items). Formerly OSPAR included a 1000 m section, for identifying objects > 50 cm, but this has been discontinued. NOAA recommends conducting a number of 5 m wide transects perpendicular to the water's edge over a distance of 100 m of shore length (Figure 4.11). (Opfer *et al.* 2012) recommends recording items > 25 mm (macro litter, under the GESAMP definition). OSPAR (2010) and HELCOM (2018) both specify all items visible to the naked eye (> 5mm, i.e. meso-plastics and above). There are benefits in adhering to a standard length, such as 100m, as it enhances data comparability. Shorter transects can be sampled on highly contaminated beaches – the operational decision depends on sampling sufficient items to obtain a representative indication of litter abundance and composition. In these types of survey all litter items above a certain size are recorded.

The upper limit of the shoreline may be well defined by a natural or artificial solid barrier. However, often this is not the case and the upper limit will be determined by consideration of the extreme high-water spring tides, tidal surges and the influence of storms. Stranded litter may be obscured by seaweed or other natural materials. We recommend sampling at least two metres into the backshore vegetation, as this often acts as a litter accumulation area. Some frequent standing stock protocols (e.g. NOAA conducts them monthly) require litter to be left in situ, whereas others require litter to be collected and removed (e.g. OSPAR, quarterly sampling; NOAA accumulation surveys).

Whichever protocol is followed the key consideration is to be consistent (e.g. area, length, time, effort). The main source of variability between methods is likely to be the selection of the lower size limit.

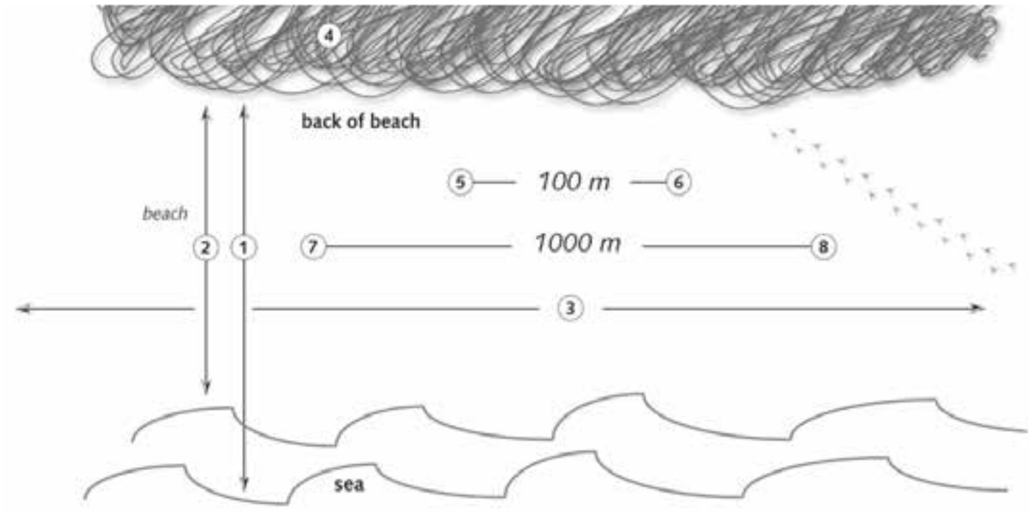


Figure 4.10 Extract from OSPAR marine litter monitoring guidelines data sheet – numbers refer to: 1 – distance from mean low water spring tide, 2 - distance from mean high water spring tide, 3 – total length of beach, 4 – description of zone beyond intertidal, 5 and 6 – GPS coordinates of 100 m sampling unit, 7 and 8 - GPS coordinates of 1000 m sampling unit (from OSPAR 2010). The 1000m transect has been discontinued.

Figure 4.11 NOAA protocol for shoreline monitoring. Shoreline section (100 m) displaying perpendicular transects from water's edge at low tide to the first barrier at the back of the shoreline section. Red circles indicate marked GPS coordinates. Shoreline width determines location and number of GPS coordinates. Figure not to scale. (from Lippiatt *et al.* 2013, images ©NOAA).

This variability can be reduced by taking account of smaller size items, using a different approach to estimate abundance by representative sub-sampling (sections 4.3.4 and 4.3.5).

4.3.4 Buried macro-plastics

Buried macro-litter is seldom sampled as part of routine monitoring. However, it can be sampled by sieving through a 10-20 mm sieve, taken from a trench along a transect. The sieve mesh should be slightly smaller than the lower limit of the macro-plastic size-range to increase the likelihood retaining irregularly-shaped macro-litter items (Filella 2015). Litter items are then easily sorted by hand from the retained material. The width of the transect is a trade-off between obtaining representative samples and the practicalities of sieving large volumes of sand. The depth of the vertical section will be determined both by practical considerations, such as the

Figure 4.12. Sampling buried macro-litter on a sandy beach, using a team of students to sieve the top 15 cm of sand from a 1-m wide transect running up the beach profile (see Figure 4.3). (©Peter Ryan).

stability of the deposits and availability of personnel (Figure 4.12), and by the dynamics of the sampling environment, such as the depth of wave mixing.

4.3.5 Meso-litter

For sampling meso-litter (5-25 mm) it is neither practical nor necessary to attempt to identify all items in the same way as for macro-litter. What is important is to adopt a consistent approach. For example, a 1 m square quadrat thrown at random along a transect perpendicular to the shoreline will provide a suitably representative sampling regime, with all the surface material within the quadrat being sieved through a 5 mm mesh stainless steel sieve (Figure 4.13). Moist sediment will need to be washed through either using a wash bottle or by careful agitation in a container of water. The sieve contents can then be examined and plastic items recovered using forceps.

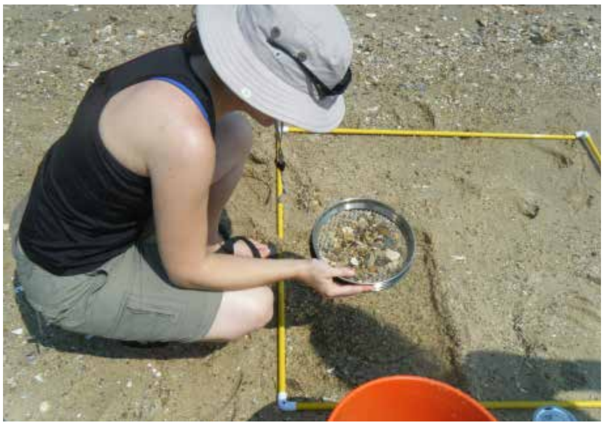


Figure 4.13 Sampling surficial beach sediments for meso-plastics, using a one metre square quadrat and a hand-held stainless steel sieve, Calvert Cliffs and Cove Point (© NOAA Marine Debris Program).

4.3.6 Micro-litter

Micro-litter can be sampled from the sediment surface in a similar manner to meso-litter by sieving, extending the range of sieve mesh sizes (e.g. < 5, < 2, < 1, < 0.5, < 0.25 mm). This can be useful when sampling for specific types of microplastics, such as resin pellets, but may be impractical for routine sampling in the field (Figure 4.14). The protocols for sampling microplastics in intertidal sediments are under development but guidance has been provided as part of the European MSFD programme (JRC 2013). This recommends the collection of at least two fractions: 1-5 mm and 0.02-1 mm). Separation of the 1-5 mm fraction can be achieved in the field, but additional fractionation is better carried out in a laboratory environment. It is recommended that five replicate samples, from the top 50 mm of sediment, be taken from the strandline, with each sample separated by 5 m.

Figure 4.14 Sampling surficial beach sediment to collect resin pellets for chemical analysis, using a coarse and a fine mesh sieve, 2014 near Busan, Rep. Korea (© Peter Kershaw).

4.3.7 Number vs. mass and other sampling considerations

The decision of whether to record the number of items or the mass of each item was introduced in Chapter 3 (section 3.3.1). Ideally, all litter items (micro, meso and macro) should be counted and weighed, given the contrasting perspectives of these two currencies on the importance of different size categories of litter (e.g. Lebreton *et al.* 2018). However, beach litter is often wet and soiled with sand, making it hard to weigh accurately in the field. Some items may be too large to weigh safely. At the same time, it is often impractical to wash and dry all macro-litter, and to weigh each item individually (e.g. soaked clothing, items heavily encrusted with goose barnacles). In this case it may be more practical to count items of a given litter type, and to estimate mass based on an independent measure of the weight (e.g. mass of an empty 1 litre drink bottle), recognising that this will introduce uncertainty in the estimated quantity. Meso-plastics should be retained and weighed to the nearest 1 mg (0.1 mg for foamed polystyrene) on an analytical scale. The methods for characterising micro-plastic particles are described in Chapters 8 and 9.

The depth to which beaches should be sampled for meso-, micro- and buried macro-litter is a trade-off between ease of sampling and the need to obtain an accurate estimate of litter loads. Litter can be buried up to at least 2 m in sandy beaches (Turra *et al.* 2014), but sampling to such depths requires considerable effort, and is impractical for surveys sampling large numbers of beaches. Sieving for meso-litter is difficult in wet sand, and so is often constrained to the top 5-10 cm e.g. (Ryan *et al.* 2018), even though these layers may support <10% of pellets on heavily contaminated beaches (Turra *et al.* 2014).

Litter on shorelines is patchily distributed at fine spatial (Fisner *et al.* 2017) and temporal scales (Moreira *et al.* 2016). This suggests that samples from a given site should be well replicated in time and space. However, this must be traded off against the number of sites that can be sampled. Some surveys might be designed to sample a few beaches in detail, to obtain a robust understanding of beach litter loads, whereas others might sample many beaches more superficially, to reveal broad-scale litter patterns. Obtaining representative data is the key concern.

4.4 Other shoreline types

4.4.1 Rocky shorelines, artificial surfaces and cobble/boulder beaches

The preceding section focused on litter stranding on sandy beaches because they are the easiest to sample and most often studied worldwide. Most of the principles discussed above apply equally to other shoreline types, but structural differences between shorelines have some impact on how best to sample

Shorelines characterised by cobbles, boulders and rocky outcrops usually reflect higher energy environments than sandy beaches, often subject to greater wave action than sandy beaches. This will affect the abundance, distribution and within-shore dynamics. Some shorelines that are modified by structures (e.g. groynes for sand retention) are functionally similar to boulder beaches and can trap large amounts of marine litter (Aguilera *et al.* 2016). Small litter items tend to work their way into the interstitial spaces between the boulders, making them harder to sample. Grinding by cobbles/boulders on high-energy beaches contributes substantially to the mechanical fragmentation of plastic litter e.g. (Convey *et al.* 2002, Chubarenko *et al.* 2018).

Bedrock shorelines vary from smooth, wave-washed rock, to more rugged structures with cracks, pools and interstitial spaces where litter can be trapped. However, most litter tends to accumulate at and above the high tide line (Convey *et al.* 2002). Sampling such shorelines is complicated by the rugged terrain and difficulty of access. High-shore caves often accumulate large litter loads, forming a long-term sink.

Many rocky shores support habitat-forming organisms such as seaweeds and an array of suspension-feeding invertebrates such as bivalves, polychaetes or corals, which help to trap litter items. Sea urchins occasionally use plastic items as sunshades. Seaweeds are particularly good at trapping fishing line and other fibrous litter items. Little is known about the role that intertidal organisms on rocky shores play in capturing microplastics, but several of the more abundant taxa are known to consume plastics (e.g. mussels and oysters) and might serve as indicator species for micro-plastic contamination (see Chapter 7).

Sampling on rocky shores
Sampling of litter in these complex, three-dimensional environments is inherently difficult, requiring careful searching in cracks and underneath rocks, turning over boulders and digging through cobbles e.g. (Thiel *et al.* 2013, McWilliams *et al.* 2018). For surveys, quadrats have been used for different sizes of litter, but sufficient numbers need to be surveyed with care, to avoid underestimating the abundance, especially for meso- and micro-litter due to the spatial complexity of the rocky shore habitat, with many inaccessible crevices where small plastic items can be trapped (McWilliams *et al.* 2018).

Regular monitoring is feasible for larger macro-litter items on some rocky shores (e.g. OSPAR 2010). Ideally, such monitoring should follow the same protocols described for monitoring litter on sandy beaches: thoroughly clean the shoreline on the first survey day and then sample all new plastic litter along well-defined lengths of shoreline on subsequent days. The impact of informal beach cleaning is likely to be less on rocky shores, because they typically attract fewer people. However, daily sampling has the advantage of reducing the chance that litter items will be buried or washed back to sea between successive surveys.

4.4.2 Vegetated shorelines: salt marshes and mangroves

The two main vegetated shoreline types are salt marshes and mangroves. Seaweeds on rocky shores trap some litter items, but they are not as efficient as flowering plants at retaining litter.

Salt marshes
Salt marshes form in estuaries and sheltered coastal wetlands. Plant composition varies regionally, but the basic structure and function of salt marshes is similar. Ecosystem services provided by salt marshes include buffering wave energy and stabilizing shorelines by trapping sediments. Their high productivity makes them important for commercially important fish, shellfish and migratory birds.

Salt marsh plants may act as a 'filter' for litter in the water column. Saltmarshes stretch from the salicornia zone, which is inundated for hours during each tide to the upper saltmarsh. This part is usually only flooded at extreme astronomical tides and under irregular conditions such as storm surges or wind-driven tidal inundations, which may only occur on a few occasions in the year. Vegetation can be a metre high and dense. Saltmarshes can be very extensive (e.g.1.5-2 km wide in the Southern North Sea). When the marshes flood floating debris penetrates the vegetation. Much of this material, including substantial amounts of plastic litter, is trapped during the ebb tide (Viehman *et al.* 2011, Lee and Sanders 2015). Stranded litter can shade and crush salt marsh plants, and block access to the sediment (Uhrin and Schellinger 2011). Most litter will collect at the mean high tide level (the start of the saltmarsh), with incursions inland during spring tides and storm events. Saltmarshes are not flat, with tide lines forming around small 'islands' of higher saltmarsh. In cool temperate regions, higher vegetation in the summer and autumn will form a barrier to litter reaching the top of the tideline.

Despite the importance of salt marsh as a shoreline habitat and the accumulation of marine litter in salt marsh vegetation, there are few litter surveys in this habitat. The dense vegetation complicates sampling of meso-litter, but sediment cores can be taken for micro-plastics e.g. (Browne *et al.* 2010).

Macro-litter sampling is relatively simple, but care has to be taken not to cause undue damage to the vegetation by trampling. Given relatively low human visitation in many salt marshes, monitoring macro-litter accumulation rates could take place over longer periods than on sandy beaches, preferably at the same stage of the tidal cycle (e.g. immediately after spring high tide). Wind often plays an important role in where litter accumulates in salt marshes, which should be factored in when deciding where to conduct monitoring. Such monitoring in estuarine salt marshes would provide a useful index of macro litter in land-based runoff.

Mangroves

Salt-water mangrove trees thrive in hot, muddy and salty conditions, forming dense forests along tropical and warm subtropical coastlines. Their complex root system holds the trees upright in the shifting sediments where land and water meet. Like salt marshes, mangroves act as natural buffers between the land and sea, absorbing wave action and stabilizing muddy sediments.

Mangrove forests act as both a trap and filter for marine litter; large litter items like plastic bags, ropes, and wooden flotsam tend to be trapped on the margins of the forests, whereas smaller litter items penetrate deeper into the forests (Debrot *et al.* 2013). Large litter items can smother mangrove seedlings (Gorman and Turra 2016) and reduce water quality, inhibiting natural growth and expansion as well as restoration efforts (Cordeiro and Costa 2010, Smith 2012). Mangroves often occur at the mouths of rivers, where they help to trap litter washing off the land. Microplastics have been identified in mangrove sediments, but there is little if any data on meso-litter in this habitat (Mohamed Nor and Obbard 2014).

Like salt marshes, there are few surveys of marine debris in mangroves, despite their importance as a shoreline habitat. Krelling *et al.* (2017) and Wills *et al.* (2017) found that almost all litter in such estuarine habitats derived from land-based sources.

4.6 Using citizen science

Volunteer participation has been instrumental to shoreline sampling in many parts of the world (Hidalgo-Ruz and Thiel 2015, Zettler *et al.* 2017). Given their easy access and attraction for people, most citizen science studies have been conducted on sandy beaches. Many of the common sampling protocols for sandy beaches can benefit from the participation of motivated and well-trained citizen scientists. Depending on the complexity of sampling programmes, volunteers may autonomously conduct surveys, or they can support professional scientists in their sampling efforts. However, quality control and assurance are important for comparability between observers. Interested volunteers should participate in existing programmes within their regions, or extend the use of existing citizen science protocols (Table 4.2) to their home beaches. Given the complex habitats and inherent difficulties with marine litter sampling in other shoreline habitats, volunteers should survey these under the supervision of professional scientists.

Table 4.2 Examples of citizen science programmes on shorelines and their main sampling objectives.

Organisation	Scientific goals	Website
International Pellet Watch	Collection of pellets for chemical analysis	http://www.pelletwatch.org/
Korea Marine Litter Institute at OSEAN (Our Sea of East Asia Network)	Macro-litter abundance and composition	http://koreamarinelitter.blogspot.com/search/label/Introduction
Ocean Conservancy: International Coastal Cleanup	Macro-litter abundance and composition	http://www.oceanconservancy.org/our-work/international-coastal-cleanup/
Ocean Conservancy: Clean Swell	App for data collection	http://www.oceanconservancy.org/do-your-part/about-clean-swell.html
NOAA	Macro-litter abundance and composition	https://marinedebris.noaa.gov
COASST	Impact on biota	https://depts.washington.edu/coasst/
Marine Debris Tracker	Marine litter composition	http://www.marinedebris.engr.uga.edu/
Cientificos de la Basura	Macro-litter abundance and composition	http://www.cientificosdelabasura.cl/en/
Following the Pathways of Plastic Litter	Macro-litter abundance and composition	https://www.save-ocean.org/
Marine Litter Watch	Macro-litter abundance and composition	https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch
Plastic Tide	Macro litter abundance and composition using drone technology and AI	https://www.zooniverse.org/projects/theplastictide/the-plastic-tide/about/results
Global Ghost Gear Initiative	Distribution of ALDFG	https://www.ghostgear.org/

A relatively new initiative, Plastic Tide[42], has combined drone technology and developments in artificial intelligence to create a platform that be used by citizens to monitor shorelines for marine litter. An algorithm has been developed that allows marine litter items to be distinguished and categorised. This has great potential to be applied for routine monitoring by both citizens and regulatory bodies, especially for monitoring inaccessible locations or sensitive habitats, minimising disturbance.

There is also great potential for applying the approach for rapid assessment monitoring in the case of natural disasters or accidental losses.

Further discussion of the role of citizen science, and maximising the benefit of using this approach is presented in Chapter 3.

See Annex V for additional protocols for monitoring the shoreline

42 https://www.zooniverse.org/projects/theplastictide/the-plastic-tide/about/results

5. MONITORING METHODS FOR THE SEA SURFACE AND WATER COLUMN

5.1 Description and relevance of the open water surface and water column compartments

5.1.1 Ocean processes and the properties of floating plastic

To understand how to monitor the open water surface and water column, it is useful to have a basic understanding of how plastic behaves in these compartments. The sea surface and upper water column are very dynamic and provide a connection with the shoreline, seafloor and biota. Plastic litter may enter from rivers, coastal or inland areas or via atmospheric fallout. It may wash off beaches, only to wash back ashore with storms or tides. It may sink to the seafloor in a relatively dense faecal pellet, and later be re-suspended back into the water column once the faecal pellet degrades. Alternatively, a marine organism might ingest plastic, only to regurgitate or excrete it elsewhere into the sea or on land. To further complicate our understanding of plastic in these compartments, there are water movements that transport, aggregate or disperse plastics horizontally and vertically.

Floating plastics will be carried by surface currents and their distribution will reflect the well-known surface ocean circulation. This includes the long-distance transport to, and partial retention of material in, sub-tropical gyres, and the long-distance transport of floating plastics to higher latitudes, some of which may be incorporated in sea-ice, driven by the global thermodynamic circulation, or 'conveyor belt' of deep-water formation.

Material density and air entrapment are the primary variables affecting the buoyancy of plastic marine litter. The density of the most common polymers is described in Chapter 2 (Table 2.1). Many plastics are denser than seawater but nevertheless may be observed in the water column. For example: an empty PET drinks bottle will sink unless it is capped, trapping air; and expanded polystyrene foam (EPS) will float, but unexpanded PS will sink. EPS may comprise a significant proportion of litter floating in some coastal zones, especially where shellfish mariculture, using buoyed lines, takes place. Some polymers, like PE and PP are less dense than seawater, so would be expected to float. Mechanisms of degradation, fragmentation and biotic interaction may change the size, morphology, and buoyancy of plastic marine litter. For example, the formation of biofilms on small microplastics, with a larger surface area to volume ratio, may increase particle density sufficiently to cause particles to sink.

Floating litter is also affected by how much of it is above the surface, described as its windage or "wind profile". When floating plastic has a high wind profile, like a buoy, it becomes subjected to wind forcing, and may be transported at a much faster rate than would be expected from surface currents alone. This was demonstrated following the devastating Great East Japan (Tōhoku) Earthquake and tsunami in 2011 (section 4.2.1). Westerly winds resulted in the rapid transfer of large floating material across the North Pacific to the shorelines of North America, relative to the expected time taken due to surface currents alone.

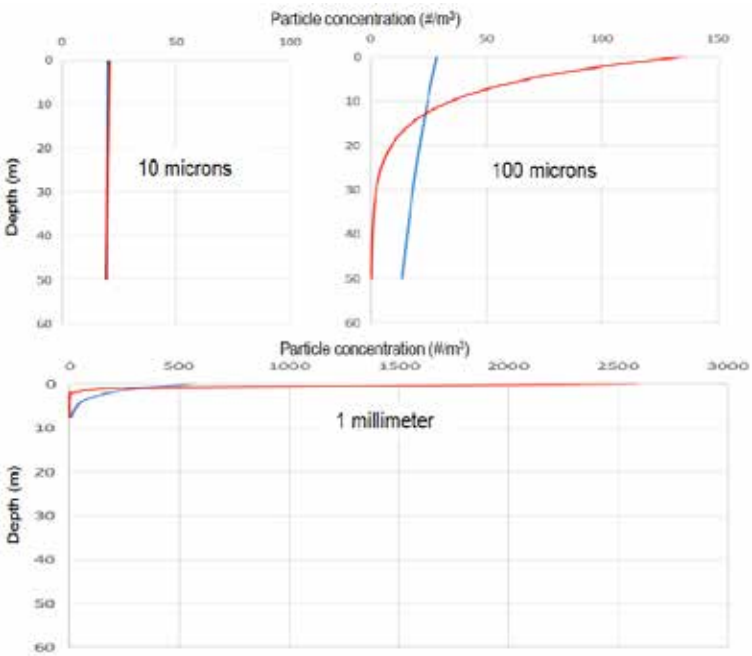


Figure 5.1 Modelled vertical distribution of particles in the upper ocean with a constant surface wind of 7 m s^{-1}, for three size categories (10 µm, 100 µm and 1 mm) and two bouyant polymer types of differing density and hence buoyancy: red – polybutylene (ρ = 0.60 cm^{-3}) and polyethylene HDPE (ρ = 0.97 cm^{-3}), (Sven Sundby unpublished).

5.1.2 Loss from the sea surface

In two global studies of microplastic distribution (Cozar *et al.* 2014, Eriksen *et al.* 2014), floating microplastics were observed to be a hundred times less abundant than expected, considering conservative fragmentation rates. The potential mechanisms for this apparent loss have not been established with certainty. It may be due to increased rates of fragmentation due to the cumulative effects of greater than expected rates of photo-degradation, hydrolysis and biodegradation, grazing or shredding by macro-fauna. It has been suggested that biofouling (i.e. the growth or attachment of organisms) may alter the buoyancy of plastics (Song and Andrady 1991, Andrady 2011, Kooi *et al.* 2017), but this process has not been quantified. What is more certain is that surface winds can cause the mixing of the upper layers of the water column, re-distributing buoyant particles depending on their diameter and relative buoyancy (Figure 5.1, Box 5.1).

5.1.3 Spatial and temporal variability in floating litter distribution

Plastics may move between compartments due to the various physical properties of the plastic (e.g. density) as well as mechanical (e.g. waves and currents), chemical (e.g. oxidation) and biological (e.g. bio-transport and bio- fouling) processes. A plastic bottle cap or fragment of fishing net or line entering the ocean surface from a river or beach, may move to any of the other compartments (except atmospheric), returning ashore by beaching or stranding, entering biota through ingestion or entanglement, or transporting to the water column or sea floor after a density shift due to biofouling (Andrady 2011). Plastic may enter the ocean surface from wind or water, transport from storm water

Box 5.1: Vertical distribution of floating microplastics

The vertical distribution of buoyant microplastics in the pelagic mixed layer is determined by the balance between 1) the buoyancy flux of the microplastics that drives the particles towards the surface and 2) the vertical turbulent mixing that forces the particles downwards. In the upper mixed layer (or the pelagic layer) turbulence is mainly caused by current shear and breaking waves from wind forcing, but in certain coastal and shallow-water regions tidal mixing may become equally important. The principles of the vertical distribution are similar to what have been developed for pelagic fish eggs in the mixed layer (Sundby 1983). Here, the balance between the above two forces may be formulated:

$$-w \cdot C(z) = K \cdot \partial C(z)/\partial z$$

where w ($m\ s^{-1}$) is the vertical speed of the particles, C(z) (# m^{-3}) is the particle concentration at depth z, and K ($m^2\ s^{-1}$) is the turbulent eddy diffusivity coefficient of the mixed layer.

Solving the equation above gives the particle concentration profile, C(z):

$$C(z) = C(a)\ e^{-w/K(z-a)}$$

where C(a) is the particle concentration at a given depth, a. The equation is visualized for three sets of particle sizes and two types of buoyant polymers in Figure 5.1.

From the above equation the vertical profile is simply determined by the ratio w/K where a large w/K ratio implies that particles are concentrated towards the surface (as for the larger particles in lower panel of Figure 5.1), while a small w/K ratio implies that the particles are more mixed down (as for the smallest particles in upper left panel of Figure 5.1).

The vertical particle speed (w, $m\ s^{-1}$) can be calculated using the Stokes equation for low Reynolds numbers:

$$w = 1/18\ g\ d^2\ \Delta\rho\ \eta^{-1}$$

where, d is the particle diameter (m), g is gravity (m/s^2), $\Delta\rho^{-1}$ is the buoyancy (density difference between particle and seawater, kg m^{-3}) and η is the viscosity (kg $m^{-1}\ s^{-1}$). The viscosity varies with water temperature, resulting in faster vertical transport rates in warmer waters (Sundby 1983). For example, vertical particle speed in the subtropical gyres are the double of similar vertical speeds in the Arctic.

The eddy diffusivity coefficient, K, was empirically determined as a function of wind speed (Sundby 1983):

$$K\ (m^2\ s^{-1}) = (76.1 - 2.26\ U^2) \cdot 10^{-4}$$

where U is the wind speed in $m\ s^{-1}$.

The particle diameter dominates the rate of upward transport for buoyant particles following a mixing event, such that larger particles will stay nearer the surface and smaller particles will be mixed to depth. This means that progressive fragmentation of floating particles will result in a net loss from the sea surface whenever mixing occurs (Figure 5.1). Consequently, standing stock estimates based solely on surface tows may underestimate the true abundance of plastic in the surface ocean.

runoff from urban centres or coastlines, or the intentional or involuntary dumping along river banks (Rech *et al.* 2015). Studies of atmospheric sources and pathways of plastics are few (Dris *et al.* 2017), yet indicate that microfibres dominate the particle types observed. The input of plastics from maritime sources may include shipping, fishing, fish farming, offshore mining, illegal dumping at sea, and other maritime activities.

5.2 Sampling strategy

The sampling strategy needs to relate to the questions the monitoring programme is intended to answer. This may be to identify, for example, an accumulation 'hot spot', the success of reduction measures for a particular type of litter (e.g. a ban on straws on tourist beaches), the distribution of floating ALDFG, the influence of river inputs, or the abundance of micro-fibres near a wastewater discharge. The sampling methods will differ depending on the compartment being sampled (sea surface or water column) and the size range of litter being monitored.

The selection of sampling locations will be based on a number of factors, in addition to the policy question being addressed. Sampling from a fixed platform or vessel of opportunity, such as a ferry, will be more constrained than when using a vessel dedicated to carrying out a monitoring programme, but both approaches can be equally valid. Knowledge of the bathymetry, sea surface temperature, salinity and surface currents will provide useful environmental context, and can be combined with information about sources of litter such the location of potential sources such fishing grounds, shipping routes, tourist beaches, wastewater outfalls and river inflows.

A common challenge in any sampling effort is for the information collected to be as representative as possible. The abundance and distribution of plastic in the water surface and water column compartments are highly variable due to seasonal changes in river outputs, ocean currents, mechanisms of degradation and fragmentation, changes in litter size, shape, buoyancy, and movement to and from other compartments.

Sampling design is key, and repeated measurements (e.g. short repeated surface trawl surveys) will help to describe the variability within the system. A minimum of three replicates is recommended to understand the variance and error around the data.

- ❑ **Temporal variation.** The distribution of marine litter and microplastic can be influenced by processes operating over hours, days, weeks or months; these include: tidal conditions, short-term wind and rain events, and seasonal extremes (e.g. monsoons). The sampling location and frequency needs to take account of the timing and influence of these events on litter distribution (e.g. downward mixing of microplastic from the sea surface due to a wind event).
- ❑ **Large- to medium-scale spatial variation.** Sample locations need to be distributed to capture large- and meso-scale variability (100s m to 100s km) in open water surface and water column differences in currents, river outflows, direct beach inputs, urban outfalls, industrial or maritime activities. Access to medium- to fine-scale surface circulation models (e.g. of salinity or sea surface temperature) can be helpful in site selection.
- ❑ **Medium to small-scale spatial variation.** This variability can exist at a scale of < 1 m to several tens of metres, creating significant differences in plastic particle abundance. One solution is to divide a sampling event into multiple short samples to capture the nuances of these differences. For example, CSIRO conducts a 45-minute surface tow with a neuston net, but it is divided into three 15-minute trawling events conducted one after the other. This replicate sampling enables the variability and average value to be estimated.
- ❑ **Baseline studies.** It is important to establish a baseline by carrying out an initial survey, which will form the basis for monitoring future changes in the type, abundance and distribution of plastic marine litter.

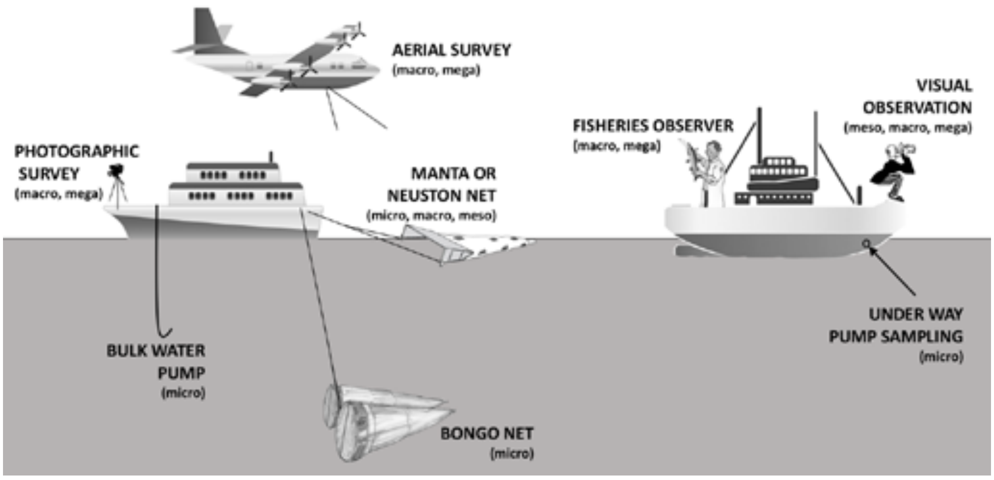


Figure 5.2 Schematic of possible methods used for sampling the sea surface and water column (see Table 5.1 for further details of the methods advantages and challenges and examples of use) (image courtesy of Marcus Eriksen).

5.3 Selecting the most appropriate sampling methods

5.3.1 An overview of potential methods

There are several sampling methodologies to choose from (Figure 5.2). Sampling the water surface includes five main methods (Table 5.1). The most common is the surface net tow, using a neuston net, manta trawl or mega trawl, to collect floating micro-, meso- and (to a limited extent) macro-plastic items. Mega-plastics items (> 1 m) tend to be rare, so typically methods like aerial surveys, photographic surveys, and direct observations from ships are applied. There are of course different methodologies for monitoring micro- and meso-plastics. It is important to note that the frequency of occurrence of floating particles or litter items is likely to vary inversely with size, and this needs to be taken into account when planning the sampling method and sampling strategy (i.e. there will be fewer larger items) for sea surface monitoring.

Sampling the water column includes six methods (Table 5.2). Typically, the water column is monitored for smaller plastics in the micro and meso range because larger plastics are generally less abundant beneath the surface and more widely distributed.

Table 5.1 Examples of methods used for sampling plastics in the open water surface compartment.

Method	Explanation	Advantages	Limitations	Examples of use
Net tows (manta trawl, neuston net)	• Fine-mesh net attached to a large rectangular frame (e.g. 0.5 to 1.0 m wide and 0.4m high) developed for sampling surface and water column waters for plankton, insects and other small biota. • Manta trawl with floating wings to keep it on the surface. • Net length typically 1-8 m. • Mesh size typically 200-333 µm • Standard deployment configured with long side parallel to water surface	• Can be deployed from small to large vessels. • Underway sampling • Use of flow meter to estimate volume.	• Use is weather dependant • Care needed to minimize contamination from sampling vessel and tow ropes. • Can only estimate volume of water filtered when flow meter is used and the frame completely immersed • Towing speed and time must be limited to avoid clogging the net and under-sampling surface waters; vessel speed may need to be restricted • Under-samples material smaller than mesh size.	Viršek *et al.* (2016)
Mega net	• Large net, up to 4 m wide for sampling larger litter than with a standard manta or neuston net	• Captures a macro and meso litter	• Use is weather dependent • Infrastructure needs to store, deploy and retrieve are great	Lebreton *et al.* (2018)
Bulk water sample	• Sampling large volume of water and volume reducing	• Known volume sampled • Can sample from vessels of opportunity	• Limited volume can be processed, restricting it to smallest litter fractions • Volume reducing sample on a working deck may exposure sample to contamination	Song *et al.* (2014)
Visual observations from a ship	• Visual survey of floating marine litter from the surface of a vessel at sea • Use either fixed width transects (assumes all items seen) or distance sampling (corrects for decrease in detection probability with distance from the vessel)	• Easy to do from vessels of opportunity • Low cost, needs only binoculars (but ideally also a good quality digital SLR camera and telephoto lens)	• Limited to waters adjacent to the ship (up to 50 m typically) • Bias against dark items and sub-surface items; white and buoyant items easier to spot • Report start/stop observation times, observer effort, etc. to be useful.	Ryan (2013)
Photographic and aerial surveys	• Visual survey of floating marine litter from an airplane or drone	• Cover large areas; ideal for mega-litter	• High cost to charter, expensive photography equipment • Limited to macro and mega-plastic, with one study (Lebreton *et al.* 2018) observing items as small as 10-cm • Bias against dark items and sub-surface items	Lebreton (2018)

Table 5.2 Examples of methods used for sampling plastics in the water column compartment.

Method	Explanation	Advantages	Limitations	Examples of use
Bongo nets, or Horizontally hauled plankton nets	Cylindrical-Conical shaped, often used for mid-water sampling	• Can be deployed from vessels • Can be used at variable depths • Use of flow meter allows volume estimate • Not weather dependant • Paired bongo net allows replicate sampling	• Risk of sample contamination when the sample is handled on the vessel deck after each sampling procedure. • Under-samples material < 300, 110 and 65µm • Vessel speed may need to be restricted	Doyle *et al.* (2011)
Underway pumps	Utilizing seawater intakes from vessels	• Can sample a known volume of water over a given time or distance • Can control for contamination on vessel	• Intakes are small and can limit the upper size range • Adverse sea states can affect the position of vessel in water, intake depth variable. • May be contamination from the sampling apparatus including the hose	Desforges *et al.* (2014) Lusher *et al.* (2014)
Submersible pumps	• Deck pump lowered to a known depth	• Can sample a known volume of water	• Vessel needs to be stationary • Intakes are small and can limit the upper size range	Setälä *et al.* 2016
Bulk sample	• Sampling large volume of water and volume reducing	• Known volume	• Volume reducing sample on a working deck may exposure sample to contamination. Care must be taken.	Song *et al.* (2014)
CPR	• Continuous plankton recorder towed from ships underway • Have been in use since 1946	• Can be used over a large distance from vessels of opportunity • Can use archived samples	• Water depth sampled is approximately -10m, i.e. cannot sample surface waters • Restricted size of intake may underestimate larger particles	Thompson *et al.* (2004)
Fisheries observer	• Opportunistic capture of plastic marine litter by towed pelagic fishing gear	• No equipment necessary. • Observing long line fisheries that capture mostly nets and line.	• Dependent on fisheries reporting litter • Not systematic survey of a given area.	Uhrin (2018)

Because water column samples have fewer and smaller plastics, it is important here to note that water column samples brought aboard can be easily contaminated while handling, due to fibres from worker clothing, paint chips, unwashed equipment. Care must be taken to minimize contamination.

For macro- and mega-plastics, fisheries observers may opportunistically report large plastic items hauled in by fishing gear during regular fishing activities. This however results in heavily biased information, which is difficult to analyse to determine actual densities (or counts, weights of floating surface litter). It is important to know where and when observations are taking place – whether or not litter items are observed or detected. For micro- and meso-plastics net tows, pumps and bongo nets can be deployed to collect samples.

5.3.2 Micro- and meso-plastics – net tows

Net tows can be utilised to collect plastics in the micro- and meso-plastic size ranges at the sea surface and below. The typical net tow is adapted from traditional plankton nets, and may include a manta trawl with pontoons to keep it afloat, or a neuston net that must be suspended half way beneath the water's surface (Figure 5.3). They are generally comparable in what they collect, and can be used interchangeably (Eriksen *et al.* 2018). Net mesh size varies between 50 µm and 500 µm, with 330 µm the most commonly used mesh size (Hidalgo-Ruz *et al.* 2012). Online resources with schematics of net tow equipment are available[43].

43 http://testingourwaters.net.

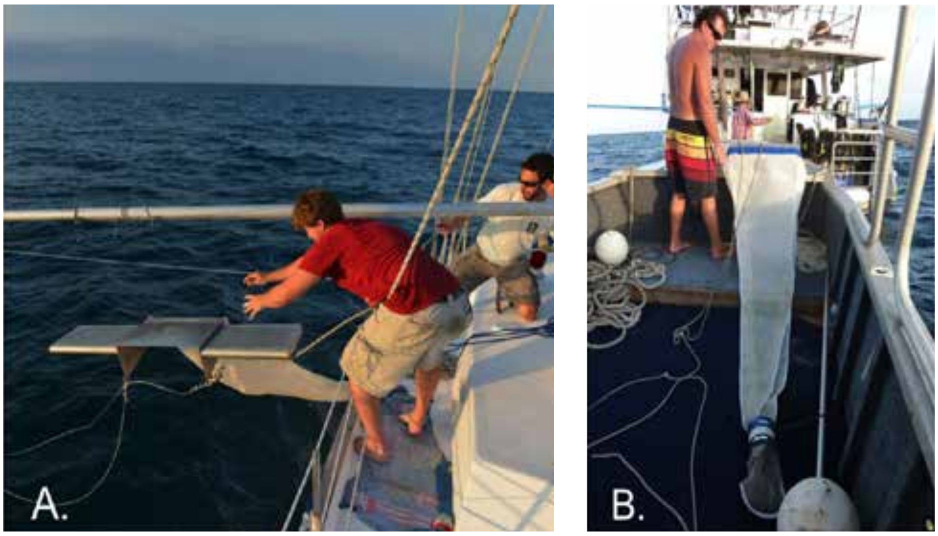


Figure 5.3. The manta trawl has wings and can float unassisted **(A)**. The neuston net must be suspended at or below the water's surface **(B)**.

Using a neuston or manta trawl to sample different sizes of floating plastic is restricted by the size of the net opening (typically £1 m wide and £0.5 m deep). Nets are usually towed for 15-30 min (rarely 60 min) at ~2 knots[44]. This is equivalent to roughly 0.5-1 nautical mile of trawling distance if you are towing a 1 meter-wide neuston net. If the net opening is narrower then it should be towed for longer, for a time proportional to the difference in lengths, to sample the same quantity of water and obtain a representative sample.

Neuston nets are typically used for capturing microplastics and meso-plastics. The chances of catching even a few smaller macro-plastic items is low given that macro-plastic densities are typically of the order of 0.01-1 km^{-2}, therefore the chance of capturing a macro-plastic item is small in all but the most polluted waters. To survey macro- or mega-plastic distribution or abundance, the larger mega trawl might be useful (Lebreton *et al.* 2018) or visual surveys.

The net tow is usually deployed from the side of the vessel and away from the boat to avoid the wake, because the disturbed water may drive plastics downward and below the net, resulting in inaccurate sampling (Figure 5.4 A, B). When the manta trawl is positioned behind the vessel, the distance behind must increase to avoid the effect of vertical mixing (Figure 5.4 C). Also, as zooplankton migrate to the

44 Insert URL for Supplementary material S2

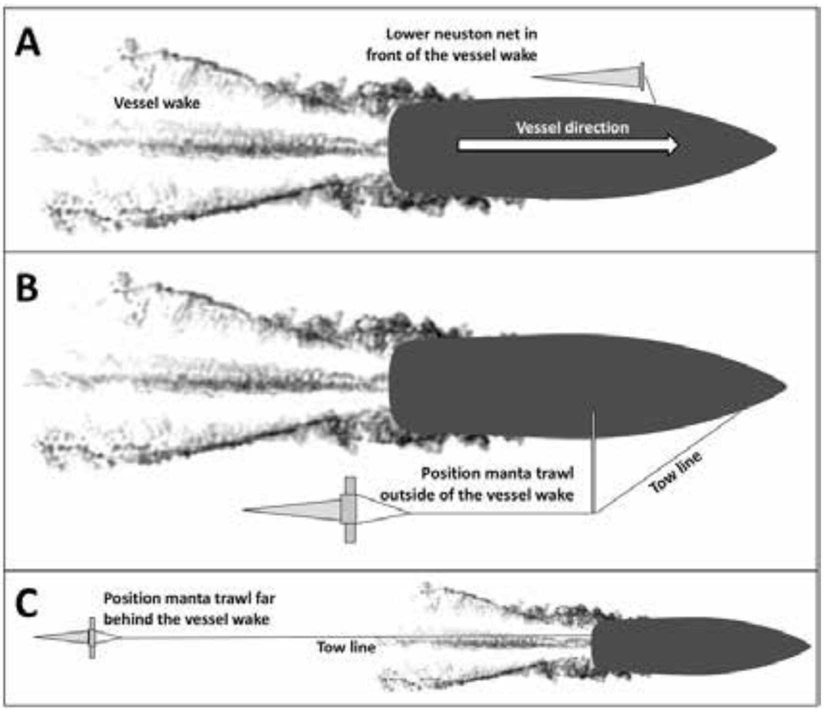


Figure 5.4 Optional net tow positions. A is a neuston net deployed in front of the wake zone. B is the manta trawl positioned away from the wake zone using a pole to move the tow line. This is ideal for large vessels that significantly disturb surface waters. C is manta trawl positioning for smaller vessels, such as sailing boats, with minimal surface disturbance, deploying the trawl far behind the stern, a distance at which the surface is not disturbed by the vessel's wake (often 20-30 m or more) (image courtesy of Marcus Eriksen).

surface at night, a large number of zooplankton often are captured, the mesh is easily blocked, increasing the difficulty of pre-laboratory processing. Sampling during night should be avoided if you are investigating numerical abundance of marine litter only.

Similarly, the sea state influences surface abundance due to wind-driven vertical mixing of surface waters. Methods have been utilised to correct for vertical distribution of plastic particles in the form of equations that can be applied to particle count (Kukulka *et al.* 2012), differences in particle buoyancy, particle size and water viscosity are all critical factors (Sundby 1983, see section 5.1.2). Sea state also influences the performance of manta nets or neuston tows, as higher sea states cause nets to rise above or below the water's surface, which results in missing an unknown portion of the sample area passed. Therefore, sampling should be conducted in relatively calm sea conditions with a wave height less than 0.5 m, or Beaufort Sea State 3.

To accurately measure the area of sea surface sampled, a flow meter is often attached to a manta or neuston net to tell the observer how much water has passed through the net. With this distance estimate and the width of the trawl, one can estimate the "true" portion of area sampled.

Data sheets typically include the start and stop time and location (latitude and longitude), as well as wind and wave conditions at the time of sampling, vessel speed and direction, and general information about the vessel and observer. Information on the wind and wave conditions prior to sampling are highly recommended to estimate the degree of vertical mixing of the near surface waters. Contamination may result from multiple vessel sources (paint chips, fibres, unwashed nets), resulting in overestimates of particle abundance. Paint chips from the vessel deck or hull are caught often while sampling, so collecting a few chips of ship paint for comparison is useful.

Figure 5.5 The Bongo net captures sub-surface microplastics.

The collection of blank samples is recommended, whereby a sample is collected from the equipment without it having touched the water. Blank samples give the observer an opportunity to see how clean their process is. Blanks with consistent contamination (from clothing or the vessel) can be used to subtract average contamination from the monitoring samples.

For sampling in deeper waters, a Bongo net is typically utilized. Bongo nets generally have two large round net openings and are deployed beneath the surface to collect deeper particles (Figure 5.5).

5.3.3 Visual observation surveys for macro- and mega-plastic

Visual surveys of marine litter from boats or ships have a long history, dating back almost 50 years, and can be especially effective using ferries or other vessels running regular transects, or from fixed platforms. Visual surveys require little equipment, other than binoculars, a stopwatch and a datasheet. However, a digital camera and telephoto lens is useful to help identify litter items and to discriminate litter from other floating litter (see below). Several factors are worth considering when undertaking visual surveys. The preferred observation area for biological or litter surveys from a ship is the bridge wing, though the bow is often used on smaller craft (Figure 5.6). When observing from vantages behind the bow, the ships bow-wave often obscures items close to the ship's track. Other factors that affect the visibility of items floating at sea include:

1. The size of the item (larger items are generally more visible) – estimating size takes some practice, and is best done by assessing how large a known item (e.g. 1 litre bottle) appears at a given distance from the observation position;

2. The distance item from the ship's track – this is best estimated by timing how long it takes an item to travel from a 45° angle until it is perpendicular to the observer; the distance the ship travels in this time is the same as the perpendicular distance of the item from the ship's track (assuming the item isn't moving much, relative to the ship);

3. The colour and to some extent the shape of the item (pale items that stand out against the sea are easier to see);

4. Buoyancy (items drifting below the surface are much harder to detect at a distance than items at the surface, and those protruding above the surface are most visible);

5. The height of the observer above the water (high is good for spotting large items at a distance, low is good for detecting small items close to the ship's track), time of day and reflectance;

6. Sea state (detection probability is higher in calm than in rough seas) and lighting conditions (time of the day; reflectance - select the side of the ship with the reflected sunlight in the observer's eyes) (Ryan 2013).

Ideally, all of these factors are noted when conducting observational studies with an aim of detecting floating marine litter. Additional information to record includes the type of item, both in terms of material (plastic, glass, metal etc.) and the category of use (bag, bottle, fishing net etc.). Parameters pertaining to each survey also need to be recorded: vantage height, distance from bow, start and end positions of each transect, sea state, wind strength and visibility, survey start and end time, distance travelled.

There are two approaches to quantify the abundance of floating marine litter from vessels:

1. Fixed-width transects assume that all macro-plastic items within a specified search area are detected. The width sampled depends on the size of the vessel, the height of the observer above the water, and the location of the observer. Transect widths typically extend to 30 meters from the ship (after which distance the probability of detection drops precipitously). If the observation vantage is behind the bow, the transect should be located on one side of the vessel, and typically encompasses 90 degrees (from the front of the ship to one quadrant, recording only items that are observed in that quadrant as the ship is moving through an area (i.e. the observer does not record items detected behind that 90 degree quadrant if they were initially missed).

2. Distance sampling is another approach. There are statistical approaches used to compensate for the decrease in detection probability with increasing distance from the ship. Here it is essential to record the distance to each item, with correction factors for other variables such as size, colour and buoyancy e.g. (Ryan 2013). An assumption of distance sampling is that the probability of detection is 1 on the transect line. If the observation vantage is behind the bow, you might have to discard items within the wash of the ship's bow wave, or compensate for its effect (Ryan 2013).

There are advantages and disadvantages of either approach. Observing along a narrow fixed-width transect (10 m from an 8 m vantage on the bow) may result in a greater density of litter items being detected, because the observer focuses exclusively on the transect. A distance-based approach may be expected to capture a greater diversity of items, including a higher count of plastic items, depending on the observed size range, viewing angle and sea state. Whichever method is used, it is important to be consistent for the duration of the survey and with repeat surveys. Switching methods yields difficulty in comparing and provides biased results.

It is useful to specify the minimum size of items detected and recorded, particularly if reporting densities in terms of the numbers of items (Ryan 2013). GESAMP recommends that efforts should be made to record down to a lower size limit of 25 mm, with the following size ranges being recorded for monitoring purposes: 25-1000 mm and > 1000 mm, to allow comparison with shoreline surveys. If conditions permit (e.g. sea state, light intensity, size of vessel), lower (< 25mm) and intermediate size intervals can be recorded. Work is on-going, within the EU-funded MEDSEALITTER project[45], to produce recommendations for intermediate size classes, to be used under the European MSFD, and will be available later in 2019.

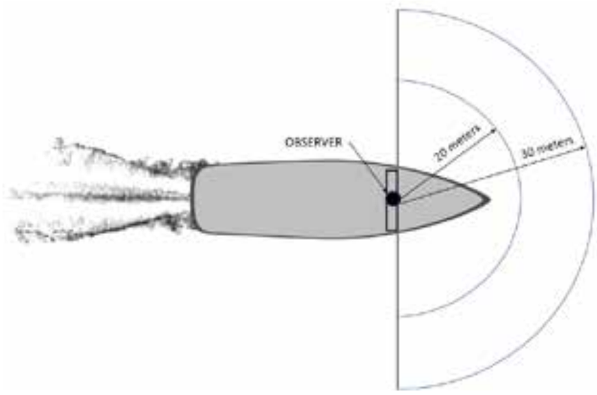


Figure 5.6 The observer positions himself on the bridge, bridge wing, or bow, with a 180° observation field.

5.3.4 Photographic surveys for macro- and mega-plastic

Photographing plastic items during visual surveys greatly enhances your ability to confirm the nature of floating litter and the detection of surface-dwelling organisms on litter items. Digital SLRs with fast telephoto lenses provide detail on items not readily detected even using binoculars, which can assist with identifying items, avoiding spurious records of e.g. barnacles that may attach to buoys, foam shells and other floating biota as plastic marine litter. While photographing plastic litter allows for later analysis, it does take away from visual survey time while in the aircraft. Photographing plastic litter is best used simultaneously with visual surveys.

Another approach is to use a fixed camera mounted the bow or mast of a vessel. Such a system may use an automated digital camera to take still images at a fixed time interval. The Littercam approach (Hanke in press) has taken this one step further, by pioneering the use of an automated digital camera mounted on the bow of a commercial vessel. This system records floating litter, taking 4 images per second, and uses image recognition software that compares

45 https://medsealitter.iterreg-med.eu

successive images to discriminate between sunlight reflections and litter items. To date, the software to process images has been relatively slow (taking almost as long as an observer would to view and score the images), but optimisation is underway. Minimum size resolution depends on the size of the ship and resultant height of the camera above the water and the camera sensor resolution. The massive number of images captured on a typical cruise preclude the use of consumer cameras, so industrial cameras are required that can take and store high numbers of images (in excess of a million images). The system requires access to the ship's power supply, a secure housing for the camera and associated computer system to store the images.

5.3.5 Aerial surveys and remote sensing for floating macro- and mega-plastic

Aerial surveys, while more expensive than visual surveys from ships, provide useful abundance calculations for macro and especially mega-plastic marine litter, because they can sample large areas. There are some databases of images that might be useful, including satellite images, like Sentinel 1, or Google Earth images, though their resolution may limit detection to large litter items only. To most effectively conduct an aerial survey, you ideally want a plane that can go "low and slow". A plane with a high wing is ideal, which increases visibility to the water's surface. These have been used historically for macro-litter estimates. Most recently, Lebreton *et al*. (2018) sampled the North Pacific, stitching together 7298 aerial photographs to create 31 ≈10km² mosaics covering 310 km². They observed 1,595 objects, dominated by fishing gear (nets, rope, and containers). In this survey, photographs were utilized to improve litter identification.

5.3.6 Using ship intake water for sampling microplastics while underway

Another method that can be applied is to sample a ship's sub-surface intake of seawater. This intake water is often used to cool engine parts internally, and a measured amount can be diverted to a filter. (Lusher *et al*. 2014) utilised a marine grade stainless steel 250 µm sieve to filter seawater drawn from an intake valve 3 m below the surface during 12,700 km of ship cruises in the North Atlantic. Samples of 2000 litters of seawater were collected while the ship was underway at 10 knots. The material in the sieve was suspended and subsequently filtered under vacuum onto glass filter paper. This allowed for visual analysis of the filters under a dissecting microscope and potential microplastics were identified. 94% of the 470 samples taken contained plastics between 0.25mm and 5mm. While sampling ship intake may appear much easier than surface trawling, the detectable concentrations are low and plastic litter below the surface is greatly affected by sea state. Therefore, it is important to collect all data on sea and boat conditions.

Like all sampling methods, contamination is a constant threat to validity. After filtration, the sample may be immediately folded and wrapped in aluminium foil. Contamination may occur from fibres shedding of clothing or floating in air. It is essential that quality control measures be in place for all sampling methods, such as washing all equipment with de-ionised water, and minimizing contact with collection jars and equipment. Collecting blanks are essential to controlling contamination. See further details on contamination in Chapters 8 and 9.

5.3.7 Bulk water and Pump sampling

Bulk water sampling is utilised primarily to collect microplastics from a few litters to over 100 L from the water surface or subsurface using a container (bucket, tray or bottle) or submersible water pump. This water is then typically filtered through a small mesh (e.g. 20-80 µm) net, sieve or filter paper (e.g. pore size of 0.45 – 20 µm). Glass fibre or stainless steel filters are preferred over nylon mesh because they can be examined by the human eye for particles greater than 1mm, and then directly using micro-FTIR spectroscopy without the mesh interfering with the detection of plastic samples. Bulk water sampling is preferred over net tows, which typically use a 330 µm mesh, for very small microplastics and micro-fibres. Repeated bucket samples provide an alternative way to sample surface waters.

The limiting factor to bulk water sampling is the volume of water collected, primarily because small pore filters clog more easily, but this can be overcome by increasing sampling frequency. In addition, an intensive sample-processing step such as chemical digestion may be required to remove organic material from some filter samples, which adds to the time and resources needed to collect and analyse samples.

Figure 5.7 Bulk water sampling at sea. (image courtesy of Marcus Eriksen).

A simple way to sample surface water for bulk sampling is to use a steel bucket with a natural fibre rope deployed from the bow, ahead of the vessel's bow wave (Figure 5.7). With practice, bucket samples can be collected while the vessel is in motion, but great care should be exercised to minimise potential risks. Using this method is very likely to result in contamination of the water sample from the sampling rope.

Pump sampling can be used in different ways; while underway, *in situ* submerged filtration pumps or on-deck pumps with deployed hoses. There are a few examples of applied in situ pumps for microplastics, with both custom-made prototypes and commercially available system, including filter holder, flow meter and pump. The more common pump sampling system is to have the pump on deck and deploy a hose to the preferred depth. Typically, the pump is placed after the filter, so that water passes through the filter before it gets to the pump. This will minimize risk of contamination and damage to fragile particles or filters. Remember, pumps do not sample the sea surface layer, so floating particles are missed (Karlsson *et al.* 2018).

5.3.8 Continuous Plankton Recorder

The Continuous Plankton Recorder (CPR) is useful for subsurface plastics sampling over long distances. The CPR is a plankton sampling instrument designed to be towed from merchant ships or ships of opportunity, on their normal sailings. It is towed at a depth of approximately 10 metres. Water passing through the CPR is filtered through a slow-moving band of silk, trapping plankton and microplastics, which are spooled into a storage tank containing a preservative, like formalin.

(Thompson *et al.* 2004) utilized archived samples from CPR surveys in the North Atlantic, dating back to 1931, to show the emergence of microplastics in the 1960s. A recent study (Sadri, 2015) investigated 130 CPR silk samples from the northeast Atlantic Ocean and the North Sea revealing 89 microplastic pieces, of which most were in the form of filaments such as polyester fibres and lines similar to those used in the fishing industry. In this study, the occurrence of fragments was rare. These studies indicate that CPRs are useful to monitor sub-surface microplastics, though to date, they have primarily detected micro-fibres.

5.4 Sample processing in the field

5.4.1 *In situ* sample processing

Field processing is what you do to a sample after it is collected before it gets to the lab for further processing and analysis. Provided you have a sample-processing site on board and the sea conditions allow, you can process samples for the lab. How a sample is field processed using any of the methods described here, depends largely on the size and type of plastic, as small microplastics are prepared very differently from macro-plastic. The research questions you are asking will also influence how you prepare your sample. For example, if you are interested in abundance of plastic particles, then biological material can be discarded and preservatives are not needed. Different marine litter sizes require different methods for processing, and raise different issues of contamination. The smaller the particle size, the greater the likelihood that contamination will occur from varied sources, like fibres from clothing or paint chips from the hull or deck of a vessel.

5.4.2 Processing a sample from a net tow or bongo net for numerical abundance and biota.

In each of these methods, plastics are collected at the end of the net, usually in a detachable cod end. Once the net is removed from the water surface, it should be rinsed thoroughly from the outside to wash all plastic particles stuck to the sides of the net into the cod end. The contents of the cod end are then transferred into a glass vial or HDPE bottle. HDPE containers are often preferred over glass because of issues of breakage during vessel movement or transport. To limit decomposition of biological material, samples can be stored at 4 °C or isopropyl alcohol can be added, though this is not absolutely necessary.

It is very important to note that using the net trawl during the evening will likely result in high volumes of zooplankton as they migrate to the surface at dusk, therefore sampling for numerical abundance of floating plastic is best conducted during the day.

5.4.3 Processing a pump sample for plastic.

Pump sampling is a process that filters water while underway through a sieve, filter or membrane, retaining micro or meso-plastics. Even further, the water can be led directly through a set of stainless steel sieves to collect different size fractions. Filtered water can then be used to wash the retained material from the sieves into containers (glass or HDPE) for transport back to the lab for further analysis. As an alternative to sieves, water can be vacuum filtered onto glass micro-fibre paper (GF/C), which can then be stored in glass petri dishes or aluminium foil envelopes until returned to the laboratory for analysis. Depending on the intended analysis or research questions (such as POPs analysis) storage of the samples at reduced temperature (4 or -20°C) may be necessary. Ideally all items would be triple washed with milli-Q™ water to reduce the risk of contamination, and if possible to operate in a closed, wind-less space. As this is not likely possible within many field operations, appropriate blanks should be taken and bright coloured uniforms worn so that any background contamination is easy to detect and/or account for.

5.4.4 Processing data from visual observations, photographic or aerial surveys.

Data sheets for visual observations are typically handwritten onto paper or notepad (waterproof paper is preferred for outdoor fieldwork). Alternatively, electronic devices such as tablets, apps and voice recording of observations can be utilized and transcribed into hard copies at a later time. Aerial surveys may also include handwritten datasheets, while photographic and some aerial surveys use cameras. It is essential that all print and digital formats be duplicated and stored separately from original data. These backup files are valuable insurance in case datasheets are lost. As soon as possible, these data and digital files should be uploaded and/or stored elsewhere.

5.5 Monitoring and Citizen Science

5.5.1 Size limits for visual observation

With growing public interest comes an opportunity to engage the public in contributing meaningfully to plastic monitoring through citizen science (Zettler *et al.* 2017). However, citizen scientists need easy-to-understand methods that do not require specialised equipment or extensive training, and therefore rely on simple visual observation. Kroon *et al.* (2018) recently compared visual sorting to FTIR analysis (Chapter 9), finding substantial error when relying on human eyesight to identify particles smaller than 1 mm. We suggest limiting citizen science methods to surface tows for meso and macro-plastic and visual observations for macro and mega-plastics. Microplastics pose a particular problem for monitoring because they are too small to see with the naked eye. The smaller the particle observed, the greater the need for complex equipment and observer skills to collect data, which citizen scientist typically do not have. Understanding that complex equipment, like FTIR polymer analysis, is unrealistic and cost-prohibitive for citizen science monitoring, we must understand the limits of visual observation to meso-plastics and larger.

5.5.2 Net tows and direct observation

Net tows, including both neuston nets and manta trawls, are relatively easy to deploy from many kinds of non-commercial vessels, but they require some training and commitment on behalf of the citizen scientist to follow protocols that ensure proper sample collection. If the citizen scientists are going to process the samples in the field, the mesh size of the net should be at least 1 mm, or a sieve with a 1 mm mesh may be used to filter material captured in the net. A data sheet must be completed according to the protocol, and care taken to preserve and document the collected plastics sufficiently.

Direct observation of macro-litter is deceptively easy, and should lend itself to citizen science efforts. However, observers need to be well trained and motivated. Observation stints should be short (0.5-1 hour at most), and for most purposes, a narrow fixed-width observation approach should be encouraged (e.g. 10-m wide strip from the bow of a vessel). Accurately estimating the correct sampling area is a key skill that needs to be taught to observers.

5.5.3 Examples of citizen science efforts to sample surface waters

Understanding that gathering useful data from citizen scientists must utilize simple methods for sample collection and analysis, there are several institutions that employ programmes aimed at collecting meaningful data on open water surface microplastics. What all of these efforts have in common, which any citizen science programme must consider, is the balance between the quality of data collected from citizen scientists and the time and resources needed to train and monitor their collection activities. Examples of citizen science efforts to monitor sea-surface plastics are listed as listed in Box 5.2.

Box 5.2 Resources for citizen science initiatives and advice:

A comprehensive guide to conducting marine debris surveys using CSIRO's methodology: https://research.csiro.au/marinedebris/resources/

Testing our waters - examples of Do-it-Yourself designs and schematics for building a net tow: http://testingourwaters.net

RIMMEL app. – Riverine and marine floating macro litter Monitoring and Modelling of Environmental Loading project. A European project coordinated by the EC's Joint Research Centre (González-Fernández and Hanke 2017, with a citizen science app. in development (beta testing stage): https://ec.europa.eu/jrc/en/news/new-app-helps-scientists-map-riverine-litter-entering-european-seas

5 Gyres Institute Trawl Share – manta trawls can be loaned to organisations for up to a year in exchange for data sharing: https://www.5gyres.org/trawlshare/

'Plastic Pirates' – a citizen science campaign which contributes to research on the distribution of macro- and microplastics along German rivers: https://www.wissenschaftsjahr.de/2016-17/weiterfuehrende-informationen/englisch/plastic-pirates.html

See Annex VI for additional protocols for monitoring seawater

6. MONITORING METHODS FOR SEAFLOOR

6.1 Description and relevance of the seafloor compartment

The morphology of the seabed, extends from the coastline across the continental shelf, of varying width, to the continental slope which descends until reaching the bathyal or abyssal plain (4,00 – 5,000 m), with the hadal zone as the lower boundary at about 6,000 m. The greatest depths occur in ocean trenches on sub-ducting ocean margins (e.g. the Pacific 'Ring of Fire') with the deepest location being at approximately 11,000 m in the Mariana Trench in the western Pacific (Peng *et al.* 2018).

The sea floor is a sink for marine litter (Galgani *et al.* 2000, Pham *et al.* 2014, Woodall *et al.* 2014) and seafloor surveys are of major importance, as most litter comprises higher-density materials found on the sea bottom, but includes low-density polymers, that may sink due to fouling. Accumulation trends in the deep sea are of particular concern, since most polymers are highly persistent in the marine environment and only degrade slowly via photo-catalysis when exposed to UV radiation (Andrady 2015) that are not present in the deep. Estimates for the longevity of plastics are variable but are believed, for some of them, to reach the range of hundreds of years depending on the physical and chemical properties of the polymer, but this is likely to be greatly increased at depth where oxygen concentrations are low and light is absent.

6.2 Macroplastics

6.2.1 Introduction

There have been relatively few studies dedicated to detecting seafloor litter. Rather data have been acquired during the course of other investigations, such as surveys of biodiversity of during routine fish stock assessment. As a result the survey coverage is very patchy, largely limited to areas of continental shelf subject to commercial fisheries and areas of biological interest such as seamounts, canyons and certain abyssal regions, including trenches (Pham *et al.* 2014, Lopez-Lopez *et al.* 2017, Miyake *et al.* 2011, Woodall *et al.* 2014).

Factors influencing the distribution of seafloor litter include proximity of maritime activities (e.g. fisheries, aquaculture, shipping, construction, energy extraction, recreational activities) (Pham *et al.* 2013, Loulad *et al.* 2017) and shore-based 'leakage points' (e.g. major river outlets, populated and industrialised coastlines, coastal tourism). This will be combined with environmental factors such as water depth, bottom topography, surface and near-bottom currents, and with the physical characteristics of the litter, especially the size and density. Seafloor litter will tend to become trapped in areas with lower circulation, where sediments accumulate, along rifts, in depressions, channels, on biological structures and around wrecks.

The systematic collection of litter data via trawling, on continental shelves and adjacent canyons, began in the 1990's. Harmonisation of data collection was developed in several Regional Seas programmes, including HELCOM[46] (Baltic Sea), NOWPAP (Northwest Pacific), OSPAR (Northeast Atlantic) and UNEP-MAP (Mediterranean Sea). In addition, this approach has been adopted at a national level, in Australia, China and Morocco.

Long-term data on seafloor litter abundance are scarce and monitoring has been performed on a regular basis in only a few countries. It has been difficult to establish reliable time trends. For example, litter abundance remained stable between 1994 and 2014 in the Gulf of Lion, France, with a slight statistically significant increase in the last 4 years (Gerigny *et al.* 2018). In the North Sea no change was apparent over a 25-year period in the weight of litter and the percentage of plastic observed in the International Bottom Trawl Survey (IBTS, Maes *et al.* 2018), apart from some specific plastic litter categories only. In China, no clear trend in litter abundance was found between 2007 and 2016 (SOA 2017).

However, sub-regional differences can occur. For example, a significant decreasing trend was observed in the coastal waters of the Wadden Sea in the southern North Sea, possibly due to the decline of coastal fisheries in the North Sea during the last decades (Schultze *et al.* 2015). In some areas around Greece, the abundance of seafloor litter at depth has increased over a period of 8 years (Koutsodendris *et al.* 2008). Seafloor litter increased at the deep-sea HAUSGARTEN Observatory (2,500 m) in the Fram Strait, between Greenland and Svalbard, between 2003 and 2016, correlating with changes in the number and origin of visits to Svalbard (Tekman *et al.* 2017).

The interpretation of temporal trends is complicated by annual variation in debris transport, such as seasonal changes in flow rate of rivers, and the intensity of currents and upwelling. Significant geographic differences in categories of litter may occur due to variations in the distribution of litter sources, such as in the Baltic Sea.

6.2.2 Monitoring strategies

The existing methods for monitoring litter on the sea floor present the associated with applying compatible and harmonized methods and their limitations. Any location will be characterized by the depth and the nature of the bottom, that may be sandy, muddy or rocky. The monitoring of litter on the seafloor may not be logistically feasible for all coastal areas because of limited resources, requiring setting of priorities to target the key areas to be monitored. Opportunistic

46 "Litter on the seafloor in the HELCOM area- analyses of data from BITS trawling hauls 2012-2016" ("Theme 2_Deliverable 2.1.2")

Figure 6.1: Diving in shallow waters (Pacific Coast, US, <30m), the results of trawling on soft bottoms (French Mediterranean coast, 50m) and an image captured by a Remote Operated Vehicle on rocky/mixed bottoms (NW Mediterranean Sea, 1000m): these are the most relevant approaches to monitor mega and macro litter (credit NOAA and IFREMER).

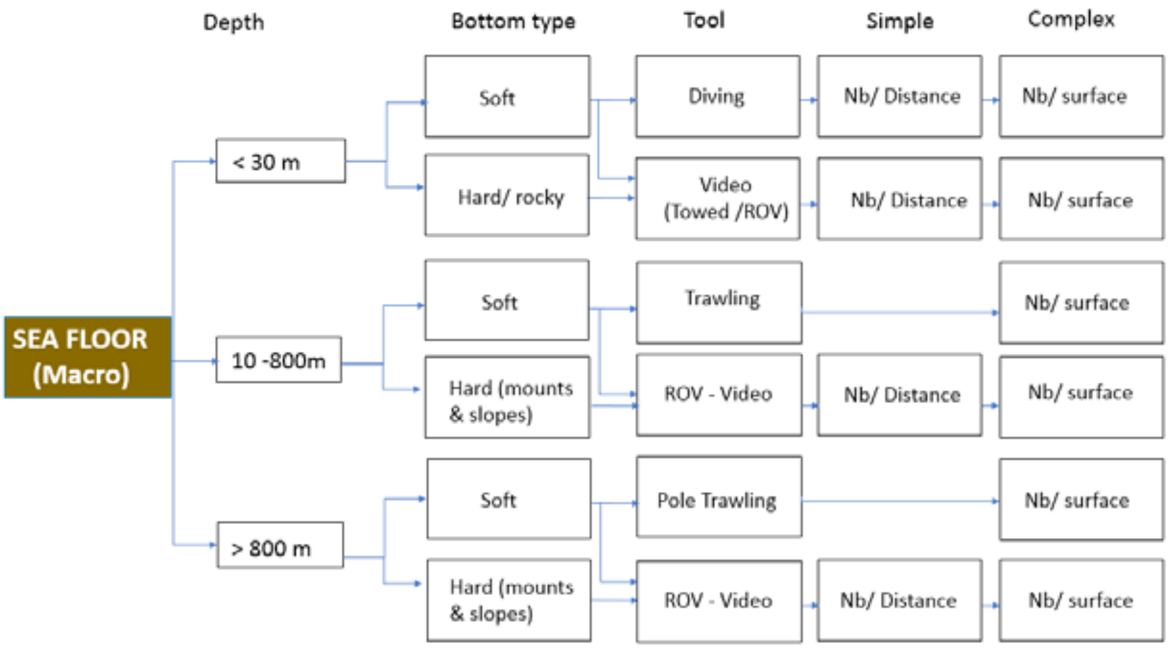


Figure 6.2: Decision flowchart for monitoring Macro-litter on the sea floor (Nb: Number).

approaches may be used to minimize costs. Simple protocols based on existing trawl surveys, visual surveys via SCUBA and video imagery via Remote Operated Vehicles (ROVs) are the most common approaches.

The monitoring of litter on the sea floor will tend to reflect gradual accumulation processes, in particular if the litter is not retrieved. Timescales of observation should therefore be adapted, requiring multiannual frequencies for deep sea floor surveys. General strategies for the investigation of seafloor litter are similar to those used to assess the abundance and composition of benthic species. This enables an opportunistic evaluation to be achieved through widespread biodiversity sampling by diving, trawling and video/photographic surveys.

Shallow areas

For shallow waters, information can be obtained from on-going monitoring of benthic species through regular diving activities, usually coupled with regular surveys (marine reserve, offshore platforms, etc.) and programmes on biodiversity, since methods for determining seafloor litter distributions (e.g. diving, video) are similar to those used for biodiversity assessments.

The most common method to estimate marine litter density in shallow areas is through underwater visual surveys, using distance sampling, mainly transect sampling, a method for estimating abundance and/or population density (Buckland *et al.* 2001, Spengler and Costa, 2008, Galgani *et al.* 2013) that is compatible with UNEP protocols (Cheshire *et al.* 2009). This method requires SCUBA equipment and skilled observers and is limited to depths of 20-30m for regular surveys. Surveys are conducted using at least 2 line transects, 2-4 meters wide for each site, randomly chosen, along a 50-100 m nylon line, deployed on the bottom, and recording individual items within 2-4 meters width delineated using a plastic rod. Characteristics of the site (habitat, bottom type, depth, turbidity are also recorded and results are expressed in density (items m^{-2} or items 100 m^{-2}) among various litter categories (e.g. plastic, metal), specific items (e.g. bags, bottles) or sources (e.g. fishing gears, sanitary). Sites should be selected with flat and uniform substrata without risks of wrecks, munitions and/or endangered or protected species.

Trawling

In deeper waters (approximately ≥ 10 m), trawling, towing a bottom trawl net (e.g. demersal/otter or beam/pole trawl), is an effective method for large-scale evaluation and monitoring of seafloor litter, with control of the mesh size and opening width of the trawl (Goldberg 1994, Galgani *et al.* 2013). A particularly efficient and cost-effective approach is to take advantage of trawl surveys that are undertaken as part of routine fish stock assessments. Fisheries monitoring programmes for demersal (bottom-dwelling) fish stocks operate at large regional scales, providing fisheries data using a harmonized protocol[47], providing an opportunity to develop a consistent approach for monitoring seafloor litter.

It should be noted that the seafloor topography may effect the accumulation of litter on the seafloor and impose some sampling restrictions in rocky areas (incompatible with trawling). This may lead to the underestimation of the quantities present. Nets are designed to collect epibenthos (surface-dwelling organisms) and not deeply-buried items, although both demersal and beam trawls do disturb the upper layer of sediment. Existing assessment programmes of well-managed coastal fisheries take place annually in many regions, facilitating a more harmonised approach and a future global management of data.

The collection of litter on board allows the abundance, typology and potentially sources of litter to be evaluated. Harmonized and common tools and conditions of sampling are necessary for reliable large spatial scale monitoring; for example, fixed aperture of the net, consistent towing speed at 2-3 knots, 20-40 mm mesh, 30-60 minutes tows. Environmental information (temperature, salinity, wind and sea conditions) should be collected at the same time. A minimum of 20 sampling units is recommended within each region (Cheshire *et al.* 2009). For regular monitoring, preliminary statistical power analysis is beneficial to test the robustness of the sampling design. Bottom trawling does have a significant impact of benthic ecosystems and creating a new monitoring programme simply to monitor seafloor litter may not be justified from an environmental perspective, especially when other methods are available.

47 http://www.ices.dk/marine-data/data-portals/Pages/DATRAS.aspx

Remotely operated vehicles (ROV)

Using trawls for seafloor monitoring is limited largely to low-relief, smooth substrata and is not appropriate for steep slopes or rocky bottoms, where specialised equipment is necessary. Remotely Operated Vehicles (ROVs), when available, are recommended for litter surveys on continental slopes, uneven terrain and the deep seafloor. Then the approach is very similar to the distance/line transect approach for shallow waters with different specification for the survey location, choice of sampling units, and methodology for collection, if any

Higher priority may be given to coastal canyons (Figure 6.4), and other areas where litter accumulates, and through an opportunistic approach in order to limit costs. This approach is of great use for areas inaccessible by other means, such as steep slopes, rocky bottoms, and ultra-deep areas, down to the oceanic trenches (Galgani and Lecornu 2004, Bergmann and Klages 2012, Miyake *et al.* 2011, Ioakeimidis *et al.* 2015, Tekman *et al.* 2017, Chiba *et al.* 2018).

Images (high resolution) are usually recorded with video cameras, moveable or not, during surveys performed at low speed (0.5-2 knots). When possible, two laser beams allow measuring the size of objects and distances on the seafloor. Altimeters are necessary to evaluate the altitude and then, depending on the focus of the camera, the surface of the area sampled during surveys may be estimated.

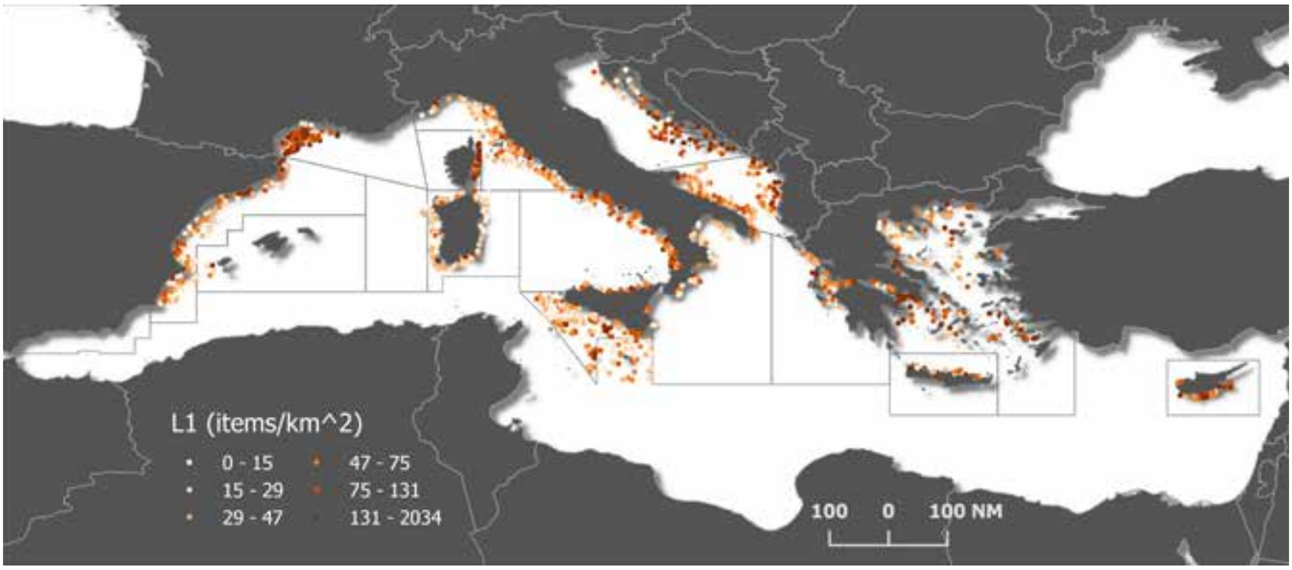


Figure 6.3: Harmonized monitoring of plastic litter (L1) in the northern Mediterranean Sea, based upon marine litter data collected by 12 institutions from 7 countries. Data was collected at 1279 survey stations sampled during fish stock assessment cruises (Medits PROJECT[48]) using the same protocol and trawl net. Results are expressed as plastic densities (items km^{-2}) (with permission Spedicato *et al.* in press).

48 http://www.sibm.it/SITO%20MEDITS/principaleprogramme.htm

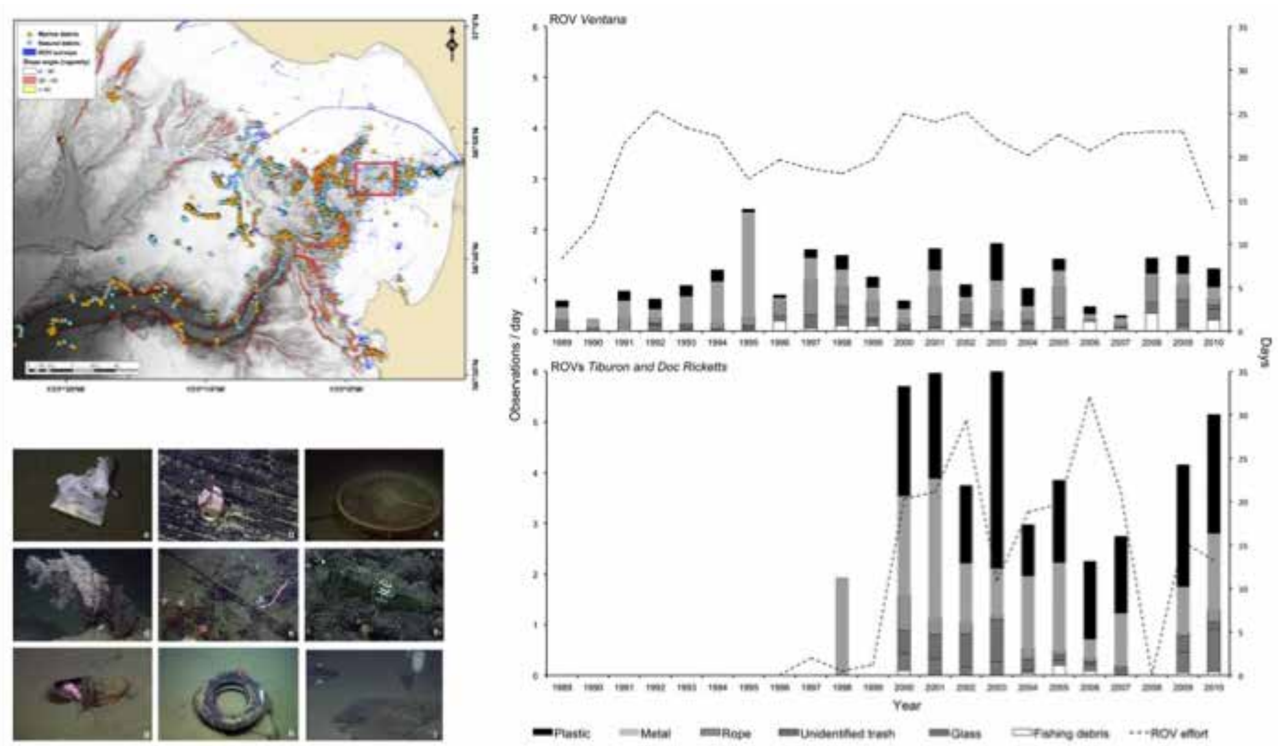


Figure 6.4 Distribution and relative frequency of marine litter observed by ROV surveys in Monterey Canyon off the coast of California USA, 1998 – 2010; upper left – morphology of seabed and location of observed items; lower left – selection of items observed; right -relative frequency of marine litter observations of the six most common categories shown by year for MBARI's three ROVs (normalized by ROV effort indicated by the dotted line overlay). ROV Ventana capable to 1850 m; ROVs Tiburon (1998–2007) and Doc Ricketts (2009, 2010) capable to 4000 m. Image reproduced under Creative Commons (Licence © Schlining *et al.* 2013).

Usually, transect routes are strategically distributed in order to delineate surveys along canyon heads, floors and flanks at various depths to obtain an overall visual picture of the distribution. The cumulative inspected seafloor distance is recorded. Images are also referenced on navigation logs, with time of observation, water depth and geographic position along a given transect route. Single frames may be extracted from video records for further analysis and identification.

The area inspected during ROV transects results from multiplying the transect length by the field of vision width of the ROV camera estimated from the laser pointer scale in the video images or from the altitude. Items are counted for each dive and results are then expressed in densities (items per unit area; m², km2 or hectares (1 ha – 0.01 km²)) or in numbers (items per unit length; m or km) when lasers are not available. Main categories of litter are considered by type, often considering also specific sources such as fishing gears. Litter objects may also be quantified by size (Mordecai *et al.* 2011), when weight cannot be determined directed when using imagery. An estimate can be made of the mass of an object from a consideration of the volume and type of material (e.g. metal, glass, plastic) and category of the object (e.g. 1 litre bottle, car tyre), although this will not be very reliable (Buhl-Mortensen and Buhl-Mortensen 2017). It is important to record metadata such as the location of the sections explored, the geographic coordinates of the middle point of each dive, the depth range and total length per dive enables each of the approaches to calculate the density and abundance of litter, the average depth and distance to the coast of litter items.

Recently, learning algorithms were proposed for the successful visual detection of litter in underwater environments, with the eventual goal of exploration and mapping of such litter by using underwater platforms, including Autonomous Underwater Vehicles (AUVs) (Fulton *et al.* 2018). The approach appears to support future real-time surveys and analysis. In some specific cases, AUVs can be also successfully used with acoustic tools to detect lost/derelict traps (Clark *et al.* 2012). The approach remains however limited to areas with reduced ridges (rugosity <15 degree slope).

Each of the approaches used has its advantages and limitations. A comparison of the possible approaches was reported in 2013 (Galgani *et al.* 2013) (see table 8.1), based on depth of use, equipment requirements, seafloor characteristics, applicability and limitations. Typically, when visual observations are relevant for shallow (through diving) and deep sea (through ROV surveys), trawling is more adapted for flat sandy bottoms at intermediate depths. Some are requiring high skills (ROVs) and/or considerable means (deep sea surveys) when costs may be limited through opportunistic surveys.

Table 6.1: A comparison of approaches for monitoring marine Litter on the Sea floor (derived from the Marine Strategy Framework directive - Technical Group on Marine Litter, Galgani *et al.* 2013)

Protocol	Diving	Trawling	Pole* trawling	ROVs	Microplastics
Maximum depth	30 m	800-1000 m	2500m	20-6000m	11000
Equipment	Diving Equipment	Net	Pole net	ROV/ SUB	Grab/corer
Supporting vessel	Small	Large	Small / Large	Small / Large	Small / Large
Maturity (Low/ Medium/High)	H	H	M	M	M (extraction procedures)
Expertise	M	L/M	H	H	M/H
Applicability	Coastal	Shelves and bathyal	Shelves/bathyal/ abyssal	Any location, including slopes	Any flat area
Bottom type	Any	Soft bottom	Soft bottom	Any	Soft bottom
Limitations	Depth, Depends on accessibility to diving area	Restricted to flat/smooth bottoms	Restricted to flat/ smooth bottoms	Expensive, unless coupled with existing deep-sea bottom surveys	Spatial representativity
Opportunistic approach	Yes, in MPAs or cleaning operation	Yes	No regular surveys	Yes, recommended	Opportunistic cruises

* also referred to as beam trawling

Case study: Detection of lost or abandoned commercial fishing gear on the sea floor

In a dedicated workshop, NOAA (Morison and Murphy, 2009) reviewed the existing methods, including acoustic, to locate, and assess derelict pots, to define best detection system. Key environmental and technological factors were considered to select a detection system able to locate pots items of the appropriate shape and size. The detection methods tested were side scan sonar, side imaging, sounder, multibeam sonar, towed diver and video, with due consideration given to the survey environment, survey approach and logistical background. Taken together on the following table, this information allows the selection of the best method to detect derelict pots. Further details of different categories of fishing gear are described in Annex IV.

Table 6.2: information and variables to consider to select a detection method for derelict pots for a given survey area (after Morison and Murphy 2009)

Environment	Side scan sonar	Side imaging sounder	Multi beam Sonar	Diver tow	Video
Flat bottom	YES	YES	YES	YES	YES
Soft Bottom	YES	YES	YES	YES	YES
Pebbles <Rocky	NO	NO	NO	YES	YES
Boulders > Rocky	NO	YES	YES	YES	NO
Sea mounts	YES	YES	YES	YES	NO
High relief bottom	YES	YES	YES	YES	YES
High Turbidity	YES	YES	YES	NO	NO
Protocols	**Side scan sonar**	**Side imaging sounder**	**Multi beam Sonar**	**Diver tow**	**Video**
Depth	2-600m	1-10m	> 2m	2-15m	2-6000m
Elevation/altitude	10% of water depth	N/A	N/A	Topography dependent	Visible dependent
Frequency	300-600 kHz	455 kHz	240-255 kHz	N/A	N/A
area coverage / Width	20-50	20-25	3.5 x Elevation	Visible	Visible
Speed	4-5 kts	4-5 kts	4-5 kts	< 1,6 kt	> 1 kt
Logistics	**Side scan sonar**	**Side imaging sounder**	**Multi beam Sonar**	**Diver tow**	**Video**
Platform	Vessel	Vessel	Vessel	Vessel	Vessel
Recording	Portable HD	Portable HD/ USB	Portable HD	Video-still camera/ writing tablet	Video-still camera/ surface
Geo referencing	GPS	GPS	GPS	GPS	GPS
Data tracking	Processing software	database	Processing software	database	database
Recommended equipment	Winch	Pole/cable		Manta tow bar	Pole/mount

6.2.3 Categories, reporting units and data management

Ideally, all protocols can supply quantitative data, and allow the assessment of trends. Some approaches may also identify sources by using a detailed list of identifiable items. For sea floor litter, there is no regional difference in the protocols, and most of them can be applied across large scales.

Data on litter should be collected using common templates and agreed items categories, with various subcategories for more detailed descriptions of litter items. These categories must be defined in accordance with the types of litter found at a regional level, enabling common main categories and comparability. Ideally, a hierarchal system should consider the main categories of material (plastic, metal, rubber, etc.) and include subcategories with more details on items. Standardized litter classification systems have been defined for such an approach (Cheshire 2009, Galgani *et al.* 2013) both considering the specificity of the sea floor. A possible template for sea floor litter is proposed by GESAMP, considering a limited number of main categories that include the top items to support possible reduction and management measures. An analysis of literature indicates that plastic bags and sheets, plastic bottles, food wrappers, synthetic ropes, fishing ropes and nets, metallic cans and other remaining plastics are the main categories to be considered in priority. Additional specific categories or items may be added, mainly on regional or local basis but with an open door for harmonized procedures for data management and analysis. Moreover, as an analysis of sources will indicate the importance and differences between ships or land-based litter and the impact of some activities such as fishing or tourism, the definition of categories will have to take this in account when defining a protocol. This may also affect the strategy for monitoring specific items of greatest importance locally

When local surveys may require harmonisation and adequate data storage and management, the use of a central database may favour global data management and has been already considered at continental or oceanic basin scales. For example, the European Marine Observation and Data Network (Emodnet[49]) has started to gather, aggregate and harmonise seafloor litter data scattered over Europe, through close collaboration with many data providers and experts from among Regional Seas Conventions and European project initiatives The data are from trawling operations, with 5500 hauls included currently in the database. The tool is open to wider contributors and may serve as a database for larger scale data management of sea floor litter data collected through trawl operations.

The Global Oceanographic Data Center (GODAC) of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) launched the Deep-sea Debris Database for public use in March 2017 (Chiba *et al.* 2018). The database archives photographs and videos of litter that have been collected since 1983 by deep-sea submersibles and remotely operated vehicles. Establishment of international frameworks on monitoring of deep-sea plastic pollution as an Essential Ocean Variable and a data sharing protocol are the keys to delivering scientific outcomes that are useful for the effective management of plastic pollution and the conservation of deep-sea ecosystems. Extending this existing database to other existing videos/pictures from other institution/surveys may provide a valuable support for monitoring, analysis of distribution, impacts and trends in the deep-sea environment.

6.2.4 Limitations

Each of the techniques used for estimating the distribution of litter on the seafloor has advantages and disadvantages, but can provide information that can be used in assessments and for guiding management actions. A trawling survey is an efficient technique for providing an area average, although does not allow the precise distribution of litter to be recorded. Once litter is recovered on the ship it can be examined, weighed and retained for further analysis. Different gear types may differ in their efficiency of 'catching' seafloor litter (Kammann *et al.* 2018), introducing an uncertainty when comparing regions or establishing time trends unless a harmonised methodology is used. Trawling surveys cannot sample buried litter and will under sample small items.

Visual surveys, by diver or ROV, can provide the coordinates of items as well as additional information

Table 6.3: A summary of reporting units for sea floor litter

Type of monitoring	Method	simple units[a]	complex units[b]	Mass
Shallow water/ Diving	Visual/ Distance sampling	items/ 100m	Items 100 m^{-2}	After clean-ups only
Trawling	Collection/ stratified sampling, fishing net		Items ha^{-1} or items km^{-2}	Possible
Trawling	Collection/ Pole trawling		Items ha^{-1} or items km^{-2}	Possible
ROVs	visual/ Distance sampling	items/ 1000m	Items ha^{-1} or items km^{-2}	Not possible

[a] Investigations using divers or submersibles often consider the number of items per linear distance (100m or kilometre) because of the variability in transect width.
[b] Area measurements may be reported in m^2, km^2 or hectares (I ha = 0.01 km^2).

49 http://www.emodnet.eu

Table 6.4: Evaluation of costs for the various approaches used to monitor marine Litter on the sea floor (L/LOW: < 10k€; M/ MEDIUM: 10 - 50k€; H/ HIGH: 50-100 k€; VH/ VERY HIGH: > € 100k), derived from (Galgani *et al.* 2013).

Protocol	Diving (<30m)	Trawling (20-800m)	ROVs (20-6000m)	Microplastics
Cost categories	L/LOW: < 10k€; M/MEDIUM: 10 - 50k€; H/ HIGH: 50-100 k€; VH/ VERY HIGH: > € 100k			
Collection of samples	M	L/M	H/VH	M
Analysis of samples	L/M	L/M	M	H/VH
Statistical analysis	M	L/M	M	M/H
Equipement	M	L/M	VH	VH
Expertise*	M	L/M	H	M/H
Overall	M	L/M	H	H

* trained personnel without (L) or with (M) specific formation, or with high expertise and special skills (H).

about the local environmental and the biological setting, but only for visible meso- and macro-scopic litter. Several studies have analysed still images, a sort of sub-sample of video surveys (Tubau *et al.* 2015, Mordecai *et al.* 2011, Pham *et al.* 2014), whereas others have analysed continuous video (Pham *et al.* 2013, 2014) or a combination of still and video images (Fabri *et al.* 2014). Whichever approach is used it is important to quantify the area or transect length of seafloor being observed (e.g. quadrat, laser markers, distance towed, camera angle).

In its guidance, the EU-MSFD Technical Group on Marine litter analysed the costs of monitoring the different compartments of the environment through diving, trawling and through Remote Operated Vehicles (Table 6.4).

6.3 Microplastics

6.3.1 Introduction

Microparticles, mainly microplastics have already been identified in sediments throughout the world's seas and oceans even in remote and ultra-deep locations, as summarised by (Peng *et al.* 2018). The highest microplastic concentrations were found at concentrations of up to 4300 microplastics/kg of dry sediment in a harbour sediment sample in Tasmania (Willis *et al.* 2017).

Generally, there are three main aspects of the analytical process for measuring microplastics in sediment samples: sampling, extraction, and quantification. Here we discuss mainly sampling when the two other processes are described and discussed in the chapter 11 of this volume.

6.3.2 The Monitoring strategy methods

There can be significant heterogeneity in the distribution of microplastics in marine sediments (GESAMP 2015, 2016), emphasising the need to harmonize sampling methodologies. Sampling sediments can require significantly more effort and resources, depending on the water depth. In addition to differences types of sediments, most studies have reported various polymer types that have created methodological challenges, especially for targeted, quantitative analyses of small microplastics. The observed variations in environmental samples are due to many factors, including: local sedimentary dynamics, proximity to point sources (e.g. waste water treatment plants, rivers draining industrialised or heavily populated catchments (Dris *et al.* 2015, Hanvey *et al.* 2016, Lebreton *et al.* 2017), the diversity in the type and size of particles, the sample matrix. There is however no clear trend between sediment grain size and microplastic deposition in sediments (Alomar *et al.* 2016). Defining a consistent sampling strategy is critical to achieve robust and comparable datasets. The nature of the prevailing currents and types of sediment must be considered when choosing an appropriate sampling site.

Sediment samples are collected using some form of sampling grab (surface and near-surface sediment from a bulk sample) or coring device (surface and sub-surface distribution). Sediment samplers can be utilised by divers, ROVs or from surface vessels.

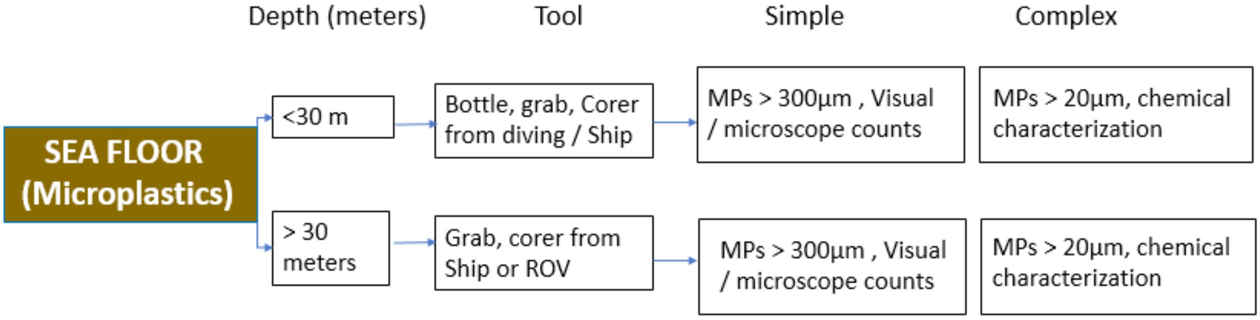


Figure 6.4: Decision flowchart for monitoring microplastics on the sea floor.

Attempts should be made to obtain replicate sediment samples (minimum of three if possible), and it is important to measure the area and volume of sediment sampled, to calculate the abundance. Sampling sediments for microplastics is a relatively new field and further advice will be developed with greater experience (e.g. number of replicates, frequency of sampling, most appropriate method(s))

Sediment cores can be sliced into sections (e.g. 0-10, 10-20, 20-30mm) to record the vertical distribution of microplastics. If the sediments have been relatively undisturbed by physical or biological (bioturbation) processes then it may be possible to measure the approximate age of deposition, and hence the deposition history, using a radiological dating method, such as that based on the naturally occurring radionuclide 210Pb (Pereira *et al.* 1999).

As with any form of microplastic monitoring, precautions must be taken to avoid background plastic contamination by air exposure (covering samples, subsamples and filters), using glassware wherever possible and sample blanks to correct results for background contamination. Recommended methods for sediment sample processing are described in Chapter 8.

6.3.3 Monitoring strategy

A lack of harmonisation between sampling methods in published studies has hindered an inter-comparison of the relative abundance of microplastics in sediments worldwide (Hanvey *et al.* 2016). The choice of sampling strategy and sampling approach reviewed by (Hidalgo-Ruz *et al.* 2012) will determine the categories and units in which observed abundances will be reported. While a simple conversion can sometimes be made to compare among studies, comparison is often impossible or requires assumptions that lead to biased results. Studies sampling an area (using quadrants) will often report numbers per unit of surface area (m^{-2}) (Frias *et al.* 2016). If bulk samples from the surface to a specific depth are taken, the reporting unit is usually numbers per unit volume sampled (m^{-3}). The total sample mass of microplastic should be reported per unit mass dry sediment.

Figure 6.5: Fishing For Litter initiatives aim at collecting marine litter and may support the collection of data and participative monitoring (image courtesy of KIMO International).

6.4 Citizen science

Citizen science can play a useful role in monitoring sea floor litter, but only for those 'citizens' who have specialist skills or occupational experience. Recreational and professional scuba divers have been involved in regular observations or cleaning operations (Galgani *et al.* 2013). Many underwater clean-ups organized by clubs or NGOs can be a valuable source of information and part of a regular surveys. For example, Project AWARE's 'Dive Against Debris' programme provides guidelines and field protocols for scuba divers on how to collect and report marine litter found underwater[50]. Divers are encouraged to conduct surveys at the same dive site on a regular basis, removing the litter, recording the amounts and types of litter and disseminating the compiled information to the general public. With common methodologies and approaches, this may support an efficient network for shallow-water litter monitoring. The Global Ghost Gear Initiative (GGGI)[51] was launched in September 2015, bringing together existing initiatives and organisations from the fishing industry, private sector, academia, governments, intergovernmental and non-governmental organisation. Harnessing this 'group of the willing' has the potential to make a major contribution to monitoring (and removing) ALDFG

More regionally, KIMO[52], representing municipalities in several countries in north-western Europe, coordinates an initiative called 'Fishing for Litter'. This aims to reduce marine litter by involving one of the key stakeholders, the fishing industry. The scheme works by providing participating fishing vessels with large bags in which litter picked up in the fishing nets can be temporally stored, before being offloaded and properly disposed of at the port, at no cost to the fishers. The initiative not only involves the direct removal of litter from the sea, it also raises awareness of the problem in the fishing industry and provide information on litter that may be useful to support regular assessments and monitoring.

See Annex VII for additional protocols for monitoring the seafloor

50 https://www.projectaware.org/issue/marine-debris
51 www.ghostgear.org
52 www.kimointernational.org

7 MONITORING METHODS FOR MARINE BIOTA

7.1 Description and relevance of interaction of marine litter with biota

Marine biota interact with both large and small items of plastics. Depending on its size, plastic can have different impacts on biota (Figure 7.1). For example, entanglement in large marine litter not only affects individual organisms, but also smothers sensitive habitats including coral reefs. On the other hand, consequences of biota ingesting plastic items will depend on the both the size of the organisms and the size of the plastic itself. A larger piece of plastic might lead to blockages of digestive tracts whereas smaller particles could translocate from stomachs into other organs, with sub-lethal and cellular effects. For more information on the effects refer to the earlier GESAMP reports (GESAMP 2015, 2016). Monitoring the interactions and effects of plastics on biota is heavily reliant on organisms' physiology and life history, as this influence the susceptibility of the organism to experience negative consequences. To understand the effects and answer relevant policy questions, suitable monitoring methods must be identified.

7.2 Biota as indicators for monitoring plastic litter: deciding what to sample

7.2.1 Policy relevant aspects of biota monitoring

Biota is an important and informative compartment to assess and monitor marine litter. Where marine litter is present in the environment, there are four policy-relevant aspects that can be assessed when utilizing biota as a monitoring tool:

1. Impact on biota
2. Impact on human health and wellbeing
3. Impact on the ecosystem
4. Overall indicator of ecosystem contamination

Impact on biota
As an example, policy relevant questions could be related to where (main hotspots) and to what extent (quantity and types/sizes of items) biota are impacted. The impact may occur at different levels of organization; i.e. individual, population or ecosystem. Information on the impacts of marine litter on marine biota has been recorded mostly during the last decade, focussing on ingestion and entanglement of individuals. The quantity of litter present in an individual will represent a combination of the exposure (i.e. quantity of litter in the surrounding environment) and the residence time in the digestive tract or tissues, which will differ amongst different types of organism.

Impact on human health and wellbeing of microplastics
The ingestion (presence in the digestive tract) and assimilation (into tissues) of microplastics by biota represents a potential risk to human health, as a result of seafood[53] consumption, as well as to higher

53 seafood – broadly defined as any living matter originating in the marine environment that is consumed by humans

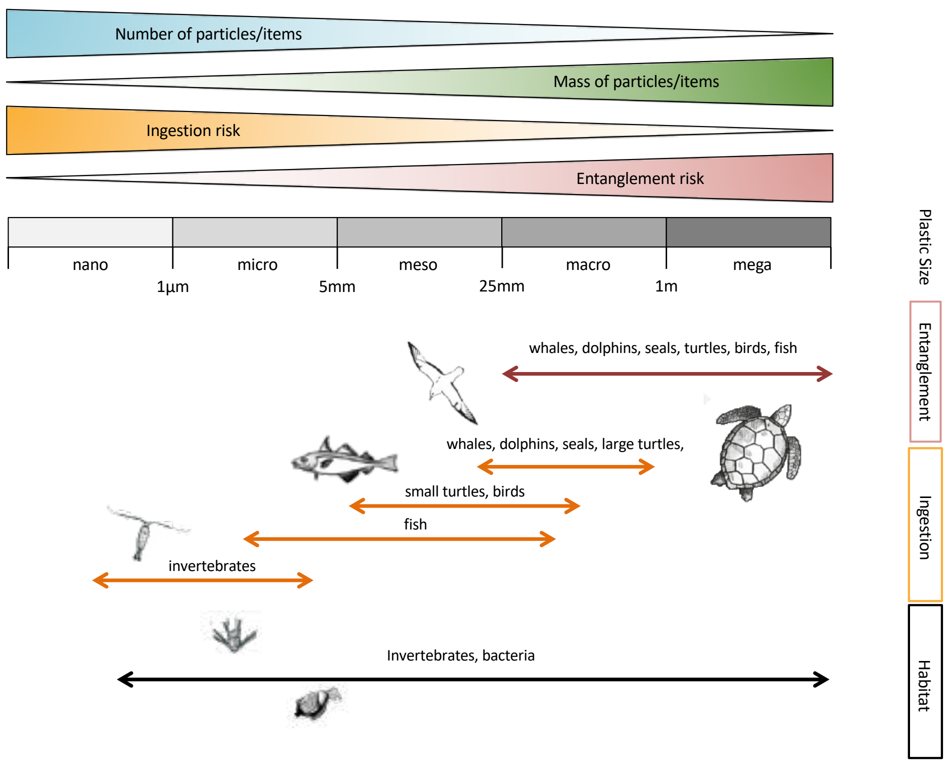


Figure 7.1 Schematic representation of the impacts of different sized plastics on marine biota including entanglement, ingestion and habitat associated risk (Adapted from GESAMP 2015).

trophic levels (predators). This can be the result of a reaction by the consumer to the physical presence of the particle, or by exposure to chemicals associated with the plastic (section 2.3.3). The current body of scientific evidence leads to the conclusion that this risk minimal, at present, although further research is required to improve the knowledge base and reduce uncertainty (SAPEA 2019[54]). Nevertheless, monitoring may be required to reassure consumers and the market, as well as establish whether exposure levels are increasing or decreasing.

Impact on ecosystems
Some of the most obvious examples of ecosystem-wide impacts concern the interaction with fishing gear. ALDFG can smother or damage sensitive habitats, such as coral reefs and seagrass beds. Nets, pots and traps can continue to attract and entangle or capture biota, both target and non-target species, a phenomenon referred to as 'ghost fishing'. This can alter the species composition and influence the way the ecosystem functions. More subtle changes can be caused by the filtration and absorption of microplastics by coral polyps (Hankins *et al.* 2018).

Marine plastic litter and microplastics provide additional, durable surfaces for the attachment and growth of organisms. This provides a vector for the transport of organisms, including the transfer of non-indigenous species, between ocean compartments (sinking due to buoyancy changes) or between geographical regions (floating on ocean currents). This was dramatically illustrated following the 2011 Tōhoku earthquake and tsunami (section 4.2.1), following which there was a significant transfer of species from the east coast of Japan to the western seaboard of North America (section 7.4.1). This has been described in reports and scientific publications from a major joint study undertaken by Japan, Canada and the USA (ADRIFT)[55].

Monitoring biota as an overall indicator of ecosystem contamination
Biota can be used as an indicator of overall environmental contamination by marine litter. In this case the impact on biota is of secondary importance to utilising the habits of particular species to reflect the degree of contamination, especially due to ingestion. The selection may be of a sessile species, such as a filter-feeding bivalve, providing an indicator of microplastic contamination at the sampling location. Alternatively, the selected species may be mobile, providing a spatially-integrated indicator. Several species of seabird have proved to be suitable indicators of floating plastics. A bio-indicator can be defined as an organism that gives information about the environmental conditions of its habitat, by its presence or absence or by its behaviour (van Gestel and van Brummelen 1996). This differs from a biomarker, defined as a measurement revealing an interaction between a biological system and a potential hazard (chemical, physical or biological) (WHO 1993). Section 7.3.5 provides further examples.

54 https://www.sapea.info/topics/microplastics/
55 https://meetings.pices.int/ adrift projects/

Bio-indicator: an organism giving information on the environmental conditions of its habitat by its presence or absence or by its behaviour (Van Gestel and Van Brummelen 1996).

Biomarker: includes almost any measurement showing an interaction with a biological system and a potential hazard (chemical, physical or biological) (WHO, 1993).

7.2.2 Selection of biota for monitoring

Utilizing biota for monitoring requires the selection of a suitable species to act as a bio-indicator of plastic contamination. It is important to identify species that are representative of different life histories, phylogeny, size, age and development stage. Impacts of plastics on organisms can vary dramatically between species, as well as between individuals.

Box 7.1: Criteria for good indicator species (or groups of species)

- ❑ Regional representation (e.g. sessile or mobile species within a specific geographic range)
- ❑ Ethically sound (e.g. non-threatened or not protected, opportunistically sampling dead organisms)
- ❑ Abundant in chosen environment
- ❑ Already used as bioindicator/biomonitoring species
- ❑ Cost of routine sampling/analysis (e.g. sampling simultaneously for other pollutants and merging with other programmes, easily accessible)
- ❑ Easy, practical analysis in the laboratory
- ❑ Commercially and ecologically important (e.g. regional food source)
- ❑ Species that are directly linkable to impact and effects
- ❑ Integrated at a source
- ❑ Comparable globally- similar species identified worldwide (e.g. mussel watch)
- ❑ If more than one species are to be chosen:
  - Species should together cover several ecological niches: pelagic, demersal and benthic
  - Species should cover several feeding strategies (e.g. filter feeders, scavengers etc.).

Size
The size of an organism can influence the nature and extent of interaction with different sizes and types

of marine litter, depending on feeding strategy and other life traits. But the relationship is quite complex.

Patterns of activity
Diurnal patters of activity need to be considered, as some organisms feed during the night and carry out migrations to greater depths during the day. Therefore the presence of plastic items in the gut may be influenced by time of sampling if the residence time of plastic in the gut is relatively short (Lusher *et al.* 2017). Some economically important species, such as sea cucumber (*Holothuroidea*) are only active at night. In addition, fishing for certain species may be dependent on the time of day. For example, anchovies (*Stolephorus sp.*) are fished at night in Indonesian waters.

Feeding strategies
Marine organisms have different feeding strategies which may influence how, or to what extent, they interact with plastic litter and microplastics (GESAMP 2016):

Filter-feeding and suspension feeding

These are very common feeding strategies in the ocean. Sessile filter feeders such as barnacles, bivalves and polyps, pump seawater and strain plankton from it. Mobile filter feeders include many species of fish, which swim with their mouth open letting water flow through gill rakers, or baleen whales which force water through a comb-like baleen filter. Suspension feeders pick material from the water as it falls. This feeding is non-selective and therefore increases the likelihood of ingesting plastics during normal feeding routines (Fossi *et al.* 2014).

Deposit feeding organisms

Deposit feeding organisms consume detritus once it has settled on the sediment. Examples include annelid worms and echinoderms (Bour *et al.* 2018).

Predation and scavenging

Predation and scavenging provide mechanisms for the transfer of microplastics in the prey. Predation may lead to the accumulation of microplastics in higher trophic level predator species (Lusher *et al.* 2016).

Grazing

Biota which utilise this feeding strategy include many species of gastropod (snails) including true limpets (*Patella sp.*) and the common periwinkle (*Littorina littorea*) which scrape algae from surfaces in the water. Any particles adhering to the algae will tend to be ingested (Gutow *et al.* 2016).

Intergenerational transfer

Possibly the best-known example of this phenomenon is the transfer of plastic litter by the Laysan albatross (*Phoebastria immutabilis*) during the feeding of chicks by regurgitation of a food bolus. As a result, fledglings often have large plastic loads (Figure 7.2). The relative quantity transferred does depend on the feeding strategy of the parents, in particular the geographical extent of their foraging territory and correspondence with the distribution of floating plastic litter (Young *et al.* 2009).

Figure 7.2 Plastic in the gut of a Laysan albatross chick (*Phoebastria immutabilis*), Green Island, Paphanaumokuakea Marine National Monument in the Northwestern Hawaiian Islands (image taken from ©Young *et al.* 2009 – Creative Commons Attribution License).

7.3 Strategies for monitoring

7.3.1 General strategies

A summary of monitoring strategies using biota is presented in Figure 7.3. Strategies include specifically targeting biota, market sampling of commercial species and opportunistic sampling. For example, regular surveys of beaches for stranded marine mammals, seabirds and turtles provide a measure of entanglement or ingestion risk. They can also yield samples that can be checked for plastic ingestion, if they are still intact and sufficiently fresh to examine the gut contents. Such surveys potentially also could collect data on encrusting biota on litter items, but expecting observers to collect too many types of data at once is likely to impact search efficiency. Each of these approaches is described in more detail in the following sections.

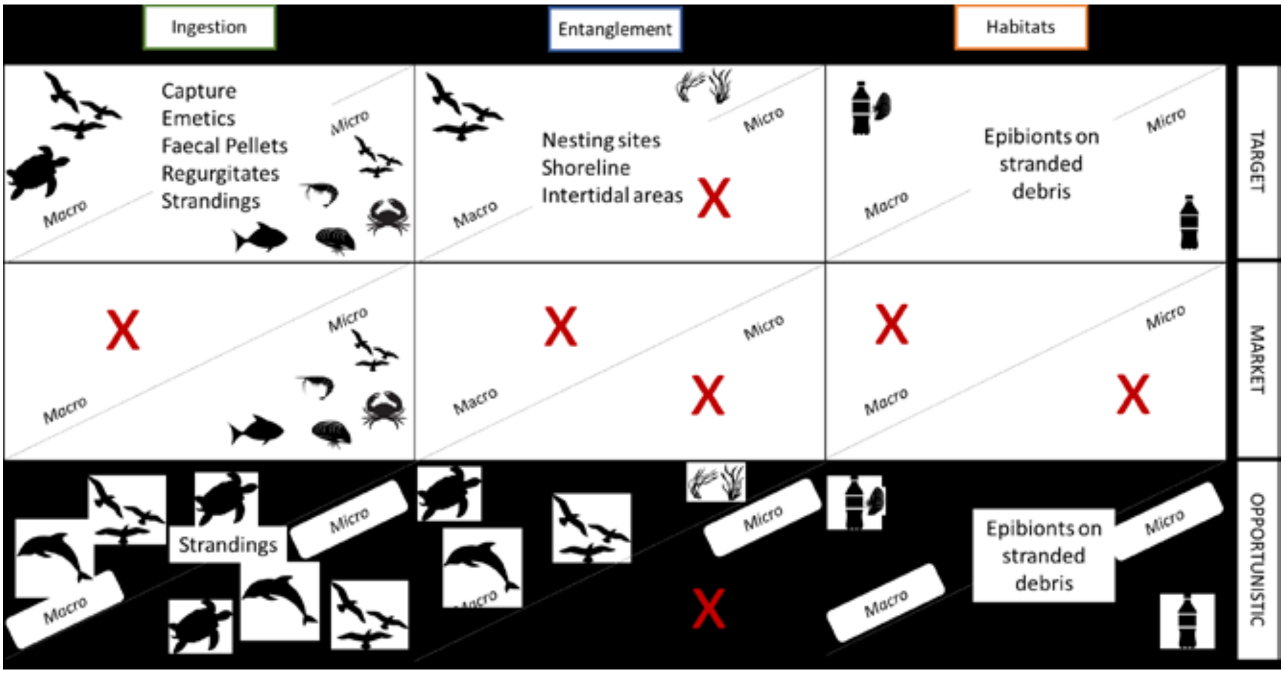


Figure 7.3 A summary of monitoring strategies using biota, with figurative outlines of some of the major taxonomic groups (non-exhaustive). An 'X' indicates the lack of an appropriate organisms in either the micro- or macro-litter size range.

Monitoring may target specific organisms depending on their biology, behaviour or relationship with the environment or humans. Target species may vary from place to place, but some organisms are more suitable for use in global monitoring schemes, including sessile invertebrates such as mussels (*Mytilus sp.*) and oysters (*Ostreidae*, e.g. *Crassostrea gigas*). These examples are eaten whole by the human consumer, so any particles in the gut will be ingested. This also applies to other organisms which are eaten whole, such as small pelagic fish, echinoderms and sea cucumber. Organisms whose edible parts do not include the digestive tract – such as larger fish, squids and crustaceans - may also be used for monitoring, from a human health perspective.

Sessile organisms will tend to reflect local levels of plastic contamination. Organisms with higher mobility, such as fish, turtles, birds and mammals, may represent the availability of litter at larger spatial scales. Organisms with different feeding habits may provide information from different sea compartments. For example, small pelagic filter-feeding fish, such as sardines, will be exposed to floating litter (less dense) in the water column or sea surface, while bottom deposit-feeding fish may be exposed to a different set of denser particles. Thus, a monitoring strategy based on biota samples should consider a combination of organisms that reflects the amount of litter in different compartments and spatial and temporal scales.

7.3.2 Monitoring of biota for plastic ingestion

Some species can provide a convenient means of assessing the abundance and types of litter in the environment (Table 7.1). The ingestion of litter will depend on the feeding strategies and relative size of the organisms, with some species appearing more susceptible to ingestion than others. Two main approaches are possible:

(i) taking samples from dead organisms, for example either found opportunistically stranded on the shoreline or captured by fisheries operations; and,

(ii) taking samples from, or associated with, live animals, for example regurgitated pellets, scat, nesting material or entangled litter. Sampling live animals should be done with appropriate care to minimise disturbance or harm.

Seabirds

Seabirds most at risk from ingested plastic are those species that accumulate plastics in the gizzard, such as the petrels, storm petrels, phalaropes and fulmars (Kühn *et al.* 2015, Ryan *et al.* 2016). Because the gizzard is the lowest part of the stomach, it is hard to sample their plastic loads non-destructively. Stomach pumping or emetics can be used to sample stomach contents, but neither approach reliably recovers all ingested plastic (Ryan and Jackson 1987), and emetics in particular can cause mortality (Bond and Lavers 2013). Species still exploited for food (e.g. some auks and shearwaters) or those killed accidentally (e.g. fishery by-catch, birds attracted to lights on breeding islands), offer the opportunity to regularly examine adequate numbers of individuals without having to resort to destructive sampling specifically to assess plastic loads (Bond *et al.* 2013, section 7.3.5). Methods can be used for both macro and microplastics, although current monitoring methods are not focused on particles <1 mm (Van Franeker and Law 2015).

Some seabirds, such as gulls and skuas, regularly regurgitate indigestible prey remains. Examining their pellets for plastic can be used to target and monitor plastic interactions. This approach can use citizen scientists to sort the pellets provided they are well trained (Lindborg *et al.* 2012). However, the pellets have to be collected while still intact, and with due care to exclude plastic contamination from environmental sources after regurgitation. Some species of gull have adapted to forage on land, being attracted to waste bins, littering and open landfill sites, so care should be taken in the selection of suitable indicator species for monitoring the marine environment. Skuas that prey on petrels and similar species, on their breeding islands, are a more productive source of ingested plastic, however any monitoring of plastic loads in skua pellets should be attributed to the putative prey species e.g. (Ryan 2008).

Little is known about the excretion of plastics by birds. Some waterfowl can excrete pieces of flexible packaging up to 4 mm across and fibres up to 12 mm long (Gil-Delgado *et al.* 2017), but their faeces are much coarser than those of seabirds, linked to their consumption of more plant matter. Seabirds seldom excrete hard particles >1 mm (van Franeker and Law 2015, Ryan 2015), so their faeces typically only contain microplastic fragments. Fresh faecal samples can be examined for plastics (e.g. Provencher *et al.* in 2018), but there is considerable risk of environmental contamination, and great care is needed in processing samples (cf. Hermsen *et al.* 2017).

Invertebrates
Filter-feeding bivalve molluscs are widely distributed and can be obtained relatively easily from shoreline sampling or by purchasing from seafood suppliers. Sessile forms such as mussels (*Mytilus sp.*) have been used as indicators in monitoring studies of heavy metals and organic contaminants in particular as the basis for the long-running Mussel Watch programme (Melwani *et al.* 2013). Relatively high levels of microplastics have been reported in cultivated blue mussels in the southern North Sea (van Cauwenberghe and Janssen 2014). Assessment and monitoring of microplastics in cultivated shellfish, such as oysters (*Ostreidae*, e.g. *Crassostrea gigas*) and mussels, may provide a convenient and cost-effective approach. It has great potential to be undertaken in many regions, given the widespread distribution of shellfish mariculture. Mussels, as with other benthic filter-feeders, are potential indicators of local availability of microplastics. As they are eaten whole, both ingested and assimilated particles are available to be ingested and assimilated by humans.

Market sampling of fish and shellfish
Market sampling of fish and shellfish can provide a cost-effective method of estimating human exposure to microplastics and associated chemicals through seafood consumption (Rochman *et al.* 2016). It is less reliable as an overall indicator of environmental contamination, unless the origin (i.e. collection site, location trawled) can be established with some certainty. Sampling for plastics can be incorporated tin statutory programmes of sampling for fisheries

Table 7.1. Suitability of biota groups for biological monitoring of plastic ingestion. Adapted from (Bråte *et al.* 2017).

	Phytoplankton			**Zooplankton**		**Shellfish**		**Other invertebrates**
	Cyanobacteria	Flagellates	Diatoms	Copepods	Cnidaria	Bivalves	Crustaceans	Annelids
				Calanus sp.		*Mytillus sp.*	*Nephrops sp.*	*Arenicola marina*
Ecological niche	Planktonic	Planktonic	Planktonic	Planktonic/ benthic	Planktonic/ benthic	Benthic	Benthic	Benthic
Feeding strategy	Producer	Producer	Producer	Filter feeding	Filter feeding	Filter feeding	Scavengers	Detritivores
Key requirements of an indicator								
Sessile	N	N	N	N	Y/N	Y	Y/N	Y/N
Globally distributed (or similar species available)	Y	Y	Y	Y	Y	Y	Y	Y
Ethically sound	Y	Y	Y	Y	Y	Y	Y	Y
Already used as a bioindicator	Y	Y	Y	N	N	Y	Y	Y
Abundant / easy to sample	Y	Y	Y	Y	Y	Y	Y	Y

Table 7.1. Suitability of biota groups for biological monitoring of plastic ingestion. Adapted from (Bråte *et al.* 2017).

	Phytoplankton			Zooplankton		Shellfish		Other invertebrates
	Cyanobacteria	Flagellates	Diatoms	Copepods	Cnidaria	Bivalves	Crustaceans	Annelids
Low cost	Y	Y	Y	Y	/	Y	Y	Y
Effects observed	Y	Y	Y	Y	N	Y	Y	Y
Commercially important	N	N	N	N	N	Y	Y	Y
Ecologically important	Y	Y	Y	N	N	Y	N	N
Ease of analysis: microplastic	Y	Y	Y	Y	Y	Y	Y	Y
Ease of analysis: macroplastic	N	N	N	N	N	N	N	N
Example in studies	Long *et al.* (2015)	Cole *et al.* (2013)	Long *et al.* (2015)	Cole el al., (2013)	Taylor *et al.* (2016)	Li *et al.* (2016)	Welden and Cowie (2016)	Wright *et al.* (2013)

Table 7.1. Suitability of biota groups for biological monitoring of plastic ingestion. Adapted from (Bråte *et al.* 2017).

	Marine mammals		Birds	Fish			
	Baleen whales	Toothed whales	Procellariforms				Large fish
	Humpback whale	Beaked whale	Fulmar	Cod	Mackerel	Herring	shark/tuna
Ecological niche	Pelagic	Pelagic	Pelagic	Demersal/ pelagic	Pelagic	Pelagic	Pelagic
Feeding strategy	Filter feeding, ram, bubble	Predatory	Predatory	Scavenger, predatory	Filter feeding, opportunistic	Filter feeding, opportunistic	Ram, predatory
Key requirements of an indicator							
Sessile	N	N	N	N	N	N	N
Globally distributed (or similar species available)	Y	Y	Y	Y	Y	Y	Y
Ethically sound	N	N	N	N	N	Y	N
Already used as a bioindicator	N	N	Y	Y	Y	Y	Y
Abundant / easy to sample	N	N	N	Y	Y	Y	N
Low cost	N	N	N	Y	Y	Y	N
Effects observed	N	N	N	N	N	N	N
Commercially important	N	N	N	Y	Y	Y	Y/N
Ecologically important	Y	N	N	N	N	N	N
Ease of analysis: microplastic	Y	Y	Y	Y	Y	Y	N
Ease of analysis: macroplastic	N	N	Y	Y	Y	Y	Y
Example in studies	Lusher *et al.* (2018)	Lusher *et al.* (2015)	Kuhn and van Franeker (2012)	Bråte *et al.* (2016)	Rummel *et al.* (2016)	Foekema *et al.* (2013)	Romeo *et al.* (2015)

management, disease surveillance or human health perspectives.

7.3.3 Opportunistic monitoring of ingested plastic from strandings

Opportunistic sampling of stranded animals also can yield useful information. For example, many reports of the ingestion of plastics by turtles and cetaceans are based on samples collected from animals reported by members of the public Clearly there is a benefit in developing a more systematic reporting structure for the public to alert the appropriate administrative or scientific institution of stranding events, so that animals can be checked for the presence of ingested plastic.

One drawback to assessing entanglement and ingestion rates in stranded animals is that they are a non-random sample of the population; their

Case study: micro-, meso- and macro-plastics in seabirds

The northern fulmar *(Fulmarus glacialis*) is one many species of seabird that have been shown to be susceptible to plastic ingestion due to an apparent inability to discriminate between natural prey and floating plastic. Monitoring plastic ingestion rates in dead northern fulmars, collected during North Sea beach surveys, has been developed into an Ecological Quality Objectives (EcoQOs) by OSPAR (van Franeker *et al.* 2011, van Franeker and Law 2015). The policy target for an ecologically acceptable level of plastic litter is defined as <10% of stranded fulmars in the North Sea containing >0.1 g of plastic in their gizzards (OSPAR 2010). These thresholds were selected arbitrarily, based on the observed distribution of plastic loads in fulmars (Figure 7.4). An analysis of the findings up to 2014 revealed that over 50% of stranded birds contained plastic loadings above the target, over most of the North Sea (Figure 7.5) (OSPAR 2017). Concerning the risk of sample bias from using starved animals, mentioned above, it has been shown (van Franeker and Meijboom 2002) that the quantity of plastic in stomachs of fulmars that had slowly starved was not statistically different from birds that had instantly died in healthy conditions (e.g. collision or drowning victims).

Figure 7.4 Northern fulmar (*Fulmarus glacialis*) and the gut contents from one stranded individual (image credits: Jan Andries van Franeker).

This approach, using the fulmar, has been extended to other regions in the North Atlantic and in the eastern North Pacific. The results reflect widespread contamination by plastics, but also reveal significant regional trends, with much lower concentrations in the more remote areas of Alaska and the Canadian Arctic.

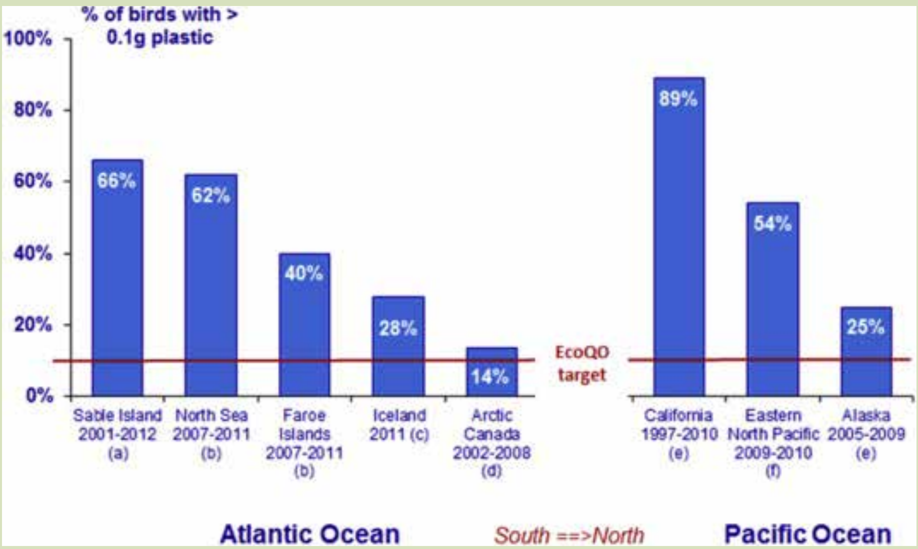


Figure 7.5 Comparison of percentage of birds with gut contents of plastic exceeding the target of <0.1 g, from different regions of the North Atlantic and eastern North Pacific (image used under the Creative Commons Licence, ©van Franeker and Law (2015), slightly modified.

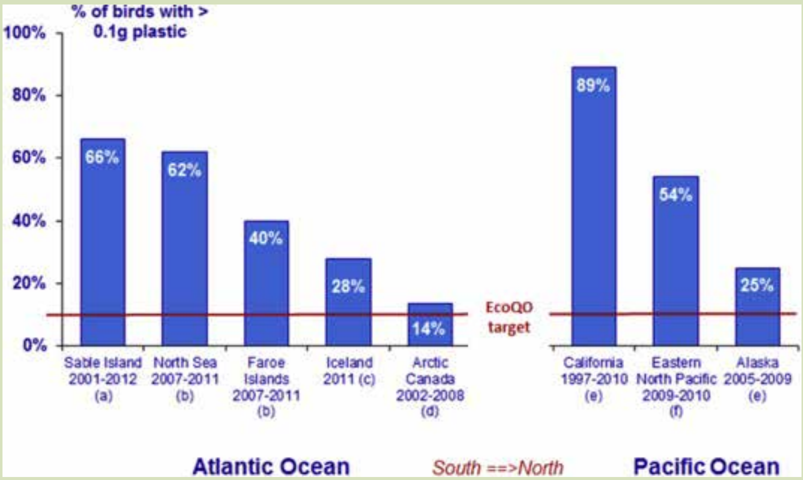


Figure 7.5 Comparison of percentage of birds with gut contents of plastic exceeding the target of <0.1 g, from different regions of the North Atlantic and eastern North Pacific (image used under the Creative Commons Licence, (© van Franeker and Law 2015), slightly modified.

The benefit of building long-term monitoring programmes is demonstrated in Figure 7.6, showing the decline in the frequency of occurrence of 'industrial' plastic (i.e. resin pellets) in gut contents of fulmars in the North Sea (Figure 7.6a) and in net samples from the North Atlantic Gyre (Figure 7.6b). This appears to be due to improved industrial waste management in the coastal states.

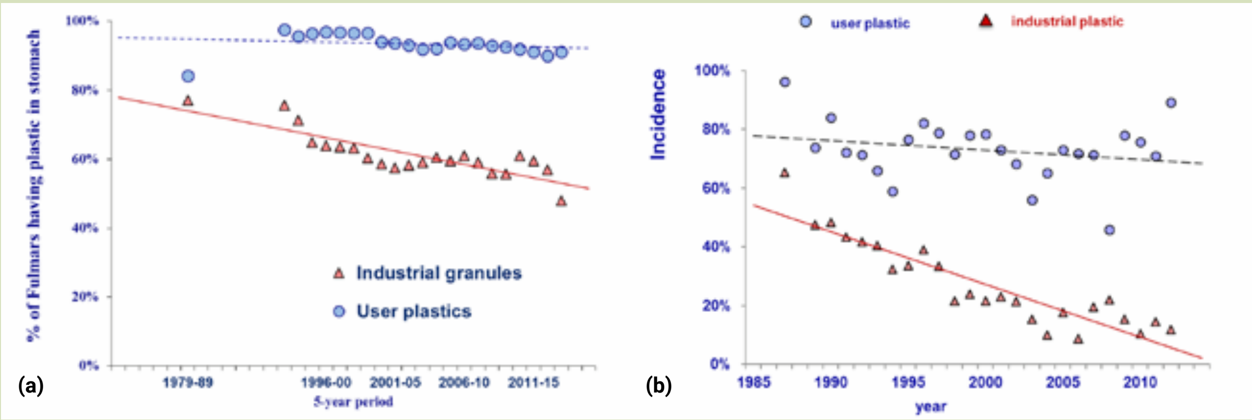


Figure 7.6 Long term time trends in the plastic composition in a) the gut contents of the northern fulmar in the North Sea (graph derived from Table 3.B in Van Franeker and Kühn 2018) , and b) surface net samples in the North Atlantic Gyre (image used under the Creative Commons Licence, ©van Franeker and Law 2015) showing a very small decline in 'user' plastic but a much greater decline in 'industrial' plastic.

For most seabird species, ingested plastic loads appear to be strongly right skewed, with only a small proportion of individuals containing very large plastic loads (Ryan *et al.* 2016). Clearly, the selection of appropriate indicator species and appropriate statistical interpretation of the data is critical. (Provencher *et al.* 2014) reported that surface plungers (e.g. great shearwater and northern fulmar) had a much greater prevalence of plastic litter than surface divers (e.g. common eider, long-tailed duck, Atlantic puffin). Other options for sampling, e.g. from regurgitated stomach contents are discussed in (Provencher *et al.* 2017) and (Provencher *et al.* 2019 *in press*).

levels of interactions with plastics may be inflated if the interactions increase the chance of death (e.g. through entanglement or blockage of the digestive tract) or the animals display abnormal behaviour prior to stranding (e.g. during storms, birds might ingest more plastic because they are starving).

As a result, comparisons of rates of interaction with randomly sampled animals need to be interpreted with caution. However, animals found dead have the advantage of being able to assess whether plastics have contributed directly to the cause of death (e.g. through blocking the digestive tract).

7.3.4 Monitoring associated chemicals from ingested plastics

Sampling preen gland oil offers a non-destructive method for monitoring the composition and concentrations of plastic-associated toxic compounds in birds, but the volumes of preen oil available are limited, especially for small birds, presenting significant analytical challenges. Great care has to be taken to avoid contamination of samples (Hardesty *et al.* 2014). Sampling adipose tissue from dead birds allows larger samples to be taken, with less risk of contamination (Tanaka *et al.* 2013). The selection of species will be region-dependent. For example, the Sooty Shearwater (*Ardenna griseus*) and Short-tailed Shearwater (*A. tenuirostris*) are native to Australia and New Zealand. Both species regularly contain large plastic loads. Routine monitoring of fat from the fledglings ('muttonbirds') provides a reliable indicator of exposure to organic contaminants (Cousin *et al.* 2015).

Sampling marine mammals for indicators of plastic ingestion can be achieved using a non-destructive approach by collecting skin biopsies from live individuals, using a modified crossbow. Obtaining information relating to additives has proven effective in some ocean basins and has been discussed for use as a monitoring tool under the Marine Strategy Framework Directive e.g. (Fossi *et al.* 2017). Targeting individuals can be challenging due to limited interaction with live organisms and should therefore be considered opportunistic.

7.3.5 Monitoring of entanglement

Monitoring entanglement should consider several taxonomical groups, including invertebrates, and be organised by ecosystem compartments. Most records involved abandoned, lost, or otherwise discarded fishing gear (ALDFG), with an incidence that can vary strongly according to regions, the type of fishing activities/gears and the quantity of marine litter in the environment. Entanglement may impact individual organisms or sensitive habitats, such as coral reefs and seagrass beds. Policy concerns may include:

(i) damage to habitats

(ii) damage or mortality of rare or endangered species

(iii) population-level impacts, especially due to 'ghost fishing'

Case study: macro-plastic in birds' nests

Several seabirds (e.g. gannets, cormorants, gulls) regularly use plastic items in their nests. The frequency of plastic items in nests varies regionally within species, linked to the local availability of natural materials for nest building the abundance of plastic wastes as well in the immediate environment (Bond *et al.* 2012, Witteveen *et al.* 2017). The items used for nest construction typically are ropes, straps and fishing line, which pose an entanglement threat to adults and chicks (Votier *et al.* 2011) (Figure 7.7).

Figure 7.7 Northern gannets (*Morus bassanus*) using fishing net litter as nesting material on Helgoland in the southern North Sea. – this may lead to entanglement and death by starvation (©Nadja Ziebarth, courtesy of Dorothea Seeger).

Monitoring nests at the same colonies can provide insights into changes in the abundance of marine litter. For example, Black-legged Kittiwake *Rissa tridactyla* nests containing plastic at a colony in Denmark increased from 39% in 1992 to 57% in 2005 (Hartwig *et al.* 2007). However, care needs to be taken to not unduly disturb breeding birds when checking for plastic in nests. The advantage of working on colonial seabirds is that a large sample of nests can be checked in the same site, and thus provide a robust measure of plastic use at a given location that can be tracked over time. However, it also increases the risk of disturbance to large numbers of birds if sampling takes place during the breeding season. The addition of regurgitated plastics during the breeding season (e.g. in gulls) also means that comparisons should be made at the same stage of the breeding season for these species (Witteveen *et al.* 2017).

(iv) impact on food security

ROVs and visual surveys conducted on the seabed and on the sea surface can provide opportunistic observations of entanglement. Opportunistic sampling of stranded animals also can yield useful information. Many studies of entanglement are based on samples collected from animals reported by members of the public to monitoring or interest groups (e.g. Irish Whale and Dolphin[56]). Another example is in Spain where concerned individuals call 112 and are directed to the stranding networks (CEMMA[57]). If not already established, authorities could consider setting up reporting mechanisms to alert biologists to stranding events, so that animals can be checked for entanglement as well as the presence of ingested plastic.

7.3.6 Monitoring to ensure seafood safety

Seafood consumption represents one pathway for human microplastic exposure. Monitoring seafood for the presence of plastic and plastic associated compounds can provide evidence regarding human exposure via seafood consumption and infer potential human health effects. Organisms that are consumed whole, including shellfish and small pelagic fish, pose particular concern for human exposure. Organisms that have assimilated particles in their digestive tract can act as transfer vectors of microplastics to consumers.

The European Food Safety Agency (EFSA[58]) made a preliminary assessment of the problem of plastic particles related to food safety in 2016. There is insufficient information to assess the true amount of human microplastics following consumption of seafood. EFSA called for increased investigations, as there was too little data to infer consequences of consumption from seafood with confidence. Microplastics have been found in many species intended for human consumption including invertebrates, crustaceans and fish, from wild and farmed sources. Scientific evidence has outlined numerous pathways of microplastic exposure via food including evidence of microplastics in species contributing to the global marine fisheries. For a review of scientific knowledge, we refer readers to the 2017 Food and Organisation report on Microplastics in Fisheries and Aquaculture' (Lusher *et al.* 2017). One study estimated that a top European shellfish consumer could eat approximately 11,000 plastic particles annually (Van Cauwenberge and Jansen 2014). In addition, ingestion of microplastics may expose humans to the risk from associated chemicals.

Monitoring to ensure seafood safety can utilise both targeted and market sampling. Targeted monitoring can include the routine investigation of organisms caught for human consumption. Targeting digestive tracts as well as edible tissue can provide information on levels of plastic contamination as well as the presence of additives. ICES have developed a protocol for the monitoring of plastics in routine fish stock management cruises (Annex III.2), at the request of OSPAR[59].

Market sampling of seafood at the point of purchase can provide information on the presence of microplastics entering the human food chain. Species of interest are those which are consumed whole, such as small pelagic fish and bivalves (Rochman *et al.* 2016, Li *et al.* 2015). Countries are already initiating targeted monitoring on species such as blue mussels, including those wild-caught and those collected from point of sale.

7.4 Ecosystem level monitoring (Habitats)

7.4.1 Marine litter as a habitat

Plastic litter affects marine systems at different levels, ranging from impacts at the individual to population and ecosystem level. While plastic litter can facilitate transport of non-indigenous species (NIS), with potentially far-reaching impacts, there are also certain habitats that – due to their particular characteristics - may accumulate plastics, thereby becoming especially susceptible to plastic-mediated impacts such as smothering or an increased risk of disease. Herein we describe possible methods to monitor plastic-related risks at the ecosystem level.

Floating plastic litter as a habitat
Plastic litter provides extensive attachment substratum for diverse organisms, including micro- or macro-biota (Kiessling *et al.* 2015). This is especially relevant where these substrata are of limiting supply for sessile organisms, such as at the sea surface, or on sedimentary soft-bottoms, potentially leading to changes in community structure (Katsanevakis *et al.* 2007).

The risk of the transfer of non-indigenous species (NIS) by rafting on plastics has been highlighted frequently e.g. (Barnes 2002)., There have been numerous reports of NIS identified from floating or stranded plastics e.g. (Rech *et al.* 2018). One of the most comprehensive studies to date, named ADRIFT (Assessing the Debris-Related Impact of Tsunami), was developed following the devastating tsunami caused by the Great Japan Earthquake in 2011. Tsunami litter started washing ashore on the western seaboard of North America within one year of the earthquake. It quickly became apparent that many coastal Japanese species had been rafted across the Pacific (Figure 7.8). This led to the development of a major three-nation study (Japan, Canada, USA), overseen by the Ministry of Environment of Japan and carried out in conjunction with the North Pacific Marine Science Organization (PICES). The final scientific report of the study was completed in 2017[60], and there have been a series

56 http://www.iwdg.ie/
57 http://www.cemma.org/principal_eng.htm
58 https://www.efsa.europa.eu/
59 http://www.ices.dk/sites/pub/Publication Reports/Advice/2015/Special_Requests/OSPAR_PLAST_advice.pdf
60 https://meetings.pices.int/publications/projects/ADRIFT/funded-projects/08_Hansen_Year3_report_rr.pdf

of individual peer-reviewed publications and journal special issues, accessible though the PICES ADRIFT webpage e.g. (Miller *et al.* 2018). A collection of over 1,000 marine invertebrate samples, from 650 tsunami litter objects, is housed at the Royal British Columbia Museum in Victoria, as a research resource[61].

Figure 7.8 Upturned hull of a Japanese boat on the shoreline of Oregon, USA showing colonisation by invertebrates, the boat was transported across the North Pacific following the Great East Japan earthquake and tsunami in 2011. (©NOAA credit).

Identification of organisms is mostly based on morphological traits, but recent studies have also used genetic data (Garcia-Vazquez *et al.* 2018, Rech *et al.* 2018). The species growing on stranded litter can be identified by three different approaches:

(i) visually from photographs,

(ii) by detailed visual inspection of specimens in the laboratory, and

(iii) using genetic codes that can be contrasted with existing databases (e.g. GenBank) (for details on methods see Rech *et al.* 2018).

During surveys, the length of surveyed beach should be registered, but samplings can also be opportunistic (Garcia-Vazquez *et al.* 2018). Whenever possible, surveys should include floating plastics collected at sea in order to sample mobile and soft-bodied species.

Since motile organisms or those without skeletal structures rapidly disappear from floating items, there is typically a bias towards sessile species with attached skeletons, such as cnidarians, bryozoans (Figure 7.9), some bivalves and polychaetes with calcareous tubes (Kiessling *et al.* 2018). If items are collected at sea, motile and soft-bodied organisms are also commonly observed (Astudillo *et al.* 2009). While small-sized organisms (including microbes) also colonize microplastics e.g. (Zettler *et al.* 2013, Reisser *et al.* 2014), there is generally a positive relationship between litter size and the number of epibiont species e.g. (Kiessling *et al.* 2015). Consequently, to document the inventory of species arriving on floating plastics it may be preferable to survey macro-litter.

61 https://royalbcmuseum.bc.ca/collections/natural-history/invertebrate-zoology

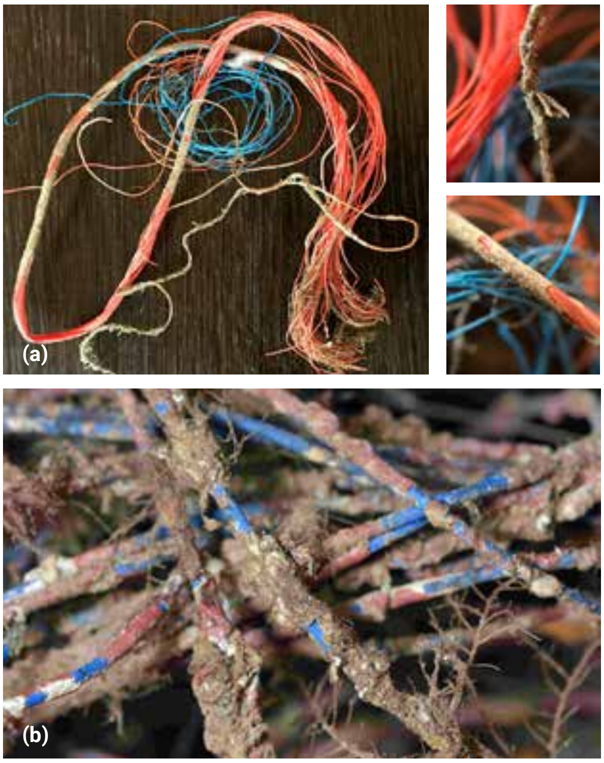


Figure 7.9 Examples of colonisation of marine litter by Bryozoa and Hydrozoa: **(a)** strands of fishing rope; in this example the rope is used on the base of bottom trawls to protect the net, in the southern North Sea fishery ('Dolly rope'), sampled from the shoreline on Norderney Island in the Wadden Sea World Heritage Marine Site, November 2018 (©Soledad Luna); and, **(b)** telephone wires collected form the seafloor off the coast of France.

Seafloor plastic litter as a habitat

In soft-bottom environments, plastics may serve as habitat for organisms that could not usually grow in these areas, thereby influencing the organism assemblage and the ecological function of these systems (Katsanevakis *et al.* 2007). Diverse organisms have been observed, including molluscs, bryozoans, cnidarians, polychaetes and others (Gündoğdu *et al.* 2017).

7.4.2 Monitoring the impacts of marine litter on habitats

Assessments through opportunistic approaches such as the monitoring of biodiversity in coral reef assemblages by diving, or through the use of submersible / ROV operations in deeper areas, are possible. Retrieving information on marine litter that is recorded in underwater visual surveys but also adding marine litter as a routine survey variable in long-term reef monitoring programmes (e.g. Reef Check[62]) are recommended (Carvalho-Suza *et al.* 2018) and should be implemented on regular basis.

Passive capturing of larger plastic items

Many ecosystem engineers (macrophytes, bivalve or sponge beds, coral reefs) generate complex structures that favour entanglement of larger plastics (Figure 7.10). For example, in a recent review, entanglement was reported in 418 species of coral across eight taxa (Carvalho-Suza *et al.* 2018).

62 https://www.reefcheckaustralia.org/methods

Gorgonians, habitat-forming sponges, hydrocorals and reef-building corals are associated with enhanced water circulation, with greater exposure to marine litter. Litter tends to be more abundant in the crest zone (Figueroa-Pico *et al.* 2016) and, for the deep sea, higher over rocky bottoms (Consoli *et al.* 2018).

Figure 7.10 Fishing net and rope entangled with cold-water coral reef (*Lophelia pertusa*), 700 m water depth in the Northeast Atlantic (image courtesy of Jason Hall-Spencer, Univ. Plymouth).

Damage resulting from fisheries activities (mainly netting and lining) is the most commonly recorded direct human impact on coral reefs worldwide, but most importantly the likelihood of diseases, increased 20-fold once a coral is smothered or entangled in plastic (Lamb *et al.* 2018). In addition, a recent study demonstrated that corals are also exposed to microplastics (Reichert *et al.* 2018). Cleaning mechanisms such as mucus production, ingestion and egestion were observed, and negative effects (bleaching and necrosis) were documented in various species.

7.5 Citizen science

The role of citizen science

Beach surveys typically rely on volunteers/citizen scientists to cover long enough stretches of coastline, and thus locate enough birds to provide sufficient power to detect changes in the rates of entanglement or ingestion. For example, regular surveys along the North Sea coast have found 225,500 dead seabirds since 1970, of which 550 have been entangled in marine litter (Camphuysen 2008). A total of 27 species have been found entangled, with northern gannets (*Morus bassanus*) consistently having the highest entanglement rate of all species (6-9%). The entanglement rates of birds stranded on beaches in the Netherlands remained fairly constant from 1979-2003 (average 0.3% of all stranded birds), but increased to 0.7% in 2004-2007 (Camphuysen 2008). Typically, such surveys are conducted monthly, although more frequent surveys would yield more samples especially in areas with variable weather, a higher proportion of which would be suitable for examining for plastic ingestion.

Entanglement events also are relatively rare, making them hard to study. However, they are also a very visible impact of marine litter, attracting public attention. A recent review of entanglement in birds, based largely on searches of Google images and related internet searches increased the proportion of seabirds reported to be entangled in marine litter from 25% based on a comprehensive literature review up to the end of 2014 (Kühn *et al.* 2015) to 35%, including the first records from the only two seabird families that had not had any representatives reported to be entangled (Ryan 2018). Establishing a website that encourages people to post images of entangled marine wildlife would be a cheap and effective way to gather data on this issue while also educating people to the dangers posed by marine litter[63].

See Annex VIII for additional protocols for monitoring biota

63 www.balloonsblow.org

8 SAMPLE PROCESSING FOR MICROPLASTICS

8.1 Overview

The characterisation of macro-plastics following sampling can usually be achieved without an intermediate stage, using the approach described in Chapter 9 (Section 9.2). However, for micro- and meso-plastics some form of additional processing may be needed, depending on the objectives of the monitoring programme. This may include physical methods such as:

- ❑ visual identification to categorise litter items (macro-plastics),
- ❑ filtration/sieving to extract particular size fractions,
- ❑ density separation to extract particles of differing densities, and
- ❑ microscopic identification to establish size, shape and colour (micro- and meso- plastics).

Environmental samples often contain quantities of organic matter. This can prevent the efficient separation of plastic particles from the sample matrix (water, sediment, biological tissue) and lead to difficulties in subsequent chemical analysis. Organic matter can be reduced or eliminated by using chemical and biological means. As well as aiding separation, this will reduce the possibility misidentifying natural materials as polymeric (false positives) and avoid polymeric signals being camouflaged by natural materials, improving signal quality. In the following sections we provide brief descriptions of the most common methods of processing samples within a laboratory environment (Figure 8.1).

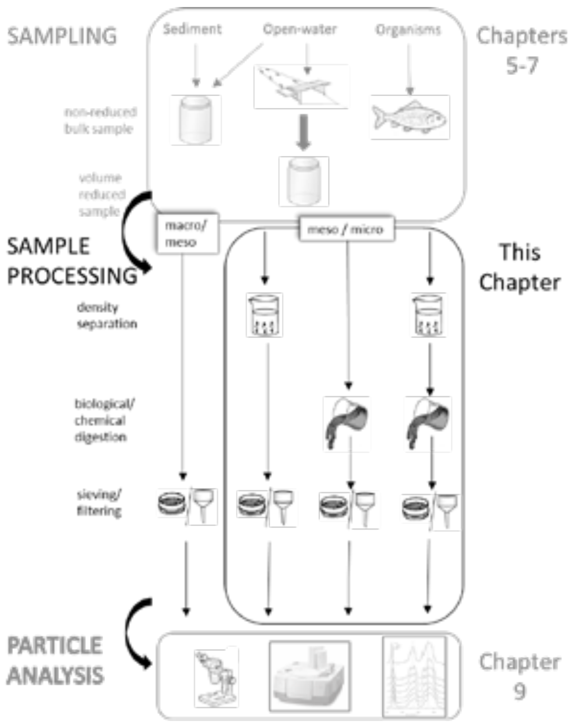


Figure 8.1 Schematic flowchart showing the sequence from the collection of environmental samples (Chapters 4-7), processing via a number of physical, chemical and biological methods (Chapter 8) and further analysis to establish the polymer composition (Chapter 9).

Each of these methods can be used in isolation or in concert, as depicted here going from less to more complex (left to right). Methods may also be employed in a different order. After sieving or filtering particles are visually sorted from samples and, especially those <1mm in size, can be further analysed using the methods discussed in chapter 9.

8.2 Contamination controls

The contamination of samples by external microplastics following collection is a major problem. There are some basic safeguards that can be made, but it has become increasingly clear that the minimisation of contamination has not received sufficient attention, introducing uncertainty to the reliability of many published studies. This emphasises the need the use of controls and blanks in order to account for any such possible influence.

In order to prevent/reduce potential contamination from external sources, such as airborne fibres, the laboratory workspace should be frequently wiped down and work should occur within a laminar airflow cabinet when possible. All glassware should be washed thoroughly, oven-dried and be covered (i.e. with a watchglass) when not in use. Burning away microscopic traces of plastic heating the glassware in a burnout furnace (<600°C) before use is also recommended. Filters and/or sieves should be inspected under a microscope prior to use. Personnel should wear natural (i.e. cotton) clothing and laboratory coats, as well as powder-free examination gloves, throughout the experimental procedure.

To account for possible contamination, which could be coming from fieldwork materials (i.e. nets), atmospheric deposition, chemicals used, glassware or other aspects of the testing environment, controls and/or blanks should be utilized. Field blanks can be made, for example, by rinsing nets and other field equipment used into a sample container. Similarly, lab blanks containing only deionized or Milli-Q water (such as is used to wash all glassware) or other chemicals used within the sample processing (i.e. homogenizing solution) can be created. In either case these blanks are processed in a manner identical to the samples themselves. This allows for quantification of any possible cross- or laboratory- contamination, which can then be used to reduce quantities found within the samples to more accurately account for actual environmental contamination.

A recent critical review of quality criteria for the analysis of microplastics in biota samples was published by (Hermsen *et al.* 2018). This examined all stages of the sampling and analysis process and defined a series of protocols for each of 10 stages

(Table 8.1). The authors evaluated 35 studies, assigning a score to each stage, where: 2 = reliable without restrictions; 1 = somewhat reliable but with restrictions; and, 0 = unreliable. All the studies had at least one processing stage that attracted a score of 0. The average overall score was 8.0 out of 20. This evaluation does not necessarily invalidate the conclusions of all 35 studies, but it does suggest that the need for significant improvement in how sampling and analysis is undertaken, which much greater emphasis placed on minimising and accounting for sample contamination.

Table 8.1 The main stages of processing microplastic samples for which quality assurance criteria should be applied from (Hermsen *et al.* 2018).

Processing stage		
Sampling	1	Sampling methods
	2	Sample size
	3	Sample processing and storage
Contamination mitigation	4	Laboratory preparation
	5	Clean air conditions
	6	Negative control
Sample purification/ handling	7	Positive control
	8	Target control
	9	Sample treatment
Chemical analysis	10	Polymer identification and reporting

The detailed protocols recommended for each stage are provided in Annex IX.

8.3 Density separation and filtration using aqueous solutions

Plastics have varying specific densities based upon the polymer type and any chemicals added during their manufacture (Table 2.1). Chemicals included during product manufacture, such as plasticizers, UV stabilizers and pigments, can alter these densities. Physical separation methods aim to utilize density differences to separate different types of polymers from organic and inorganic natural particles. Usually this process is initiated by mixing the sample with a dense solution and agitating it for a period of time (30 sec. up to 2 hrs.). Commonly employed solutions for density separation are provided in Table 8.2.

After agitation, the sample is allowed to settle (covered) for a period of time (10 min. up to 24 hrs.), with the more dense constituents sinking and the less dense particles floating or remaining in suspension. While particles can be extracted directly from the liquid surface, most often the supernatant is then filtered (through filter paper) or sieved (through a fine mesh screen) prior to visual sorting. Optical (dissection) microscopes (x 8-40) are generally utilized to aid in visual identification. Given the sometimes only slight difference in density between the extraction solution and the inherent plastics, it is possible that a single extraction step may not remove all particles. Repetition of density separation of the sample remains is advised (Hidalgo-Ruz *et al.* 2012).

Table 8.2. Commonly employed solutions for density separation of microplastics.

Salt	Density (g cm-3)	Reference
Sodium Chloride (NaCl)	1.2	Hidalgo-Ruz *et al.* 2012
Sodium Polytungstate (PST)	1.4	Hidalgo-Ruz *et al.* 2012
Sodium Iodide (NaI)	1.6	Claessens *et al.* 2013
Zinc Chloride (ZnCl2)	1.7	Imhof *et al.* 2012
	1.6	Zobkov and Esiukova 2017

Two systems have been developed to provide more effective and automated separation of plastic particles from sediment. (Imhof *et al.* 2012) developed a sediment separator with a top valve, allowing the floating plastic to be trapped in an up-down funnel. This facilitates the trapped microplastic to be filtered in a simple operational step by turning the funnel again. The separator, known as the Munich Plastic Sediment Separator (MPSS), is equipped with an electromotor and stirrer in the bottom to ensure proper mixing of sediment and solution. (Claessens *et al.* 2013) developed a density separation device based on the principle of elutriation, which uses an upward stream of gas or liquid to separate less dense particles from heavier ones. As devised aerated tap water is used as the upwardly mobile liquid/gas mixture being fed into the base of a column/pipe allowing for the separation of particles of differing densities. The lighter particles are carried up with the rising water to an outflow at the top of the column where they are retained by a sieve or stack sieve set (for varying size distributions). Particles are removed from the sieve and visually sorted, generally with the use of an optical microscope, in a manner identical to the supernatant solution above.

8.4 Biological and chemical digestion

8.4.1 Oxidative digestion

Biological or chemical digestion is carried out to organic matter from the sample matrix, purifying the sample and aiding the subsequent identification of the polymeric composition. Several chemical digestion methods have been utilized, broadly classified into oxidative (this section), acidic (section 8.4.2), alkaline/basic (section 8.4.3) and enzymatic (section 8.4.4). These digestions can be used in isolation or in combination with one another. A summary of advantages and disadvantages of each approach is provided in Table 8.3.

Oxidative digestion can be carried out using hydrogen peroxide, utilizing Fenton's reagent (a

Table 8.3 Advantages and disadvantages of different methods for extracting and purifying microplastics in organic matrices.

Purification method	Advantages	Disadvantages	Reference
Oxidative digestion	• Inexpensive	• Temperature needs to be controlled • Several applications may be needed	Masura *et al.* (2015)
Acid digestion	• Rapid (24 h)	• Can attack some polymers	Claessens *et al.* 2013
Alkaline digestion	• Effective • Minimal damage to most polymers	• Damages cellulose acetate	Dehaut *et al.* (2016)
Enzymatic digestion	• Effective • Minimal damage to most polymers	• Time-consuming (several days)	Löder *et al.* (2017)

solution of hydrogen peroxide with ferrous iron as a catalyst), for the removal of natural organic material (Masura *et al.* 2015). In brief, 20 mL each of an iron (II) catalyst solution (7.5 g of FeSO4°7H20 in 500 mL of deionised water water with 3 mL of concentrated sulphuric acid) and 30% hydrogen peroxide is added to a sample and allowed to react in a covered beaker. Subsequent additions of hydrogen peroxide can be utilized until little to no labile organic material remains. The sample is then filtered or sieved prior to visual analysis (Masura *et al.* 2015). While the original protocol utilizes elevated temperatures (i.e. 70°C) to accelerate the reaction, more recent studies (Munno *et al.* 2018, Hurley *et al.* 2018) found that such temperatures may lead to the loss of some types of microplastic particles. Thus, while there will be some lag time as this exothermic reaction initiates, it is recommended to perform this digestion at room temperature or lower (through the use of an ice bath). However, the solution should not be allowed below 15°C as it may lead to a yellow precipitate being formed (Simon *et al.* 2018).

8.4.2 Acid digestion

Typically a strong mineral acid (e.g. HNO3, H2SO4) at either room or elevated temperature for a specific period (overnight to 2 h) of time has been employed (Claessens *et al.* 2013, Cole *et al.* 2014). However, it has been found that these conditions can destroy or damage certain polymers (Claessens *et al.* 2013, Enders *et al.* 2017). To counter this issue, (Cole *et al.* 2014) used lower concentrations of the non-oxidizing, mineral acid HCl, but found its use inconsistent and inefficient with regard to removal of natural materials. These studies and others e.g. (Lusher *et al.* 2017) focused on methods development and optimization favour the use of other chemical digestion protocols over acid digestion. For these reasons GESAMP has concluded that acid digestion is inappropriate for isolating microplastic.

8.4.3 Alkaline digestion

Relative to any acid digestion, studies have found an alkaline hydrolysis utilizing a strong base (which denature proteins and hydrolyze chemical bonds) more efficient and generally less damaging to inherent plastics, especially with regard to fish and invertebrates (Claessens *et al.* 2013, Cole *et al.* 2014, Lusher *et al.* 2017). The impact of this method on polymeric material depends on the plastic, with some conflicting reports for certain polymers. Polyethylene, polypropylene, and polyamides are all reported to be resistant, while polycarbonate and polyesters seem to be degraded (Lusher *et al.* 2017). The optimized alkaline digestion protocol recommends 40 mL of 10 M KOH per 0.2 g dry weight of sample maintained at 60°C for 24 h. This mixture is then neutralized using HCl prior to ultrasonification (using a bath for 10 min), filtration, and visual analysis.

8.4.4 Enzymatic digestion

Specialized enzymes for breaking down lipids, proteins, cellulose, chitin etc. are now commonly used in the work up of organisms. An assessment of the biological composition is useful to determine the optimal sequence of enzymatic treatment, e.g. fat-rich samples are typically treated with lipase before proteinase. For practical reasons technical enzymes can be used to reduce the costs (Löder *et al.* 2017).

As a first step it is common to pre-treat samples with a detergent (e.g. 5% or 10% sodium dodecyl sulphate) to make the biological material more accessible to the enzymatic treatment. This is followed sequential by treatment with a variety of enzymes, depending on the nature of the sample matrix. Löder *et al.* (2017) developed a protocol (Basic Enzymatic Purification Protocol – BEPP) for separating microplastics from plankton samples collected in net tows:

1) protease – catalyses the decomposition of protein into peptides, which are easily dissolved
2) cellulase – catalyses the decomposition of cellulose
3) hydrogen peroxide – destroy residual organic material on surfaces prior to chitinase treatment
4) chitinase - catalyses the decomposition of chitin
5) hydrogen peroxide – second treatment to destroy residual organic material

Although the protocol was developed for processing seawater samples, it has been used successfully to purify other matrices including: wastewater, tissues samples from mussels, daphnia and fish organs, extracted sediment samples and commercial fish food.

The authors have developed this approach further to create the Universal Enzymatic Purification Protocol, involving addition stages. They suggest this has the potential to be implemented as a standard operating protocol for routine monitoring studies of microplastics. However, enzymatic treatment is time-consuming, and chemical treatment is often preferred as a cheaper solution when considering both personnel and acquirement costs.

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9 METHODS OF PHYSICAL, CHEMICAL AND BIOLOGICAL CHARACTERISATION OF PLASTIC LITTER

9.1 Introduction

Plastics represent a mixture of particles differing in properties with varying physical, chemical, and biological characteristics (e.g. size, shape, polymer, and surface characteristics). This huge diversity of particle characteristics presents several challenges in terms of understanding the consequences of plastic presence in the environment, transport and fate, interaction with biota, implications to ecosystem service and humans, and the subsequent risk management. Obtaining information to support management decisions requires a thorough and detailed understanding of plastic particle characteristics. This includes appropriate analytical methods to characterise physical (shape, size, colour and functional information), chemical (polymer composition, weathering status, and additive chemicals, and sorbed contaminants) and biological (associated biota, etc.) properties of plastics (Figure 9.1). This information can be used to develop reliable risk assessments and management procedures. Among the characteristics observed or analysed, some (e.g. confirmation of microplastics by chemical characterization) are very crucial and the others (e.g. colour) give additional information to meet the purpose of the monitoring program.

It is likely that not all properties of plastics pose threats towards ecosystems. Therefore, to ascertain the hazardous effects of particle properties all characteristics should be analysed. However, researchers are presented with a challenge, as most plastics obtained from the environment will have undergone weathering caused by biological, chemical and physical processes altering their characteristics from pristine raw materials. These processes should be considered when investigating the characteristics of plastics sampled from the environment.

9.2 Physical characterization

9.2.1 Macro-plastic litter

Marine litter comprises of a variety of material types (e.g. plastics, glass, metal, paper, cloth, rubber, and wood), and can be classified into several distinct categories based on use or function (e.g. fishing gear, household trash, and industrial garbage), in accordance with the recognized list of categories (section 3.2). Visual examination is the most common method used to assess size and quantities of plastics litter. Usually marine litter surveys on beaches and coastal and marine environments consider variables such as size, colour, material type, or degree of weathering and wear. Different material uses and physical characteristics of plastics litter may indicate possible sources. Collecting and recording information about the environmental setting and conditions under which sampling occurs (e.g. sea state, timing of tidal cycle) can help in the evaluation of status and trends. Thus, it is important to use methods that identify the physical characteristics.

From the physical characterisation (shape, colour and packaging labels) of plastic products, the use and origin place of manufacture of some products can be identified. These plastic products range from common domestic material (e.g. bags, bottles, expanded polystyrene cups and food containers, toys and balloons) to industrial products (e.g. plastic sheeting and electronics packaging) and discarded fishing gear (e.g. nets, ropes, buoys, and lines). Plastic

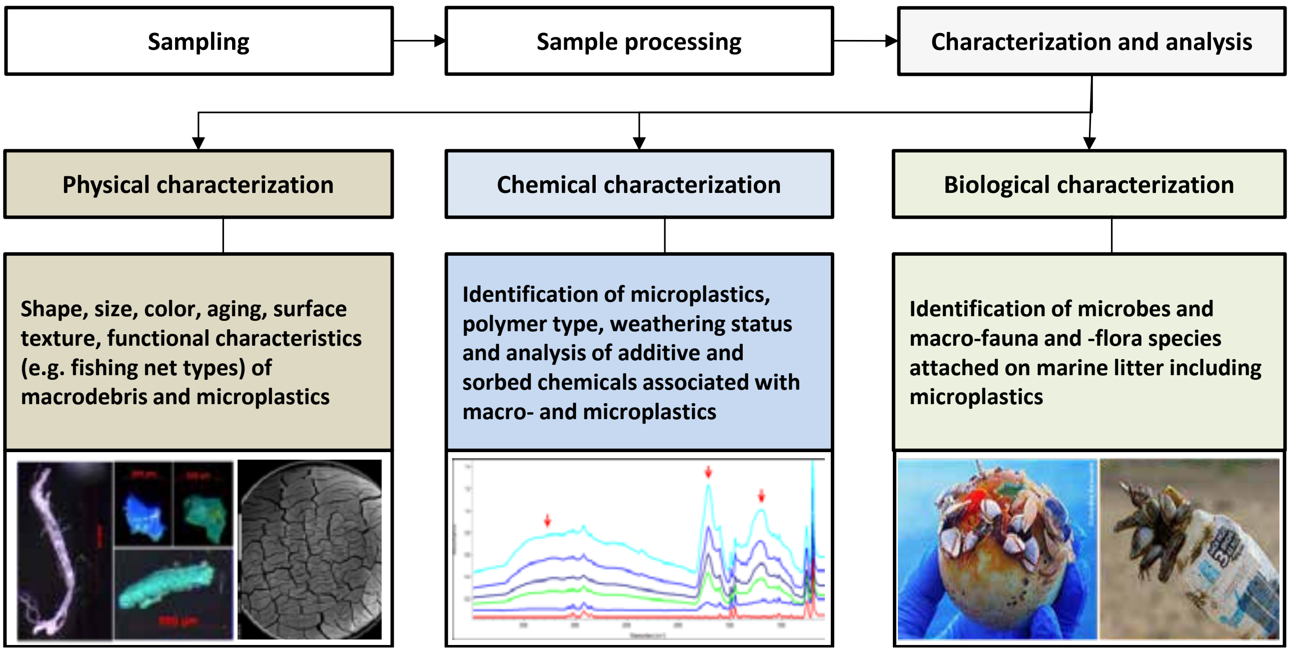

Figure 9.1. Flow chart of marine litter analysis.

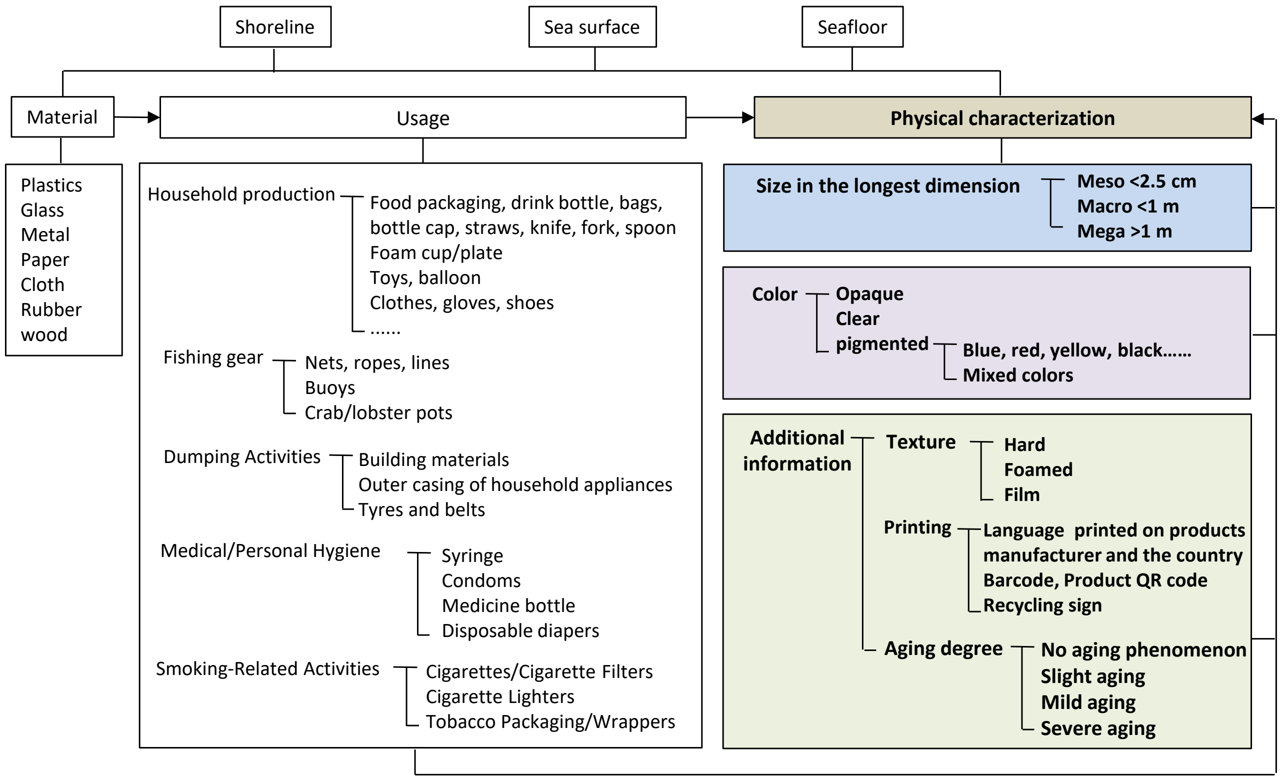

Figure 9.2. Physical characterization of macro-litter.

recycling symbols (the recycling code constitutes of the numbers 1 through 7) appearing on the discarded items can help investigators identify the components and polymer types of marine plastic litter. In addition, from the colour degradation situation, the degree of plastic aging can be described. However, some information is potentially lost, since not all the possible information available in each plastic item is recorded during field or laboratory observation. Harmonisation of criteria (Figure 9.2) to classify macro-plastics is important, in order to help observer completing their tasks.

The language, manufacturer address and/or barcode in labels give additional information in the possible origin (domestic vs. foreign) of the items. Structure and knot types of fishing nets also give valuable information of the origin of certain fishing industry. Fishing gear marking can help to identify source and origin of ALDFG[64]. However, there may be differences in the proportion of macro-plastics in different categories depending on the compartment of the ocean being monitored/surveyed.

64 http://www.fao.org/3/MX136EN/mx136en.pdf

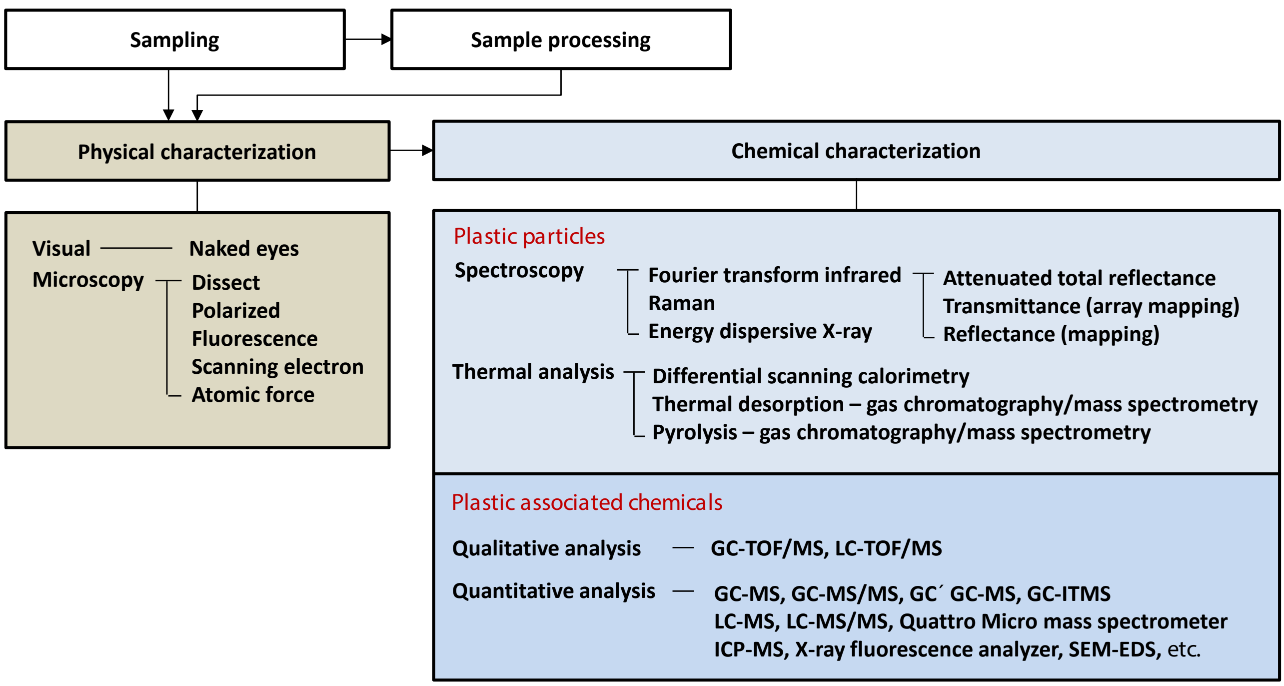

Figure 9.3. Physical and chemical characterization methods.

9.2.2 Micro- and meso-plastic litter

It may be possible to characterise meso-plastic litter in a similar manner to macro-plastic litter if the items are sufficiently well formed and distinctive. However, this category is often dominated by weathered and fragmented objects, preventing a more detailed description. It For microplastics, it is even more difficult to describe the sizes, shapes and polymer types fully and reliably, from complex environmental matrices, using a single analytical method. Therefore, the combination of more than two analytical technique has been widely used (Figure 9.3). In general, microplastic analysis consists of two steps: physical characterization of potential plastics (e.g. microscopy) followed by chemical characterization (e.g. vibration spectroscopy) for confirmation of plastics. In special cases also co-contaminant chemical analysis is performed on extracted chemicals. Through physical characterization, size (maximum dimension or particle image), shape and colour can be observed and recorded based on the classification proposed in the previous section.

Visual observation with the naked eye
Regardless of the sample processing employed (i.e. biological/chemical processing &/or density separation), visual examination of the sample remains an obligatory step in the data collection process prior to possible spectroscopic confirmation. Visual identification employs naked eyes and optical (dissection) microscopes. This step in the sample processing tends to be the most tedious, but is also among the most important in order to separate the plastics from other materials.

During this visual identification process, particles are generally categorized according to their morphology (fragment, pellet, fibre/line, film and foam), size and/or colour (Figure 9.4, Chapter 2). The specific size for each particle can be determined by measuring its longest edge. It has also been advised that major and minor dimensions are measured. Estimating the third dimension allows for calculating particle volume and thus particle mass through relative density (Simon *et al.* 2018). This is especially important when it is not feasible to measure the mass of each particle due to small size or large numbers. Both number of particles, size and mass are considered important parameters when reporting data.

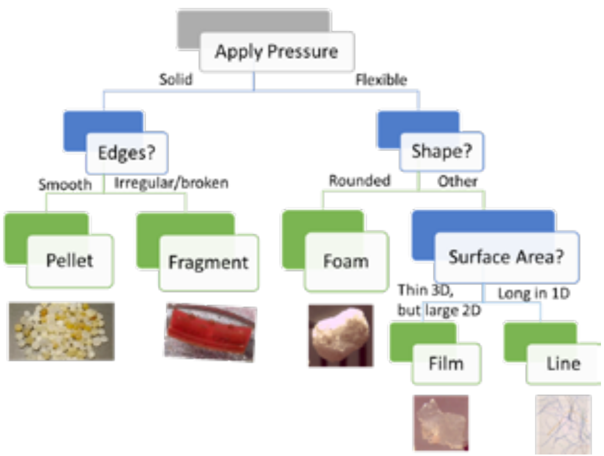

Figure 9.4 Flowchart to aid the categorisation of large micro and meso-sized plastic particles and fragments.

Due to the relatively large size range of meso-plastics (5–25 mm), sorting and identification are usually performed simultaneously in a tray with forceps and the naked eye. Some small plastics can be identified using this visual method, and colourful plastic fragments and pre-production resin pellets that have a size range of 2–5 mm can be identified with the naked eye (Heo *et al.* 2013). However, there is a higher probability of missing small plastic particles by sorting if there are high numbers of inorganic and organic particles with similar colours and shapes, leading to ambiguity, especially for particles < 1mm in diameter. Such situations can occur in strandline deposits on the shoreline (Shim *et al.* 2017). However, visual sorting and identification of large microplastics offers an easy, simple and fast method for both experts and the non-professional volunteers who have received brief training (Hidalgo-Ruz and Thiel 2013).

Microscopy
Stereo- (or dissecting) microscopy is a widely-used identification method for microplastics whose size falls in the hundreds of micron range (e.g. neuston net samples). Magnified images using microscopy provide detailed surface texture and structural information of objects, which is essential for identifying ambiguous, plastic-like particles (Shim *et al.* 2017). Although most particles of this size range are usually identifiable by microscopy, particles of the sub-hundred-micron size range (< 100 µm) with no colour or specific shapes (e.g. fibres) are difficult to characterise with confidence as plastics (Song *et al.* 2015). Sediment samples for which light sediment particles are poorly separated by density can interfere with microscopic identification of microplastics on membrane filters. In addition, biogenic materials from sediment and neuston net samples that have not been properly eliminated by chemical digestion also make microscopic observation difficult. Although high magnification optical microscopy, with optimized illumination methods, allows high resolution visual inspection, there is limited validation of visual characteristics to chemical compositions. This makes visual inspection of small microplastics subjective and prone to errors. Some basic criteria for selecting suitable particles include:

(i) no visible cellular or organic structures;

(ii) fibres should be equally thick throughout their length; and,

(iii) particles should appear to have homogeneous colouring reduce possibility of false positive identification (Hidalgo-Ruz *et al.* 2012).

Previous studies have shown that false identification of plastic-like particles using microscopy was often over 20%, and over 70% for transparent particles; these results were confirmed with subsequent spectroscopic analysis (Hidalgo-Ruz *et al.* 2012, Song *et al.* 2015). Synthetic (e.g. polyester) and natural (e.g. coloured cotton) fibres were difficult to distinguish by microscopy alone (Song *et al.* 2015)

A simple staining method can provide an alternative and complementary method to address these problems. Nile Red is a useful dye for staining highly hydrophobic microplastics selectively (Andrady 2011, Shim *et al.* 2016, Maes *et al.* 2017, Erni-Cassola *et al.* 2017) (Figure 9.5). A combination of fluorescence microscopy after NR staining followed by FTIR confirmation would reduce the likelihood of missing microplastics in the identification of field samples, as well as the time required to check every plastic-like particle using spectroscopy. One of the main limitations in applying the NR staining method to field samples is the co-staining of natural organic material. Therefore, it is important to remove natural lipids and organic matter from the samples before NR staining. The fluorescence can interfere with subsequent Raman spectroscopy and this may require an additional clean-up procedure, although the extent to which this is significant is a matter of debate (Araujo *et al.* 2018). A potential cause of uncertainty is that Nile Red will also stain any lipids present in the sample.

Scanning electron microscopy (SEM) can provide extremely clear and high-magnification images of plastic-like particles. High-resolution images of the surface texture of the particles facilitate the discrimination of microplastics from organic particles (Cooper and Corcoran 2010). But, it is hardly applicable for routine analysis of large number of samples.

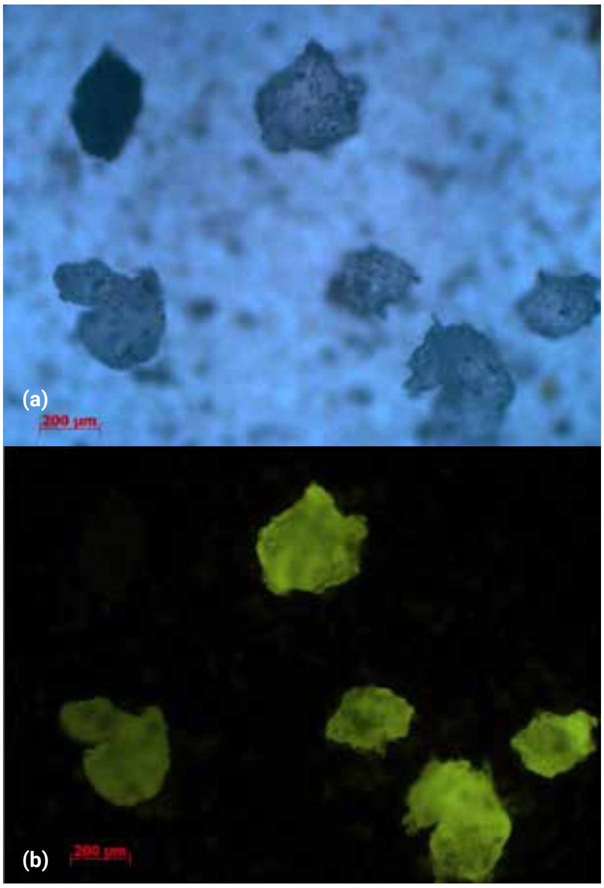

Figure 9.5 Use of staining plastic particles with Nile Red do distinguish plastic from other particles: **(a)** no staining, **(b)** stained with Nile Red (image courtesy of Wonjoon Shim).

Other advanced microscopy techniques have been used to identify plastic particles in specific cases. Polarised optical microscopy was successfully used to identify polyethylene (PE) particles in laboratory accumulation and toxicity experiments (von Moos *et al.* 2012).

9.3 Chemical characterization

9.3.1 Identification of microplastics

Chemical characterization is a final step to identify microplastics from the other natural materials, when visual and microscopic observation is not enough to confirm particle nature. In addition, this step provides polymer composition of microplastics which can be useful to get better understanding of their parent materials and possible sources and input pathways and grouping of polymers for further instrumental analysis of plastic associated toxic chemicals (Figure 9.6). Most common method in chemical characterization of microplastic particles is spectroscopy (e.g. Fourier-Transform Infra Red (FTIR) and Raman). Alternative methods such as thermal analysis coupled with mass spectrometry have recently been proposed for bulk analysis of micro- and nano-plastics. Novel methods including staining and semi- or fully automated spectroscopic observation are being developed and begun to be applied to real environmental samples. The advantages and disadvantages of the most common characterisation techniques are summarised in Table 9.1.

Fourier Transform Mass Spectroscopy FTIR

FTIR spectroscopy provides information on the specific chemical bonds and functional groups of each plastic polymer, which are easily identified with this method. The different bond compositions produce unique spectra that discriminate plastics from other organic and inorganic particles (Löder and Gerdts 2015). Transmission, reflectance (transflectance), and attenuated total reflectance (ATR) modes are available in FTIR analysis for microplastics. The transmission mode requires that the IR light can pass through the particles, while the reflectance and ATR modes does not require the sample preparation step for thick and opaque microplastics. Due to the typically irregular surfaces of environmental microplastics ATR-IR spectra are usually of better quality compared to spectra obtained in reflectance mode, but of lower quality compared to spectra obtained in transmission mode (Shim *et al.* 2017). The smallest detectable particle size is typically smaller for ATR than for transmission, however the drawback with ATR-IR is the need for contact between sample and ATR crystal. Small microplastics require the use of micro-FTIR (µFTIR), which is used to perform microscopic observation of micro-sized plastic-like particles prior to spectroscopic confirmation on a single platform by switching between the object lens and IR beam. With µFTIR microscopy, it is possible

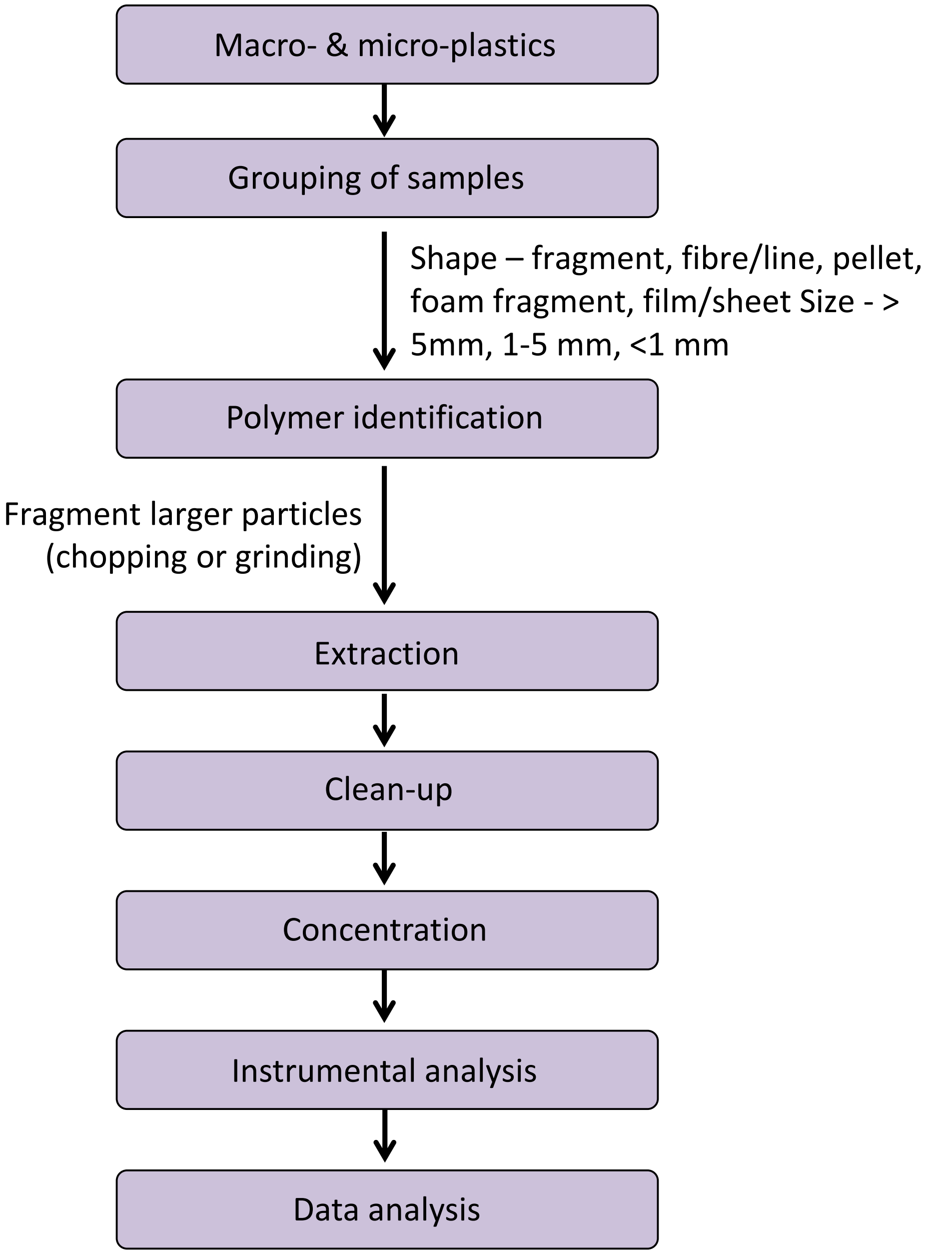

Figure 9.6 Flowchart for the characterisation of polymer type and associated chemicals by instrumental analysis.

to image and characterize polymer particles down to 20µm size on e.g. a 10 x 10 mm filter with reasonable time. The best microscopes can even be used to image smaller particles with synchrotron quality. Automated processing methods are being developed making the technique promising for routine analyses (Primke *et al.* 2017).

Man-made cellulosic fibres (Rayon/Viscose) are difficult to discriminate by microscopy alone. With spectroscopic techniques it is important to examine the spectra cautiously, to minimise the generation of false positives (e.g. misidentification of natural fibre to rayon) or false negatives (e.g. misidentification of rayon to natural fibre), (Comnea-Stancu *et al.* 2017). Natural and man-made cellulosic fibres can be differentiated successfully with FTIR spectra acquired by using both ATR microscopy and ATR spectroscopy, and the application of ATR spectrum search libraries (Comnea-Stancu *et al.* 2017).

Raman spectroscopy

Raman spectroscopy has also been used to identify microplastics. A laser beam falling on an object results in different frequencies of back-scattered light depending on the molecular structure and atoms present, which produce a unique spectrum for each polymer. Raman analysis not only identifies plastics, but also provides profiles of the polymer composition of each sample similar to FTIR. In terms of the combination of non-destructive chemical analysis with microscopy, Raman spectroscopy is comparable to the FTIR method, including the requirement for expensive instrumentation. The different responses and spectra between FTIR and Raman spectroscopy from a microplastic can compromise each other in complex microplastic identification. The smaller diameter of the laser beam in Raman spectroscopy relative to FTIR allows the identification of microplastics as small as a few μm in size (Cole *et al.* 2013). The non-contact analysis of Raman spectroscopy offers the benefit that the microplastic samples remain intact for possible further analysis. However, Raman spectroscopy is sensitive to the additive and pigment chemicals in microplastics, which interfere with the identification of polymer types (Shim *et al.* 2017). When compared to μFTIR microscopy, μRAMAN is significantly slower and sample preparation is even more important since residual organic material that fluorescence would effectively influence the results.

Scanning electron microscopy SEM-EDS
After physical characterization done by SEM, the target particles can be further analysed with energy-dispersive X-ray spectroscopy (EDS) to get the elemental composition of the same object. The elemental composition of particles is useful for identifying carbon-dominant plastics from inorganic particles. It is particularly useful for plastic polymers containing heteroatoms, e.g. the presence of chlorine atoms in PVC and fluorine atoms in (e.g. PTFE). SEM-EDS is expensive, and requires substantial time and effort for sample preparation and examination, which limits the number of samples that can be handled. The colours of plastics cannot be used as identifiers in SEM. The method is recommended for further surface characterization and elemental analysis of specific plastic particles, particularly when examining for weathering or chemical damage to particle surface (ter Halle *et al.* 2017).

Thermal analysis DSC/TGA
The thermo-analytical technique, which measures changes in the physical and chemical properties of polymers depending on their thermal stability, has been recently tested for microplastic identification (Dümichen *et al.* 2015). Differential scanning calorimetry (DSC) is a useful method for studying the thermal properties of polymeric materials. The method requires reference materials to identify polymer types because each plastic product has different characteristics in DSC. Thermogravimetry (TGA) combined with DSC identified some polymers (Majewsky *et al.* 2016). When TGA was coupled with thermal desorption gas chromatography mass spectrometry (TDS-GC-MS), this combined the advantages of larger sample size with TGA compared with pyrolysis (pyro)-GC-MS and higher resolution with GC-MS compared with DSC (Dümichen *et al.* 2015).

Pyrolysis-GC/MS
Py-GC-MS is another method that analyses thermally decomposed gas from polymers. The obtained programmes from samples are compared with reference programmes of known polymer samples. Relatively small samples of plastic particles were pyrolised at a higher temperature than in TGA, and subsequently separated and analysed using GC-MS. Pyro-GC-MS analysis identified the isolated potential plastic particles from sediment samples (Nuelle *et al.* 2014). However, thermal analysis is a destructive method, preventing subsequent additional analysis of microplastic samples. DSC analysis is relatively simple and fast, but has limitations in identifying microplastics from some polymer products in environmental samples. Information relating to the number, size and shape of analysed microplastics is not provided with bulk analysis. This method requires a well-trained and experienced operator as well as considerably more time and effort for instrument runs and data processing compared with FTIR spectroscopy (Käppler *et al.* 2018). Py-GC/MS has been successfully applied to biota samples after enzymatic/oxidative decomposition (Fischer and Scholz-Böttcher 2017). A method for optimising the performance of pyrolysis-GC/MS has been reported by (Hermabessiere *et al.* 2017). This method would be useful for screening analyses of bulk samples or further complementary analyses of microplastics that have not been fully characterised with spectroscopy

Novel methods including automation
Atomic force microscopy (AFM) combined with either IR or Raman spectroscopy is a potential candidate for nano-plastic analysis. AFM can provide images at nanometre resolutions, and AFM probes can be operated in both contact and non-contact mode with objects. IR or Raman spectroscopy combined with AFM can determine the chemical composition of the object, but is a slow technique, not suitable for larger areas.

Pre-programed, semi-automatic mapping without the need for the microscopic pre-selection of particles for analysis can be used to reduce manual effort in the FTIR process. The focal plane, array-based, reflectance imaging method can provide information on the identification of microplastics on larger surface areas, at faster times and without compromising spatial resolution, compared with single beam mapping (Primpke *et al.* 2017). Another possible analytical combination that may be applicable to microplastic identification is that of automated particle tracking, image analysis, and Raman spectroscopy (Kinnunen *et al.* 2015). Particles are automatically tracked one by one, and microscopic image and Raman spectroscopic analyses are also automatically conducted. Fully-automated particle analysis and subsequent spectroscopy can save time and effort, but the tracking may fail when confronted with transparent particles.

The simple staining method could provide an alternative and complementary method to address these problems. Nile Red is a useful dye for staining highly hydrophobic microplastics selectively (Shim *et al.* 2016). A combination of fluorescence microscopy after NR staining followed by FTIR confirmation would reduce the likelihood of missing microplastics in the identification of field samples, as well as the time required to check every plastic-like particle using spectroscopy. One of the main limitations in applying the NR staining method to

Table 9.1. Advantages and disadvantages of microplastic characterization methods, including identification of polymer types adapted from (Shim *et al.* 2017).

Identification method	Advantages	Disadvantages
Microscopy	Simple	No chemical information for confirming composition
	Low cost	High possibility of false positives
	Colour and morphological information	High possibility of missing small and transparent particles
		Subjective in interpretation
Microscopy + spectroscopy (sub-set)a	Polymer composition of a sub-set of the sample	Possibility of false positives
		Possibility of missing small and transparent particles
		Sub-set may not be representative
		Potential bias in sub-set selection
Microscopy + FTIR spectroscopyb	No false positives – confirmation of all plastic-like particles	Manual selection of particles means some plastic may be missed
	Reduction in false negatives	Expensive instrument
	Non-destructive	Laborious and time-consuming for identification of all particles
	Detection limit 20 µm particles	Requires expertise in spectral interpretation
		Contact analysis (ATR)
		Need to transfer particles from filter paper to metal plate
		Removal of organic material a prerequisite
Microscopy + Raman spectroscopyb	No false positives – confirmation of all plastic-like particles	Manual selection of particles means some plastic may be missed
	Reduction in false negatives	Expensive instrument
	Detection limit 1 µm particles	Laborious and time-consuming for identification of all particles
	Non-destructive analysis	Requires expertise in spectral interpretation
	Non-contact analysis	Interference by pigments
		Risk of laser damage to particles
		Removal of organic material a prerequisite
		Exact focussing required
Semi-automated spectroscopy (mapping based)	No manual particle selection error	No visual image data on single particles
	High automation potential	Production of a large volume of data
	In principle no false negatives	Long post-processing time
		Still requires expertise in spectral interpretation
		Efficient removal of interfering particles a pre-requisite
		Still lacks validation for smaller particles
		Expensive instrument
Semi-automated spectroscopy (image analysis directed point analysis)	High automation potential	Production of a large volume of data

Table 9.1. Advantages and disadvantages of microplastic characterization methods, including identification of polymer types adapted from (Shim *et al.* 2017).

Identification method	Advantages	Disadvantages
	Fewer false negatives	Long post-processing time
	Potential for faster sample throughput	Still requires expertise in spectral interpretation
	Size and morphology of single particles	Efficient removal of interfering particles a pre-requisite
		Still lacks validation for smaller particles
		Expensive instrument
Thermal analysis	Simultaneous analysis for polymer type and additive chemicals (Pyro-GC/MS)	Destructive analysis
	Mass-based information	No number – and size-based information
		Limited polymer type identification (DSC)
		Complex data (Pyro-GC/MS)

[a]FTIR or Raman analysis of subset of particle samples
[b]FTIR or Raman analysis of whole particles / require microscopy before

field samples is the co-staining of natural organic material. Therefore, it is important to remove natural lipids and organic matter from the samples before NR staining.

9.3.2 Characterization of weathering

Characterization of weathering state can be done with a combination of physicochemical characterization methods. Environmental degradation of polymers typically involves oxidation processes that are catalysed by increased temperature, UV irradiation or otherwise available radicals. Polymer backbones are becoming increasingly functionalized with hydroxyl, aldehyde and carboxylate functional groups, which can be experimentally followed by ratios of specific peaks in FTIR. The molecular weight of the polymers are sequentially decreased by scission of the polymer chains at the points of oxidation, which can be determined by size exclusion chromatography after dissolving the polymer in warm solvents but a simpler proxy is measurements of tensile strength at break. The plasticity of the polymer decreases and the increased brittleness facilitate mechanical fragmentation, which can also be seen as physical micro-cracks in SEM. The functionalization decreases hydrophobicity and facilitates biofilm formation (Karlsson *et al.* 2018). Furthermore, the level of crystallinity increases, which also influences material density. Due to the functionalization of the pristine polymers, database matching to pure reference polymer spectra is rarely good for environmentally weathered particles, and thus availability of reliable environmental microplastic reference materials and associated spectroscopic data, is important for increased quality in spectroscopic material identification.

9.3.3 Quality assurance and quality control for microplastic analysis

Ensuring reliable and traceable results as with any environmental analytical work is a key factor when data are going to be used to support decision-making (Hermsen *et al.* 2018). Contamination of samples is a well-known problem in microplastic surveys (section 8.2), but there are several other quality aspects that need to be cared for during the entire analytical chain from sampling, sample processing, analysis and data interpretation. That includes statistical under-sampling, contamination at any point, bias in sampling certain particles with some sampling methods, recovery and losses of particles during matrix removal or microplastic extraction from sediments, detection window in terms of size and characteristics of selected analytical method. Contamination of samples from their surroundings should be minimized by cleanliness standard operating procedures, and controlled for by procedural blanks from field to analysis. Blanks can be subtracted as: i) a total, ii) separately for each identified category, or iii) reported as an uncertainty variable together with the data results. Sample size need to be taken into account in order to obtain enough particle counts per sample to limit the counting statistical uncertainty (Poisson statistics), and to significantly supersede the levels of the procedural blanks. This is essential to be able to draw conclusions that answer the underlying questions of the monitoring programmes (how much of any given microplastic category is distributed among the samples). Extraction efficiency or loss in digestion protocols or density separation can be assessed by spiked recovery tests, using relevant reference particles (similar properties as sample particles but still clearly distinguishable, e.g. by distinct colours). Rigorous protocols and training are important to minimize subjectivity, and estimation of operator bias, is best assessed by repeatability measurements by different analysts on the same samples.

9.3.4 Analysis of chemicals associated with plastic litter and microplastics

Rationale for including the assessment of associated chemicals

Chemicals associated with plastic litter and microplastics can be categorized into two groups according to their origins:

i) intrinsic, i.e. included as part of the production process, and

ii) external, i.e. chemicals already present in the environment that become sorbed to the plastics, particularly hydrophobic organic compounds. Consequently, plastic particles represent both a source and a vector for the transfer of a wide range of contaminants.

Many plastics contain organic or inorganic additives that are included during production to enhance certain properties (e.g. flexibility, flame retardation, thermal stability, pigmentation, dyes, inert filler, anti-microbial resistance and resilience to UV radiation). The degree to which additives are permanently bound into the plastic matrix varies, and this influences the rate and extent of leaching to the surrounding environment during use or after disposal. Many of the additive chemicals are known to have endocrine disrupting potentials. These include phthalates as plasticisers, polybrominated diphenyl ethers (PBDEs) and hexabromododecanes (HBCDs) as flame-retardants, bisphenol A in polycarbonate, and nonylphenol and octylphenol in phenol formaldehyde resins.

Plastic particles have a high affinity for hydrophobic environmental contaminants such as organic pollutants and metals. Microplastics can efficiently concentrate these contaminants due to their large surface-area-to-volume ratio (Mato *et al.* 2001). Commonly reported contaminants include: polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides, brominated flame retardants, phthalates, and alkylphenols, with high detection frequency and in a wide range of concentrations from ppt to ppm levels (Hong *et al.* 2018, Yamashita 2018).

Consequently, plastic litter is sometimes referred to as a "chemical cocktail", and be a source and a vector of these chemicals to the marine environment and marine wildlife (Jang *et al.* 2016, Tanaka 2018), and with the potential to have negative impacts, although these are difficult to establish at environmental concentrations (Browne *et al.* 2013, Li *et al.* 2016, Tanaka *et al.* 2013). Many studies have reported that marine litter and microplastics contained non-polymeric chemicals; for example, one non-target screening analysis identified over 200 organic compounds in marine plastic litter (Gauquie *et al.* 2015, Rani *et al.* 2015). Information on chemical levels and profiles in marine litter and microplastics is valuable in understanding chemical dispersion through plastic pollution in the marine environment and their environmental health risk.

Sampling and sample storage

On the collecting of microplastic samples for the analysis of associated chemicals, several points should be taken care. Contamination through the collection and storage should be minimised. For trace organic analysis, solvent-rinsed glassware or stainless-steal equipment and containers are used. To prevent degradation, storage in a freezer or refrigerator is preferable. Adding organic preservative such as formaldehyde may contaminate the samples or may change the partitioning of the target contaminants. The possibility of fragmentation of plastics during freezing should be considered. Caution should be taken not to modify the partitioning. In addition, the cleaning process for removing organic materials from plastic samples (such as acidic, alkaline/basic, and oxidative digestions) before chemical analysis may change the levels of chemicals in the samples (e.g. chemical leaching or contamination). Therefore, it is recommended to avid or minimise the cleaning process for the samples that will be used for chemical analysis.

Pre-treatment of plastic samples in the laboratory

Before detailed chemical analysis, it should be established whether the sample is a synthetic polymer or a natural material. It may be desirable to remove other organic or inorganic materials (such as biomaterials and tarry residues) attached to the surface of plastic samples, which can cause erroneous analytical results. Plastic litter and fragments have a wide variety sizes, shapes, colours, polymeric compositions, and weathering conditions. If the sample amount is sufficient, it can be sorted according to these characteristics prior to chemical analysis.

i) Sample amount (weight): Sample amount is an important parameter to be considered prior to chemical analysis, which directly affects not only detection limits of target chemicals but also the amount of interfering materials. As plastic litter becomes smaller, obtaining sufficient amounts of samples for chemical analysis would be more difficult, which leads to high detection limits and low detection frequencies for target chemicals. This is the reason of data limitations on microplastics (especially smaller than 1 mm). According to a recent review (Hong *et al.* 2017), sample weights of microplastics used per extraction was 0.15–5 g (frequently ≤ 1 g), and 5 pellets, and 0.15–0.3 g foams.

ii) Shape: Plastics can occur as fragments, fibres / filaments, beads / spheres, films / sheets, and pellets. The shape of plastic litter and microplastics can be closely related to that of their original products (e.g. fibre type for fishing rope or clothing, foam type for Styrofoam buoy or box or building panel, and pellet type for plastic raw material). Some plastic products contain large amounts of certain additive chemicals for their end use purpose. For example, a large amount of a brominated flame retardant, hexabromocyclododecane (HBCD) is contained in expanded polystyrene (EPS) construction materials, of used for aquaculture buoys (Rani *et al.* 2014, Jang *et al.* 2017). Therefore, the chemical concentration according to the shape of plastics could give a good insight of environmental exposure and dispersion of chemicals through certain plastic products or pollution sources.

iii) ***Sample dimension (size):*** The overall size of plastic litter ranges from a few micrometres to a few meters. Among the physical characteristics of plastic samples such as polymer type, colour, and shape, the size of plastics would be the most important factor for their impacts on marine organisms because their potential for encountering with or ingestion by marine animals could greatly increase from large marine mammals to small marine organisms (GESAMP, 2016). Therefore, the information of chemical levels and compositions in different size groups of plastics would be valuable to understand chemical exposure for marine organism via plastic ingestion. Among different size groups, very few studies have measured the chemical contents of small microplastics < 1 mm (Hong *et al.* 2018, Yamashita *et al.* 2018) due to the difficultly in collecting samples of sufficient amounts for chemical analysis. More sensitive detection techniques and methodologies will be of help to overcome this difficulty.

iv) ***Colour and surface condition:*** Pigments are sources of some chemicals including some metal elements (e.g. Cd, Cr, Filella and Turner 2018). Therefore, sorting in terms of colour is recommended before extraction. The residence time of plastics in the ocean can affect chemical concentration in plastics because of the partitioning processes (e.g. sorption and desorption) of chemicals between seawater and plastics. Discolouration (yellowing) and surface erosion are indicative of a longer environmental exposure time. Yellowing is due to formation of quinone or semi-quinone compounds from phenolic additives such as benzotriazoles via environmental weathering, which are formed mainly via photo-oxidation. (Endo *et al.* 2005) found relatively high PCB concentrations in discoloured pellets.

v) ***Associated chemicals – absorbed chemicals:*** The sorption capacity of different polymers to contaminants chemicals in seawater varies according to the chemical structure of the polymers. PE has the highest sorption capacity of PBTs with order of PE>PP>PS>>PET (Rochman, 2013, Yamashita, 2018). High contents of chemicals are contained in certain polymers; for example, phthalates in PVC products, flame retardants in EPS, bisphenol A (monomer) in polycarbonate, phthalic acid (monomer) in PET. Some are specific additives and the others are unreacted or degraded monomers of corresponding polymers. Furthermore, by-products of polymerisation are contained in some polymers, such as PAHs in EPS. Therefore, sorting in terms of polymer type is recommended before analysis of associated chemicals.

Separation of chemicals from plastic samples

Quantitative and qualitative analyses of chemicals in plastics require a series of sample preparation steps, including extraction, clean-up, and instrumental analysis (Table 9.2). The overall analytical process used for plastic samples is similar to those commonly applied to environmental matrices such as water, sediment, soil, and biota. Extraction is the separation process of chemicals from a polymeric matrix, and clean-up is the removal process of undesired interfering substances from the extract. The extraction method (e.g. solvent types, volumes, and temperature) should be chosen, and optimized based on the physicochemical properties of plastic matrices and chemicals of interest (e.g. polarity, solubility, and stability of chemicals, and diffusion rate of the solvent into polymer). A clean-up process is usually applied to enhance the selectivity and sensitivity of target chemicals in the instrumental process. Extraction and clean-up methods commonly used for plastic associated chemicals were reviewed by Hong *et al.* (2017) (Annex X).

Instrumental analysis: quantitative or qualitative measurement

The final sample extracts are subjected to instrumental analysis to obtain the quantitative or qualitative chemical data. Gas chromatography (GC) is widely used for non-polar organic chemicals, and liquid chromatography (LC) is commonly used for the analysis of large, polar, ionic, thermally unstable, and non-volatile compounds, coupled with a number of types of detectors. Instruments commonly used for analysing plastic-associated chemicals are summarized in Table 9.1 (Hong *et al.* 2017).

Quality assurance and quality control for chemical analysis

A global risk assessment of marine plastic litter, as intended under the SDG 14.1.1 framework, will require the integration of analytical data from many sources. To do this, the data quality should be ensured. Quality control is particularly important if the concentrations of chemicals in the sample are extremely low and near the detection limit. To ensure the reliability of the analytical results, it is recommended to run quality control samples such as procedural blank, replicate sample, spiked blank sample, matrix spike sample, and certified reference materials with every batch of samples analysed. There is a growing need to develop reference materials for not only plastic particle analysis but also chemical analysis. Currently, PE and PVC containing bisphenol A and phthalates are commercially available, as certified reference materials. Inter-laboratory comparison studies will help harmonise and validate analytical methods currently used across laboratories, and also help improve analytical performance of laboratories. There have been recent attempts at inter-laboratory calibration exercises on analysing microplastics from blind samples. One was co-led by NOAA[65] and the Ministry of the Environment, Japan[66]. A second was arranged within the European JPI Oceans Baseman project[67]. A third is planned for 2019 as part of the European QUASIMEME programme (Quality Assurance of Information for Marine Environmental Monitoring in Europe)[68]. This attempt should be expanded to chemical analysis associated with plastics and microplastics. Reporting the limit of detection (LOD) or the limit of quantitation (LOQ) for analytical method is also recommended.

9.4 Biological characterization

9.4.1 Plastics as a substrate

When released into the environment, plastics attract a host of biological material, from bacteria to planktonic organisms, which use the surfaces as a substrate for colonisation. In turn this may create new habitats and food source for other marine organisms (Zettler *et al*. 2013). Using the presence of associated biota on plastics may help classify marine litter in terms of estimating time at sea and possible source locations, so it represents an important component of a marine litter monitoring strategy.

Macro plastic litter can be characterised based on its biological properties. Plastic litter acts as a substrate for settling biota and microorganisms, often acting as a transport vector for marine species. Organisms have utilised neuston and natural marine litter as transport vectors for rafting for millions of years. However, the introduction of plastics as a form of marine litter has transformed marine rafting (Barnes and Milner 2005). Plastics can act as a different substrate and support different species for example, the bacteria that colonize plastic particles were shown to differ from those in the surrounding water (Zettler *et al.* 2013) and sediment. The association of biological organisms with plastic items can enable researchers to understand the spread of non-indigenous species attached to floating items. Artificial substrata, in this case plastic items, provide novel habitat for species and they can be transported between beaches, or further afield to oceanic regions. For example, exotic species have been reported far from their traditional habitat when associated with marine litter (Barnes and Milner 2004).

Further more specialised investigations are possible once the sample is returned to the laboratory. For example, (Zettler *et al*. 2013) investigated the characteristics of the microbial community on microplastic particles using a combination of scanning electron microscopy (SEM) and DNA extraction. This level of analysis would normally only be justified for very specific policy reasons, such as assessing the risk of transfer of pathogenic bacteria on human health.

9.4.2 Identifying the source of litter

Utilising the species identity and assemblage composition can allow researchers to identify possible origins of large items of plastics. Possibly one of the best examples for this is the recent study by (Carlton *et al.* 2017) where species identity confirmed that many litter items stranded between 2011 and 2017 on the North American Pacific coast had originated in Japan. Similarly, species assemblages on detached aquaculture buoys were used to trace their origin back to nearby aquaculture centres (Astudillo *et al.* 2009). In north-west Europe several reports have used the appearance of indicator species to infer that floating litter had arrived from the North American coast or the North Atlantic subtropical gyre (Franke *et al*. 1999, Hoeksema *et al.* 2012).

Organisms growing on marine litter can also be used to estimate the proportion of ocean-based litter, or the time periods that litter has been floating in the sea. Using known growth rates of *Lepas* barnacles (see synthesis table in Thiel and Gutow 2005), the sizes of these barnacles have been extensively used to estimate floating times of seaweeds (e.g. Fraser *et al.* 2011). This can also be applied to stranded litter.

65 https://marinedebris.noaa.gov/research/detecting-microplastics-marine-environment
66 http://www.env.go.jp/en/water/marine_litter/outline.pdf
67 http://jpi-oceans.eu/baseman/workpackages
68 http://www.quasimeme.org/about

10 RECOMMENDATIONS

10.1 Recommended definitions and strategies (Chaps 2-3)

10.1.1 Marine litter definitions

The Guidelines reflect the fact that several size categories are in routine use in established monitoring programmes. In addition, several of the commonly used descriptors, such as meso, macro and mega, are not recognised as international standards, which would otherwise provide a basis for making a recommendation. Table 10.1 provides a summary of definitions for four broad size categories, giving the commonly-used size range together further alternative options that are in regular use, in particular for litter in the micro and meso categories. GESAMP recommends that < 5mm should be used as the upper size limit for microplastics for routine monitoring purposes. GESAMP acknowledges that research scientists may choose to use other definitions but concludes it is not helpful for regulatory authorities to have to wait until a scientific consensus is achieved.

GESAMP recommends that <5mm be used as the upper size limit for microplastics for monitoring purposes, based on its common usage in existing national and regional monitoring programmes

The selection of which size ranges to use is the responsibility of those designing and implementing new monitoring programmes. They will need to take into account the policy concern being addressed as well as the capacity and expertise of those personnel and organisations entrusted to carry this out.

Table 10.1 Recommended size categories for routine marine litter monitoring **R** = recommended **F** = feasible/ acceptable.

Size	Recommended	Alternatives options for operational monitoring and research purposes	
≈		Alternative 1	Alternative 2
Mega	**R** > 1m		
Macro	**R** 25mm – 1m		
Meso	**R** 5-25mm	**F** 1-25mm	**F** 1-5mm and 5-25mm
Micro	**R** <5mm	**F** <1mm	**F** <1mm

There is currently no standardized scheme for morphological characterization of plastic litter, but five general categories are used (fragments, foams, films, lines and pellets). While these morphological descriptions can be subjective, it is recommended that these 5 general categories may be subdivided in finer portions (granules/flakes, EPS/PUR, sheets, fibres/filaments/strands, beads/pellets) with the recognition that subdivisions can be combined for ease of harmonizing and comparing data.

Like morphology, there is currently no standard scheme for colour designation for plastic litter. While broad colour classifications are not sufficient, being too particular would be unreasonably time-consuming, if not impossible on a large scale, understanding also that colour may fade/change. We recommend either the 12 basic colour terms of the ISCC-NBS (Inter-Society Colour Council National Bureau of Standards) System of Colour Designation or the eight-colour classification scheme being proposed by the European Marine Observation and Data Network (EMODnet)[69] (Galgani *et al.* 2017).

For larger litter, the monitoring of specific items may require additional specific categories to better source marine litter and assess the efficiency of targeted reduction measures. As an example, the monitoring of abandoned or lost derelict fishing gears and action to lower their amounts in a specific area may require the consideration of specific categories of fishing related items (buoys, nets, ropes, lines, boxes, tags, etc.).

10.1.2 Developing a national or regional monitoring strategy

The selection of the most appropriate monitoring strategy must include a consideration of the policy question being addressed as well as the resources available to carry it out. This section provides a hierarchy of methods to assist in the selection of the most resource-efficient approach to answer a series of typical policy concerns.

In terms of fishing gear, it is probably useful to highlight that fishing industry stakeholders may need to be included in the process of developing such a strategy since they may play an active role in delivering it. Table 10.2 presents a list of environmental compartments and litter size categories, summarises the resource requirements (personnel, equipment) for each combination and provides examples of typical policy questions that government agencies may be facing.

It is critical to design and implement monitoring programmes that are cost-effective, to make best use of often scarce resources and ensure that programmes are more likely to be maintained. A number of factors are key and the following approaches are recommended:

i) prioritise the monitoring programme to address the most significant risks and associated indicators (i.e. scientific, technical, policy/social relevance, data requirements),

69 www.emodnet.eu

Table 10.2 Summary of the recommended sampling approaches for different compartments and plastic sizes, regarding their feasibility (1, more feasible; 7, less feasible; based on resource sampling and processing requirements) and common policy concerns addressed, with reference to the specific chapters in the report. The policy relevance index is the sum of the policy concerns addressed by the sampling approach. Compartments: SL – shoreline, SF – seafloor, B – biota, SS – sea surface. Sub-compartments: BE – beach, FISH – fish, INV – invertebrate, SEAB – seabird, MEG – mega-fauna. Plastic sizes: MA – macro-plastic, ME – meso-plastic, MI – micro-plastic.

	Compartments and plastic size			Resource sampling and processing requirements (costs increase from left to right)							Examples of policy concerns									
													Impacts on							
Feasibility	Compartment	Sub-compartment	Plastic size	People	Basic field equipment	Sieves	Nets	Dissecting microscope	Ship	Chapter	Distribution and Abundance	Source identification	Tourism	Seafood safety	Human health and injuries	Navigational hazards	Fisheries and aquaculture	Animal welfare	Biodiversity	Policy relevance index
1	SL	BE	MA	R	R					4	R	R	R		R				R	5
2	SL	BE	ME	R	R	R				4	R		R						R	3
3	SF		MA	R			R		R[a]	6	R	R				R	R		R	5
3	SF		MA	R[b]	R					6	R	R	R			R	R	R	R	7
4	B	FISH	ME MI	R		R		R		7	R			R			R	R	R	5
4	B	INV	ME MI	R				R		7	R			R			R	R	R	5
5	B	SEAB[c]	ME MI	R		R		R		7	R	R						R	R	4
5	B	MEG[c]	MA ME MI	R				R		7	R							R	R	3
6	SS		ME MI	R		R	R	R	R[d]	5	R						R		R	3
7	SS		MA	R	R				R[e]	5	R					R	R	R	R	5

[a] Opportunistic sampling using fishing vessel, [b] Opportunistic observations using recreational divers, [c] Stranded organisms, [d] Research vessel, [e] Visual observation from ship of opportunity.

ii) favour innovative and opportunistic approaches,

iii) encourage cooperation (common services; common cruises),

iv) build on existing monitoring activities, and finally

v) encourage monitoring by organisations responsible of the environmental effects (industry, municipalities).

Table 10.3 provides a summary of estimated costs, based on experience in a European setting (Galgani *et al.* 2013). It is appreciated that staff costs may vary considerably between countries.

10.2 Summary of recommended sampling methods (Chapters 4 – 7)

10.2.1 Recommended sampling methods for the shoreline

Recommended methods for different litter components on shorelines are summarised in Table 10.4

Table 10.3: Estimated costs and level of expertise for the different protocols adapted from (Galgani *et al.* 2013). L: Low (< 10K USD) ; M Medium (<50K USD); H High (<100K USD); VH Very High (>100K USD) *ROV: Remote Operated Vehicles.

Component	Beach	Seafloor			Seawater		Biota		Microplastics			
Protocol	**Visual**	**Diving <20m**	**Trawling <800 m**	**ROV***	**Trawl**	**Ship surveys**	**Ingested**	**Entanglement**	**Beach**	**Seawater**	**Sediment**	**Biota**
Sampling	L	M	M	VH	L	M	M/H	M/H	L	M/H	M/H	M/H
Processing	L	L	L	M	L	M	H	M	M	M	M	H
Analysis	M	M	M	M	M	M	H	M	H	H	H	H
Expertise	**M**	**M/H**	**M**	**H**	**L**	**M**	**M/H**	**M/H**	**M**	**M**	**M**	**M**
Equipment	L	M	H	H	M	L/H	M	L/M	M	M	M	M
Overall costs	L/M	M	M	H	L/M	M	M/	M	M	M/H	M/H	M/H

Table 10.4. Overview of sampling protocols for different litter size categories at three main shoreline types: Sandy Beaches, Rocky Shores (including cobble and boulder beaches) and Mangroves and Salt Marshes. R = recommended, F = feasible,. Values in parentheses indicate approximate transect widths to sample for different litter size categories.

Survey goal	Size	Sandy beaches	Rocky shores	Mangroves and Salt Marshes	Comments
Baseline surveys	Mega	R	F	F	One-off visual surveys
	Macro Surface	R	F[a]	F	One-off visual surveys
	Macro Buried	F			Sieve to collect litter; sample to at least 10 cm deep
	Meso	R			Sieve to collect litter to ≥5-10 cm deep
	Micro	F (cores[b])		F (cores)	Surface sieving or sediment cores
Monitoring	Mega	R	F		Mark litter and resample at regular intervals
	Macro Surface	R	F	F	Remove litter and re-sample
	Macro Buried	F			Accumulation estimates not feasible
	Meso	R			Sampling with 1 m quadrats by sieving > 5 mm
	Micro	R			Dry or wet sieving two or more size categories

[a] only larger items on boulders, [b] across beach profile

10.2.2 Recommended sampling methods for the sea surface and water column

Sampling the open water surface and water column, while technically is an easy task, is clearly more challenging to make results meaningful due to heterogeneous distribution, mechanisms of degradation and buoyancy, and the many influences of the type of plastic polymer, and the size and shape of the product or packaging. These variables affect the distribution and persistence of microplastics, which are also confounded by the location of the input, whether it is from maritime activities, effluent, rivers or shorelines. If the objective is to understand source or simply understand a local or regional standing stock of marine plastics, all of the above variables must be considered. Recommended methods for sampling different litter components on the sea surface or in the water column are summarised in Table 10.5.

10.2.3 Recommended sampling methods for the seafloor

Macro-plastics

Monitoring marine litter on the sea floor is not common since working in underwater areas is based on the use of specialist and expensive means, such as the need for support vessels and skilled operators (divers, trawl specialists and ROV pilots). It is recommended to focus on the most common or critical litter items, particularly monitoring the effectiveness of specific reduction measures. To reduce costs, litter can be monitored using opportunistic approaches such as:

i) including marine litter as additional and relevant indicator in regular monitoring of biodiversity by divers or ROVs in Marine Protected Areas

ii) recording the recovery of litter in bottom trawls during fisheries assessment surveys of demersal fish stocks

iii) recording the presence of litter in ROV and submersible surveys of the seafloor, carried out for other purposes such as engineering or mineral exploitation

Microplastics

One of the main difficulties at present is the lack of harmonisation of sampling and extraction methods for microplastic particles. We recommend the following:

i) use box-corers/corers rather than grabs, when available, to provide more reliable estimates of sampling volume

ii) sample through opportunistic approaches when possible to limit excessive costs in the deep sea,

iii) report microplastic abundance as number per sediment dry weight (kg-1)

More effort is required to improve methods and develop new products and initiatives, such as reference materials, proficiency testing schemes, ring tests, inter-calibration exercises and standard operating protocols.

Recommended methods for sampling different litter components on the seafloor are summarised in Tables 10.6 and 10.7.

Table 10.5 Overview of sampling protocols for different plastic size categories in two compartments. R = recommended, F = feasible.

Compartment	Size	Recommendation	Method	Comments
Water Surface	Mega	F	Aerial survey	Expensive to charter a plane.
	Mega	R	Visual survey	Use ship as the platform to conduct survey.
	Macro	R	Visual survey	See above
	Meso	R	Net tow	Affordable and litter is restricted to surface.
	Micro	R	Net tow	Affordable and litter is restricted to surface.
	Micro	F	Bulk water pump	Costs involved, and training, but will get good microplastic data.
Water Column	Mega	F	Fisheries observer	Cost effective, as you only need to train staff.
	Macro	F	Fisheries observer	Cost effective, as you only need to train staff
	Meso	F	Bulk water pump	Costs involved, and training, but will get good microplastic data.
	Meso	R	Underway sampling	Cost effective. Some equipment involved and training.
	Meso	F	Bongo net	Need vessel with winch, net relatively expensive
	Micro	F	Bulk water pump	Costs involved, and training, but will get good microplastic data.
	Micro	R	Underway sampling	Costs involved, and training, but will get good microplastic data.
	Micro	F	Bongo net	Need vessel with winch, net relatively expensive

Table 10.6: Overview of sampling protocols recommended for initial assessments for different plastic size categories by survey method, water depth and type of seafloor (soft or rocky). R = recommended, F = feasible.

Survey Goal	Water Depth	Size	Soft bottom	Rocky bottoms	Mixed
Initial Assessment					
Diving	Shallow (0-30m)	Mega/Macro	R	R	R
		Meso	F	F	F
		Micro	not visual		not visual
	Deep	any size			
Trawling	Shallow (Net + pole)	Mega/Macro	R		
		Meso	F		
		Micro			
	Deep (<200m), net + pole	Mega/Macro	R		
		Meso	F		
		Micro			
	Ultra deep (<5000m) (pole only)	Mega/Macro	< 5000 m		
		Meso	F		
		Micro	R	R	R
Remote Operated Vehicle (Imagery)	Shallow	Mega/Macro	R	R	R
		Meso	F	R	R
		Micro			
	Deep (shelves/ slopes)	Mega/Macro	R	R	R
		Meso	F	R	R
		Micro			
	Ultra deep	Mega/Macro	R	R	R
		Meso	F	R	R
		Micro			
Core/grab	All depths	Mega/Macro			
		Meso			
		Micro	R		F

Table 10.7 Overview of sampling protocols recommended for routine monitoring for different plastic size categories by survey method, water depth and type of seafloor (soft or rocky). R = recommended, F = feasible.

Monitoring					
Diving	Shallow (0-30m)	Mega/Macro	R	R	R
		Meso	F	F	F
		Micro	not visual		not visual
	Deep	Any size			
Trawling	Shallow (Net + pole)	Mega/Macro	OPP		
		Meso			
		Micro			
	Deep (Shelves slope), net + pole	Mega/Macro	OPP		
		Meso			
		Micro			
	Ultra deep (pole)	Mega/Macro	F		
		Meso	F		
		Micro			

Table 10.7 Overview of sampling protocols recommended for routine monitoring for different plastic size categories by survey method, water depth and type of seafloor (soft or rocky). R = recommended, F = feasible.

Monitoring					
Remote Operated Vehicle	Shallow (0-30m)	Mega/Macro	F	F	F
		Meso	F	F	F
		Micro			
	Deep (shelves)	Mega/Macro	OPP	OPP	OPP
		Meso	F	F	F
		Micro			
	Ultra deep	Mega/Macro	OPP	OPP	OPP
		Meso	F	F	F
		Micro			
Core/grab	All depths	Mega/Macro			
		Meso			
		Micro	R		

10.2.4 Recommended sampling methods for biota

Monitoring the interactions and effects of plastics on biota is heavily reliant on organisms' physiology and life history which express whether organisms are more or less likely to experience negative consequences. Suitable monitoring methods must be adapted to the life cycle of these organisms and consider the regional representation, the abundance and a large distribution, the availability of scientific background, the costs, the ecological and commercial importance, and the feeding strategy. Recommended methods for sampling different litter components associated with biota are summarised in Tables 10.8.

10.3 Recommended methods for marine litter characterization (Chapters 8 – 9)

10.3.1 Recommended methods for sample processing

Recent developments have led to the sample processing of ever-smaller sizes of plastics (to micro- and now nano). There has been a growing interest in employing chemical and biological means of reducing interference by natural organic and inorganic material (matrix removal) to avoid misidentification of natural materials. The methods include density separation, biological /chemical digestion and sieving/filtering; each of these can be used in isolation or in concert, in a different order (Table 10.9).

Obtaining information to support management decisions requires a thorough and detailed understanding of plastic particle characteristics. This includes appropriate analytical methods to characterise physical, chemical and biological properties of plastics. Once collected, this information is vital or optional to develop reliable risk assessments and management procedures. Among the characteristics observed or analysed, some are very crucial to meet the purpose of the monitoring program. The strategies defined to characterize plastic particles rely on two main options, that are the relevance of analytical procedures (option 1, robustness, validity, maturity, etc.) and the costs (options 2).

Table 10.8 Overview of sampling protocols for different litter size categories in biota **R** = recommended, **F** = feasible.

Survey goal	Size	Marine mammals	Birds	Fish	Invert-ebrates	Corals	Epibionts	Remarks
Ingestion	Mega	F						Opportunistic, strandings
	Macro	F	R					OSPAR monitoring
	Meso	F	R					
	Micro	F	R	R	R	F	F	
Entanglement	Mega	R	R			F		Opportunistic strandings
	Macro	R	R			F		
	Meso				F	F		
	Micro							
Habitat	Mega					R	R	
	Macro		R			F	R	
	Meso		F			F	R	
	Micro						R	

Table 10.9 Overview of sampling processing protocols for different environmental compartments and litter size categories. **R** = recommended, **F** = feasible.

Environmental compartment	Size of litter	Hand sorting	Sieving/ filtering	Density separation	Digestion		
					Enzymatic	Alkaline	Oxidative
Shoreline (Chapter 4)	Meso	R	R	R			
	Micro	F	R	R		R	R
Seawater (Chapter 5)	Meso	R	R	R			
	Micro	F	R	R	F	R	R
Sea Floor (Chapter 6)	Meso	R	R	R			
	Micro	F	R	R	F	R	R
Biota (Chapter 7)	Meso	R	R	F	R	R	R
	Micro	F	R	F	R	R	R

Table 10.10 Overview of physico-chemical characterization methods applicable for different litter size categories. Note: R = recommended, F = feasible.

Size	Visual observation (naked eye)	Visual observation (microscopy)	Microscopy and spectroscopy (FTIR, Raman)	Alternatives (FTIR-FPA Nano-IR Pyro-GC/MS SEM-EDS)	Comment
Mega	R				
Macro	R				
Meso 5-25 mm	R				Confirmation spectroscopy
Large micro 1-5 mm		R	R	R	Microscopy + spectroscopy
Small micro 0.02-1 mm			R	R	
Very small micro 0.001-0.02 mm			F[a]	R	[a]FTIR/Raman Challenging
Nano < 1 µm				R[b]	[b]Exploratory

Complexity

10.3.2 Physical characterization of macro-plastics

Option 1: Categorization of selected core (major) items on the UNEP guideline-based survey list regarding situation of different compartment (beach, surface water, and seafloor) or region/nation specific items is recommended.

Option 2: Categorization of full items on the UNEP guideline-based survey list regarding situation of different compartment (beach, surface water, and seafloor) or region/nation specific items is recommended.

It is further recommended to record additional information: 1) label (brand name, barcode, address, and production country) to infer origin, 2) functional characteristics of fishing nets (knot types) to infer origin of fishing industry, and 3) other physical characteristics to provide specific information.

10.3.3 Physico-chemical characterization of microplastics

Option 1: It is recommended to identify mesoplastics (5 - 25 mm) and large microplastics (~0.3 - 5 mm) by visual identification (naked eyes, magnifying glass and stereomicroscopy) and to record shape, size and colour. Additional physical observation with probing particle with tweezers, a hot needle, and solvent dissolution assay provide additional confirmation whether the particles are plastic or not.

Option 2: It is recommended to characterize large microplastics (0.3-5 mm) by microscopy, and subsequently at least sub-set samples should be confirmed by spectroscopy. In case of small microplastics (0.02-0.3 mm), it is recommended to identify every plastic-like particle by spectroscopy or alternative novel methods, such as staining with Nile Red (Shim *et al.* 2016, Maes *et al.* 2017).

It is recommended to record basic physical information (shape, size and colour) and polymer type (e.g. PE, PP, PS, etc.). Further categorization/ classification of microplastics by physical characteristic (e.g. blue fibre, red fragment, and microbeads) is recommended.

Quality assurance and quality control procedure should be strictly applied from plastic sampling in the field to instrumental analysis in the laboratory.

10.3.4 Analysis of chemicals associated with plastics

The monitoring of chemicals associated with plastic litter will provide a better understanding of the relative contribution of plastic ingestion to the total chemical exposure of organisms as well as humans. Methods for chemical contaminant monitoring of a variety of environmental media (seawater, biota, sediments, suspended particulate material) are well established[70], and are not discussed further here. It is likely that these exposure routes will be more significant than for Quality assurance and quality control procedure should be strictly applied from plastic sampling in the field to instrumental analysis in the laboratory.

70 https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/contaminants/

Recommended options for chemical analysis

Option 1 - simple: Analyse shoreline resin pellets, or plastic fragments of the same shape, colour and polymer, for at least one sorbed chemical (e.g. PCBs) and one additive chemical (e.g. BDE209).

Option 2 – more comprehensive: Analyse plastic litter categorized based on size (e.g. 1 mm – 5 mm and >5 mm), shape (e.g. fragment, pellet, fibre, and foam), colour (e.g. pigmented, gray, non-pigmented yellowed, white), polymer type (e.g. PE, PP, PS, PET, PVC), and weathering status (e.g. fresh vs. aged). It is recommended to target chemicals of concern including both sorbed (e.g. PCBs, DDTs, HCHs, and PAHs) and additive chemicals (e.g. PBDEs, HBCDs, Phthalates, and UV stabilizers).

10.3.5 Biological characterization

Biological characterization of macro-litter can be conducted using the identification of attached epi-biota, including for example, *Lepas* sp. Gooseneck barnacles.

Identification of microorganisms on both micro and macro plastic items is expensive and requires advanced methods. Therefore this is not recommended for basic monitoring and more suited to scientific investigations.

11 FUTURE STEPS

11.1 SDG 14.1.1 indicator development

A key intention of the guidelines is to support the further development of the marine litter monitoring framework under SDG 14.1.1. This includes the selection of sub-indicators related to the source (or attribution), the environmental state and the impacts of marine litter. Using more harmonised methods will encourage the development and implementation of regional or global monitoring programmes, and facilitate the exchange of monitoring results. In so doing it is expected that it will be possible to move SDG 14.1.1 from tier 3 (‘*no internationally established methodology or standards are available*’) to tier 2 (‘*Indicator is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries*’).

Regional Seas Programmes and action plans have actively been involved in the development of harmonised methodologies for monitoring and have been involved in the review of the guidelines. In addition, the guidelines will be considered by the Ad hoc Open-ended Expert Group on marine litter, under the UNEP Assembly (UNEA) process.

11.2 Data management

The greater harmonisation of sampling protocols and reporting will help to reduce barriers to data sharing, and support the development of effective global data management, linked to existing regional and global platforms where possible. For example, at a regional scale the European Commission has developed the European Marine Observation and Data Network (EMODnet)[71], a system designed to collect, harmonise and share a wide range of marine environmental data in partnership with those Regional Seas covering the NE Atlantic (OSPAR), Baltic (HELCOM), Mediterranean (UNEP MAP) and the Black Sea (Black Sea Commission). Recently, EMODnet has been extended to include data on marine litter, specifically from the shoreline, seafloor (trawl surveys) and sea surface (microplastics).

At a global scale, the Deep-sea Debris Database was launched in March 2017 to allow public access to seafloor images collected since 1983. The database is managed by the Global Oceanographic Data Center (GODAC) of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC)[72]. It contains data from multiple sources from the North and South Pacific, Indian, North and South Atlantic Oceans. The deepest record was of a plastic bag found at 10898 m in the Mariana Trench.

A key priority will be to ensure the inter-operability of different databases, to ensure that disseminated data storage and management is not a barrier to data exchange and integrated regional and global monitoring.

11.3 Towards more effective monitoring programmes

The guidelines are based on sampling and analysis methods that are generally accepted, and that are commonly available at least in relatively well-resourced institutions. They are not intended for research purposes.

Several of the current monitoring methods are based on techniques developed for investigating natural features of the environment, such as the abundance of zooplankton using towed nets (floating microplastics) or fish stock assessment using bottom trawls (seafloor macro-litter). Both techniques under-sample smaller size categories of litter. This means that estimates of litter abundance based on these methods will be subject to a consistent bias. There may be an advantage to improving to how we capture a more representative sample of the actual size range of marine litter present in the environment. However, this will also present a challenge when comparing spatial or temporal trends on marine litter that were obtained using different sampling methods.

A common challenge is to account for the inherent heterogeneity of marine litter distributions, resulting in variations of abundance that may exceed a factor of 10 at any one ‘site’. This needs to be addressed as part of the overall sampling strategy. In future, increasing automation of sampling and sample analysis may allow a greater throughput of material and reduce some of the uncertainty in the measurements. The UN Decade of the Ocean presents an opportunity to collaborate with the wider ocean science community, to develop a more effective, more reliable and more cost-effective global monitoring framework to address this pressing issue.

71 www.emodnet.eu
72 Chiba *et al.* (2018).

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ANNEXES

Annex I Membership of GESAMP Working Group 40

Table AI.1 Working Group 40 membership, affiliations and sponsoring agencies

Name	Role	Country	Affiliation	Sponsoring agency
Marcus Eriksen	Member	USA	5 Gyres NGO	UNEP
Francois Galgani	Co-Chair (microplastics)	France	IFREMER	IMO
Denise Hardesty	Member	Australia	CSIRO	IOC-UNESCO
Martin Hassellov	Member	Sweden	Univ. Gothenburg	EU-BASEMAN
Sang Hee Hong	Member	Rep. Korea	KIOST	NOWPAP
Peter Kershaw	Chair	UK	GESAMP	IMO
Amy Lusher	Member	Norway	NIVA	IMO
Sheri Mason	Member	USA	Freedonia Univ.	NOAA
Peter Ryan	Member	South Africa	Univ. Cape Town	UNEP
Won Joon Shim	Member	Rep. Korea	KIOST	Min. Oceans and Fisheries, Korea
Akbar Tahir	Member	Indonesia	Hasanuddin Univ., Makassar	UNEP
Hideshige Takada	Member	Japan	Tokyo Univ. Agriculture and Technology	Min. Environment, Japan
Martin Thiel	Member	Chile	Universidad Catolica del Norte, Larrondo	UNEP
Alexander Turra	Co-Chair (Macro-plastics)	Brazil	Univ. Sao Paulo	UNEP
Chris Wilcox	Member	Australia	CSIRO	IOC-UNESCO
Weiwei Zhang	Member	China	Nation Marine Monitoring Centre	State Oceanic Administration, China
Amy Uhrin	Observer	USA	NOAA Marine Debris Program	
Henrik Enevoldsen	Observer	IOC	UNESCO-IOC	
Joana Akrofi	Observer	UNEP	UNEP	

Annex II Summary of existing monitoring programmes and protocols, used by national and regional organisations

Protocol		Compartment								URL link
name	date	shoreline		seafloor		biota		Sea surface		
		Mic	Mac	Mic	Mac	Mic	Mac	Mico	Mac	
OSPAR	2010		x							https://www.ospar.org/ospar-data/10-02e_beachlitter%20guideline_english%20only.pdf
PERSGA	2014		x							http://www.persga.org/publications.html
NOAA	2012		x							https://marinedebris.noaa.gov/sites/default/files/ShorelineFieldGuide2012.pdf
NOAA	2015	x		x				x		https://marinedebris.noaa.gov/sites/default/files/publications-files/noaa_microplastics_methods_manual.pdf
EU-MSFD*	2013	x	x	x	x		x	x	x	http://mcc.jrc.ec.europa.eu/documents/201702074014.pdf
FAO**	2016		X		x				x	http://www.fao.org/3/a-i5051e.pdf
FAO	2016					x				http://www.fao.org/3/a-i7677e.pdf
NOWPAP	2007		x							http://www.cearac-project.org/RAP_MALI/monitoring%20guidelines.pdf
NOWPAP	2007				x					http://dinrac.nowpap.org:8080/documents/NOWPAP_MERRAC_Marine_Litter_Monitoring_Seabed.pdf
UNEP	2009		x		x		x		x	http://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/13604/rsrs186.pdf?sequence=1&isAllowed=y
DeFishGear	2016	x	x		x		x	x	x	http://www.defishgear.net/media-items/publications
INDICIT	2017						X***			https://indicit-europa.eu/protocols/
CSIRO	2017		x							http://www.marine.csiro.au/apex/f?p=120:LOGIN::::::
5 gyres Institute								x		https://www.5gyres.org/trawlshare-resources/
HELCOM	2018		x							https://portal.helcom.fi/meetings/STATE%20-%20CONSERVATION%208-2018-500/MeetingDocuments/3MA-3%20HELCOM%20monitoring%20guidelines%20for%20marine%20litter%20on%20beaches.pdf
ICES	2018				x					http://ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/HAPISG/2018/01%20WGML%20-%20Report%20of%20the%20Working%20Group%20on%20Marine%20Litter.pdf

*Update planned in 2019
** focusing on Abandoned or Lost Derelict Fishing Gear (ALDFG)
*** Sea turtles

Annex III Examples of marine litter category lists

Annex III.1 UNEP-IOC (Cheshire et al. 2009)

Number	Material	Code	Litter type
1	Plastic	PL01	Bottle caps & lids
2	Plastic	PL02	Bottles < 2 L
3	Plastic	PL03	Bottles, drums, jerrycans & buckets > 2 L
4	Plastic	PL04	Knives, forks, spoons, straws, stirrers, (cutlery)
5	Plastic	PL05	Drink package rings, six-pack rings, ring carriers
6	Plastic	PL06	Food containers (fast food, cups, lunch boxes & similar)
7	Plastic	PL07	Plastic bags (opaque & clear)
8	Plastic	PL08	Toys & party poppers
9	Plastic	PL09	Gloves
10	Plastic	PL10	Cigarette lighters
11	Plastic	PL11	Cigarettes, butts & filters
12	Plastic	PL12	Syringes
13	Plastic	PL13	Baskets, crates & trays
14	Plastic	PL14	Plastic buoys
15	Plastic	PL15	Mesh bags (vegetable, oyster nets & mussel bags)
16	Plastic	PL16	Sheeting (tarpaulin or other woven plastic bags, palette wrap)
17	Plastic	PL17	Fishing gear (lures, traps & pots)
18	Plastic	PL18	Monofilament line
19	Plastic	PL19	Rope
20	Plastic	PL20	Fishing net
21	Plastic	PL21	Strapping
22	Plastic	PL22	Fibreglass fragments
23	Plastic	PL23	Resin pellets
24	Plastic	PL24	Other (specify)
25	Foamed Plastic	FP01	Foam sponge
26	Foamed Plastic	FP02	Cups & food packs
27	Foamed Plastic	FP03	Foam buoys
28	Foamed Plastic	FP04	Foam (insulation & packaging)
29	Foamed Plastic	FP05	Other (specify)
30	Cloth	CL01	Clothing, shoes, hats & towels
31	Cloth	CL02	Backpacks & bags
32	Cloth	CL03	Canvas, sailcloth & sacking (hessian)
33	Cloth	CL04	Rope & string
34	Cloth	CL05	Carpet & furnishing
35	Cloth	CL06	Other cloth (including rags)
36	Glass & ceramic	GC01	Construction material (brick, cement, pipes)
37	Glass & ceramic	GC02	Bottles & jars
38	Glass & ceramic	GC03	Tableware (plates & cups)
39	Glass & ceramic	GC04	Light globes/bulbs
40	Glass & ceramic	GC05	Fluorescent light tubes
41	Glass & ceramic	GC06	Glass buoys
42	Glass & ceramic	GC07	Glass or ceramic fragments
43	Glass & ceramic	GC08	Other (specify)
44	Metal	ME01	Tableware (plates, cups & cutlery)
45	Metal	ME02	Bottle caps, lids & pull tabs
46	Metal	ME03	Aluminium drink cans
47	Metal	ME04	Other cans (< 4 L)
48	Metal	ME05	Gas bottles, drums & buckets (> 4 L)
49	Metal	ME06	Foil wrappers
50	Metal	ME07	Fishing related (sinkers, lures, hooks, traps & pots)
51	Metal	ME08	Fragments
52	Metal	ME09	Wire, wire mesh & barbed wire
53	Metal	ME10	Other (specify), including appliances
54	Paper & cardboard	PC01	Paper (including newspapers & magazines)
55	Paper & cardboard	PC02	Cardboard boxes & fragments
56	Paper & cardboard	PC03	Cups, food trays, food wrappers, cigarette packs, drink containers
57	Paper & cardboard	PC04	Tubes for fireworks
58	Paper & cardboard	PC05	Other (specify)
59	Rubber	RB01	Balloons, balls & toys
60	Rubber	RB02	Footwear (flip-flops)
61	Rubber	RB03	Gloves
62	Rubber	RB04	Tyres
63	Rubber	RB05	Inner-tubes and rubber sheet
64	Rubber	RB06	Rubber bands
65	Rubber	RB07	Condoms
66	Rubber	RB08	Other (specify)
67	Wood	WD01	Corks
68	Wood	WD02	Fishing traps and pots
69	Wood	WD03	Ice-cream sticks, chip forks, chopsticks & toothpicks
70	Wood	WD04	Processed timber and pallet crates
71	Wood	WD05	Matches & fireworks
72	Wood	WD06	Other (specify)
73	Other	OT01	Paraffin or wax
74	Other	OT02	Sanitary (nappies, cotton buds, tampon applicators, toothbrushes)
75	Other	OT03	Appliances & Electronics
76	Other	OT04	Batteries (torch type)
77	Other	OT05	Other (specify)

Annex III.2 ICES International Bottom Trawl Survey (IBTS)

The ICES International Bottom Trawl Survey is a long-established programme for fish stock assessment on the Northeast Atlantic continental shelf. The survey is optimised for stock assessment, with the standard haul being 30 minutes with a fishing speed of 4 knots. The type of gear is specified and fishing is only carried out during daylight hours on a pre-arranged grid. A protocol has been developed to allow the consistent monitoring of marine litter recovered in the trawl net. It divides items of litter into 7 major categories. It is simpler that protocols developed for shoreline surveys, reflecting the difficult operating conditions and primary aim of the survey.

A: Plastic	B: Sanitary waste	C: Metals	Related size category
A1. Bottle	B1. diapers	C1. Cans (food)	A: <5*5 cm= 25 cm^2
A2. Sheet	B2. cotton buds	C2. Cans (beverage)	B: <10*10 cm= 100 cm^2
A3. Bag	B3. cigarette butts	C3. Fishing related	C: <20*20 cm= 400 cm^2
A4. Caps/ lids	B4. condoms	C4. Drums	D: <50*50 cm= 2500 cm^2
A5. Fishing line (monofilamen	B5. syringes	C5. appliances	E: <100*100 cm= 10000 cm^2= 1 m^2
A6. Fishing line (entangled)	B6. sanitary towels/ tampon	C6. car parts	F: >100*100 cm = 10000 cm^2= 1 m^2
A7. Synthetic rope	B7. other	C7. cables	
A8. Fishing net		C8. other	
A9. Cable ties			
A10. Strapping band			
A11. crates and containers			
A12. other			
D: Rubber	**E: Glass/ Ceramics**	**F: Natural products**	**G: Miscellaneous**
D1. Boots	E1. Jar	F1. Wood (processed)	G1. Clothing/ rags
D2. Balloons	E2. Bottle	F2. Rope	G2. Shoes
D3. bobbins (fishing)	E3. piece	F3. Paper/ cardboard	G3. other
D4. tyre	E4. other	F4. pallets	
D5. glove		F5. other	
D6. other			

An example of a data sheet is provided below, taken from Hal (2017).

sample	date	Litter Type (A1; B2; C...)	Description (Label/ Brand)	Size category (A; B; C..)	Weight (g)	attached organisms (yes/no) Taxonomy Info	number of items (0= multiple material**,1 in most cases, >1 monofilament)
3000001	29/01/2015	G1	some stocking like piece of cloth	A	1		1
3000002	30/01/2015	A2	blue sheet	B	1	briozoa	1
3000002	30/01/2015	A7	string orange rope	A	1		1
3000003	30/01/2015	A2		D	52		1
3000003	30/01/2015	A2		E	637		1
3000003	30/01/2015	G1	ripped piece of cloth	A	20		1
3000003	30/01/2015	D5		A	5		1
3000003	30/01/2015	A7		A	40	hydrozoa	1
3000004	30/01/2015	A7		A	1		1
3000004	30/01/2015	A7		B	70		1
3000005	30/01/2015	A7	strings of blue and orange rope	A	1		3

** A 0 is reported when an item exists of multiple materials. The main material is than reported as 1, but other materials are registered but recorded as 0. For example: A bottle with a cap, is report as A1 number =1 and A4 number =0. In a similar way items existing of wood and metal etc. are recorded.

Annex III.3 NOWPAP Guidelines for monitoring seafloor litter

NOWPAP have published guidelines for monitoring marine litter on the seafloor in the Northwest Pacific region (NOWPAP 2007). The guidelines include a data sheet for recording the litter recovered, which is reproduced below.

Data Card for Monitoring Marine Litter on the Seabed

Monitoring Location

Monitoring Site: States ______ Country ______ Date: Month ______ Day ______ Year ______

Location: N ______ E ______ ~ N ______ E ______

Survey Time: AM/PM ______ ~ AM/PM ______

Ship's Name: ______ Gross Tonnage: ______

Name (Affiliation) : ______

Method & Notes

☐Seaside area (underwater), ☐Coastal area (☐Habour, ☐near-shore, ☐open sea)

Survey Area: ______ km², Velocity of Ship: ______ knot,

Monitoring Methodology: ______, Type of Trawl Tool: ______

Size of Trawl Tool: ______, Mesh Size: ______

Equipment: ______

Results

Types		Number (ea)	Weight (kg)	Estimated Amount (m²)	Other Remarks
Plastic	Bags				
	Bottles				
	Container				
	Line/Rope				
	Fishing nets				
	Resin pellets				
	Others				
Sub-total					
Rubber	Balls				
	Balloon				
	Gloves				
	Rubber boots				
	Tire				
	Others				
Sub-total					
Metal	Cans				
	Fishing gear				
	Wire/Rope				
	Plates				
	Others				
Sub-total					
Styrofoam	Container				
	Buoys				
	Others				
Sub-total					
Paper	Container				
	Packages				
	Book/Newspaper				
	Others				
Sub-total					
Wood	Timber/Log				
	Box/Basket				
	Chopstick				
	Others				
Sub-total					
Clothes and Fabrics	Blanket/Carpet,				
	Awning				
	Clothes				
	Leather				
	Others				
Sub-total					
Glass/ Ceramics	Bottle				
	Glass products				
	Tableware				
	Others				
Sub-total					
Others	Electronics				
	Sunken ships				
	Others				
Sub-total					
Total					

Note (picture, etc.)

Annex III.4 CSIRO category list

Site Name: **ITEMS LIST** **Page _____ of ______**

Date: **Transect No. ____ of ____** **Subsampled? Y N**

ITEMS		ID	Fragment	Whole
Hard Plastic	Pipe/PVC	H1		
	Beverage bottle <1 L	H2		
	Other bottle	H3		
	Bottle cap/lid	H4		
	Food container	H5		
	Utensil/plate/bowl	H6		
	Bucket/Crate	H7		
	Lighter	H8		
	Lollipop stick/earbud	H9		
	Unknown/other hard	H10		
Soft Plastic	Thin film carry bag	S1		
	Food wrapper/label	S2		
	Sheeting	S3		
	Cup/lid	S4		
	Straw	S5		
	Unknown/other soft	S6		
	Other plastic bag	S7		
Plastic Straps	String/rope/ribbon	BP1		
	Packing strap	BP2		
	Cable ties	BP3		
	Unknown/other strap	BP4		
Metal	Pipe	M1		
	Wire	M2		
	Aerosol	M3		
	Beverage can	M4		
	Food can/tin	M5		
	Lid/cap	M6		
	Food wrapper	M7		
	Aluminium foil	M8		
	Bucket/drum	M9		
	Unknown/other hard	M10		
	Unknown/other soft	M11		
Glass	Beverage bottle	G1		
	Jar	G2		
	Light globe/tube	G3		
	Unknown/other glass	G4		
Rubber	Thong/shoe	R1		
	Tyre	R2		
	Balloon	R3		
	Rubber band	R4		
	Unknown/other	R5		
Cloth	String/rope/strap	C1		
	Clothing/towel	C2		
	Wipes/cloths	C3		
	Insulation/stuffing	C4		
	Unknown/other	C5		
Timber	Wood/timber	T1		
	Utensil/food stick	T2		
	Bottle cork	T3		
	Pallet	T4		
	Unknown/other	T5		

ITEMS Cont.		ID	Fragment	Whole
Foam	Food container	D1		
	Cup/plates/bowls	D2		
	Polystyrene	D4		
	Unknown/other	D5		
Paper	Cigarette/butt	P1		
	Paper/cardboard	P2		
	Magazine/newspaper	P3		
	Bag	P4		
	Box	P5		
	Food container/box	P6		
	Food wrapper/bag	P7		
	Beverage container	P8		
	Cups	P9		
	Plates/bowls	P10		
	Unknown/other	P11		
Fishing	Net	F1		
	Fishing line	F2		
	Fishing Lures	F3		
	Buoys/floats	F4		
	Glow stick	F5		
	Fishhook/sinker	F6		
	Unknown/other	F7		
Miscellaneous	Battery	Z1		
	Brick/cement	Z2		
	Carpet	Z3		
	Ceramic	Z4		
	E Waste	Z5		
	Furniture	Z6		
	Appliances	Z7		
	Large car parts	Z9		
	Large boat parts	Z10		
	Bag/box dom. waste	Z11		
	Nurdles	Z12		
Other		O1		
		O2		
		O3		
		O4		
		O5		
		O6		

Size class (and sub-sampling intervals)

Interval start (m)	Dist on tran	ID (F/W)	Size class
1 0 -			
2			
3			
4			
5			
6			
7			
8			
9			
10 - (end)			

Annex III.5 OSPAR category list

OSPAR Marine Litter Monitoring Survey Form **100 metre area**

OSPAR ID	Unep ID	Items	Total
		Plastic • Polystyrene	
1		4/6-pack yokes	
2		Bags (e.g. shopping)	
3		Small plastic bags, e.g., freezer bags	
112		Plastic bag ends	
4		Drinks (bottles, containers and drums)	
5		Cleaner (bottles, containers and drums)	
6		Food containers incl. fast food containers	
7		Cosmetics (bottles & containers e.g. sun lotion, shampoo, shower gel, deodorant)	
8		Engine oil containers and drums <50 cm	
9		Engine oil containers and drums > 50 cm	
10		Jerry cans (square plastic containers with handle)	
11		Injection gun containers	
12		Other bottles, containers and drums	
13		Crates	
14		Car parts	
15		Caps/lids	
16		Cigarette lighters	
17		Pens	
18		Combs/hair brushes	
19		Crisp/sweet packets and lolly sticks	
20		Toys & party poppers	
21		Cups	
22		Cutlery/trays/straws	
23		Fertiliser/animal feed bags	
24		Mesh vegetable bags	
25		Gloves (typical washing up gloves)	
113		Gloves (industrial/professional gloves)	
26		Crab/lobster pots	
114		Lobster and fish tags	
27		Octopus pots	
28		Oyster nets or mussel bags including plastic stoppers	

OSPAR Survey form 100m.2010.010

100 metre area OSPAR Marine Litter Monitoring Survey Form

OSPAR ID	Unep ID	Items	Total
29		Oyster trays (round from oyster cultures)	
30		Plastic sheeting from mussel culture (Tahitians)	
31		Rope (diameter more than 1 cm)	
32		String and cord (diameter less than 1 cm)	
115		Nets and pieces of net < 50 cm	
116		Nets and pieces of net > 50 cm	
33		Tangled nets/cord/rope and string	
34		Fish boxes	
35		Fishing line (angling)	
36		Light sticks (tubes with fluid)	
37		Floats/Buoys	
38		Buckets	
39		Strapping bands	
40		Industrial packaging, plastic sheeting	
41		Fibre glass	
42		Hard hats	
43		Shotgun cartridges	
44		Shoes/sandals	
45		Foam sponge	
117		Plastic/polystyrene pieces 0 - 2,5 cm	
46		Plastic/polystyrene pieces 2,5 cm > < 50 cm	
47		Plastic/polystyrene pieces > 50 cm	
48		Other plastic/polystyrene items *(please specify in other item box*)*	
		Rubber	
49		Balloons, including plastic valves, ribbons, strings etc.	
50		Boots	
52		Tyres and belts	
53		Other rubber pieces *(please specify in other item box*)*	
		Cloth	
54		Clothing	

OSPAR Marine Litter Monitoring Survey Form **100 metre area**

OSPAR ID	Unep ID	Items	Total
55		Furnishing	
56		Sacking	
57		Shoes (leather)	
59		Other textiles *(please specify in other item box*)*	
		Paper • Cardboard	
60		Bags	
61		Cardboard	
118		Cartons e.g. tetrapak (milk)	
62		Cartons e.g. tetrapak (other)	
63		Cigarette packets	
64		Cigarette butts	
65		Cups	
66		Newspapers & magazines	
67		Other paper items *(please specify in other item box*)*	
		Wood (machined)	
68		Corks	
69		Pallets	
70		Crates	
71		Crab/lobster pots	
119		Fish boxes	
72		Ice lolly sticks / chip forks	
73		Paint brushes	
74		Other wood < 50 cm *(please specify in other item box*)*	
75		Other wood > 50 cm *(please specify in other item box*)*	
		Metal	
76		Aerosol/Spray cans	
77		Bottle caps	
78		Drink cans	
120		Disposable BBQ's	
79		Electric appliances	
80		Fishing weights	

OSPAR Survey Form 100m 2010.010

OSPAR Marine Litter Monitoring Survey Form **100 metre area**

Presence of other pollutants		
Pollutant	Size of pieces or lumps *(estimates)*	Frequency *(estimated number per metre of strandline)*
Paraffin or wax pieces	*Size range*	
108	0 - 1 cm	
109	1 - 10 cm	
110	> 10 cm	
Other *(please specify in other item box*)*		
111		

Pellets* (nurdles): ☐ Yes ☐ No

**(photo in field guide)*

100 m

***Special observations and notes (please refer to number!)**

Other Item Box

Annex IV Categories for describing fishing gear

The FAO has issued a revised International Standard Classification of Fishing Gears, which was adopted in 2016. Regional organisations may choose to adopt additional descriptors to reflect the types of fishing gear used more locally.

Food and Agriculture Organization of the United Nations

Coordinating Working Party on Fishery Statistics (CWP)

Handbook of Fishery Statistics

International Standard Statistical Classification of Fishing Gear (ISSCFG Rev. 1, 2013)

Gear categories	Standard abbreviations	ISSCFG code
SURROUNDING NETS		**01**
Purse seines	PS	01.1
Surrounding nets without purse lines	LA	01.2
Surrounding nets (nei)	SUX	01.9
SEINE NETS		**02**
Beach seines	SB	02.1
Boat seines	SV	02.2
Seine nets (nei)	SX	02.9
TRAWLS		**03**
Beam trawls	TBB	03.11
Single boat bottom otter trawls	OTB	03.12
Twin bottom otter trawls	OTT	03.13
Multiple bottom otter trawls	OTP	03.14
Bottom pair trawls	PTB	03.15
Bottom trawls (nei)	TB	03.19
Single boat midwater otter trawls	OTM	03.21
Midwater pair trawls	PTM	03.22
Midwater trawls (nei)	TM	03.29
Semipelagic trawls	TSP	03.3
Trawls (nei)	TX	03.9
DREDGES		**04**
Towed dredges	DRB	04.1
Hand dredges	DRH	04.2
Mechanized dredges	DRM	04.3
Dredges (nei)	DRX	04.9
LIFT NETS		**05**
Portable lift nets	LNP	05.1
Boat-operated lift nets	LNB	05.2
Shore-operated stationary lift nets	LNS	05.3
Lift nets (nei)	LN	05.9
FALLING GEAR		**06**
Cast nets	FCN	06.1
Cover pots/Lantern nets	FCO	06.2
Falling gear (nei)	FG	06.9
GILLNETS AND ENTANGLING NETS		**07**
Set gillnets (anchored)	GNS	07.1
Drift gillnets	GND	07.2
Encircling gillnets	GNC	07.3
Fixed gillnets (on stakes)	GNF	07.4
Trammel nets	GTR	07.5
Combined gillnets-trammel nets	GTN	07.6

Coordinating Working Party on Fishery Statistics (CWP)

Handbook of Fishery Statistical Standards

Revised International Standard Classification of Fishing Gears (ISSCFG, Rev.1 21 October 2010)

Adopted by the CWP at the 25th Session, Rome 2016

Gillnets and entangling nets (nei)	GEN	07.9
TRAPS		**08**
Stationary uncovered pound nets	FPN	08.1
Pots	FPO	08.2
Fyke nets	FYK	08.3
Stow nets	FSN	08.4
Barriers, fences, weirs, etc.	FWR	08.5
Aerial traps	FAR	08.6
Traps (nei)	FIX	08.9
HOOKS AND LINES		**09**
Handlines and hand-operated pole-and-lines	LHP	09.1
Mechanized lines and pole-and-lines	LHM	09.2
Set longlines	LLS	09.31
Drifting longlines	LLD	09.32
Longlines (nei)	LL	09.39
Vertical lines	LVT	09.4
Trolling lines	LTL	09.5
Hooks and lines (nei)	LX	09.9
MISCELLANEOUS Gear		**10**
Harpoons	HAR	10.1
Hand implements (Wrenching gear, Clamps, Tongs, Rakes, Spears)	MHI	10.2
Pumps	MPM	10.3
Electric fishing	MEL	10.4
Pushnets	MPN	10.5
Scoopnets	MSP	10.6
Drive-in nets	MDR	10.7
Diving	MDV	10.8
Gear nei	MIS	10.9
GEAR NOT KNOWN		**99**
Gear not known	NK	99.9

Annex V Monitoring/sampling protocols - shorelines

Annex V.1 NOAA – Standing stock surveys

Site Characterisation Sheet

Standing-Stock Survey Site Characterization | Version 2.0 | March 2016

NOAA MDMAP Site Characterization Sheet Standing-Stock Surveys	Organization		Name of organization responsible for collecting the data
	Surveyor name		Name of person responsible for filling in this sheet
	Phone number		Phone contact for surveyor
Complete this form **ONCE** for each site location	Date		Date of this survey
SAMPLING AREA			
Shoreline name			Name or ID by which this section of shoreline is known (e.g., beach name, park)
State/County			State and county where your site is located
Coordinates at start of shoreline section	Latitude	Longitude	Recorded as XXX.XXXX (decimal degrees) at start of shoreline section (in both corners if width > 6 meters)
Coordinates at end of shoreline section	Latitude	Longitude	Recorded as XXX.XXXX (decimal degrees) at end of shoreline section (in both corners if width > 6 meters)
Photo number/ID			The digital identification number(s) of photos taken of shoreline section
SHORELINE CHARACTERISTICS			
Length of sample area (usually 100 m)			Length parallel to water measured along the midpoint of the shoreline (in meters)
Shoreline slope (°)			Slope above horizontal (between 0 – 90°)
Substratum type			For example, a sandy or gravel beach
Substrate uniformity			Percent coverage of the primary substrate type (%)
Tidal range			Max & min vertical tidal range. Use tide chart (usually in feet).
Tidal distance			Horizontal distance (in meters) from low- to high-tide line. Measure on beach at low and high tides or estimate based on wrack lines.
Back of shoreline			Describe landward limit (e.g., vegetation, rock wall, cliff, dunes, parking lot)
Aspect			Direction you are facing when you look out at the water (e.g., northeast)

Standing-Stock Survey Site Characterization | Version 2.0 | March 2016

LAND-USE CHARACTERISTICS			
Location & major usage	Urban		Select one and indicate major usage (e.g., recreation, boat access, remote)
	Suburban		
	Rural		
Access			Vehicular (you can drive to your site), pedestrian (must walk), isolated (need a boat or plane)
Nearest town			Name of nearest town
Nearest town distance			Driving distance to nearest town (miles)
Nearest town direction			Direction to nearest town (cardinal direction)
Nearest river name			If applicable, name of nearest river or stream. If blank, assumed to mean no inputs nearby
Nearest river distance			Straight line distance to nearest river/stream (km)
Nearest river direction			Direction to nearest river/stream (cardinal direction from site)
River/creek input to beach	YES	NO	Does nearest river/stream have an outlet within this shoreline section?
Pipe or drain input	YES	NO	Is there a storm drain or channelized outlet within shoreline section?
Notes (including description, landmarks, coastal hydrography, offshore barriers, etc.):			

Survey datasheet

Transect #

Standing-Stock Survey Debris Datasheet | Version 2.0 | March 2016

NOAA MDMAP **Standing-Stock Survey Debris Datasheet**	Organization		Name of organization responsible for data collection
	Surveyor name		Name of person responsible for filling in this sheet
	Phone number		Phone contact for surveyor
Complete one form for **EACH** transect	Email address		Email contact for surveyor
	Date		Date of this survey
ANCILLARY INFORMATION			
Shoreline name			Name for section of shoreline (e.g., beach name, park)
Transect #			Transect # (1-20)
Coordinates of start of shoreline site	Latitude	Longitude	Recorded as XXX.XXXX (decimal degrees). Record in both corners if width > 6 m. If transect, record at water's edge.
Coordinates of end of shoreline site	Latitude	Longitude	Recorded as XXX.XXXX (decimal degrees). Record in both corners if width > 6 m. If transect, record at back of shoreline.
Width of beach			Width of beach at time of survey from water's edge to back of shoreline (meters)
Time start/end	Start	End	Time at the beginning and end of the survey
Time of low tide			Time of the most recent or upcoming low tide.
Season			Spring, summer, fall, winter, tropical wet, etc.
Date of last survey			Date on which the last survey was conducted
Storm activity			Describe significant storm activity within the previous week (date(s), high winds, etc.)
Current weather			Describe weather on sampling day, including wind speed and % cloud coverage
Number of persons			Number of persons conducting the survey
Large items	YES	NO	Did you note items > 1 ft in the large debris section?
Debris behind back barrier?	YES	NO	Is there debris behind the back barrier of the site (do not include it in tallies below)
Photo ID #s			The digital identification number(s) of debris photos taken during this transect.

Transect #

Standing-Stock Survey Debris Datasheet | Version 2.0 | March 2016

ITEM	TALLY (e.g., ~~IIII~~)	TOTAL
RUBBER		
Flip-flops		
Gloves		
Tires		
Balloons - Latex		
Rubber fragments		
Other:		
PROCESSED LUMBER (no natural wood)		
Cardboard cartons		
Paper and cardboard		
Paper bags		
Lumber/building material		
Other:		
CLOTH/FABRIC		
Clothing & shoes		
Gloves (non-rubber)		
Towels/rags		
Rope/net pieces (non-nylon)		
Fabric pieces		
Other:		
OTHER/UNCLASSIFIABLE		

LARGE DEBRIS ITEMS **(larger than 1 foot or ~ 0.3 m)**

Item type (vessel, net, etc.)	Status (sunken, stranded, buried)	Approximate width (m)	Approximate length (m)	Description / photo ID #

Notes on debris items, description of "Other/unclassifiable" items, etc:

Annex V.2 OSPAR survey data sheet and list of categories for beach litter

OSPAR Marine Litter Monitoring Survey Form

Name of beach: ....

OSPAR beach ID: ....

Country: ....

Date of survey: ..../........../.......... (d/m/y)

Name of surveyor 1: ....

Phone number: ....

E-mail address: ....

Name of surveyor 2: ....

Phone number: ....

E-mail address: ....

Additional Information

100 m

Was litter collected during this survey: ☐ Yes ☐ No

When was the beach last cleaned: ..../........../.......... (d/m/y)

Did you divert from the predetermined 100 metres: ☐ No ☐ Yes, please specify: ....

....

Did any of the following weather conditions affect the data of the surveys. If so please tick appropriate box:

☐ Wind ☐ Rain ☐ Snow ☐ Ice ☐ Fog

☐ Sand storm ☐ Exceptionally high tide

Did you find stranded or dead animals: ☐ Yes ☐ No If so how many: ....

Please describe the animal, or note the species name if known: ....

☐ Alive ☐ Dead

Sex of animal (if known): ....

Age of animal (if known): ....

Is the animal entangled in litter: ☐ Yes ☐ No

If so please describe nature of the entanglement and type of litter: ....

....

Were there any circumstances that influenced the survey. For example tracks on the beach (cleaning or other), recent replenishment of the beach or other.

Please specify: ....

....

Were there any events that lead to unusual types and/or amounts of litter on the beach.

For example beach events or other.

Please specify: ....

....

OSPAR Survey Form 100m.2010.010

Annex VI Monitoring/sampling protocols - seawater

Annex VI.1 CSIRO protocol for surface net tow

Survey Methodology Cheat Sheet
SURFACE TRAWL

Refer to this one-page document when you are in the field

1. Before leaving shore, make sure that you have all necessary equipment, and ensure that the net is free of holes.
2. Once on the vessel, attach the cod end, making sure that it is clean of debris. Attach the flow meter and ensure that it is turning freely.
3. Attach the tow rope to the net, and to the tow point on the vessel, ensuring that the net will be towed alongside. If towing from a large boat you might need to put weights on the rope to keep the net from skipping across the top of the water.
4. Before you deploy the net, fill in as much of the trawl datasheet as possible.
5. Make sure the boat is going at a speed of 2-3 knots (3.7 – 5.5km/h), and double check all net rigging and cod end before you begin.
6. Deploy the net over the side of the vessel and record start latitude and longitude and start time, in decimal degrees (dd.dddd). Make sure to write in the 5 digit number from the flow meter as well.
7. Tow the net for approximately 15 minutes, while vessel is moving at a speed of 2-3 knots, then pull the net out of the water. The goal is to travel approximately one nautical mile (just under 2 kms).
8. Record end latitude and longitude, end time, duration of tow, boat speed, and flow meter end count on the data sheet.
9. Take the cod end off and wash contents into a bucket using sea water. Make sure to wash cod end thoroughly to get all debris out. Label bucket with station and tow number, and attach a new, clean cod end.
10. Repeat steps 4 to 10 for tow 2 and tow 3.
11. Once you have finished the station, wash the net and cod ends thoroughly making sure that there is NO debris in the cod end or net as this will contaminate the next sample.
12. Once you have finished all stations, wash all gear thoroughly and leave to dry before packing back up in bag.

Trawl sample sorting - WHEN YOU'RE BACK ON LAND

Sorting of the trawl samples occurs back on land, not in the boat. Note that you will be doing three separate sorts for each tow sample that you have done, so a total of 9 for each station.

1. Tip the contents of station 1 tow 1 into a clear plastic tub. Wash the cod end out into the bucket, making sure that the rinse water also goes into the bucket.
2. Remove any natural/organic material such as seaweed etc. from the bucket, making sure there are no pieces of debris stuck to the organic material.

3. Using metal tweezers, remove all pieces of debris you see (using ambient light) and put them in a gridded clear plastic petri dish.
4. Tally the debris on the datasheet.
5. Take a 15 minute break, then repeat steps 3-4 to do a second sort
6. Do a third sort by repeating steps 3-4, but this time use torch light (if available) to search for debris.
7. Once you have completed your three sorts, take a photo then empty contents into a piece of foil and label.

SURFACE TRAWL SITE INFORMATION

STATION DETAILS			
Country			
Location		*(e.g. river name, nearest city, etc)*	
Station Number			
Surveyor name and organisation			
Date *(local; dd/mm/yyyy)*			
Net type			
Net mesh size			
Net mouth dimensions			
Salinity *(if known, ppt)*		**Sea surface temperature** *(℃)*	

TOW DETAILS			
Tow Number	**1**	**2**	**3**
Wind speed *(true, kn)*			
Wind direction (degrees)			
Start latitude (decimal deg)			
Start longitude (decimal deg)			
Start time *(local / UTC)*			
Start flow meter count			
End latitude *(-S)*			
End longitude *(E)*			
End time *(local / UTC)*			
End flow meter count			
Average vessel speed *(ground, kn)*			
Average vessel direction (degrees)			
Average depth *(local, m)*			
Notes			

Annex VII Monitoring/sampling protocols - seafloor

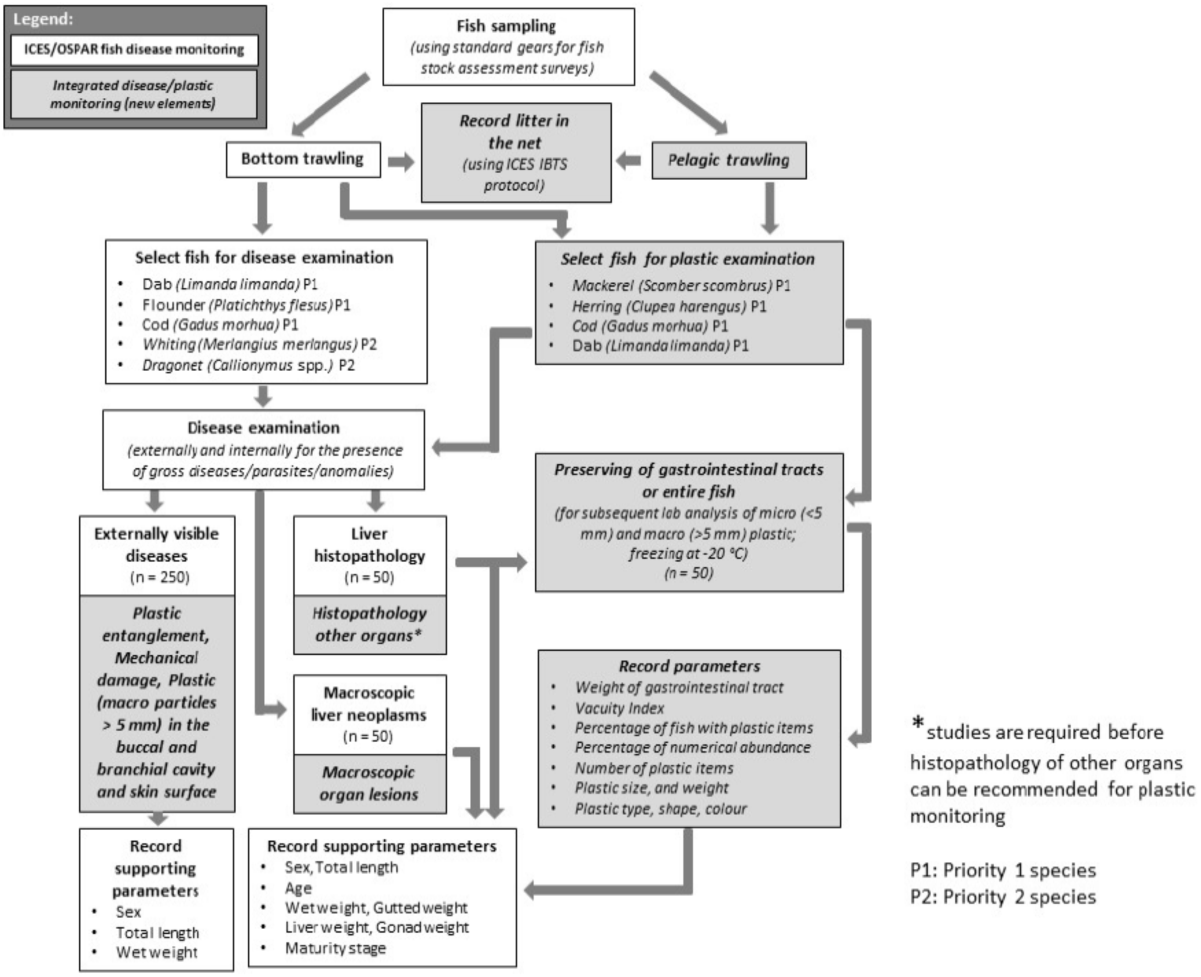
Protocols for seafloor micro- and macro-litter				
Name	Year	MI	MA	URL link
NOWPAP	2007		x	http://dinrac.nowpap.org:8080/documents/NOWPAP_MERRAC_Marine_Litter_Monitoring_Seabed.pdf
UNEP	2009		x	http://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/13604/rsrs186.pdf?sequence=1&isAllowed=y
EU-MSFD*	2013	x	x	http://mcc.jrc.ec.europa.eu/documents/201702074014.pdf
NOAA	2015	x		https://marinedebris.noaa.gov/sites/default/files/publications-files/noaa_microplastics_methods_manual.pdf
FAO**	2016		x	http://www.fao.org/3/a-i5051e.pdf
DeFishGear	2016		x	http://www.defishgear.net/media-items/publications

** Update planned in 2019*
*** Focus on ALDFG*

Annex VIII Monitoring/sampling protocols - biota

Annex VIII.1 Sampling plastic particles in fish stomachs

ICES have developed a common monitoring protocol for plastic particles in fish stomachs and selected shellfish, at the request of OSPAR (ICES 2015). This applies to fish samples collected as part of an existing fish disease monitoring programme.



Annex IX Recommended protocols for minimising microplastic contamination

Table AIX.1 Recommended protocols for each step of microplastic sampling, contamination mitigation, sample purification/ handling and chemical analysis, adapted from Hermsen *et al.* 2018 (see original publication for further details). The authors used these criteria to evaluate the completeness and reliability of 35 published studies of microplastic incidence in biota.

Processing stage			Recommended protocol
Sampling	1	Sampling methods	Several sampling characteristics should be recorded: this includes the exact sampling gear and information on the net type, material and its mesh sizes. Furthermore, the sampling location and depth ("upper 10 m", "bottom trawling," are sufficient) need to be recorded, as well as the date and time of the day sampled. This will enable identifying any potential contamination from the gear, or occurred during the sampling. This information also enables the replication of the sampling, and provides insight in comparability with other studies.
Sampling	2	Sample size	50 or more individuals per research unit are defined as a suitable sample size. The confidence interval of the ingestion incidences should be reported. In larger animals, e.g. marine mammals, this criterion is difficult to achieve but samples should be as diverse and large as possible.
Sampling	3	Sample processing and storage	Biota samples should be stored between the moment of capture and the examination in the lab. At best, the samples should be frozen at -20°C. For small species the preservation in a glass container using a fixative is an option. However, the effects of the fixative on different types of plastic should be evaluated before application. Recently, the usage of formaldehyde/ ethanol were found to have no effects on different microplastics. If any other fixative is used, an application test will be required. Additionally, any sample handling, such as dissections, should be left for the lab, never on board.
Contamination mitigation	4	Laboratory preparation	All materials, equipment, and laboratory surfaces need to be thoroughly washed and rinsed. After rinsing, all materials should be kept in clean air conditions. All other materials, such as solutions and filters, should be checked before usage and covered afterwards. If possible, the sample specimens should be rinsed and checked for external contamination. Sample contamination originating from researchers' clothing should be avoided by solely wearing 100% natural fibre clothing and a cotton lab coat. The coat alone may not be sufficient; wearing a polyester shirt underneath, it is imaginable that some fibres could end up in the samples. However, for the current scoring, a 100% cotton lab coat was considered sufficient when all other precautions were met.
Contamination mitigation	5	Clean air conditions	The handling of samples should be performed in clean air facilities, such as a (positive pressure) laminar flow cabinet or a "clean room". Samples should not be taken out of the clean air facilities without being sealed off. Since the analysis often cannot be conducted under clean air conditions the implementation of negative controls becomes an even higher necessity.
Contamination mitigation	6	Negative control	Controls (in triplicate) should be included for each batch of samples and should be performed in parallel to the sample treatment. The controls should be conducted using filtered water, or biota tissue that is free of plastic. Only then a contamination deriving through air, clothes, added chemicals or used equipment can be discovered. Additionally (not instead!), controls might be taken again at "high risk moments" that are moving materials or samples in-/ outside the clean air facilities, or during analysis outside the clean air facilities (e.g. visual inspection, or polymer identification). Here, clean petri dishes or soaked paper can be placed next to the sample, and checked for any occurred contamination.
Sample purification/ handling	7	Positive control	Positive controls (triplicates) should be included to determine the microplastic detection efficiency. This is a necessary quality assurance, providing information on the effectiveness of the purification and analysis methods applied. Positive controls should be performed in parallel to the sample treatment using samples with an added number of microplastic particles of known polymer identity. Then, the numbers of retrieved microplastic particles are tallied to the amounts added.

Table AIX.1 Recommended protocols for each step of microplastic sampling, contamination mitigation, sample purification/handling and chemical analysis, adapted from Hermsen *et al.* 2018 (see original publication for further details). The authors used these criteria to evaluate the completeness and reliability of 35 published studies of microplastic incidence in biota.

Processing stage			Recommended protocol
Sample purification/ handling	8	Target component	To ensure monitoring of all ingested microplastic, a suitable target component for larger species, such as fish, is the full gastrointestinal tract (GIT). For smaller species, such as bivalves, the entire organism should be used.
	9	Sample treatment	A digestion step must be included to dissolve organic sample matter so that especially small microplastics are not overlooked. The digestion method described by Foekema *et al.* (2013) using a 10% KOH-solution is considered suitable for fish. However, heating of the samples during digestion should be omitted. For smaller organisms, applying an enzymatic digestion is considered adequate as well. The digestion of organic material can be circumvented when focussing solely on the ingestion of bigger microplastics. A lower size limit needs to be defined by e.g. sieving the sample over 300 µm.
Chemical analysis	10	Polymer identification and reporting	For all microplastics a polymer identification is required. The choice of the analytical method depends on the targeted microplastic sizes. The most common methods are FTIR or Raman (micro)spectroscopy, and pyrolysis- or TGA GC-MS. Any of these can be applied. For pre-sorted particles and when these numbers are < 100, all particles should be analysed. For particle numbers > 100, >50 % should be identified, with a minimum of 100 particles. The reporting should include: particle counts with confidence intervals, detection limits for the count and for minimum particle size, detected microplastic sizes, polymer types and percentages.

Annex X Analytical methods for chemicals associated with plastics

Summary of analytical methods used for plastic associated chemicals (Hong *et al.* 2017).

Compound	Extraction	Clean-up	Detector
PAHs (16)	Soxhlet (6) Ultrasonication (4) Solvent soaking (4) Accelerated solvent extraction (2)	Silica (9) Silica/Alumina (4) Silica/Florisil (1) Alumina (1)	GC-MS (12) GC-MS/MS (1) GC-ITMS (1) GC×GC-TOF-MS (1)
PCBs (25)	Soxhlet (10) Ultrasonication (4) Solvent soaking (11)	Silica (17) Silica/Alumina (1) Silica/Florisil (1) Silica, Florisil, Alumina (1) Alumina (2) Florisil (1) GPC, Florisil (1)	GC-MS (15) GC-ECD (6) GC-MS/MS (1) GC-HRMS (1) GC-ITMS (2) Quattro Micro mass spectrometer (1)
OCPs (18)	Soxhlet (8) Ultrasonication (5) Solvent soaking (14)	Silica (19) Silica/Florisil (3) Alumina (2) Florisil (2) GPC, Florisil (1)	GC-MS (12) GC-ECD (10) GC-ITMS (1) Quattro Micro mass spectrometer (1)
PBDEs (5)	Soxhlet (3) Ultrasonication (1) Solvent soaking (2)	Silica (4) Silica, Florisil, Alumina (1) GPC, Florisil (1)	GC-MS (1) GC-HRMS (1) GC-ITMS (3) Quattro Micro mass spectrometer (1)
HBCDs (1)	Solvent dissolution (1)	-	HPLC-MS/MS (1)
NP (2), BPA (2)	Soxhlet (1) Solvent soaking (1)	Silica (1) Florisil (1) Oasis HLB sorbent (1)	GC-MS (1) LC-MS/MS (1)
Hopanes (1)	Solvent soaking (1)	Silica (1)	GC-MS (1)
PFASs (2)	Ultrasonication (1)	-	LC-MS/MS (1)
Metals (3) (w/o Hg)	Acid digestion (2)	-	ICP-MS (2) X-ray fluorescence analyser (1) SEM-EDS (1)
Hg (1)	-	-	Hg analyser based on sample pyrolysis, gold amalgamation, and atomic absorption spectrometry (1)

(n) refer to number of publications, ECD: electron capture detector, EDS: energy-dispersive X-ray spectroscope, GC: gas chromatograph, GPC: gel permeation chromatograph, HRMS: high-resolution mass spectrometer, ICP-MS: inductively coupled plasma mass spectrometer, ITMS: ion-trap mass spectrometer, LC: liquid chromatograph, MS: mass spectrometer, MS/MS: triple quadrupole mass spectrometer, SEM: scanning electron microscope, TOF-MS: time-of-flight mass spectrometer.

Annex XI Examples of marine litter data repositories.

Name / Institution	Type of data	Link
LITTERBASE, Alfred-Wegener Institute	Data reported in scientific studies	http://litterbase.awi.de/
MDMAP, NOAA Marine Debris Monitoring and Assessment Project online database	Amount and types of marine litter on shorelines	https://mdmap.orr.noaa.gov/login
EMODnet, European Marine Observation and Data Network	Amount and types of litter on the shoreline and seafloor; Microplastics in sediments and water	http://www.emodnet-chemistry.eu/welcome
International Council for the Exploration of the Sea (ICES) data portal	Data portal used by OSPAR, HELCOM, AMAP and Expert Groups in the management of chemical and biological data for regional marine assessments	http://www.ices.dk/marine-data/data-portals/Pages/default.aspx
NOAA Marine Debris Program and the Southeast Atlantic Marine Debris Initiative (SEA-MDI)	Records of marine or litter anywhere in the world	http://www.marinedebris.engr.uga.edu/
IFREMER, French Research Institute for the Exploitation of the Sea	Marine litter on the shoreline, at the surface and on the seafloor	https://wwz.ifremer.fr/en/Public-policy-support/Water-Biodiversity/Marine-Strategy-Framework-Directive
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Deep-sea Debris Database	http://www.godac.jamstec.go.jp/catalog/dsdebris/e/
Fighting for Trash Free Seas, International Coastal Cleanup (ICC)	Results of Coastal Cleanups	https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup
Global Ocean Data Platform, REV Ocean	General data on marine litter	https://revocean.org/platform/project
Global Alert Platform	Reports of trash pollution	http://www.globalalert.org/
Marine Debris Database, Santa Monica Bay Restoration Commission and California Coastal Commission	Trash and other litter picked up by schools, companies, and other volunteers as part of Heal the Bay's various Beach Cleanup Programs	http://sites.healthebay.org/MarineDebris/MDDB/
International Pellet Watch, Laboratory of Organic Geochemistry, Tokyo University of Agriculture and Technology	Persistent Organic Pollutants (POPs) in resin pellets	http://www.pelletwatch.org/

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