Marine Plastic Pollution - Evidence Review

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1. Introduction

1.1 Context for the Marine Plastic Pollution Evidence Review and Action Plan

This review has been prepared for the Defra Marine Litter Policy team in order to provide a summary of evidence of relevance to addressing marine plastic pollution. Whilst developing appropriate policy is a key challenge for this emerging issue, this review and associated workshop is primarily evidence, rather than policy driven.

The Marine Litter Policy team at Defra leads, and is consulted on, a wide range of interventions related to plastics and microplastics in the environment. These measures can range from designing the ban on microplastics in personal care products, to contributing to the revisions of the Ports Reception Facilities Directive (2000/59/EC).

Whilst the remit of Defra Marine is primarily litter in the marine environment, evidence relating to the underlying drivers and interventions on land are key to solving the problem.

Examples of evidence gaps identified by Defra ahead of this review include:

- The state of science concerning the entrance of pre-production plastic pellets into the marine environment
- The state of science concerning the sources, transport and fate of abandoned, lost or otherwise discarded fishing gear in the marine environment
- The extent to which fragmentation of larger plastics contributes to proportions of microplastics in the marine environment
- The extent to which microplastics may cause harm to marine life
- Environmental trade-offs in plastic reduction/removal strategies
- The extent to which some marine litter might have positive impacts to the marine environment

These evidence gaps present barriers to well-informed, effective policy. Defra adopts a precautionary, risk-based approach where appropriate in designing and implementing policy. Potential policy needs include:

- Guidance on how to best direct funding to areas of marine litter research which are least developed or most appropriate for policy development
- Better inform our understanding of the UK's needs and requirements in international and multilateral negotiations
- Identify how best to approach issues where evidence is lacking, in order that we can better balance the needs of the marine environment and other stakeholders

- Inform a harm-based approach in terms of which types of litter present the most risk in the marine environment or are the most underdeveloped, in the absence of agreed conventions on hazard and risk assessment

What is required therefore is an assessment of the evidence base, the knowns and unknowns, and how this then leads to an evidence 'action plan' to address those gaps.

1.2 Relevant Policy Leads for Plastic Pollution

It was recognised in this process that Defra is Government's lead in tackling plastic pollution, through its' broad policy remit of:

- Marine fisheries, and environmental protection
- Waste and resources management
- (Fresh) water quality environment and public water supply
- Protecting and enhancing biodiversity
- Marine management
- Chemical Regulation

Within these policy areas, there are a broad range of regulatory instruments, and approaches, and existing policy interventions that are, or could be, aligned to the plastic pollution issue. This ranges from duties to protect habitats and species to discharge controls and the management of waste. The Defra Group delivery bodies (Environment Agency, Marine Management Organisation, Natural England, and the Joint Nature Conservation Committee) play an essential role in both gathering evidence, as well as delivering mitigations.

Wider Government Departments identified as relevant to this issue include:

- Department for International Development;
- Department for Business, Enterprise and the Industrial Strategy;
- Department for Communities and Local Government;
- HM Treasury
- Foreign and Commonwealth Office
- Department for International Trade

Whilst Defra is Government's lead on this topic, collaboration across Government departments is essential in order to have a comprehensive and robust responses to this issue. The evidence base being outlined will deliver critical information to support wider interventions, for example the economic impacts of the pollution.

1.3 Critical Unknowns that Relate to UK Marine Policy on Plastics

The issue of marine litter has been recognised as a threat to environmental quality for many years, with a range of potential impacts on wildlife, the economy and human-wellbeing. Litter at the macro size range (e.g. single use packaging, sanitary items fishing gear, shipping-related waste) to micro (e.g. fibres, microbeads as well as fragmentation of macro-debris) are recognised as potentially harmful to a wide range of marine organisms from mammals to invertebrates through entanglement, and ingestion. Over 700 species are known to encounter plastic litter in the marine environment including fish, bivalves and zooplankton (Thompson, 2017).

Yet the acceleration of the issue of marine litter, particularly plastics, has only recently (Sutherland et. al. 2009) been identified as a major threat to ocean health on a global scale, threatening the marine food chain from zooplankton upwards. Plastics leakage directly into the World Ocean, as well as via freshwaters and land-air pathways represents a global system failure. This impacts on marine ecology causing physical and chemical contamination. Whilst plastic debris on land contaminates the soil, an increasing volume of plastic waste (estimated to be >8 million tonnes (range 4-12 million Tonnes) per annum (Jambeck et al, 2015)) enters the Ocean and every coast around the world, with enormous economic costs (for example, £1.265 billion USD pa in the Asia-Pacific region alone) due to loss of revenue from tourism, clean-up and repair, and the social impacts of polluted and degraded environments (UNEP, 2014). Factors affecting the challenge include the wide scale of consumption and production of plastic, especially single use items which have a very short life in service, coupled with inadequate waste management practices.

This challenge demands scientific evidence at the largest of spatial scales, as well as more focused laboratory experiments. But what science is needed to underpin 'policy'? Awareness that plastic is in both freshwater and marine environments is increasing, yet much less is known about the underlying systemic causes and pathways to the environment. This is inhibiting progress towards several UN Sustainable Development Goals (SDGs), as the numerous positive and negative feedbacks have not yet been investigated comprehensively and scientifically (Thompson R (2015); Galloway et al (2017)).

At this time, the amount of information emerging on the broad topic of ocean plastics is burgeoning. From a place where plastics were minor elements in major scientific conferences, ocean plastics are now dominating the marine debris debate, with dedicated conferences (MICRO2018). The granular nature of increasing scientific study is not necessarily driving the overall quality of the evidence upward, nor fundamentally the utility of that knowledge to deliver action. This has been seen before in other scientific endeavours.

However, with ocean plastic pollution becoming ever more visible in the media, and to the public, rapidly rising up the global environmental, social and political agendas; there are already international and regional commitments to reduce contamination of marine habitats by 2025 involving both Governments and Industries (e.g. UN Environment, GESAMP, UKRI/Policy Connect, Plastics Europe, 2016). Many actions and efforts to reduce or manage plastics entering the Ocean show potential, but to date have been fragmented, incremental or uncoordinated, lacking both impact at scale and the bedrock of rigorous research.

1.4 Identifying Critical Science Areas Related to UK Marine Policy on Plastics

The UK Government has set out a pledge through its 25 Year Environment Plan to reduce ocean plastic, but identifying the policies and actions requires a sound evidence and assessment. The challenge is therefore to understand the evidence and examine potential interventions in a peer review environment against regulatory and policy needs. This issue has escalated from the simple aesthetic marine litter problem, to a 'perceived' global challenge. Whilst the accumulation of plastics in the marine environment is clear, the origins are nuanced, and complex.

There are already actions being taken internationally on a range of single-use plastics, but whilst the effect of these measures may take time, understanding what further measures may be needed to reduce plastic pollution is essential, so as to close the policy and action 'gap'. Therefore, against the myriad of research programmes, there is an urgent need to make sense of what is known in relation to key evidence gaps, and build out from there to identify remaining questions, and the research effort needed. Critical thematic areas that relate to marine policy include:

- **Monitoring of plastics:** data are being reported for plastic pollution on a global scale. However, data are based on a broad range of monitoring methods and include little information on change over time. In addition, there is debate about the definition of 'microplastics'. Whilst there are many monitoring programmes and modelling around the data that arise, these projects should be considered as 'estimates' at best as there are considerable limitations, variations and assumptions in those data. Therefore, it will be important to clearly define the questions behind monitoring, and then set out appropriate techniques and programmes to answer those questions, with appropriate temporal and spatial bounds.

- **Understanding the source, pathways and fate of macro and microplastics to the marine environment**: plastics are entering the marine environment from land freshwater, and marine inputs, with variable quantities and types of plastic between sources. Plastic monitoring methods are not well-benchmarked, and there is a diversity in analytical methods limiting data comparability. Decisions on monitoring to assess presence and change over time will need to be taken to ensure monitoring is fit for purpose and cost effective.

- **Understanding the environmental distribution**: much has been made of the main sources of plastic pollution being in the Asia-Pacific region, and the 'top 10' rivers that discharge to this vast marine basin. This focuses attention to improve the waste management practices in these regions but questions for Defra science and policy relate to the relevance of this to the UK. The majority of litter on UK beaches has originated locally in the NE Atlantic and so it is clear that marine litter is not merely an issue in developing nations, and that current practices in developed nations are also inadequate. In addition to this, marine plastic discharged in the Pacific could contribute to pollution around British Dependent Territories, so understanding of impacts and consideration of how to manage this issue (particularly in relation to Marine Protected Areas) is also important. Moving closer to the UK, what is the relevance of the UK as a source of plastic? There are 'estimates' at best as there are considerable limitations, variation and assumptions to the marine environment both locally and further afield. And what is the UK responsibility to manage those releases? The UK is also a significant exporter of plastic waste and recent media reports suggests that since the closure of the Chinese market, waste has been diverted to other countries for reprocessing. What is the UK's responsibility for the effective scrutiny of that activity, and the management of the waste in those countries, so as to minimise any release to the environment? Being clear about the knowns and uncertainties of plastic movements will influence the measures in the UK to meet both our local needs, and international obligations.

- **Understanding the impacts of plastics and microplastics:** Ingestion of microplastics in the environment is apparent from analysis of a range of marine biota from zooplankton, shell-fish and fish to mammals. Laboratory based exposure studies have provided evidence for the impact of such ingestion, but population and ecosystem consequences are not known. Understanding risk is challenging, because of the lengthy degradation pathways, processes and timelines coupled with continued accumulation. When compared to microplastics, impacts of macroplastics may be more easily detected due to visibility of entanglement of larger marine vertebrates, and fatalities due to ingestion of plastics, leading to starvation or enteric damage. How can impacts across the plastic debris size range be evaluated effectively, so that appropriate interventions are developed to mitigate those risks?

- The ultimate fate of macro and microplastics may well be the ocean floor, what are the risks to biota on the Ocean before that? Fundamental research will be needed to elucidate evidence of harm, that can support policy interventions to minimise these risks?

- **Understanding Economics:** Whilst accumulation of microplastics has been shown in commercially important fish and shellfish, the consequences need to be properly evaluated from the perspective of harm to marine life, as well as using from an economic perspective. In addition, the aesthetic impacts of plastics on coastlines need to be evaluated. This is an area which will be critical to policy direction as well as cost-benefit analysis to underpin regulatory impact assessments. The Natural Capital approach is a critical lens through which to consider the impacts of plastic debris on ecosystem services. The all-pervasive nature of plastic pollution requires broad assessment to ensure a comprehensive overview of the true costs of the impacts.

- **Behavioural change**: Despite widespread awareness of the 'issue', specific actions remain elusive. Ideally, interventions need to engage the 'audience' in a way that supports and incentivises change, but measures that 'regulate' will also be needed. It is also critical that Government understands the public appetite for change and expectations for Government action, particularly in the absence of full data to underpin policy. Therefore, this area poses a number of challenges for Government – to work with the public to reduce plastic pollution in a manner that encourages industry to change the way they design, use and dispose of plastics and enhance, for example, recyclability or material reduction, without leading to unintended consequences such as increasing food waste.

This science review aims to provide an evidence base upon which Defra can assess what further evidence is needed to support policy development, so to meet Government obligations.

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2. Thematic Review Areas and Process

2.1 Thematic Review Areas

The review process identified six thematic areas:

- Marine Plastic Monitoring and Methods
- Sources and Pathways of Marine Litter
- Transport and Fate of Marine Plastic Pollution
- Impacts of Marine Plastic Pollution on Biota and Ecology
- Ecosystem Service and Economic Impacts of Marine Plastic Pollution
- Behaviour Change in People and Business Towards Plastic Pollution

2.2 Thematic Review Process

These reviews were compiled over a two-month period, February to March 2019, and provide a 'snapshot' review process focused on drawing together and evaluating evidence, from key papers and reviews. Each review has individual co-authors who are acknowledged as experts in their field. The structure of the reviews has been standardised as far as possible, so as to ensure each theme was covered to a similar depth. However, the quantity of relevant publications varies between themes, and this is reflected in content and conclusions of each. The reviews were focused on science that is relevant to maritime and fisheries policy areas, however interventions may be outside of these policy areas (e.g. municipal waste management).

The geographical scope of the review was centred on the UK and related convention areas (such as OSPAR) and the implications to UK marine policy in these areas. Therefore, publications focussing on data and evidence from other regions were included only where relevant to the UK situation, for example monitoring methods.

Following their submission, the six draft reviews, were then examined in a critical review workshop, delivered by ALP Synergy Ltd. and Environmental Sustainability Associates Ltd. on 12th and 13th March in London. Attendees are listed in Annex 2 to this document, including Defra and Defra Group officials, as well as leading academics from the UK and Internationally. At the workshop, the six thematic reviews were presented to the participants so as to ensure comprehensive coverage of the topic areas, to reflect on the conclusions and the science gaps identified, and evaluate where possible, the linkages to Defra marine litter policy areas.

Whilst the thematic reviews were independently produced, it is clear that there are overlaps and dependencies across the themes, and this provided areas of discussion between the workshop delegates. This document presents the finalised thematic reviews, reflecting both the authors content and the input from the plenary review process at the critical review workshop.

3. Review of Marine Plastic Monitoring and Methods

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3.2 Background to the Problem

Plastic debris has been reported in all environmental compartments - soil, air, marine and freshwaters, as well as in biota. This debris is a highly heterogeneous mixture spanning orders of magnitude in size (from fishing nets that can be 1000s metres in length to microplastics measured in µm in diameter, and even smaller), a wide range of shapes and polymer types, from an equally diverse range of sources.

While initial concerns around plastics were first reported in the late 1960s, following observations of the detrimental effects on wildlife through entanglement and ingestion (see Gall & Thompson, 2015, for a review of species impacted by marine litter), there is now also concern regarding the potential impacts on food security (Rochman et al., 2017). Plastic pollution has now been quantified across a range of marine environmental compartments, including sea surface, beach, sediment, and ocean floor (Scientific Advice for Policy by European Academics (SAPEA) report, 2019). In view of the potential impacts that plastics can have on marine organisms, the Marine Strategy Framework Directive (MSFD) requires that European Member States develop strategies that aim to achieve or maintain ‘Good Environmental Status’ in European Seas. Monitoring programmes – the regular sampling and analysis of environmental media – that evaluate the state of marine waters are a critical part of this process.

The fate of plastic once it has entered an environmental compartment can depend on a number of factors, including the physical properties of the plastic itself (e.g. size, shape, density), environmental conditions and transport processes that it interacts with (e.g. biofouling, wind, tide, UV). Almost limitless combinations of these factors make it difficult to predict where an item of debris has come from, or will ultimately be transported to, especially as interactions can occur both within and between different environmental compartments. Furthermore, while a number of methods exist for monitoring different types of plastic debris in different environmental compartments, monitoring protocols vary in their maturity, with some such as beach litter monitoring being much more well-developed and tested than others.

Although standardisation of methodologies would help reduce uncertainties, and facilitate policy- and decision-making processes, this is currently not feasible (Rochman et al., 2017). There is no ‘one size fits all’ method of monitoring such a diverse mixture of plastics, across a range of environmental compartments. Some methods may be highly technical, others may be designed to facilitate citizen science programmes. It is therefore important to determine exactly *why* the monitoring is being undertaken, for example: to assess environmental status and harmful effects (covered in Thematic Review #3); to determine critical thresholds and targets; source identification; or to measure the effectiveness of policy or other implemented measures. It is then necessary to design appropriate sampling protocols considering locations, equipment, number of replicates etc., to answer the specific questions posed (Rochman et al., 2017). Unless this approach is adopted, it is unlikely that the monitoring programme will deliver reliable, relevant and 'fit-for-purpose' data, at an affordable cost (Joint Research Centre (JRC), reference report, 2013).

In order to facilitate this process, Annex V of the MSFD lists seven recommendations for monitoring programmes. In brief, monitoring programmes should (see JRC, 2013, pp. 10-11):

1. Deliver the core purpose of the "on-going assessment of the environmental status" and related environmental targets in accordance with the MSFD strategies and management cycles;
2. Be "coordinated", "compatible", "coherent", "consistent" and "comparable";
3. Build upon and integrate already established monitoring programmes, relevant Directives (e.g. Habitats and Birds Directive; Water Framework Directive), EU legislation, the Regional Sea Conventions (RSC), and other international agreements;
4. Make data and information available for interoperable use, and feed into the "Marine Knowledge 2020" process;
5. Adapt with appropriate reaction to changes in the marine environment and understanding of emerging themes;
6. Link monitoring to assessment needs, including the use of risk-based approach as a basis for flexible monitoring design;
7. Take into account the differences in scientific understanding for each description in the monitoring programmes and apply the precautionary principle.

Although the above recommendations are in place and progress is being made, there is considerable variation across the different methodologies with, as mentioned, some being more effective and well-developed than others. In the absence of other drivers, it would seem sensible for the UK to follow approaches adopted by its neighbours in the EU.

3.3 Monitoring methods

3.3.1 Overview

The various approaches used to monitor litter depend on a number of factors, such as the size of litter and the environmental compartment from which it is sampled. Plastics range in size from the 'mega' to 'nano' (see Figure 1). The current lower limit of environmental detection is in the 'micro' range at around 20µm, but most scientists working in the field consider that even smaller nano-particles are also likely to have accumulated in the environment. Large items are clearly visible and identifiable to

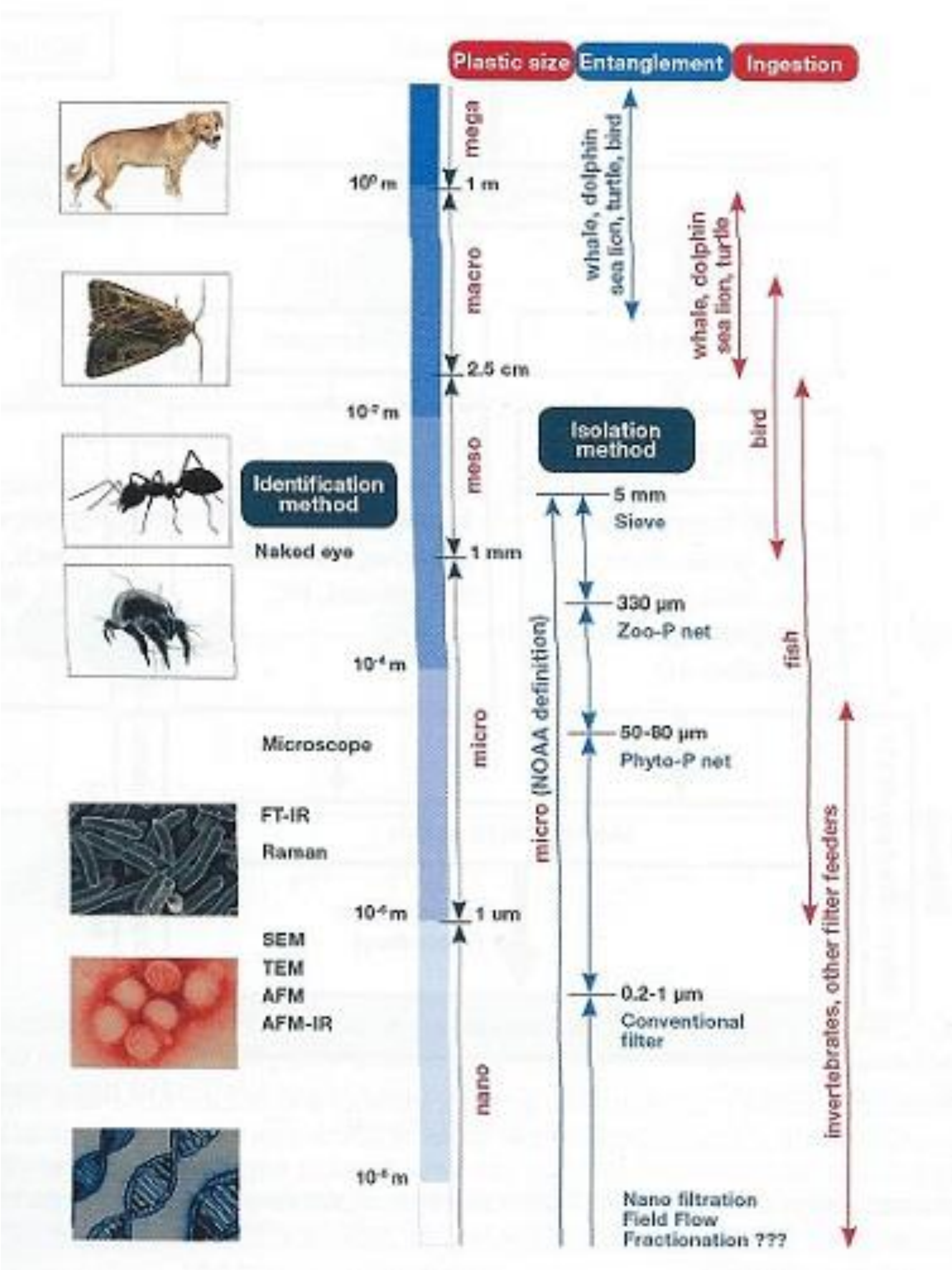

Figure 1: Size range of plastic objects observed in the marine environment and some comparisons with living material (Source: GESAMP, 2015)

the naked eye, but smaller pieces may require considerable processing and the use of detailed analytical techniques to facilitate identification and quantification, for example microplastics and microfibres.

3.3.2 Summary of Available Monitoring Protocols

Table 1 below provides a summary of monitoring protocols for different sizes of plastics and where they occur as reported in JCR reference report, 2013, pp. 30-35). The 'High/Medium/Low' criteria are defined as follows:

- Level of maturity of monitoring programme
    - High – protocol has been systematically applied for more than a decade, extensively in one or more regions
    - Medium – applied systematically on a few regions/countries, for less than a decade
    - Low – tool is under development/has only been pilot tested (i.e. further R&D required)

- Technical/Equipment (costs to undertake work)
    - High > £45,000
    - Medium £9,000 – £45,000
    - Low £900 – £9,000

- Expertise
    - High – high expertise and specialise skills required
    - Medium – trained personnel with specific professional formation
    - Low – trained personnel without specific professional formation

- Cost (total cost to undertake work)
    - High > £45,000
    - Medium £9,000 – £45,000
    - Low £900 – £9,000

This summary of monitoring protocols highlights the current difficulties that would be encountered trying to standardise such an array of methods of differing technical complexity. Furthermore, it highlights the disparity in maturity between the macro- and microplastic monitoring programmes. For instance, macro beach litter monitoring programmes are well-developed and extensive: costs for technical equipment are low and many programmes can make use of trained volunteers.

In contrast, microplastic monitoring (particularly for the smallest particles) is far less developed; the costs involved, especially for technical equipment, are high, and a high level of expertise is required. Some citizen science-focused programmes are beginning to address microplastics (www.microplasticsurvey.org) but this will be much more challenging than programmes focused on macro debris. Overall, far less is known about the occurrence, fate and effects of microplastics than other types of marine litter.

Table 1. Summary of monitoring protocols (adapted from Table 2 "Summary of monitoring protocols", JCR reference report, 2013, pp. 30-35).

Environ. matrices	Method/ protocol	Level of maturity	Technical/ equipment	Expertise needed	Cost	Level of detail generated	Geographic applicability	Limitations	Opportunities to reduce cost
Beach	Visual/ collection	High (although R & D required on statistical analysis)	Low	Low/ Medium	L/M	High (Size ≥2.5 cm)	High (but dependent on-site accessibility)	Great variability among sites. Weather etc. can influence number of items deposited	Yes (e.g. trained volunteers)
Floating	Visual	High	Low	Low/ Medium	L/M	Medium (Size ≥2.5 cm)	High	Observation can be affected by weather etc. and must be adapted so the item's min, size is detected	Yes (e.g. can be integrated with other operations, such as cruises)
	Aerial survey	Low	High	Medium	H	Low	High	Expensive (unless coupled with aerial surveys. Best for large floating items	Yes (e.g. other aerial surveys)
	Automated camera	Low (in development)	Medium	High	M	Medium	High	Still in development. Dependent on good sea conditions	Yes (e.g. can be integrated with other operations, such as cruises)

Sea-floor (shallow)	Diving	Medium (low for video)	Medium (Low for video)	Medium	M	Medium (Size ≥ 2.5 cm)	High	Depends on accessibility to diving area	Yes (e.g. volunteer divers)
Sea-floor (20 – 800 m)	Bottom-trawl	Medium/ High	Low/ Medium	Low/ Medium	L/M	Medium (Size ≥ 2.5 cm)	Medium (although some areas may be restricted)	Flat, smooth bottoms only	Yes (e.g. can be coupled with other programmes)
Sea-floor (Deep)	ROV/Video	Medium	High	High	H	Medium (Size ≥ 2.5 cm)	Medium (only for countries with deep seas)	Expensive, unless coupled with other deep-sea bottom surveys	Yes, with other programmes
	Sea-birds (ingestion)	High	Low	Medium	M	Medium (Size ≥ 1 mm)		Depends on geographic coverage; feeding behaviour; availability of dead birds	Yes (can be coupled with other activities)
	Turtles (ingestion)	Medium/ Low	Low	Medium	M	Medium (Size ≥ 1 mm)	Medium (e.g. *Caretta caretta* only occur in certain locations)	Depends on geographic coverage of species and availability of animals	Yes (e.g. collaborate with turtle recovery centres)
Biota	Fish (ingestion)	Low (in development)	Medium/ High	Medium/ High	M/H	Medium/ Low	High	Depends on geographic coverage of species. Can be costly depending on species size and methodologies etc.	Yes (e.g. other programmes)

	Sea-birds (plastics as nesting material and entanglement)	Low (in development)	Low	Medium	L	Low/ Medium	Medium	Depends on geographic coverage of breeding colonies	Yes (e.g. combined with other surveys)
	Beached animals entanglement	Low in development	Low	Medium	L/M	Low/ Medium	Medium	Low occurrence of sea birds. High nos. of cetaceans. Pathologists may be able to distinguish cause of death	Pathologic investigations should include assessment of cause of death
	Marine mammals (ingestion)	Low In development	Medium	Medium/ High	M	Medium	Medium (depends on occurrence of species)	Known rates and investigations are low. Needs development.	Yes (e.g. can be applied as part of necropsies procedure)
	Marine invertebrates (ingestion)	Low in development	Medium/ High	Medium/ High	H	Low/ Medium	High	Insufficient data	Yes (e.g. coupled with other monitoring)
Micro	Beach	Low	High	High	M/H	Medium (Size ≥ 5 mm)	High	Probably most widely sampled compartment but approaches have been varied (limits comparability)	Yes (e.g. can be coupled with other (macro) beach sampling or monitoring)
	Sub-tidal	Low	High	High	H	Medium (Size ≥ 5 mm)	High	Can be insensitive fraction < 3 mm	Yes (e.g. with other sea-floor monitoring programmes)

	Water (manta trawl)	Low	Medium	Medium/ High	H	Medium (Size ≥ 5mm)	High	Can be insensitive fraction < 3 mm	Yes (e.g. with other sea surface monitoring programmes)
	Water (continuous plankton recorder – CPR)	Low	High	High	H	Medium (Size ≥ 5 mm)	High	Equipment used by one company only and along standard shipping routes (limits flexibility)	Yes (e.g. coupled with CPR surveys)
	Biota (if sampling for macro litter is conducted)	Low	High	High	H	Medium (Size ≥ 5 mm)	Medium (depends on species)	Currently no indicator species only protocol to analyse this fraction as part of protocol too analysed ingestion of litter	Yes (e.g. can be part of the analysis on biota ingestion of macro-litter

3.3.3 Use of a Master List

The use of standard lists and definitions of items can facilitate the comparison of data from different regions and environmental compartments (e.g. beach, floating, sea-floor). If lists are detailed enough, it may be possible to make inferences about potential sources (e.g. fishing gear), type of item (e.g. packaging), and even potential harmful effects (e.g. entanglement).

For larger plastic pieces, and some microplastics, a 'Master List' is used. The basis of this list (subject to change as the science develops), is the OSPAR beach litter list, together with categories of items used in other monitoring programmes (e.g. CEFAS). For ingested litter, the monitoring programme of Fulmars (ingestion) is used in the North Sea (see JCR reference report, 2013 for details).

3.4 Monitoring Programme Considerations for Microplastics in Marine and Freshwater Environments

3.4.1 Overview

In an attempt to help harmonize how scientists and others monitor and assess marine plastic litter, GESAMP published a report (March 2019) which aims to provide "recommendations, advice and practical guidance, for the establishment of programmes to monitor and assess the distribution and abundance of plastic litter, also referred to as plastic debris, in the Ocean. 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 and also, to inform the establishment of national and regional field Monitoring programmes" (GESAMP 2019).

Prior to the GESAMP report, a number of publications had provided key factors to consider when undertaking microplastics monitoring programmes (Rochman et al., 2017). Other publications had reviewed the actual methods used for identification and quantification, summarising their 'pros' and 'cons' (e.g. Hidalgo-Ruz et al., 2012; Lusher et al. 2017), including quality control measures (e.g. Prata et al., 2019). A new standardised method for benthic sediment microplastics is currently being developed by OSPAR,

Key considerations when undertaking a monitoring programme, as highlighted by Rochman et al. (2017):

- Consideration of temporal and spatial scales (microplastic distributions varies greatly across space and time)

- Methods chosen should capture the size-range of interest; ensure that the microplastics are extracted from the media without damage and enable identification of a mixture of plastics
- Data collected should be described in such a way as to prevent ambiguity, (e.g. ensuring that it is clear which unit has been used e.g. number of pieces or mass per km^2 and/or m^3)
- Ensure design methods address the questions around the issue (e.g. relating to harmful effects). For instance, plastics are associated with range of chemicals which can increase on entry to aquatic habitats. Plastics can also gain a biological load via a 'fouling community' that attaches to its surface. It is therefore important that methods related to the fate and occurrence of chemicals, and hitch-hiking communities, is used to understand the impacts of transported chemicals and/or biological communities (e.g. see Koelmann et al., 2016, review of microplastics as vectors of chemicals in aquatic environments and their potential effects on biota when ingested).

Rochman et al. (2017) state the importance of designing protocols around clear objectives and hypotheses. They further stress that, while standardisation of methods is unachievable, they believe a harmonisation of methods will enable data to be gathered in individual locations and worldwide, that will be useful across different scales (e.g. local, global) and disciplines.

3.4.2 Sampling Strategies

Hidalgo-Ruz et al. (2012) review the methods used for the identification and quantification of microplastics in the marine environment (Table 2). Protocols for sampling macroplastic are better developed than for microplastics (See JCR reference report, 2013, OSPAR 2010 for details). For all sampling it is important to take into account the considerations in Rochman (2017) and the select appropriate sampling (mass versus abundance) units in relation to the specific aims of the work.

Table 2. Strategies for Sampling Microplastics in the Marine Environment

Sampling Strategy	Technique
Selective	Direct extraction from the environment of items visible to naked eye
Volume-reduced	Reduced during sampling process (e.g. water and sediment samples)
	Requires further processing in laboratory
Bulk sampling	No reduction in volume during the sampling process
	Used when microplastics can't be easily identified
	Requires further processing in laboratory

Table 3. Sampling Techniques Microplastics in the Marine Environment Compartments

Sampling in specific compartments	Technique / Environment
Sediment microplastics	Instruments - tweezers, teaspoons, by hand
	Location – varied: some at high tide line only, others covered all the beach
	Depth – varied: most on horizonal surface, some studies also used vertical sampling
Pelagic microplastics	Sea surface instruments - neuston net/other neuston sampler
Note: across reviewed studies net size varied from 50 – 3000 µm (with the most common being in the 300-390 µm range)	Water column instruments - bongo/zooplankton net or other plankton sampler

In light of the wide range of monitoring methodologies employed across the 68 studies they reviewed, Hidalgo-Ruz et al. (2012) recommended some standardization of sampling procedures, in order to allow spatial and temporal comparisons of microplastic abundance across marine environments. They also pointed to a number of evidence gaps that require additional research.

Prata et al. (2019) also employed a step by step approach in their critical review of the methods used for sampling and detecting microplastics in water and sediment. During their review (49 studies), they identified flaws in some study designs and proposed potential alternatives. They suggested that sample representativeness and reproducibility would be improved "through the determination of bulk sample volume, filter's pore size, density separation and digestion solutions, but also through the use of novel methods, such as the enhancement of visual identification through staining dyes, and the generalized use of chemical characterization".

Both visual (e.g. microscopy) and analytical (e.g. spectroscopy) methods are used to identify and characterise microplastics and type of method used can influence the quality of the data collected. Method selected will depend on what is being monitored (i.e. mass or volume).

Using microscopy alone to identify microplastics presents a high risk of misidentification and therefore it is common to use a combination of physical and chemical analyses (Shim et al., 2017). Certain polymers are especially prone to misidentification and, as there is currently no reliable indicator for microfibre pollution from textiles, Henry et al., 2019, suggest focusing initially on the shedding of fibres during consumer washing of textiles. They propose that a "simple metric, based on the mass or number of microfibres released combined with data on their persistence in the environment, could provide a useful interim mid-point indicator in sustainability assessment tools to support monitoring and mitigation strategies for microplastic pollution”.

Table 4. Separation, Characterisation and Quantification methods for Microplastics in the Marine Environment

Sample Management		**Method**
Sample Processing	Density separation	Method required shaking to separate out material of different densities (e.g. after shaking sand will settle to the bottom of a vessel more rapidly than lower density particles that may remain in suspension or float to the surface)
		NaCl (and other solutions) often facilitate this process
	Filtration	Passing the solution over a filter (often aided by a vacuum pump) to remove microplastics from sample
		Various pore sizes used in studies (range 1 – 2 μm)
	Sieving	Microplastics separated from sample using one sieve or sieves cascades (up to six sieves of varying mesh size)
		Sieve sizes used across studies (range 0.038 mm to 4.75 mm). All studies included 1 mm sieve.
	Visual sorting	Done by eye or dissecting microscope – removed plastic from other material such as dried algae, glass etc.
		Microplastics > 1 mm can usually be visually determined from a range of criteria (e.g. colour, fibre construction)
Microplastics Characteristics	Size fraction – depends on sampling and process methods	Wide range from 1µm to 29 mm
	Morphology and physical characterisation	Descriptions, e.g. origin, shape, type, colour, degradation stage
	Chemical composition	Several methods used but most reliable method is by infrared spectroscopy (e.g. Fourier transform infrared spectroscopy, near-infrared spectroscopy, and Ramen spectroscopy)
		Alternatives available but higher cost
Quantification and reporting	By number or weight/mass	sediment samples = microplastic items per m^2;
		sea surface = gram or items per m^2
		water column = items per m^3

The most common microscopy methods used for chemical characterisation (i.e. Fourier transform infrared (FTIR) and Raman spectroscopy), employ a particle by particle approach for chemical characterisation. Although this can identify individual polymers, the quantity of data generated can be challenging (Renner et al., 2018). Renner et al. (2018) suggest that thermal extraction and desorption gas chromatography, which allows multicomponent characterization without the need for complex sample preparation, as an alternative. Prata et al. (2019) agree that this method does allow for the processing of high mass and heterogeneously complex samples, but point out that it is destructive, and the data obtained only relate to chemical composition.

With microplastics being prevalent in all environments, including laboratories, Prata et al. (2019) advise that it is paramount for methods to employ strict protocols to avoid as far as possible, and also to account for, the risk of cross contamination.

Table 5. Considerations for Laboratory Quality Control for Analysis of Microplastics in Environmental Samples

<table>
<tr><th>Quality Control Methods</th><th colspan="2">Technique / Environment</th></tr>
<tr><td rowspan="5">Management of cross contamination (from Prata et al., (2019)</td><td colspan="2">Use glass and metal equipment rather than plastic</td></tr>
<tr><td colspan="2">Avoid using synthetic textiles during sampling and sample handling (100% cotton lab coats preferred)</td></tr>
<tr><td colspan="2">Clean surfaces with 70% ethanol and paper towels; wash equipment with acid followed by ultrapure water; use consumables straight from packaging; filter all working solutions</td></tr>
<tr><td colspan="2">Use open petri dishes, procedural blanks and replicates to control for airborne contamination</td></tr>
<tr><td colspan="2">Keep samples covered as much as possible, limit access and control air circulation</td></tr>
<tr><td rowspan="4">Key QC methods for microplastic quantification identification:</td><td rowspan="3">Spiked sample recovery of microplastics, in various environmental compartments</td><td>Wastewater and sludge samples - Lares et al., 2019</td></tr>
<tr><td>Aqueous sediment - Crichton et al., 2017</td></tr>
<tr><td>Fish and/or invertebrates following ingestion - Catarino et al., 2017; Lusher et al., 2017)</td></tr>
<tr><td>plastic identification methods</td><td>Nile Red Staining - Shim et al., 2016)</td></tr>
</table>

3.5 Conclusions

The first paper using the term microplastics was published in 2004 (Thompson et al., 2004). Over the last 12 months there were approximately 400 publications using the term microplastics. Although this focus on marine macro- and micro-plastics has increased markedly, together with a high demand for field data that informs policy, there is still work needed to support effective and relevant monitoring programmes. This encompasses the drivers for, and purpose of, the 'plastic' monitoring that engages relevant stakeholders from both funding and impact viewpoints.

Whilst it is 'known' that methods exist to monitor marine macro- and microplastic debris in the range of environmental compartments, the driver for that monitoring (or indeed its aim or purpose) isn't always clearly explained. The workshop identified the concern that monitoring was taking place in specific marine environmental compartments because it was 'practical to do so', or 'built on established monitoring practice or programmes'. Whilst this might be an important factor, it is also critical to consider other compartments will also require scrutiny.

Methodologies for sampling microplastics in different environmental compartments are evolving, and in some instances being subjected to inter-laboratory validation and calibration exercises. This process is important to support the comparability of datasets, and underpin assessments of risk temporally, spatially and geographically. Reproducibility of environmental sampling is also a critical consideration, particularly where citizen scientists are engaged to gather data. Following sampling, analytical processes are also now receiving widespread attention. This is critical to support the generation of 'reliable' environmental data. The development of laboratory quality control processes is welcomed and needs to be promoted widely.

The broad policy drivers for monitoring originate from commitments under MSFD/OSPAR/UNEP. However, the specific requirements and purpose of the monitoring are in many cases largely unknown and undefined. This creates considerable uncertainty in terms of identifying, optimising and developing the most appropriate monitoring methods and programmes in which they will be deployed. The risk is therefore that monitoring for microplastics will be uncoordinated, lack the spatial and temporal resolution needed, and that funded programmes will be likely driven by 'serendipity' rather than 'priority'.

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4. Review of Sources and Pathways of Marine Plastic Pollution

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4.2 Background to the Problem

Study of the sources, pathways, transformations, and impacts of plastics in the marine environment has captured the attention of scientists spanning diverse fields, including polymer science and design, environmental engineering and management, ecology, toxicology, marine biology, and oceanography (Lebreton et al., 2017). Policy makers and other stakeholders are keen to establish how big the problem is quantitatively, as well as qualitatively in terms of impacts, to both the environment and human health, in order to identify the best prevention and/or mitigation strategies. Understanding the sources of plastic marine litter, and their relative importance, is a prerequisite to identify and prioritise potential mitigation strategies. At present, evidence on the relative importance of sources, pathways and reservoirs of plastics is poorly understood, as evidence remains sparse.

4.3 Science Overview

4.3.1 Introduction

Plastics are a sub-category of a larger class of materials called polymers (Kershaw and Rochman, 2015). They are composed of long multiple chains made of small molecules, called monomers, connected by chemical bonds. There is a wide range of plastic types, according to what monomer is repeated in the chain, and the way the chains are linked. Based on the latter, a distinction can be made between thermosets and thermoplastics. Thermoset plastics are permanently cross linked together, and difficult to re-melt and re-form. Thermoplastics, can be re-melted and re-formed and are the most commonly used plastics in the economy (PlasticsEurope, 2017).

Thermoplastics make up the majority (by weight) of all plastic produced. Some of the most common types of thermoplastics are polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polyvinylchloride (PVC), polystyrene (PS), and polycarbonate (PC). A wide variety of additives such as fillers, plasticizers, flame retardants, UV and thermal stabilizers, and antimicrobial and colouring agents are added to plastics during production to enhance their performance and appearance. As a result, plastics can have a range of properties (e.g., durability, strength, thermal and electrical insulation, and barrier capabilities) and can take many forms (e.g., rigid or flexible solids, including films). Both thermoplastics and thermosets are counted within the plastic marine litter (Kershaw and Rochman, 2015). The lack of consensus on how to define and categorise plastic debris is widely acknowledged (Figure 1). Please note that Figure 1 is an illustrative rather than an exhaustive list of all existing plastic classifications. Hartmann et al (2019) have recently proposed a framework for nomenclature, restricting the definition of plastics to insoluble synthetic and semi-synthetic solid polymers, whilst categorizing particles according to their composition, size, shape, color, and origin, as illustrated in Figure 2 (Hartmann et al., 2019). This proposal is however poorly aligned with the classifications used in existing systems for UK monitoring – (microplastics: < 5mm and mesoplastics: 5mm-2.5cm) which will be an issue when assessing temporal trends – a key requirement for MSFD / OSPAR. To date, plastic litter in the environment can be mostly classified into three groups, according to particle size.

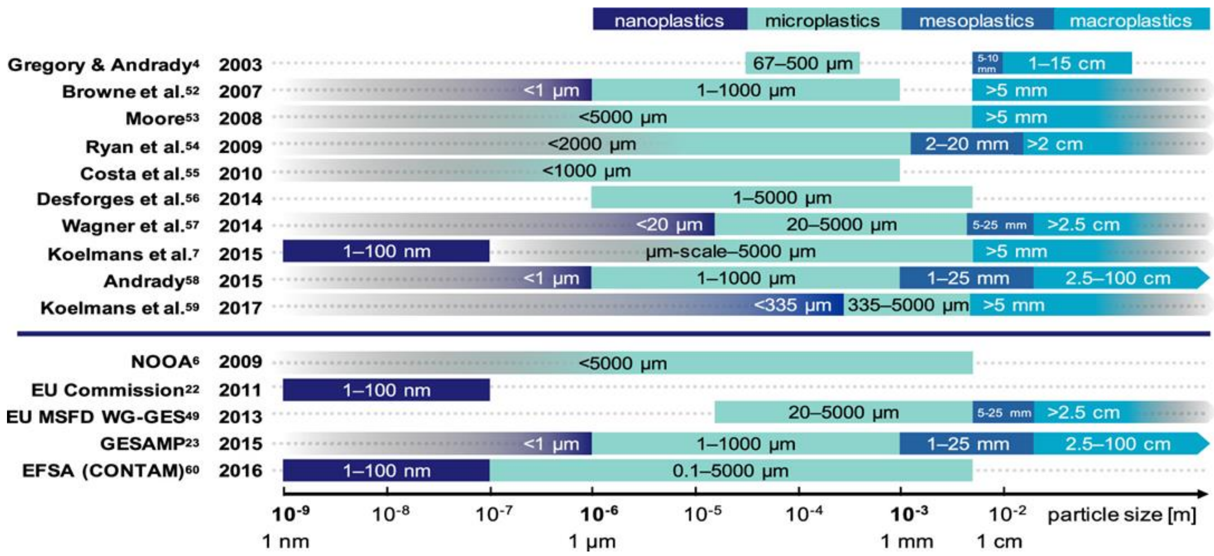

Figure 2: Examples of differences in the categorization of plastic debris according to size, reprinted with permission from Hartmann et al (2019)

Plastic materials >5 mm in size, have been classified as *macroplastics*; fragments of <5 mm in size, *microplastics* and <100 nm in size, *nanoplastics* (Axelsson and van Sebille, 2017, Schmidt et al., 2017) (See Figure 3). Generally, macroplastics represent the largest proportion of plastics in the Ocean by mass (t·km^{-3}), whereas micro- and nanoplastics represent the largest proportion by number (items·km^{-3}).

Microplastics can be further distinguished into *primary* and *secondary,* based on their origin. Primary microplastics are manufactured to be between 100 nm and 5 mm in size. They are directly released into the marine environment via their use in particular applications, e.g. microbeads in cosmetics and personal care products, industrial abrasives, or as raw materials during the production of larger plastic components and products (GESAMP, 2015, Lassen et al. 2015). By contrast, *secondary microplastics* are generated by the fragmentation and degradation of *macroplastics* in the environment. This is due to UV exposure, oxidation, and any other destructive conditions, as well as via physical abrasion of large plastic components such as tyres and synthetic textiles (GESAMP, 2015). The latter has created discrepancies in the classification of microplastics. Some authors suggest that this form of release (i.e. microplastics generated via physical abrasion of tyres and textiles) should be accounted as primary microplastics, as it is a result of materials fragmented by humans, before entering the environment (Boucher and Friot, 2017, Cesa et al., 2017). This has knock-on effects on the data reported concerning the release of secondary and primary microplastics to the environment. Nonetheless, there is consensus that microplastics are now ubiquitous in rivers and lakes and the World Ocean (Lebreton and Andrady, 2019, Wang et al., 2018, Lebreton et al., 2017).

Secondary microplastics are generally assumed to compose the majority of microplastics released in the environment (Efimova et al., 2018). For example, in Denmark it is estimated that around 5-12 kt of secondary microplastics are released to the environment each year; ten times more than the release of primary microplastics (0.5-1.7 kt/year) (Lassen et al., 2014). These figures are in line with those reported by the European Parliament, where primary microplastics (as defined herein) represent 10-15% of microplastics in the Ocean, and secondary microplastics account for over 81%. Generally, estimating the amount of primary and secondary microplastics entering the environment requires a good understanding of their life-cycle and factors that may affect their release, management (Estahbanati and Fahrenfeld, 2016) and fate in the environment (e.g. understanding of the fragmentation and degradation processes) (Efimova et al., 2018, Clark et al., 2016, GESAMP, 2015).

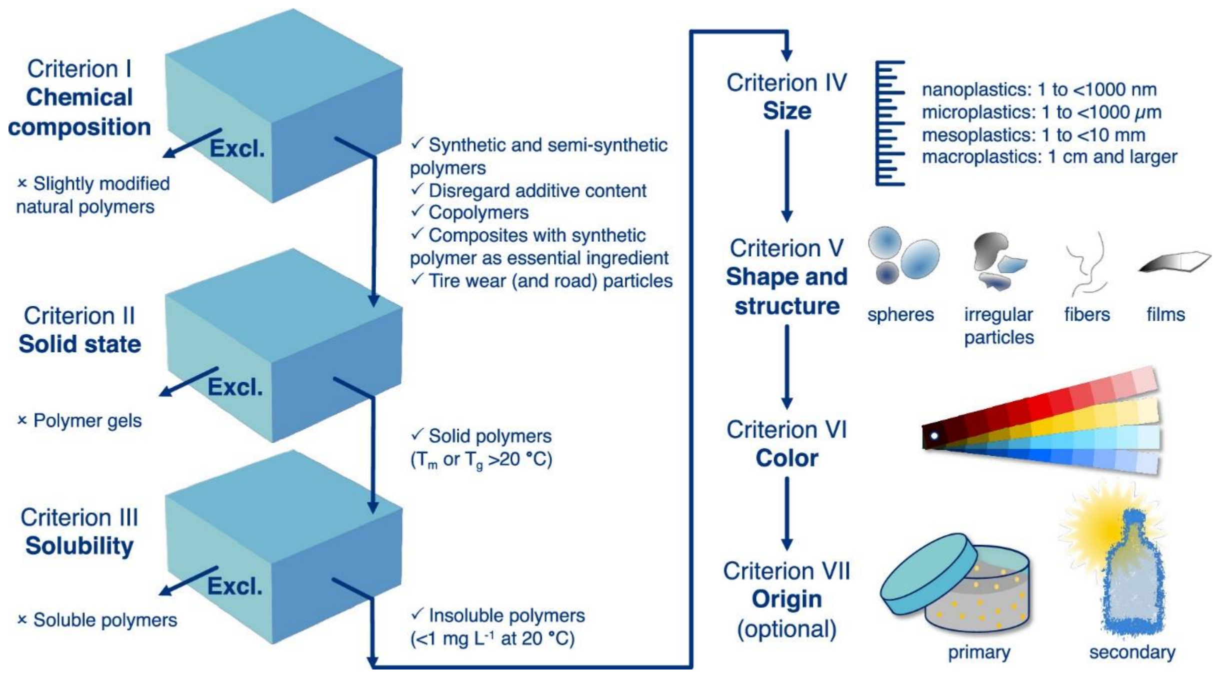

Figure 3: Proposed definition and categorization framework, reprinted with permission from Hartmann et al. (2019)

4.3.2 Sources and pathways of plastic marine litter

Plastic debris can enter in the marine environment via numerous land-based (e.g. rivers, wastewater discharge, landfills, and industrial activities, beaches), and sea-based sources (e.g. fishing and shipping). Land-based sources are considered the dominant source of plastic litter in the marine environment, accounting for 80% of plastic leaked into the Ocean by mass (i.e. 4.8–12.7 million metric tonnes of plastic annually) (Jambeck et al., 2015, Eunomia, 2016, Lebreton et al., 2017). Currently there is a lack of consensus on what constitutes a source and pathway of plastic marine debris to the environment. This accounts for different perceptions on how human behaviour, socio-economic aspects, and socio-technical regimes that are in place in different areas may impact the way plastic enters into the terrestrial and marine environment. Hence, sometimes a source can also be considered as a pathway. Herein, for consistency purposes we describe the sources and pathways as reported in the global scientific literature. These are presented in Figure 4, adopted from Grid-Arendal (GRID Arendal, 2016).

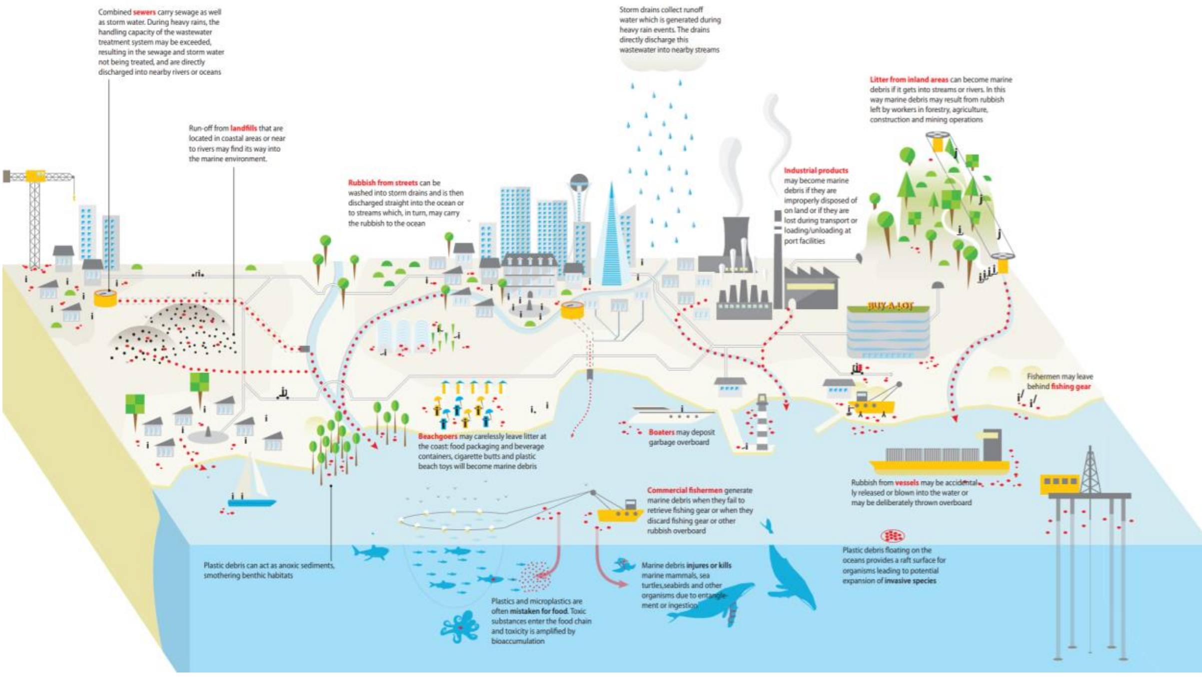

Figure 4: Sources and pathways of plastic marine litter in the Ocean (Source: GRID-Arendal)

As illustrated in Figure 4, the release of plastics into the marine environment occurs through a variety of pathways. These include wastewater discharge, urban storm-water drains and combined sewer overflows, surface and sub-surface runoff, atmospheric transport, wind blow, and rivers (Lebreton et al., 2017, Gasperi et al., 2014, Velis et al., 2017). Rivers (incl. streams) can be a major transport pathway, as well as a major source for marine plastic litter (Schmidt et al., 2017). They connect most of the global land surface to the marine environment, and therefore, facilitate the transport of all size of plastic litter over long distances into the sea (Schmidt et al., 2017). Plastics may enter the rivers either directly via littering and illegal dumping of waste - hence acting as source - or indirectly via wastewater treatment effluent, surface and sub-surface runoff or by wind blow. Atmospheric transport of plastic particles has most recently been documented providing an additional pathway for plastic particles and fibers of less than 1mm in size (Dris et al., 2016).

A conceptual framework of the sources and pathways of plastics in the environment is presented in Figure 5. The first point of loss along the plastic value chain is at the manufacture of plastic pellets, also known as nurdles. Nurdles are millimeter-sized quasi-spherical beads used in the production of plastic components and products (e.g., bottles, bags, pots, car components). Industrial activities may result in the accidental or deliberate release of nurdles directly into the waterways or washed into wastewater or storm-water drains. However, they can also be released via spillage from containers lost at sea (Entwistle, 2018) during plastic pellets trading (Dauvergne, 2018).

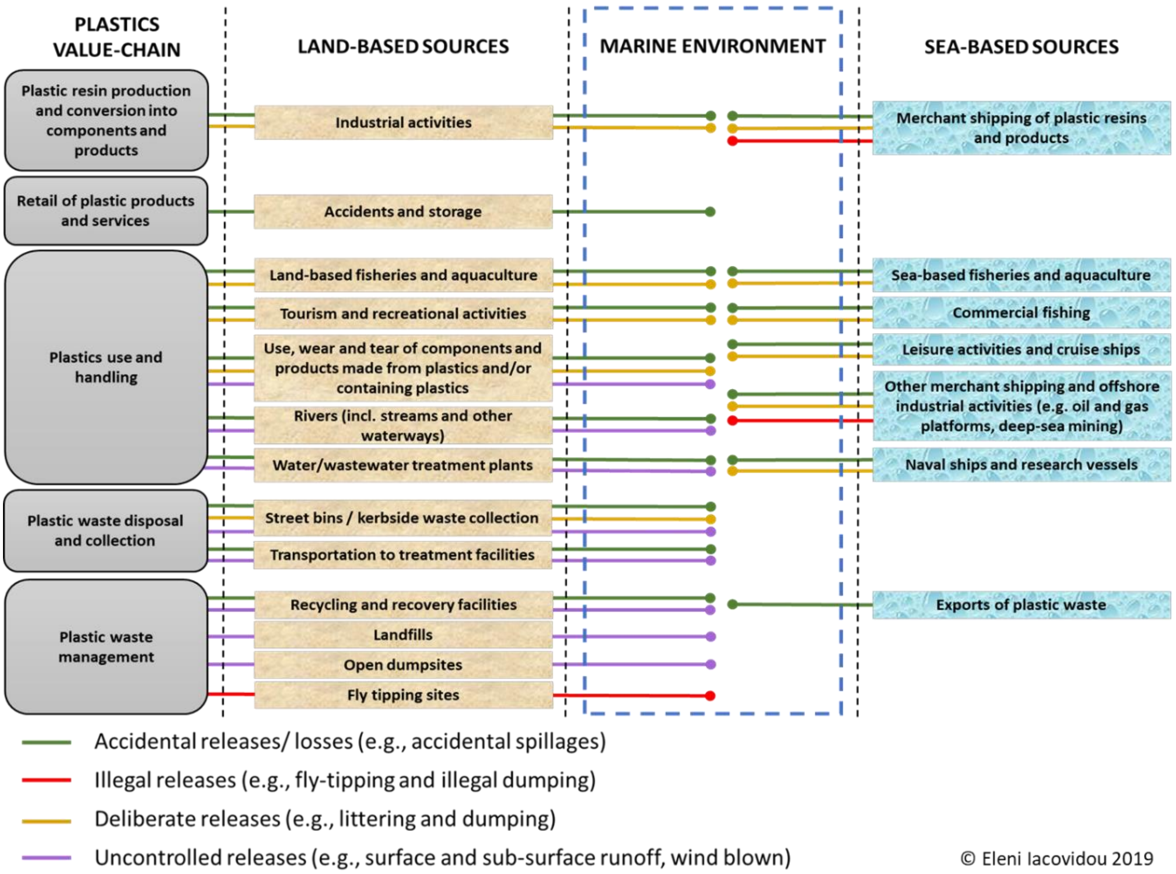

Figure 5: A conceptual framework outlining the land- and sea-based sources of plastic litter and type of release to the marine environment

Plastic pellets were among the first types of plastic debris reported in the Ocean, and since then they have been detected at sea and on beaches worldwide (Kershaw and Rochman, 2015, Law, 2017). To mitigate this problem, pellet loss prevention measures were implemented by the plastics industries. Although there is some evidence that the implementation of these measures was followed by a decline in the presence of pellets floating in the North Atlantic, the coincidental shift in the geographic location of resin producers or processors has made it difficult to generate any firm conclusions (Law, 2017).

As plastic components and products are distributed into the economy via retailers and other services, they may enter the environment unintentionally (accidentally), deliberately and/or illegally during their use and handling phase, or during their disposal and collection as waste via both land- and sea-based sources (Figure 6). At the use and handling phase, macro- and microplastics may also enter the environment uncontrollably due to urban discharges, surface and sub-surface runoff and wind-blowing (Gasperi et al., 2014, Law, 2017). Extreme weather, such as flooding, tsunamis or hurricanes, and other catastrophic events can result in the unintentional loss of in-service plastic products, carrying large amounts of plastic debris into the marine environment (Law, 2017) (Cole et al., 2011). The loss of fishing gear or cargo during maritime use is also one of the most common marine plastic sources (Andrady, 2011; Law, 2017).

Land- and sea-based aquaculture, tourism and recreational activities – coastal, inland and at sea, commercial fishing, off-shore industrial activities and marine vessels are all sources of plastic that can directly or indirectly enter the marine environment. Tourism and recreational activities, as well as major public events or busy areas of urban centres, account for an array of plastics being discarded to the environment.

The wear and tear of plastics used in a multitude of applications can also lead to microplastics being blown off-shore or washed out into the sewer for treatment at wastewater treatment plants (WWTPs). These include plastic mulching and controlled-release fertilizers in agriculture (Gionfra, 2018), tyres used in the automotive industry (Law, 2017, Boucher and Friot, 2017) tyres attached with ropes used as boat fenders, cut containers used as water bailers, bait containers or paint pots, plastic water pipes used in fisheries for lobster pot construction (Veiga et al., 2016), plastic paint and roofing material as well as repurposed plastic bottles to building components used in construction, and the use of textiles, toys, cosmetics and food packaging (Eriksen et al., 2018).

The type of the treatment processes employed in the WWTPs will determine the degree to which microplastics will be captured at this source (i.e., before the effluent is discharged to the environment) (Eriksen et al., 2014). Fibers from the washing of textile materials are an important contributor to microplastics pollution, as machine filters and WWTPs are not specifically designed to retain them (Cesa et al., 2017). These fibers are known to contaminate sewage sludge (Dris et al., 2016) that is widely used as fertilizer and soil improvement. Studies of WWTPs in Sweden, Russia, and the United States found extremely high capture rates (>95%) of plastic particles (Law, 2017). However, given the immense volume of influent processed through such facilities every day, even low loss rates could result in detectable concentrations of these plastic particles in the environment (Eriksen et al., 2014). This renders WWTPs an intermediary source of plastic particles to the marine environment.

Varying amounts of plastic waste may be released at the disposal stage. For example, wet wipes that are disposed via inappropriate means (e.g. toilet) may enter the marine environment via waste water from domestic sources. These wipes often contain plastic that persists indefinitely, leading to blockages within sewerage systems and overflows that may lead to various forms of plastic items being leaked into the environment (Nelms et al., 2017). One of the biggest indicators of the inappropriate disposal of plastic to the environment is the litter found on beaches globally (de Carvalho and Neto, 2016, Fauziah et al., 2015, Nel and Froneman, 2015). A study in the UK carried out by the Marine Conservation Society (MCS) along the British coastline collected beach litter survey data over a period of 10 years (2005–2014 inclusive). The study estimated that from the 2,376,541 items collected, plastic was the most dominant (66%) (Nelms et al., 2017). In another study in Malaysia, plastic film, foamed plastic (e.g. polystyrene), and plastic fragments were detected on an average of 399 items m^{-2} and 446 items m^{-2} respectively, in recreational and fishing beaches across the Malaysian coastline (Fauziah et al., 2015).

In developing countries the uncontrolled dumping of waste from municipal sources directly into the environment, including rivers and/or at/by the sea, is a significant problem (Velis et al., 2017). Even if a collection service is in place, releases can occur during the transportation of waste to the disposal or treatment facilities. Some deliberate release of plastic waste during disposal, occurs also in developed countries due to the limited capacity of, or linear distance between, street bins. The transport and handling of plastic waste may also result to some uncontrolled releases of plastic in developed countries, although the problem is particularly pronounced in less developed economies.

In developed countries, waste plastics are collected for management in a waste management infrastructure that is designed to minimize loss and hazards to the environment and human health. However, fly-tipping, i.e. the illegal dumping of large items or waste that may contains plastic waste, on public roads, land or into rivers, may also occur which can be a major source of pollution. Even with a developed system in place for the management of plastic waste, accidental and uncontrolled releases may also occur during the recycling (e.g. microplastics produced during reprocessing) and recovery processes (e.g. particulates from waste incineration). For example, in rural areas, where few roads are connected to sewers, may create a pathway for littered plastic items to enter the marine environment. In the study of Lassen et al. (2015) it was reported that 3.5% of losses in rural areas is assumed to end up in the Ocean at global level. In urban areas, this depends on the sewerage system; whether it has a separate sewer or a combined sewer overflow (CSO). In the first case, it is assumed that 80% of the plastic litter may enter the environment, whereas in the case of CSO, the chances are that a considerable amount of plastic is captured at the WWTPs (Boucher and Friot, 2017).

Trading of plastic waste (exported) may also result in accidental releases of plastics via spillages from containers lost at sea. Exports of plastic waste in developing countries where the waste management infrastructure is lacking, means that some plastic may end up in open dumpsites and uncontrolled landfills. From these sites, plastic can enter into the marine environment via water run-off, wind-blown lightweight plastics, as well as via open burning of waste (atmospheric fallout).

The conceptual framework presented in Figure 6, highlighting that a whole life-cycle consideration of plastic materials, components and products, from manufacturing of plastics resin to end-of-life management, is essential in identifying all points of sources and pathways leading to plastic marine pollution (Iacovidou et al., 2017). Some are less obvious than others (e.g. rubber dust from tyre wear, particles from energy recovery, blasting in shipyards, historical landfill sites and coastal erosion which can expose waste at the coastal tidal zone), and their causes are multi-faceted, requiring a diversity of mitigation measures (Hahladakis and Iacovidou, 2018). Sustainable solid waste management has an important role to play in controlling major sources of plastic waste and intercepting its pathways.

4.3.3 Methods and approaches to source apportionment

Identifying all sources and estimating the amount of plastic marine litter leaked into the environment is a challenging task. This is due to: a) the lack of accurate data; b) dynamic nature of plastics production-consumption-management system and available waste infrastructure (over time and space); c) global variations in societal attitudes and littering behavior; and d) transformation and transport mechanisms of plastics in the terrestrial and marine environment.

The best available estimates, so far, regarding global plastic waste inputs from land-based sources into the Ocean come from Jambeck et al. (2015). However, several assumptions were made in this study and may perhaps have led to an underestimation of the real amount of plastic present in the Ocean (Horton et al., 2017). One study reported that approx. 4900 Mt of the estimated 6300 Mt of plastics ever produced, have been disposed either in landfills or elsewhere in the environment (Geyer et al., 2017). Other studies suggests that the Ocean could contain more than 150 Mt of plastics (Ocean Conservancy, 2015); or more than 5 trillion micro- and macro- plastic particles (Eriksen et al., 2014).

Considering source apportionment on a global scale, estimates suggest that Asia is by far the leading source of marine plastic pollution to the marine environment. China, Thailand, Indonesia, the Philippines and Vietnam and ten rivers (Indus, Ganges, Amur, Hai he, Yellow, Mekong, Pearl, Yangtze, Nile, and Niger) are accounted as responsible for substantial quantities of global plastic waste input to the sea (Schmidt et al., 2017). However, it is also clear that the majority of litter around the UK has originated locally in the NE Atlantic. Therefore, it is clear that while substantial quantities of waste are entering the environment form developing nations, current waste management practices in developed nations are also inadequate.

With regards to microplastics, 80% of identified microparticles in freshwater systems are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PUR), and polyethylene terephthalate (PET). Nonetheless, ascertaining their sources and pathways can be complicated by the fact that these particles can travel far from their point of origin. Fahrenfeld et al. (2019) recently reviewed methods for source apportionment of microplastic particles in freshwater environments. This included linking particle characteristics to sources, source sampling and mass balance to establish inputs, and using particle surface contaminants to implicate potential sources (Fahrenfeld et al., 2019):

Linking particle characteristics to sources: This can be challenging due to differences in polymer chemical composition, particle colour, morphology, and size. The morphology of marine plastics can provide some evidence of source indication. For example, microbeads from personal care products and fibres from laundering of textiles are likely associated with wastewater inputs. Films and fragments are associated with weathering of plastic packaging or plastic bags and may be associated with terrestrial sources such as improper solid waste disposal.

Source sampling and mass balance to establish inputs: Direct sampling of waste streams has been used to characterize the sources of marine plastics pollution, e.g. looking at the impact of municipal wastewater effluent as a point source and pathway into surface water. Differentiating sources contributing to wastewater influent is complex and system specific. The pre-eminent information available to-date is related to the contribution of the laundry fraction from households. Few data are available on the loading of marine plastic from tyres, road markings and other plastic litter in (urban) storm water. Few researchers have attempted to quantify atmospheric deposition of fibres, and such studies are complicated by potential contamination of field samples from researchers clothing and/or air handling systems in laboratories. Mass balance approaches can be useful for indicating the magnitude of commonly targeted point sources (i.e., wastewater treatment plants) and for highlighting the need to study nonpoint sources. However, the robust estimation of loads requires appropriate sampling techniques and sufficient sample sizes to capture variability.

Particle surface contaminants to implicate potential sources: The contaminants present on the surface of particles may help in source tracking. Identification of pollutants as well as polymer degradation products involve multi-step processes, including extraction of the organic(s) from the particles followed by chromatography before chemical determination. One challenge of this approach is that surface contaminants are adsorbed from the surrounding environment after release in addition to the additives added during plastics manufacture. This will require knowledge and understanding of relationships between surface contaminants and sources as well as weathering processes. Environmental conditions, such as residence time, temperature, pH and exposure to sunlight, will influence equilibrium dynamics between chemicals and plastics, impacting their accumulation and transport. A further challenge is to confirm that surface contaminants are adsorbed to the particles themselves, rather than other particulate matter associated with plastic particles. Microbial biofilms on particle surfaces may also have utility for source tracking. There is some evidence that MP incubated in different water sources had unique biofilm microbial communities that can be transported long distances. This would however require a better understanding of how robust biofilms are to weathering.

4.4 Relevance to the UK situation

Marine plastic pollution is a global topic, with regional variations in quantities and types of litter, as well as variation in media attention that can sometimes be misleading. In the UK, nurdles are currently making the headlines. According to a recent report, an estimated 53 billion nurdles may be spilled from UK land-based sources each year (Entwistle, 2018). Nurdles have been found in a range of sites around the UK coasts, highlighting their presence in the UK waterways, seas and sediments. 'The Great Nurdle Hunt', Fidra's citizen-based survey project, has mapped nurdle finds from around the UK and Europe, identifying a number of nurdle hotspots in key industrial estuaries (Fidra, 2018). Regarding stakeholder action, Operation Clean Sweep, an international initiative led by the British Plastics Federation (BPF) has formed to help the plastics industry reduce and prevent plastic pellet, flake and powder loss (BPF, 2019).

Considering plastic components and products, attention has been placed on single-use plastic packaging. Single-use plastics (e.g., straws, cotton buds, bottles, stirrers, cutlery), have been found to contribute considerably to plastic litter in the UK, totalling 24 billion items (Eunomia, 2018). Food packaging and utensils, such as plastic forks, were found to be the most littered items on the UK motorways (HM Government, 2017). In the Litter Strategy for England (2017), it was reported that people are more likely to drop litter if the environment is already littered. In addition, another study showed that the presence of larger, brighter pieces of litter, such as drinks, takeaway containers and plastic bags may lead to more litter (Keep Britain Tidy, 2016).

The introduction of the 5p Carrier Bag Charge has been effective at reducing the consumption of single-use carrier bags, contributing also to a 40% decrease in bags found on beaches in the 2016 Great British Beach Clean. Different types of deposit and return schemes for plastic bottles are under consideration as a way of capturing plastics on the go, while the government is considering a ban on sales of single-use plastics, including plastic straws, from 2019 (Craggs, 2018). These measures are suggested to mitigate littering within the UK, but at an international level the UK's contribution to mitigating the littering problems needs to include better ownership of its plastic waste. At present, around two-thirds of the UK's plastic packaging waste is exported to countries including, Malaysia, Indonesia, Vietnam; some of the biggest contributors to marine litter pollution (Eunomia, 2018).

4.5 Conclusions

Understanding the sources of plastic litter in different contexts (e.g. developed and developing countries), pathways and transformations in the terrestrial and marine environment is essential to determining the risks and impacts of plastic litter. This is because plastics may undergo transformations both before and after entering the environment, meaning that macro-plastics can degrade into micro-plastics. Once this transformation has occurred, removal is much more challenging.

Therefore, interception of macro-plastics upstream before they enter the environment is the best place to take action. The input rates of plastic waste by river, wind, tidal and oceanic wave transport, as well as methodical measurements of waste generation, classification, collection rates, and waste disposal methods for rural areas and urban centers in countries around the world, are needed to obtain a robust quantitative estimate the relative importance of various sources.

Moreover, as conventional plastics are not readily biodegradable, they persist and interact with their environment, absorbing and adsorbing persistent organic pollutants (POPs). Microplastics may transfer these pollutants to new environments and transfer them into living organisms. However, current evidence suggests plastics are not a major vector for the transport of contaminants to biota (Bakir et al 2016).

The evidence presented in this chapter underlines the benefit of taking a systematic approach, particularly focusing on the waste management sector and how, and from what part(s), plastic can 'leak' plastic. Understanding this, the appropriate interventions can then be developed, targeted to the specific elements of the waste management system. The elements can be prioritised and risk assessed, for example, from those components of the waste management system most likely to reach the wider environment, or where the volume/tonnage are at their greatest from a standpoint of ‘loss’.

The review highlights that the presumed majority of plastic found in the environment arises from land-based sources. A broad range of sources, although not exhaustive, have been identified and examined in the literature, but their relative importance, in terms of quantities and risk to different environmental compartments, remains elusive.

Concerns discussed in the workshop focused on how closely the proportion of plastic types (polymers) found in the environment align to the plastic placed on the market, since that will influence the degree of environmental risk. Understanding what is found in the environment should be influencing the policies on controlling the sources of this environmental pollution risk.

There are clearly marine sources of plastics, linked to maritime activity such as fishing and shipping, but that the risks to the environment are different to marine litter and microplastics arising from land-based sources. Again, estimates of the quantities of such material within the context of the UK are difficult to find in literature, but such studies will be helpful to drive the right interventions and UK marine gear policy, and the management of ports and reception facilities.

The review also identifies that sources and pathways also considered that primary microplastics (entering the environment as microplastics) form a third and important source of plastic to the environment. Policy makers need to consider each source in turn, and their respective pathways, as part of the risk assessment to their policy areas of interest, and what mitigations are then available to manage that risk.

The relevance of datasets from across the globe was also challenged with respect to the UK context. Compared to what plastic is placed on the market in the UK (and the social and cultural norms that drive consumer behaviour), the different waste management practices, and the geography of the connectedness of rivers to the coasts. This is also an important consideration when the UK is advising other nations on their waste management.

The UK ‘dataset’ for sources and pathways of plastics to the marine environment remains at a low level of quality, and quantity. A fundamental set of data are needed to inform critical questions around the state of the environment, how presence in the environment aligns to sources and pathways, and how that then informs risks to the wider environment and sensitive areas.

In addition, the degree of change both spatially and temporally is elusive, for example how plastic pathways are influenced by weather (for example, coastal onshore storms, or prolonged spells of calm weather), water currents (for example within estuaries and coastal waters) and run off (for example, following flooding).

Whilst there are strong indications of macroplastics typically found in the environment, such as consumer ‘on the go’ packaging, the challenge for identifying environmental risk is that there is a range of polymer types and composites. There is a risk that this may be being oversimplified, whereas the situation is ‘complex’ and ‘nuanced’.

Across this topic, and the review generally, there has been a request for clarity for definitions of relevant nomenclature, and the requirement for this to be at least pragmatic, even if imperfect. The consensus in the workshop was to adopt the definitions of Hartman et al (2019). In addition, the terminology around releases of plastics to the environment also needed better clarity, so that the wider stakeholders were clear on what was being presented, for example escapement, exposure and effect.

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5. Review of Transport and Fate of Marine Plastic Pollution

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5.2 Background to the Problem

Plastic and microplastic debris is a ubiquitous marine contaminant with a global distribution (Cózar et al., 2014, Collignon et al., 2012, Derraik, 2002, Eriksen et al., 2014, Law et al., 2010a, Law et al., 2014, Lusher et al., 2014, Ryan et al., 2009, Ter Halle et al., 2017, Van Cauwenberghe et al., 2013, Courtene-Jones et al., 2017, Woodall et al., 2014, Ballent et al., 2013). Plastic is a spatially and temporally heterogeneous marine contaminant (Doyle et al., 2011, Erni-Cassola et al., 2019), identified across ecological compartments, including surface waters, the water column, the seafloor, shorelines, sea ice and biota (Hardesty et al., 2016, Auta et al., 2017). Here we summarise our current understanding of how the physio-chemical properties of plastic, abiotic and biotic drivers can all influence the vertical distribution, transport, accumulation and environmental fate of plastic debris:

5.3 Transport of Plastic and Microplastic Debris

5.3.1 Vertical distribution

On average, seawater has a density of ~1.02 g/cm^3, and as such plastic debris with a density <1.02 g/cm^3 (e.g. polyethylene, polypropylene) will typically float, while plastic with a density >1.02 g/cm^3 (e.g. acrylics, polyester) will tend to sink (Hardesty et al., 2016, Erni-Cassola et al., 2019). Given that approximately two thirds of all plastic produced is negatively buoyant in sea water, it is expected the seafloor represents the largest reservoir for plastic. While environmental concentrations are hugely variable, a meta-analysis reveals average microplastic concentrations in the order of 0.1-1 particles/m^3 for surface waters, and 10^3-10^4 particles/m^3 for sediments (Erni-Cassola et al., 2019). However, the presence of low-density plastics in sediments and higher-density plastics within the water column suggests other factors may play a role in their vertical distribution (Clark et al., 2016).

Plastic debris may be vertically redistributed through physical forcing. For example, wind, waves, eddies and temperature shifts can result in the subduction of floating plastics (Kukulka et al., 2012, Kukulka et al., 2016). However, vertical profiling of microplastics in the North Atlantic gyre showed surface mixing is limited, with an exponential decline in microplastic concentrations up to a depth of 5 m (Reisser et al., 2015, Kooi et al., 2016). In coastal waters, extreme weather events and increased riverine outflow can also drive the resuspension of plastic debris on the seabed (Lattin et al., 2004).

Biotic interactions may also influence the movement of microplastics from surface waters to the Ocean depths. For example, exposure studies have demonstrated that incorporation of microplastics into faeces, phytoplankton aggregates and marine snows facilitates their downward vertical transport (Cole et al., 2016, Porter et al., 2018, Long et al., 2015, Katija et al., 2017). Furthermore, the colonisation of plastic debris by microbial biofilms and epibionts can cause buoyant plastics to sink (Rummel et al., 2017, Chubarenko et al., 2016, Ryan, 2015, Kaiser et al., 2017). It is currently unclear whether loss of organic material at depth (owing to lack of sunlight or microbial breakdown) might result in the plastic re-suspending, oscillating, or undergoing sedimentation (Kooi et al., 2017).

5.3.2 Transport

Plastics that enter the marine environment may be subject to a number of different factors that control their movement and fate (Rocha-Santos and Duarte, 2015, Chubarenko et al., 2016, Kukulka et al., 2012). Under certain circumstances, it is clear plastic debris can be transported vast distances, as evidenced by their presence on remote islands (Imhof et al., 2017, do Sul et al., 2013) and in polar waters (Lusher et al., 2015). Transport is primarily driven by physical forces, but aeolian (airborne) pathways (Dris et al., 2016) and biota (Setälä et al., 2018) may also play a (currently unquantified) role in the movement of plastic debris. However, there is also good evidence that most plastic items are retained in the region of entry to the Ocean (Brennan et al., 2018).

In seawater, small neutral or positively buoyant plastics are transported and dispersed by oceanic currents and turbulent mixing that reflect the driving effects of tides, winds and surface heat exchange (Maximenko et al., 2012). Other factors controlling the transport of plastics – and in particular negatively buoyant particles or larger plastics – include sinking, settling and resuspension dynamics, bedload transport, beaching, stokes drift and sail effects (Lattin et al., 2004, Isobe et al., 2019, Hardesty et al., 2017, Iwasaki et al., 2017, Yoon et al., 2010). The relative influence of these processes on the movement of macro and microplastics is currently unclear, and flume tank and laboratory experiments have been recommended for providing further empirical data to help parameterise models (Hardesty et al., 2017).

5.3.3 Modelling

Numerical models have been used extensively as a cost-effective means of supplementing and scaling up environmental data to estimate the global budget of plastic debris, and gain a clearer understanding of the transport and accumulation of plastic debris across different geographic scales (van Sebille et al., 2015, Lebreton et al., 2012a, Hardesty et al., 2017). For example, oceanographic models have been applied to surface trawl data to estimate: >5.25 trillion plastic particles are floating on the World Ocean (Eriksen et al., 2014); 7,000-35,000 tons of plastic are floating on the

World Ocean (Cózar et al., 2014); and 15-51 trillion plastic particles (93,000-236,000 tons) have accumulated in the Global Ocean (van Sebille et al., 2015).

Lagrangian particle tracking (whereby the movement of individual particles suspended in seawater and subject to currents are tracked) informed by coastal population data, waste data (Jambeck et al., 2015) and sea surface currents (incorporating wind and wave-induced Stokes drift), has been used to explore the movement of microplastics in the seas around Northwest Europe. Using dispersal models with continuous release from coastal conurbations, Hardesty et al. (2016) predicted plastics debris will most frequently occur on the western coast of mainland Britain, Norway, Denmark and France (Figure 7A); and plastic debris stemming from Northwest Europe will largely flow towards the Arctic Ocean (Figure 7B). Using the Adrift tool, Sebille et al. (2016) modelled the movement of plastic stemming from the UK, showing debris will flow through the English Channel, North Sea and Irish Sea, before being transported towards the Arctic (Figure 8). Such mapping provides evidence that debris on UK shorelines will predominantly stem from the country's own waste leakage, but can contribute to plastic pollution much further afield.

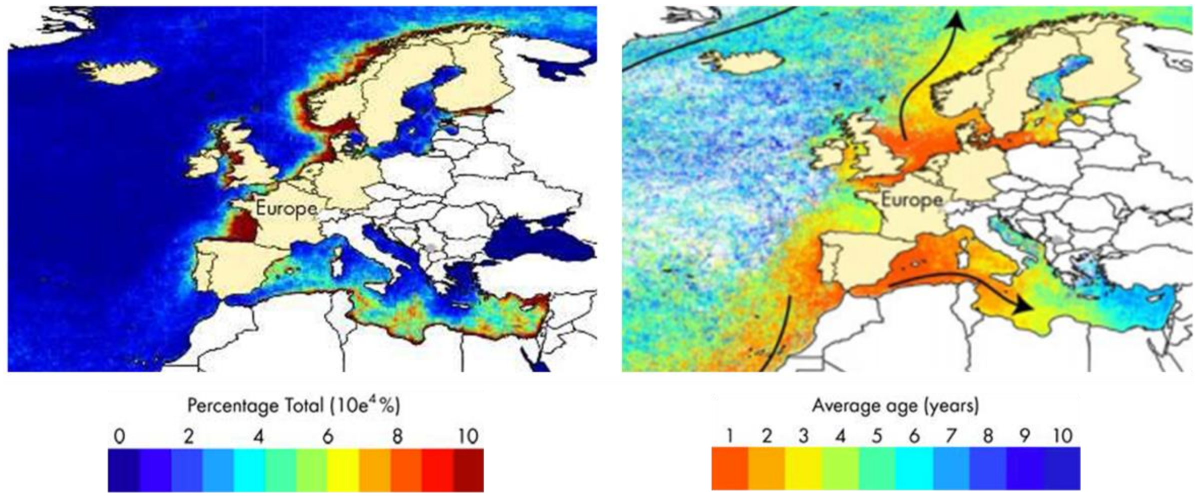

Figure 6: (A) Frequency of particle visits as a percentage of total particle number (1994-2014). (B) Average age (0-10 years) of particles originating from Western Europe in the Atlantic Ocean. Source: Hardesty et al. (2016).

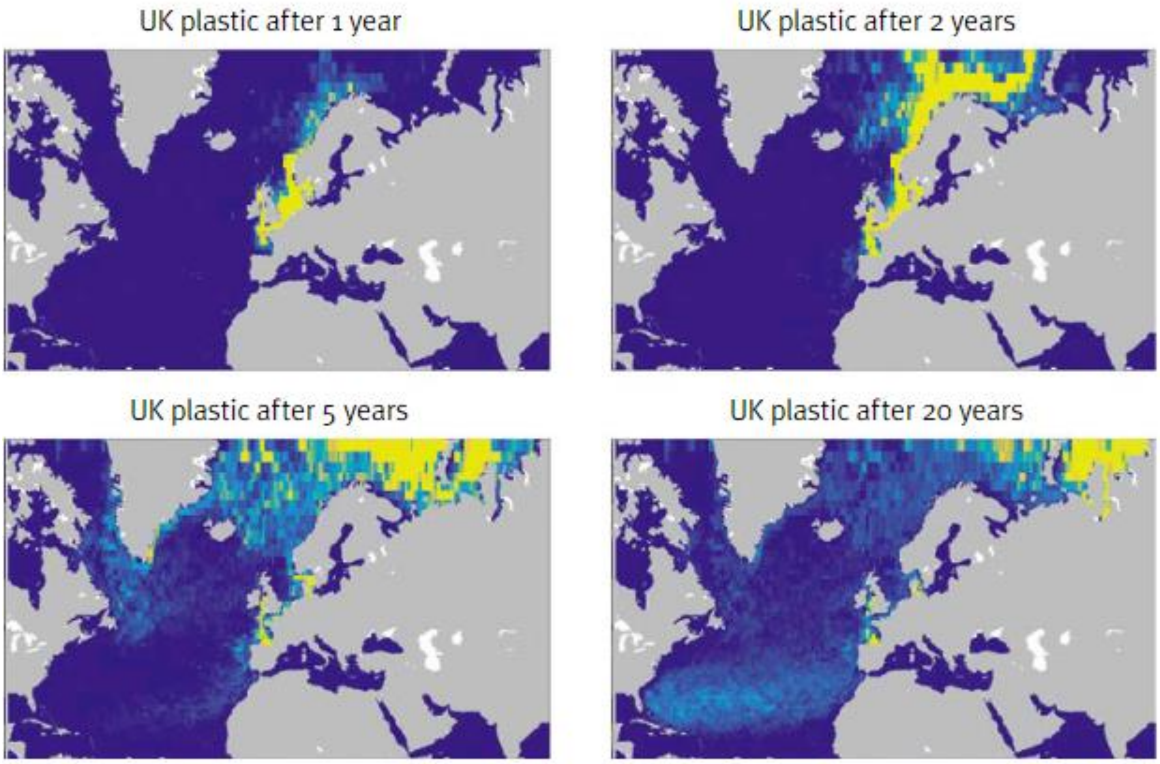

Figure 7: Modelled transport of floating plastic released from the UK, with seeding based on coastal population densities. Source: Sebille et al. (2016)

5.4 Accumulation and Environmental Fate

Our understanding of the fate of marine plastic debris remains limited (Thompson, 2016). Plastics have been shown to accumulate in ocean gyres, biota, sea-ice, shorelines and sediments, where plastics can be retained over different periods of time. Ultimately it is expected that plastics will undergo sedimentation or degrade, however their capacity to degrade and mineralise within the marine environment is largely speculative. This section assesses the fate of plastics and microplastics in the different compartments within marine environment, and the processes by which they move between them.

5.4.1 Ocean gyres

Positively buoyant plastics that sit on, or near to, the sea surface have been observed to accumulate in sub-tropical gyres of the open ocean; a finding corroborated by numerical modelling (Law et al., 2010b, Law et al., 2014, Maximenko et al., 2012, Lebreton et al., 2012b). At the turn of the century, concentrations of floating plastic in the North Pacific gyre were shown to exceed 334,000 particles/km^2 (>5 kg/km^2) (Moore et al., 2001). These hotspots of plastic debris are transitory, shifting with ocean currents and climactic conditions, but nevertheless display the capacity for microplastic accumulation (Lebreton et al., 2018).

Based on empirical data from transoceanic surveys and numerical modelling (based on the assumption that microplastics will remain buoyant for three years), it is predicted that the mass of microplastic debris in the North Pacific gyre will double by 2030, and increase four-fold by 2060 (Isobe et al., 2019). However, the amount of small buoyant plastic observed floating at the surface of the Ocean is in general orders of magnitude lower than estimates derived from a knowledge of plastic inputs (Eriksen 2013, Cozar 2014, van Sebille 2015), which points to a significant lack of understanding regarding how small buoyant plastics are moved and cycled throughout the World Ocean. These uncertainties are exacerbated by patchiness in sampling (Clark et al., 2016, Hardesty et al., 2016), inconsistencies in sampling approaches and reporting (Lusher et al., 2016, Hidalgo-Ruz et al., 2012) and the relative ease of sea-surface sampling biasing our understanding.

5.4.2 Biota

Interactions between plastics and marine life are widespread in the marine environment (Gall and Thompson, 2015). Exposure studies and analysis of environmental samples have demonstrated that plastic and microplastic debris can become entrapped in external appendages or retained within the stomachs or intestinal tracts of affected animals for extended periods (Wilcox et al., 2015, Cole, 2014, Watts et al., 2014, van Franeker and Law, 2015). Given the extent to which marine organisms consume plastic debris, it is considered that biota may represent a substantial reservoir for marine plastic (Hardesty et al., 2016).

5.4.3 Sea ice

Plastic debris has permeated into polar waters (Lusher et al., 2015, Obbard et al., 2014). Analysis of ice cores from the Arctic have revealed microplastics at concentrations exceeding those observed in seawater (Peeken et al., 2018, Bergmann et al., 2016). Sea ice is considered a temporary sink of microplastics, as thawing of the ice (owing to warming temperatures, seasonal change or ice drifting to lower latitudes) would result in the release of these plastics (Obbard et al., 2014).

5.4.4 Shorelines

Beaches and coastal sediments are considered a substantial sink for microplastic and plastic debris, with onshore currents, storms and high tides resulting in the beaching of flotsam (Browne et al., 2011). Field surveys and particle tracking has been used to explore the capacity for plastic debris to move offshore, with evidence that macroplastics were more prone to beaching, owing to near-shore trapping and onshore conveyance, while microplastics showed greater capacity to be transported further offshore (Isobe et al., 2014). Surveys coupled with statistical modelling have indicated the deposition and retention of plastic debris along shorelines is influenced by substrate, season, coastal shape, wind exposure and the complexity of the backshore, with evidence that backshore vegetation may represent a substantial reservoir for plastic debris (Brennan et al., 2018).

5.4.5 Sedimentation

The seafloor has been mooted as the ultimate repository for marine microplastic debris. Plastic and microplastic debris has been identified in coastal and deep-sea sediments (Erni-Cassola et al., 2019, Kaiser et al., 2017), with topographical features that impact hydrodynamic flow (e.g. harbours, canyons, seamounts) closely associated with regions of plastic deposition and accumulation (Woodall et al., 2014, Tubau et al., 2015, Claessens et al., 2011). Once on the seabed, microplastics can be ingested by benthic invertebrates (Courtene-Jones et al., 2017), and be conveyed downwards through bioturbation (Näkki et al., 2017), where they may eventually form part of the Anthropocene fossil record (Waters et al., 2016).

5.4.6 Degradation

Plastic are immensely durable materials resistant to degradation, with mineralisation rates typically discussed in hundreds or thousands of years, making this a long-lived, multigenerational issue (Hardesty et al., 2016, Barnes et al., 2009). Degradation can be induced through mechano-chemical damage and photo-oxidative, thermal, and biological pathways (Singh and Sharma, 2008, Andrady, 2015), resulting in the formation of vast numbers of microplastics and possibly also nanoplastics (Lambert and Wagner, 2016). On beaches, mechanical abrasion and prolonged UV exposure can result in the embrittlement of plastics, causing them to fracture and fragment over time (Song et al., 2017). However, in seawater, the relatively cold, dark and saline conditions are not conducive to degradation (O'Brine and Thompson, 2010). Grinding or maceration of plastic ingested by seabirds, shore crabs and krill, can facilitate fragmentation of plastic (Dawson et al., 2018, van Franeker et al., 2011, Watts et al., 2014). Furthermore, it has been shown that microplastics with biofilms can develop “surface pitting”, providing an indication that microogranisms could cause surface degradation of waterborne plastics (Zettler et al., 2013, Weinstein et al., 2016). However, the relative importance of biotic processes in the degradation of marine plastics is currently unclear.

5.5 Conclusions

Plastic has been identified across ecological compartments, including surface waters, the water column, the seafloor, shorelines, sea ice and biota.

Environmental concentrations are hugely variable, a meta-analysis reveals average microplastic concentrations in the order of 0.1-1 particles/m^3 for surface waters, and 10^3-10^4 particles/m^3 for sediments

Vertical profiling of microplastics in the North Atlantic gyre showed surface mixing is limited.

Plastic debris can be transported vast distances (primarily driven by physical forces), as evidenced by their presence on remote islands

Numerical models have been used extensively as a cost-effective means of supplementing and scaling up environmental data to estimate the global budget of plastic

Environmental sampling efforts have increased dramatically in recent years, but for many areas of the world there remains little or no data describing how much plastic is present, and a lot of our understanding stems from modelling. It is important to emphasise models are predictive; reporting uncertainties relating to model outputs, and validation of these models, is essential.

The relative importance of physical and biological processes in controlling the spatial distribution and fate of plastic remain unclear. Fundamental uncertainties remain regarding the flux of marine plastic debris between ecological compartments. For vertical flux, sediment traps and measures of biological transport *in situ* may help close this knowledge gap.

For many countries, the debris washing up along coastlines will predominantly stem from their own relatively local waste leakage. However, oceanic currents can result in the redistribution of plastic over vast distances. For example, some of the debris originating from the UK may be transported into the Arctic region within two years.

Mapping the overlap between the distribution of marine organisms and plastic hotspots could identify areas "at risk". Recognition that coastal waters are likely to be the biomes where plastic debris will have the greatest ecological and economic impact – those areas where exposure to macro- and micro-plastic will be of the greatest concern.

For the UK context, ocean modelling remains an important approach to assess the fate of:

- the extent to which plastics from UK are retained locally, and/or distributed to, North Sea and Arctic coastlines;
- Plastics emitted in other nations arriving in the UK (North Atlantic, North Sea and English Channel).
- Plastics emitted in other nations arriving in UK – Dependent Territories

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6. Review of Impacts of Marine Plastic Pollution on Biota and Ecology

6.1 Authors

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6.2 Background to the Problem

As global rates of plastic production have risen, so too has the amount of plastic in seas and the Ocean, potentially putting marine life and ecosystems at risk of harm. Ecological harm encompasses lethal and deleterious sub-lethal effects on biota via entanglement, physical damage, smothering, ingestion and facilitating dispersal of sessile organisms, including microbes and non-native species (Werner et al., 2016). Nearly 800 species, including threatened species, are known to be impacted by marine plastic debris, and this number is likely a vast underestimate (Dias, 2016).

For the purposes of this review, both ‘macro’ and ‘micro’-plastics that biota are ‘exposed to’ are defined and indicated as:
Macroplastics - larger plastic litter, including single-use items (e.g. plastic bags and bottles), fragments of domestic, commercial, maritime and industrial waste, and discarded fishing gear including so-called “ghost nets”;

Microplastics - plastic fibres and particulates, broadly categorised as either 1 µm-1 mm or <5 mm in size (Hartmann et al., 2019). Microplastic debris derives from the breakdown and fragmentation of larger plastic debris, or the release of primary microplastics manufactured to a microscopic size (e.g. exfoliates in cosmetics, glitter, media-blasting) (Cole et al., 2011).

6.3 Impacts on Biota

6.3.1 Impacts on Biota from Macroplastics

Macroplastic debris poses a physical threat to marine life through entanglement and ingestion (Laist, 1987, Gall and Thompson, 2015). Marine mammals, turtles and seabirds routinely consume plastic debris; in seabirds, a meta-analysis of studies from 1962-2012 showed an average of 29% seabirds sampled had plastics in their stomachs (Wilcox et al., 2015), with some studies showing that 100% of fulmar, puffins, storm petrels, albatross and guillemot populations contained plastic (LI et al., 2016). Consumption of plastic predominantly stems from these animals mistaking plastic for natural items of prey, or in the case of juvenile seabirds (e.g. albatross, petrels) receiving plastics in regurgitated feed from their parents (Pettit et al., 1981). Juveniles are unable to regurgitate such plastic, making this life stage particularly vulnerable to plastic debris. Indeed, failure to regurgitate or egest plastic may result in debris accumulating in the stomach, which can physically limit feeding capacity, give false feeling of satiation, cause physical damage (e.g. perforation, ulcerations) and stymie normal digestive function (e.g. impair production of gastric juices) (Laist, 1987, Azzarello and Van Vleet, 1987, Ryan, 1988). These impacts can result in a loss of fitness; for example, in post-hatching loggerhead sea turtles, dilution of the diet with anthropogenic debris caused significant energetic losses (McCauley and Bjorndal, 1999), and in a study of 1574 seabirds collected from the tropical Pacific, consumption of plastic was shown to negatively correlate with body mass (Spear et al., 1995). For some individuals, consumption of plastic can lead to starvation and ultimately death. In turtles, a 50% probability of mortality was associated with consumption of >14 items of plastic (Wilcox et al., 2018). Accumulation of plastic debris in the stomachs of sperm whales has likewise been attributed to beaching events and loss of life (Jacobsen et al., 2010, Unger et al., 2016, de Stephanis et al., 2013).

There are widespread reports of crustaceans, fish, turtles, seabirds and marine mammals, including endangered or critically endangered species, becoming entangled or entrapped by plastic debris (Gall and Thompson, 2015). Fishing nets, lines, rope, pots and traps, and plastic strapping used in packaging, are the most commonly cited items associated with entanglement and capture of marine life (Gall and Thompson, 2015, Macfadyen et al., 2009). Estimating losses of fishing gear has proven hugely challenging, however in the deepwater fisheries of the Northeast Atlantic, early data suggested losses were in the order of 25,000 nets per annum (Brown et al., 2005). Over its lifetime, a single derelict gillnet in the Puget Sound (USA) is predicted to result in the entanglement and loss of >4,300 crabs (Gilardi et al., 2010), and Gilman et al. (2016) calculated an average mortality rate of 92.8±47.2 fish per 100 m^2 of lost net, subject to habitat, weather conditions, longevity of net, type of net, and whether the net is moored or free-floating. Animals may become ensnared by plastic debris by chance, or be attracted through curiosity (e.g. juvenile marine mammals), in seeking shelter (e.g. fish, turtles) or in seeking prey already entrapped by the plastic (Laist, 1987, Duncan et al., 2017). As these animals become entangled, they too will attract predators, and thus the cycle continues (Derraik, 2002). Although tracking incidence of entanglement is challenging, in a review of existing studies, Li et al. (2016) indicated 0.02-2.8% of localised populations of seabirds and marine mammals are typically affected. However, a separate study found higher incidence of entanglement, with 3.6-5% of a grey seal population in Cornwall (UK) (Allen et al., 2012).

Adverse health effects stemming from entanglement can include lacerations (potentially leading to necrosis and infection), suffocation and drowning (Laist, 1987). Furthermore, entanglement may increase drag, adversely affecting behaviour, reducing swimming speed and increasing the energetic costs of movement. These impacts ultimately can lead to weakened animals that are more susceptible to predation and starvation (Feldkamp et al., 1989). Entanglement with debris accounted for 13–29% of the observed mortality of gannets in Helgoland (Germany) from 1983-1988 (Vauk et al., 1989), and Weisskopf (1988) estimated 40,000 fur seals were killed each year through entanglement with plastic.

6.3.2 Impacts on Biota from Microplastics

Owing to their small size, microplastics are bioavailable to a wide range of marine life, and can be taken up via direct ingestion (Wright et al., 2013b), ingestion of contaminated prey (i.e. trophic transfer)(Nelms et al., 2018, Farrell and Nelson, 2013), or via the gills (Watts et al., 2014, von Moos et al., 2012). Analysis of field-collected specimens has revealed that microplastics are present in organisms throughout the marine food web, including zooplankton (Steer et al., 2017, Desforges et al., 2015), shellfish (Catarino et al., 2018, Rochman et al., 2015), fish (Foekema et al., 2013, Lusher et al., 2012), seabirds (Amélineau et al., 2016), turtles (Duncan et al., 2019) and marine mammals (Besseling et al., 2015, Nelms et al., 2019). The amount of microplastic consumed by an organism is influenced by the spatial overlap and relative concentration of biota and microplastic, the characteristics of the microplastics (i.e. shape, size), and the feeding strategy (e.g. predatory, filter-feeding) (Setälä et al., 2014).

Environmental data shows the prevalence of ingested plastic can range 0-100% of an animal population (Lusher, 2015). In UK waters, microplastics have been identified in 2.9% of fish larvae and 37% of adult fish sampled from the western English Channel (Steer et al., 2017, Lusher et al., 2012), 11% of mesopelagic fish sampled from the Northeast Atlantic (Lusher et al., 2015), and 71-90% of European flounder and 20-83% of European smelt sampled from the River Thames (McGoran et al., 2017). In common mussels (*Mytilus edulis*), microplastic concentrations ranged 1.1-6.4 items of anthropogenic debris per individual (0.7-2.9 items per g) in wild mussels sampled from around the UK coastline (Li et al., 2018), and 3.2±0.5 microplastics per individual (3.0±0.9 microplastics per g) in mussels exposed in the Forth River (Catarino et al., 2018). Microplastics were identified in 100% of stranded marine mammals stranded around the British coastline, with an average of 5.5 microplastics per individual (Nelms et al., 2019).

The risks that microplastics pose to marine life has received a great deal of attention, with an exponential increase in publications on this topic over the past ten years. Based on current evidence, it is clear that microplastics can cause harm to marine life, however "the poison is in the dose" (SAPEA, 2019). Indeed, many (although not all) exposure studies use microplastic concentrations exceeding those observed in the natural environment, or use nanoplastics and microplastics (typically lab grade spherical polystyrene beads) <333 µm in size for which there is a lack of environmental data (Lenz et al., 2016). Nevertheless, such studies are valuable in elucidating the ways in which microplastics can adversely affect biota (including freshwater and terrestrial species) and provide evidence of ecological harm at a microplastic concentration that may be reached in the future without adequate mitigation (Huvet et al., 2016).

Adverse health effects have been observed across levels of biological hierarchy, with evidence of: inflammatory response in mussels (von Moos et al., 2012); oxidative stress in lugworms and clams (Ribeiro et al., 2017, Browne et al., 2013); reduced feeding in copepods, crabs and lugworms (Cole et al., 2015, Besseling et al., 2012, Watts et al., 2015); impacts on reproduction, including reduced egg size, hatching success and fecundity in copepods, diminished reproductive success in oysters, and abnormal embryonic development in green sea urchins (Cole et al., 2015, Sussarellu et al., 2016, Lee et al., 2013, Nobre et al., 2015); reduction in abyssal thread formation in mussels (Green et al., 2019); and altered behaviour, such as diminished escape response in sandhoppers and reduced predatory performance in common goby (Tosetto et al., 2016, de Sá et al., 2015). However, for some marine organisms with simplistic digestive systems microplastics cause no significant effects. For example, polystyrene microplastics had no impact on feeding, growth or mortality in oyster larvae (Cole and Galloway, 2015). The mechanisms underpinning observed health effects are not always clear, although some studies have demonstrated the underlying cause of deleterious effects. For example, in mussels, an inflammatory response and lysosomal membrane destabilisation was associated with the translocation of <10 µm microplastics from the intestinal tract into the circulatory fluid (von Moos et al., 2012). In copepods, reduced egg size and hatching success was attributed to reduced feeding, stemming from a shift in prey selectivity to avoid consumption of microplastics (Cole et al., 2015).

Adverse health effects may also arise from chemical toxicity. During manufacture, plasticizers, flame retardants, antioxidants, anti-microbials and photo-stabilisers can be incorporated into the polymer matrix to enhance the applicability and durability of the plastic (Kwon et al., 2017). In the environment, there is concern that monomers and such additives associated with the plastic may disassociate and leach out of the polymer matrix (Hermabessiere et al., 2017); these chemicals include Bisphenol A, Polybrominated diphenyl ethers and phthalates, which can permeate into marine food webs where they can cause endocrine disruption and toxicity (Hermabessiere, L., 2017). Of further concern is that the large surface area to volume ratio and hydrophobic properties facilitate waterborne contaminants, including heavy metals, antibiotics, pesticides and persistent organic pollutants, to adhere to their surface, often at concentrations exceeding those within the surrounding media (Rodrigues et al., 2018). Consumption of these microplastics may therefore facilitate the transfer of associated contaminants into biota, although the extent to which chemicals will disassociate into tissues will depend on the organism and ambient chemical concentrations (Koelmans et al., 2016, Koelmans et al., 2014).

Exposure studies have been used to understand whether microplastics might enhance the toxicity of heavy metals, additives and persistent organic pollutants. Chemical transfer between plastics and biota largely depends on whether an environmental equilibrium of the given chemical has been reached (Koelman, A.A. et al., 2016). Current evidence is patchy, with some studies showing additive or synergistic effects of microplastics, for example: enhancing accumulation of mercury in the gills of juvenile European bass causing significantly greater oxidative stress (Barboza et al., 2018); greatly increasing the lethality of the anti-microbial compound triclosan in copepods (Syberg et al., 2017); and reducing the swimming speed of juvenile barramundi co-exposed to the PAH pyrene (Guven et al., 2018). However, in other studies, microplastics have also been shown not to significantly enhance the toxicity of contaminants (e.g. pyrene, nanoparticles), and in some studies, microplastics have been shown to reduce tissue burdens of pyrene in biota (Magara et al., 2018, Chua et al., 2014).

6.3.3 Ecological impacts of plastic and microplastic

Toxicity studies have highlighted the capacity for plastics to impact on reproduction, growth, survival and behaviour in keystone organisms, with such adverse health effects being of directly relevance to animal populations and communities (Galloway et al., 2017). Community shifts may also arise from the presence of floating plastic debris, which has been shown to provide a novel substrate for egg deposition by the oceanic insect *Halobates spp.* (Goldstein et al., 2012) and host microbial communities distinct from those found in seawater and on other natural flotsam (Zettler et al., 2013). Plastic debris may also act as a long-distance vector for rafting species, including microbes, microalgae, macroalgae and invertebrates, increasing their geographical distribution, and potentially allowing them to permeate new habitats where they might outcompete native species (Kiessling et al., 2015, Goldstein and Goodwin, 2013, Calder et al., 2014).

The presence of pathogenic microbes, including *E. coli* and *Vibrio* on plastics may facilitate the spread of disease (Masó et al., 2003, Kirstein et al., 2016). In the Asia-Pacific region, plastic debris has been directly related to coral disease, with coral collapse having widespread ramifications for biodiversity and ecosystem services (Lamb et al., 2018). A handful of studies have identified biologically-mediated ecosystem processes that may be impacted by shifts in feeding or biological processing of microplastic. For example, sediment cycling may be impacted by reduced bioturbation activity in lugworms exposed to microplastics (Wright et al., 2013a, Green et al., 2016b). Moreover, the presence of buoyant microplastics can reduce the sinking speed of copepod faeces, marine snows and aggregates, thereby slowing the transport of carbon to the ocean depths via the biological pump (Cole et al., 2016, Porter et al., 2018, Long et al., 2015).

A handful of “mesocosm” (larger experiments looking at whole communities) studies have also elucidated the risks microplastic and plastic debris could have to sediments, sediment-dwelling animals and shellfish communities, which play vital roles in nutrient flux, biodiversity and coastal protection. The addition of plastic and glass bottles to subtidal sediments provided substrate that increased the occurrence of sponges, barnacles and ascidians and cover for hermit crabs, and was also linked with an increase in motile predatory species (Katsanevakis et al., 2007, Akoumianaki et al., 2008). However, the presence of both conventional and biodegradable plastic bags on intertidal muddy shores was shown to create anoxic conditions in the sediment beneath, reducing the biomass of primary producers and the abundance of benthic invertebrates, and decreasing the fluxes of inorganic nutrients (Green et al., 2015).

Polyethylene microplastics have also been shown to reduce abyssal thread formation in blue mussels (Green et al., 2019), potentially reducing the integrity of shellfish beds and reefs. In oyster dominated muddy sediments, the addition of microplastics resulted in a decrease in the flux of inorganic nutrients, a decrease in the biomass of microphytobenthos (primary producers in sediment) and a shift in community composition whereby opportunistic oligochaetes became dominant (Green et al., 2016a). Additionally, in sandy sediment dominated by European flat oysters, the number of species and the overall abundance of organisms was decreased in response to the addition of microplastics (Green, 2016). Such population and community shifts can have far-reaching impacts to marine ecosystems, with losses in biodiversity, ecosystem functioning and socio-economic value (see Section 7, this report).

6.4 Conclusions

A broad range of marine organisms (from plankton to whales) have been shown to become entangled in, or ingest, plastics. The size of particles and their concentration in environmental compartments influences the likelihood of animal exposure.

Physical encounters through entanglement and entrapment by marine debris (nets, ropes and crab pots; to car air filters and polythene bags) have been widely reported. Deaths of ‘charismatic’ sea mammal species, such as whales with plastics in their stomachs, has received widespread media attention (Jacobsen et al., 2010, Unger et al., 2016, de Stephanis et al., 2013).

The accumulation of marine debris can alter and degrade marine habitats. The literature contains a body of evidence for critical life processes that are affected by ingestion of plastic, in a range of marine species. This includes metabolism, growth, reproduction and behaviour, and mortality. However, the degree of risk at population levels remains elusive.

There is no agreed convention for hazard assessment of plastics and microplastics, that would be akin, for example, to the protocols used in assessing ecotoxicity for chemical risk assessment, and the bioavailability, uptake and chemical toxicological effect (mechanistic/mode of action).

The combination of the 'physical effects' (physical damage, reduced feeding) with the chemical toxicity (from chemicals adsorbed to the surface of the plastic, the chemicals and microbiology in the biofilm and the chemicals within the plastic material matrix) have not yet been explored in great detail.

Various reports have looked to assess the risk plastic, in particular microplastics, pose to marine ecosystems. In some coastal waters and sediments, where biota and plastics overlap, microplastic concentrations might be sufficiently high to cause ecological harm. As emissions continue to rise, the risk of ecological harm will become more pervasive (SAPEA, 2019).

Microplastics used in exposure studies are not necessarily consistent with those found in the environment. Furthermore, microplastics concentrations in exposure studies typically exceed those observed in the natural environment, although environmental concentrations for microplastics <333 µm remain elusive, owing to the constraints of sampling particles of this size.

Further work is now required to elucidate: the bioavailability and effects of fragments and fibres, the relative sensitives of different species and life-stages, better understand the mechanisms by which microplastics cause toxicity, and explore the risk nanoplastics pose to marine life (GESAMP, 2018, Burns and Boxall, 2018).

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7. Review of Ecosystem Service and Economic Impacts of Marine Plastic Pollution

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7.2 Role of the Ocean as Natural Capital

7.2.1 Natural Assets and Ecosystem Services

A healthy Global Ocean is vital to human health and well-being, providing an array of ecosystem services with wide-ranging societal benefits (Corvalan et al., 2005). Using the 'Natural capital' approach, the marine environment can be considered as a stock of natural assets (biota, habitats, ecosystems and ecological processes) that provides ecosystem services of direct benefit to society. These ecosystem services can be broadly categorised into three themes, as summarised by the UK National Ecosystem Assessment (NEA, 2013):
(1) **provisioning**, including food and water production through aquaculture, fisheries, and desalination of seawater;
(2) **regulation**, including climatic regulation of temperature and carbon dioxide, protection against extreme weather events and waste detoxification through bioremediation; and,
(3) **cultural**, including spiritual and cognitive benefits, and supporting recreational activities and tourism.

These ecosystem services provide an array of goods and benefits, including seafood, recreation and tourism, that can be economically valued giving them weight in policy decision making (Figure 8; from Costanza et al., 1997; Lee, 2014).

Figure 8: Schematic showing the relationship between natural capital, ecosystem services and the goods and benefits garnered by society

Research into how plastic pollution might impact upon these ecosystem services is in its infancy, and any economic valuation of the risk marine plastic poses to the marine environment remains hugely challenging (Newman et al., 2015). Owing to the close relationship between natural capital and ecosystem services, it is anticipated that adverse ecological impacts stemming from plastic pollution will have consequences for socio-economic wellbeing. Information on the social and economic impacts of marine plastic is key to raising awareness of the issues, as well as informing and guiding future policy and regulation development. Here, we consider the risk plastic pollution might pose to ecosystem services, based on our current scientific understanding:

7.2.2 Provisioning Services

Fisheries play an instrumental role in meeting the nutritional needs of a growing global population and providing employment to coastal communities. As of 2016, worldwide fish production reached 171 million tonnes per annum, with per capita consumption peaking at 20.3 per annum (FAO, 2018). Population levels are rising exponentially, and by 2050 the global population is estimated to reach 9.8 billion, with fisheries and aquaculture expected to play vital roles in food provisioning. Marine plastics have the capacity to negatively affect fishing yields by disrupting commercial activity and reducing the viability and economic value of commercially exploited species. Plastic debris, including derelict fishing gear (i.e. “ghost nets”), can damage boats (e.g. fouling of propellers, blocking intake pipes), and can damage or entangle fishing nets, lines and pots, causing reductions in fishing efficiency and loss of equipment (Brown and Macfadyen, 2007). In a survey of Scottish fish vessels (including trawlers, scallopers, and seine netters), 86% reported reduced catch and 95% reported snagging their nets on debris on the seabed, owing to marine debris, with an estimated financial cost of £10.2-11.4 million per annum (Mouat et al., 2010).

Plastic pollution in the form of derelict fishing gear poses a key risk for marine life, and in turn fisheries. Nets, lines and pots can all result in the continued and repeat entanglement, capture and ultimately loss of life of a vast range of animals, including commercially exploited species and charismatic fauna (Good et al., 2010). In Chesapeake Bay (US), loss of commercial crab traps are estimated to be as high as 30% per fisherman (Center for Coastal Resources Management, 2007), with abandoned pots predicted to result in the capture of 2,000,000 kg of blue crab each year, with a value of US$4 million (Anderson and Alford, 2014). Surveys have been used to estimate that 1% of larger fishing gear (e.g. gillnets, trammel nets) are lost per vessel each year (Gilman et al., 2016). The size, efficiency and durability of these nets allows for the capture of vast numbers of both target and non-target species, with an average mortality rate calculated at 92.8±47.2 fish per 100 m^2 of net, subject to habitat, weather conditions, longevity of net, type of net, and whether the net is moored or free-floating (Gilman et al., 2016).

Marine plastic is an attractive substrate that is quickly and intensively colonised by a wide range of opportunistic species (Kirstein et al., 2016). Natural flotsam such as kelp and wood tend to degrade and sink within a matter of months. Conversely, plastics can withstand prolonged exposure to UV radiation and wave action, often remaining buoyant for longer periods (decades or even longer) and travel distances of more than 3000 km from source (Barnes et al., 2005). This “rafting” (see section 6.3.3) of invasive non-native species could also potentially impact on provisioning services, through increasing competition or changing prey availability.

Microplastic debris (1-500 µm) may also pose a direct risk to commercially important marine organisms. Plastic particulates and fibres can have adverse health effects on individual organisms, with negative outcomes for fecundity and survival evidenced (Galloway et al., 2017). Microplastics are of a similar size to the prey (i.e. microalgae, zooplankton) of a host of lower-trophic organisms, and are therefore bioavailable to shellfish, crustaceans, and fish (Lusher, 2015). Microplastics loads in biota are highly variable, depending on the environmental prevalence of plastics and feeding traits of the given organism. Field studies from around the Northeast Atlantic have shown microplastics at mean concentrations of 0.37 particles/g in common mussels (*Mytilus edulis*) (De Witte et al., 2014, Van Cauwenberghe and Janssen, 2014), 0.47 particles/g in Pacific oysters (*Crassostrea gigas*) (Van Cauwenberghe and Janssen, 2014), 0.15 particles/g in brown shrimp (*Crangon crangon*) (Devriese et al., 2015), and 1-4 particles/individual for Atlantic herring (*Clupea harengus*)(Foekema et al., 2013), 1.75 particles/individual for whiting (*Merlangius merlangus*) and 1.95 particles/individual for poor cod (*Trisopterus minutus*) (Lusher et al., 2012). Microplastics have also been identified in juvenile fish sampled from the western English Channel (Steer et al., 2017).

A number of exposure studies have highlighted the potential risks to commercially exploited biota, for example: in adult common mussels polystyrene microbeads can incite oxidative stress and impair immune response (Paul-Pont et al., 2016); in brown mussel (*Perna perna*) embryos, leachate from polypropylene pellets increased developmental abnormalities and mortality (e Silva et al., 2016); and in adult Pacific oyster, polystyrene microbeads caused oxidative stress, reduced sperm motility, egg size and numbers, resulting in the production of reduced numbers of offspring with significantly slower growth rates (Sussarellu et al., 2014). Typically, these studies utilise microplastics at concentrations far exceeding those found in the natural environment, however they function to highlight the capacity for microplastics to impinge on different levels of biological hierarchy, including population level effects (Galloway et al., 2017), that could impact on stock viability. However, there remains a paucity of data, and further insight and longer term exposure studies are required to better explore impacts on growth and the commercial value of shellfish and fish, inter-species and intra-species variability, the toxicity of different shapes and polymer of plastic, and the role microplastics might play in introducing co-contaminants (e.g. metals, organic pollutants) to marine life (Lenz et al., 2016).

Marine plastic debris can rapidly develop complex biofilms (i.e. biological matrixes comprising exopolymers, microbes and microalgae), that can harbour pathogenic *Vibrio* spp. (Kirstein et al., 2016). It is currently unclear whether microplastics carrying pathogenic microbes are a vector of disease for shellfish and other commercial species. Floating plastic debris can also provide a substratum for algae and invertebrates (e.g. bryozoans, molluscs) (GESAMP, 2018); the durability and long-distance transport of plastic litter can therefore result in the dispersal of these sessile species beyond their natural geographical boundaries (Barnes and Milner, 2005). As such, marine litter is considered a key vector for invasive alien species, with the potential to negatively affect native populations of shellfish and crustaceans (Clavero and García-Berthou, 2005).

The presence of microplastics in seafood also poses a concern for human health, although these risks are poorly understood. Human uptake of microplastics through consumption of larger fish is minimal, as current evidence indicates larger microplastics do not translocate (i.e. pass from the intestinal tract into the flesh), and most fish are gutted prior to cooking (Karbalaei et al., 2018). However, for smaller fish, for example anchovy, pilchards) (Karami et al., 2018), shellfish (Rochman et al., 2015, Li et al., 2015), and edible seaweed (Gutow et al., 2015), where the entirety of the organism is consumed, there is substantial probability of humans consuming any microplastics present. As a result, the extent of risk may be elevated in cultures with a tendency towards eating these smaller fish, shellfish and seaweeds. Based on microplastic concentrations in mussels and oysters, Van Cauwenberghe and Janssen (2014) estimated an average European shellfish consumer might have a dietary load of up to 11,000 microplastics per annum. In another study, Catarino et al. (2018) estimated human uptake at 4,620 microplastics per annum for a European consumer (123 microplastic per annum for an average UK consumer).

The risks posed to humans is currently unclear (Galloway, 2015), but current evidence would suggest consumption of plastic within seafood would have a negligible impact on chemical body burden of persistent organic pollutant in humans (FAO, 2017). A survey conducted by the German Environment Agency found that 62% of the population were moderately or strongly concerned by microplastic contamination of drinking water and food (SAPEA, 2019). The perception that seafood is contaminated with plastic may be sufficient to curb the public's appetite for seafood, causing a decline in market value (Jacobs et al., 2015, Beaumont, in press) and in the nutritional health benefits from eating seafood.

7.2.3 Regulation Services

Plankton are instrumental to marine carbon cycling. At the sunlit sea surface, atmospheric carbon dioxide dissolves in seawater, where it can be utilised by photosynthetic microbes and phytoplankton to produce 50-85% of the world's oxygen. Some of the organic carbon produced will be transported to the deep ocean via vertical migration and consumption and egestion of sinking faecal matter. The sequestration of carbon in the ocean depths plays a key role in maintaining the Earth's equable climate through the maintenance of the ocean - atmosphere carbon balance (Barange et al., 2017).

Plastic particulates can hinder the growth of phytoplankton; for example, polyvinylchloride microplastics can adsorb and aggregate with the microalgae *Skeltonema costatum* inhibiting growth (Zhang et al., 2017). Zooplankton can readily ingest plastics particulates and fibres, subsequently egesting these microplastics within their faeces (Cole et al., 2013, Desforges et al., 2015). Exposure studies have indicated that buoyant microplastics within zooplankton faeces and marine snow can significantly reduce their sinking rate, potentially reducing the rate of carbon flux from sea surface to seafloor (Cole et al., 2016, Porter et al., 2018). Further work is required to understand whether such effects might have any ecological impact under environmental conditions.

Biogenic reefs, including coral reefs and shellfish beds, protect coastal communities from extreme weather events and detoxify waterborne pollutants. For example, shellfish communities are capable of filtering vast quantities of water, with the capacity to remove anthropogenic waterborne pollutants (e.g. microplastics, microbes, metals, pesticides, hydrocarbons) and suspended materials, thereby improving water quality (Viarengo and Canesi, 1991). The impacts of microplastics on shellfish (e.g. oysters, mussels) have received considerable attention, and while microplastics and associated co-contaminants can incite sub-lethal health effects (e.g. gene expression (Avio et al., 2015), immune response (von Moos et al., 2012), reduction in abyssal thread formation (Green et al., 2019)), there is little evidence that environmentally relevant concentrations of microplastics cause harm at the population level (Li et al., 2018). Larger plastic debris has been linked to widescale impacts on coral reefs, with the presence of plastic snagged on corals increasing the likelihood of disease from 4 to 89% (Lamb et al., 2018). Increased prevalence of disease has the potential to impact upon a wealth of ecosystem services provided by coral reefs, including their capacity to remediate waste and act as a physical barrier for shoreline protection.

7.2.4 Cultural Services

The marine environment is of immense benefit to human health and wellbeing, providing for the therapeutic needs, interests, physical and mental health of the public (Bell et al., 2015, White et al., 2013). The presence of plastic litter on beaches can pose a direct risk to human health. In Australia, 22% of visitors to beaches reported sustaining injuries (e.g. wounds) from litter (Campbell et al., 2016). Such plastic debris can carry pathogens harmful to human health (e.g. *Escherichia coli, Vibrio cholerae, Vibrio fluvialis*), reducing bathing water quality standards (Keswani et al., 2016). Plastic litter can also prove a visual deterrent, as the presence of litter has been shown to reduce the scenic value of beaches (Williams et al., 2016), reducing the psychological benefits of visiting these sites (Wyles et al., 2016). Tourism is one of the largest growth industries across the globe, contributing 2-10% of GDP of countries(Agency, 2006, Mouat et al., 2010) and in the UK generating £127 billion in 2013 (www.visitbritain.org). Plastic pollution on beaches can have a substantial impact on tourism. Beach litter, particularly sewage related debris, is perceived by beach users as a marker of low water quality, reducing the willingness to swim (Morgan et al., 1993, Tudor and Williams, 2003). In Geoje Bay (South Korea), high levels of litter washing onto beaches following heavy rainfall in 2011 decreased visitor numbers by 63%, with an estimated £22.4-28.6 million loss in revenue (Jang et al., 2014). In addition, Jefferson et al., (2014) found that marine litter was the top factor considered as an indicator of poor water quality by the UK public

The risk plastic debris poses to charismatic habitats and fauna may also impact on human wellbeing. As noted previously, plastic debris can increase disease prevalence in corals (Lamb et al., 2018), and any subsequent loss in habitat quality is likely to reduce the desire to visit these sites (Moberg and Folke, 1999). Ingestion of microplastics have also been shown to cause increased body burdens of persistent organic pollutants in cetaceans (Fossi et al., 2014), and morbidity and mortality in seabirds and turtles (Duncan et al., 2019, van Franeker and Law, 2015). Conservation of such iconic species is of high value to the public, and therefore any population declines or loss of welfare resulting from plastic debris would be expected to result in declining wellbeing and valuation of the marine environment (Börger et al., 2014).

7.3 Economic valuation

Based on our understanding of the ecological impacts of plastic on marine life, and the myriad ecosystem services provided by different ecological subjects, Beaumont et al. (2019) demonstrate the largely negative impact plastics are likely to have on ecosystem services, particularly provisioning and cultural services (Figure 9).

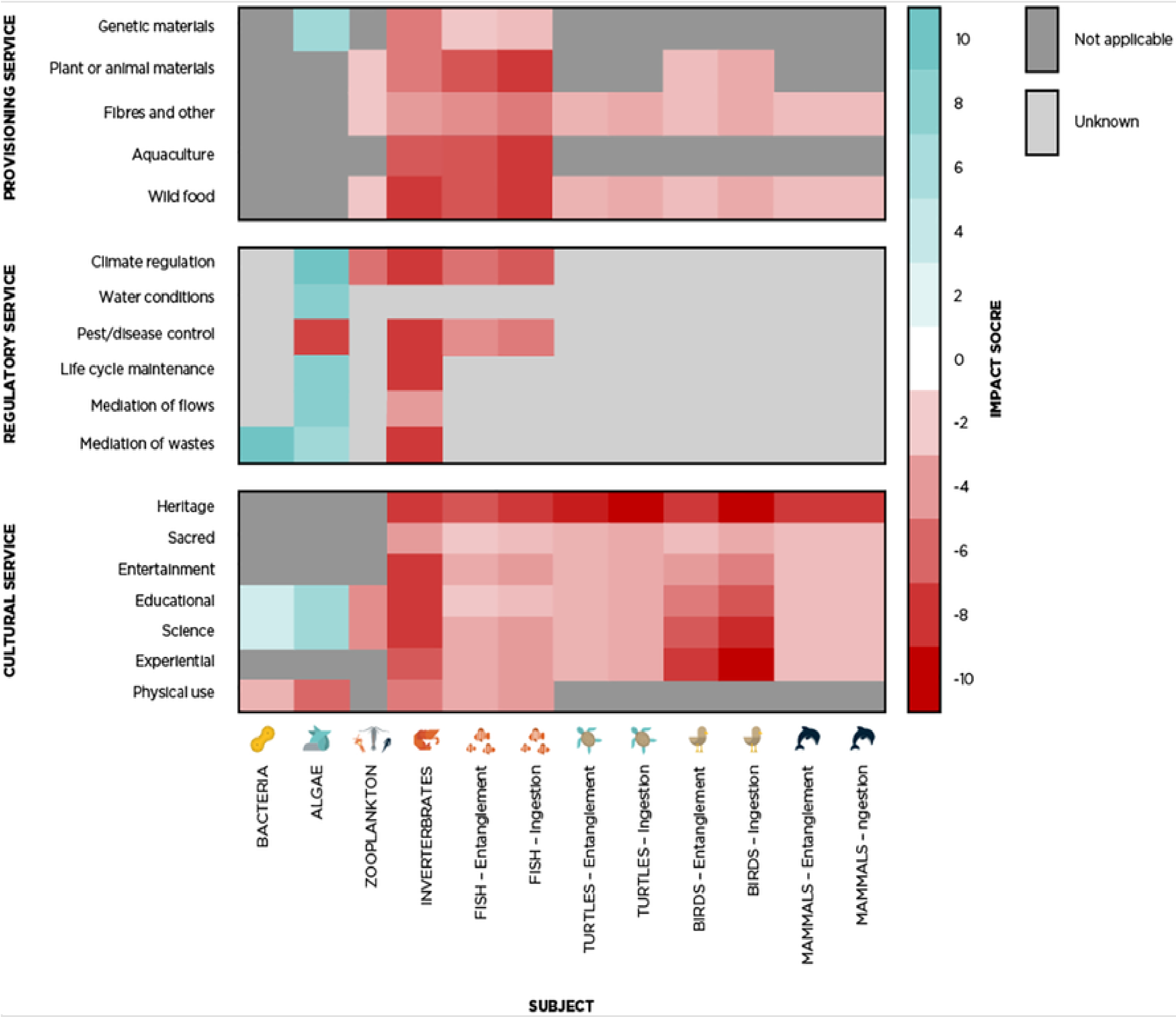

Figure 9: Ecosystem Service Impacts of Marine Plastic

A score of −10 denotes significant risk to this service at the global level with high potential social and/or economic costs; a score of +10 denotes significant potential benefit from this service at the global level, with high potential social and/or economic benefits. Dark grey shading indicates the supply of ecosystem service from the associated subject is negligible. Light grey shading indicates that the relationship between ecosystem service and subject is unknown. Source: Beaumont et al. (in press)

Marine ecosystem services comprehensively contribute to human wellbeing, meaning that their reduction will endanger the continuous welfare of human societies, especially in coastal communities (Naeem et al., 2016). From the results in Figure 9 (selecting services with the consistently high (red) impact scores) and the reviewed literature, we can identify three critical ecosystem services which are particularly at risk: 1. Provision of fisheries, aquaculture and materials for agricultural use; 2. Heritage, including charismatic marine organisms, such as seabirds, turtles and cetaceans which hold a cultural and/or emotional importance to individuals; 3. Experiential recreation.

Estimates of the costs of marine plastic pollution have been modelled for specific regions, for example: the impact of marine debris on tourism, fisheries and aquaculture on the Shetland Isles (UK) has been costed at approximately £900,000 per annum (2010) (Mouat et al., 2010); for the 21 economies of the Asia-Pacific rim, the damages caused by marine debris, losses owing to derelict fishing gear and cost of clean-up has been approximated at £1 billion per annum (2008) (McIlgorm et al., 2011); and the impacts of plastic stemming from the United States on marine natural capital is estimated at US$13 billion per annum (Raynaud, 2014).

Across the UK, volunteer effort towards beach cleans for the Marine Conservation Society and KSB National Spring Clean was valued at £115,000 in 2010, with total spend on clean-ups estimated at £15.8 million per annum in the UK (Mouat et al., 2010). Using a marine litter valuation model, considering direct and indirect costs related to fisheries, shipping, tourism, wellbeing and remediation in the UK, Lee (2014) identified fisheries and aquaculture to be at greatest economic risk (£26.8-35.6 million per annum), with overall damage and losses stemming from plastic and microplastic debris estimated at £28-56.4 million per annum.

However, the full economic cost of marine plastic pollution on the marine environment, incorporating all ecosystem services, is currently unclear. Although, given the estimated £14.5 trillion valuation of marine ecosystem services as a whole, any loss in provisioning, regulatory or cultural services can be expected to result in substantial economic losses (Newman et al., 2015, Beaumont et al., 2019). The estimated decline in marine ecosystem service delivery (Figure 9) has been equated to an annual loss of $500-$2,500 billion in the value of benefits derived from marine ecosystem services (Beaumont et al 2019). Furthermore, under 2011 levels of marine plastic pollution and based on 2011 ecosystem services values, Beaumont et al (2019) also postulated that each tonne of plastic in the Ocean will have an annual cost in terms of reduced marine natural capital of between $3,300 and $33,000 per annum.

7.4 Conclusions

Plastics can be demonstrated as causing direct effects to marine ecosystems across provisioning, regulation and cultural ‘services’.

In the absence of chemical hazard and risk paradigms, considering ecosystem services as the means to focus policy action is both pragmatic and attractive since it aligns with the economic valuation principals of ‘natural capital’.

The valuation approach will be a critical component in both identifying actions that need to be taken, but also the pace at which those actions should be progressed. It can also serve to provide evidence to Government to take action in the absence of evidence of ecological /population impact, in the current debate where public ‘opinion’ may be ahead of Government and (certainly) business.

However there is a paucity of strong UK-relevant case studies that provide the cost:benefit evidence for specific economic sectors potentially impacted by plastic pollution.

According to Beaumont et al (2019, In Press) the economic costs of marine plastic, as related to marine natural capital, are conservatively conjectured at between $3,300 and $33,000 per tonne of marine plastic per year.

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8. Review of Behaviour Change in People and Business Towards Plastic Pollution

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8.2 Background

The review draws heavily on the 2019 report for the European Commission (SAPEA, 2019) and specifically Chapter 3 that summarised the relevant academic literature on plastic pollution and behaviour (lead authors Pahl & Henderson). In that report, the authors affirm that "The social and behavioural sciences are vital to understanding the societal perceptions and social dynamics that impact on plastic pollution in order to develop effective and acceptable solutions" (SAPEA, 2019; p. 62). While SAPEA (2019) focused on nano- and microplastics, it was unique in being co-chaired by a natural scientist and a behavioural scientist, in the recognition that this complex and nuanced environmental issue requires cross-disciplinary collaboration so that the barriers, agents and motivations towards behaviour change are aligned with the discoveries of impacts on the environment. The key aim for the present DEFRA review was to provide relevant insights from the academic social and behavioural sciences in the form of a 'snapshot' of this rapidly-moving field.

There is no natural variation of plastics in the environment: human decisions and behaviours are the cause of plastic pollution (Pahl, Wyles & Thompson, 2017). The Social and Behavioural Sciences aim to investigate the principles of societal perceptions of the issue, associated risks and societal dynamics, which are relevant to decisions and behaviours, and the motivational and behaviour change principles that create effective change.

8.3 Perceptions and Understanding of Plastic Pollution by Stakeholders

8.3.1 Media reporting and risk perception

Media reporting of plastic pollution has increased over recent years (e.g., see Figure 11, for microplastics reporting), with the media exerting a considerable influence on the extent and content of public discussion of plastic pollution. The media play a critical role in reporting environmental threats: they can shape debate, public awareness and responses, and political action (SAPEA, 2019, p. 64). They can create simplified 'storylines' for complex topics and transform 'straight science' into political stories. Stakeholders may influence this process by presenting evidence for or against particular policy initiatives, aligned to their interests. Environmental pressure groups can generate public debate by holding 'media-friendly' events that trigger emotional responses. ‘Celebrity’ involvement can also increase awareness, although this does not necessarily translate into action (SAPEA, 2019).

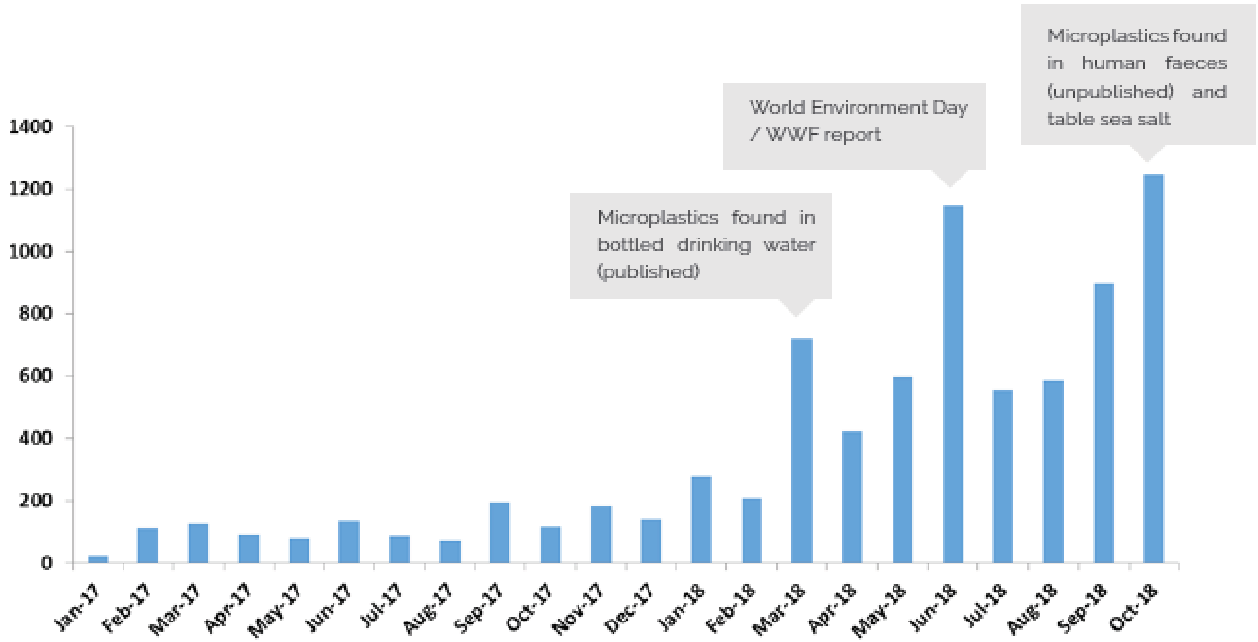

Figure 10: Monthly number of news items drawn from the European Media Monitor (EMM). Clear peaks may reflect reporting of specific news stories (although this is untested) (SAPEA, 2019, p.65).

8.3.2 Expert vs Non-Expert Perceptions of Risk

From the broader risk perception literature, we know that perceptions of risk differ between experts and non-experts. Experts tend to assess risk in a formal way (for example by looking at annual fatality rates), whereas non-experts consider additional factors (e.g., emotions, such as dread and outrage, fairness, perceived control as well as moral considerations, such as effects on future generations, ecosystems and non-human life). Differences in values and judgemental factors can determine the differences between technical or scientific assessment of risk and risk perception processes. One type of assessment is not more valid than the other. Instead, societal discussions regarding the risks and appropriate responses should consider scientific evidence as well as moral and social considerations. Communication of risk should be adapted to suit the priorities and values of the target audience.

We know that the perceived risk can decrease when the value or benefit to humans increases, when the risk is delayed, or gradual, or when the risk is less observable and tangible. The current lack of clarity and the debate surrounding the health risks to humans from plastic pollution creates uncertainties which can lead to psychological distance. If future research subsequently reveals a threat to human health from plastics, this could be associated with increased risk perception and demand for action (SAPEA, 2019).

8.3.3 Visual imagery and experiential methods

Visual imagery used in the media plays a strong role in people's perceptions of risk. Evidence for other pollutants suggests that visual images (and influential 'elite' sources such as the leading 'experts', Policy makers, high quality media such as BBC, New York Times) may attract more attention and contribute more to peer-to-peer sharing on social media. The issue of imagery may be especially relevant for plastic pollution and microplastics. While images of charismatic animals entangled in macro-plastics and general images of plastic pollution are very emotive, other aspects of plastic pollution tend to be invisible, e.g., smaller plastic particles (SAPEA, 2019, p. 69). A lack of visibility makes it more difficult for lay people to assess the risks for themselves, increasing their reliance on other sources of information in order to form opinions (SAPEA, 2019, p. 71). This is particularly problematic when there is scientific uncertainty around some of the facts and when that is not reflected in media reporting.

Additional work outside the SAPEA report also emphasises the importance of 'visibility': "visual images are associated with emotions that help develop memory traces and motivations, bridging abstract intentions to specific actions, especially where the problem and solution are disconnected" (Pahl et al., 2017). Visual methods, coupled with experiential methods (e.g. physical handling of microbeads; Anderson et al., 2016), and storytelling and narratives, are promising ways of increasing awareness and motivating change. This is in line with research showing that personally noticing marine litter when visiting the coast is associated with concern and intentions to change behaviour (Hartley et al., 2018). Moreover, Wyles et al., (2016) found that taking part in a beach clean increased future intentions to do beach cleaning and had additional well-being benefits.[1] Similar to the imagery used to warn consumers of the harmful effects of smoking, pictures depicting the effects of plastic pollution could be applied on everyday packaging of consumer goods (Pahl et al., 2017). However, images depicting the negative effects of plastic pollution may also lead to perceived helplessness in the receiver or even a loss of interest and denial. Therefore, firstly these options need to be carefully tested. The literature suggests that such strong emotional messages should be coupled with empowerment to reduce the risk of denial and disengagement (Fennis, et al., 2011).

It is worth noting that visibility may also influence research effort. Heidbreder et al. (2019) recent narrative review of research studying the perceptions, behaviours and interventions for tackling plastic pollution noted that of their 187 studies reviewed, the majority originated from countries with a coastline. This is presumably because plastic pollution is perceived as a visible threat to the marine environments.

[1] Importantly, this study used random assignment to different activities and can therefore conclude with reasonable confidence that these effects were causal, when most studies in this area are descriptive / cross-sectional.

8.3.4 Communicating uncertainty

The uncertainties introduced by insufficient scientific evidence can lead to distrust and inaction. Nevertheless, it is important to communicate transparently about the uncertainties rather than assume and communicate a lack of risk, particularly in sensitive areas such as food and human health. More cautious decision-making, and greater transparency, tends to be associated with greater trust - and people are more reliant on social trust when they are unable to assess the risks and benefits of an issue for themselves (SAPEA, 2019, p. 71).

Most science-for-policy is characterised by "high system uncertainties, high stakes, debated values, and decision urgency" (SAPEA, 2019,), and it should be borne in mind that values are not always economic values; people have a range of values beyond economic. The four main types of values are hedonic values (striving for pleasure and reduction of effort); egoistic values (improving or securing one's resources); altruistic values (caring about others); and biospheric values (caring about the quality of nature and the environment) (Steg et al., 2012), and these values should be considered alongside natural science evidence. In science communication there is rarely a 'one-size-fits-all', as target groups (e.g. industry, retailers, consumers) differ in their interests, drivers and values.

8.5 Behaviour Change

8.5.1 Facilitating behaviour change

In contrast to climate change, there is little evidence of plastic pollution 'denial' among the different societal actors (Hartley et al., 2018a). Among the public, there is a feeling of co-responsibility and a willingness to make changes where possible, and a number of citizen and stakeholder initiatives are actively engaging in campaigns and projects. For example, both the Marine Conservation Society and Surfers against Sewage have reported a doubling of UK volunteer numbers between 2017 and 2018 (SAPEA, 2019). There are many powerful examples for campaigns by Third Sector organisations, including the "3PS" campaign (only flush poo, paper and pee, see https://www.citytosea.org.uk/the-3ps/) and the Refill campaign to reduce single use plastic water bottles (https://refill.org.uk/). It would be worthwhile undertaking an exhaustive review and evaluation of these types of campaigns.

Evidence suggests that the most effective interventions are those that provide a desirable and feasible solution at the point of consumer choice and address a range of motives: people are more likely to change their behaviour if they are sufficiently motivated and there is a practical alternative or a supportive infrastructure. Although policy measures can be effective at reducing situational barriers, recent analysis demonstrates that behaviour change programmes can be faster and more cost-effective at achieving behaviour change than policy tools (Benartzi et al., 2017). Moreover, sometimes behaviour change can precede policy interventions, e.g., a large percentage of people are already reporting that they are reducing single-use plastics (https://www.globalwebindex.com/hubfs/Downloads/Sustainable-Packaging-Unwrapped.pdf).

Incentives and charges vary in effectiveness in different contexts and are not equally acceptable: different tools and instruments are effective for different actors and different behaviours. There is evidence that policies such as the plastic bag charge can catalyse wider awareness of plastic waste and lead to 'policy spill-over,' i.e. greater support for other waste-reduction policies aimed at eliminating unnecessary single-use plastics and packaging (Thomas et al., 2019). Vince and Hardesty (2018) suggest that, as already occurs for materials such as steel, copper and aluminium, putting a price on plastic may be an effective way to recover material and reduce losses into the environment. Specific examples of the effectiveness of different approaches on behaviour change are presented in Table 6. A review that focused focussed on littering behaviour and policies was undertaken by Zero Waste Scotland (Brook Lyndhorst, n.d.).

However, interventions that focus solely on incentives and charges can fall short because the intended action will stop when the incentive stops, people get used to the charge or the interventions does not lead to 'spill over' or broader attitude and behaviour change (e.g. Dikgang et al., 2012).

Additionally, care should be taken as there is the potential for 'spill over' effects to be negative. Ma et al. (2019) demonstrated that while recycling behaviours can positively increase environmental self-identify, people may feel that they have 'done their bit' and this may make higher levels of consumption more acceptable (i.e. the 'rebound effect'). They note that research into moral licencing finds similar effects.

Table 6. Examples of Environmental Initiatives and Effectiveness in Effecting Behaviour change

Examples of Behaviour Change and Academic Study	Evaluation, Findings
Campaigns vs policy waste abatement strategies - Willis et al. (2018):	*Evaluated:* *how effective various waste abatement strategies were at reducing plastic litter and waste entering the environment through interviews with 40 local councils* <u>Findings</u>: • Investment in campaigns and outreach programmes, resulted in a greater reduction in litter and waste entering the environment than did investment in state-enacted policies (cf., Benartzi et al., 2017). • Fewer litter or waste items were found on the coastlines of councils that had a budget for coastal waste management and targeted specific waste streams.
Financial incentives for container returns - Schuyler et al. (2018):	*<u>Evaluated:</u>* *the effectiveness of container deposit legislation (CDL) for reducing the quantity of debris entering the marine environment in two countries, Australia and the Unites States, by comparing results of coastal debris surveys in states with or without cash incentives for returning beverage containers.* <u>Findings</u>: • Proportion of containers found in coastal debris surveys in states with CDL was approximately 40% lower than in states without CDL (p. 250). • A greater reduction in beverage containers in areas with low socio-economic status (where debris loads are highest), suggesting that incentives may be particularly effective in areas where incomes are lower.
Beverage cups: environmental messaging, provision of alternatives, and financial incentives or charges - Poortinga & Whitaker (2018):	*<u>Evaluated</u>:* • *environmental messaging, the provision of (reusable) alternatives and financial incentives are effective ways of promoting the use of reusable cups in the short term;* • *whether they have an impact on the total number of hot drink sales;* • *whether a combination of measures, including a charge on disposable cups, can promote the use of reusable cups long term.* <u>Findings</u>: • The use of both environmental messaging and the provision of alternatives increased the use of reusable cups; • While a charge on disposable cups increased use of reusable cups as well, a discount on reusable cups did not seem to make a difference (cf., new data from Hubbub, 2019, see Appendix). This is in line with prospect theory, which says losses loom larger than gains in people's preferences; • The effect for the individual measures were modest, but additive, meaning that the greatest behavioural change was achieved with a combination of measures; • None of the measures negatively impacted the total number of hot drink sales

8.5.2 Determinants of Behaviour: How knowledge, 'norms' and other factors influence behaviour

Information can be part of a behaviour change campaign and can be useful to facilitate change. However, knowledge or information on its own lacks motivational power and it may not be a strong or direct predictor of behaviour. The assumption that experts simply need to fill an information 'deficit' is now outdated and can often be counter-productive (Abrahamse & Steg, 2013).

In particular, concern, perceived behavioural control, identity, values, attitudes, emotions and personal and social norms have been identified as important predictors of intentions and behaviour related to plastic consumption and pollution (Hartley et al., 2018; Pahl & Wyles, 2016).

Heidbreder et al.'s (2019) review found that people were distinctly aware of the problems associated with plastic yet continued to use it regularly. They report that the following four factors are obstacles to behaviour change:

- perceived practicalities and convenience in the consumption context;
- lack of knowledge on how to implement alternative or lack of opportunities;
- strong habits; and
- shift in responsibility

Concluding, they pointed out that 'habits, norms and situational factors' appeared to be the most predictive of plastic consumption behaviours.

So how can awareness and knowledge play a role in concert with other behavioural determinants? Evidence shows that awareness of the problem can translate into behaviour via outcome efficacy (sometimes labelled response efficacy) and personal norms under certain conditions, namely if people feel capable of change (empowerment). This in turn may increase feelings of moral obligation and responsibility to reduce the problems (personal norms). As people are motivated to act in line with their personal norms, they will strive to implement change, especially when the relevant behaviour is not too costly or difficult to implement (Steg, 2016; Steg & Vlek, 2009, SAPEA, 2019).

Table 7. Role of Dynamic Norms in Behaviour Change on Consumption of Single Use Plastic

Examples of Behaviour Change and Academic Study	Evaluation, Findings
Reusable cups & dynamic norms - Loschelder, Siepelmeyer, Fischer, & Rubel (2019):	*Evaluated:* *Two studies testing whether a dynamic norm can help customers to avoid disposable to-go-cups.* Findings: Data from a 14-week intervention suggested that a dynamic-norm intervention (e.g. signage such as "more and more customers are switching from to-go-cups to a sustainable alternative; "Be part of this movement and choose a reusable mug") significantly increased the use of sustainable alternatives relative to unsustainable to-go-cups by 17.3%.
	Evaluated: *Via a follow-up online experiment,* Findings: • advantageous effects of a dynamic norm relative to a no-norm control condition, a static norm, an injunctive norm, and a combination of static-and-injunctive norm (static norms – arise out of a situation of societal consensus; injunctive norms refer to your perception of what others would deem 'right' or 'wrong'; *dynamic norms* – relate to norms that are not yet established but are increasingly changing over time to elicit (pre-) conformity). • 'Dynamic norms' intervention is cheap and requires little effort; • Supporting sustainable development may not be the only reason for businesses to engage in nudging – cost savings and an increase in reputation, brand value, and sales volume create a unique business case for the use of (dynamic) norms nudging. Thus, nudges such as the present one should hopefully appeal to both the environmental consciousness as well as the business acumen of decision-makers and entrepreneurs

8.5.3 Effective Behaviour Change

There are two key factors in determining behavioural actions to target for change: the 'plasticity' or potential for change in that behaviour, and the effectiveness of the change in addressing the problem in terms of plastic pollution reduction (cf., Dietz et al., 2009, analysis in the context of energy efficiency). Expressed differently, how feasible would it be to change that behaviour, and how impactful would this change be? For example, Dietz et al. (2009) used these two factors to estimate and rank the actions that would most reduce carbon emissions. They found that insulating homes would have the most impact, whilst carpooling would have the least. This type of analysis is currently lacking for plastics pollution, but is of crucial importance to identify the most effective and acceptable actions for behaviour change programmes.

Table 8. Behaviour Change on Consumption of Single Use Plastic

Examples of Behaviour Change and Academic Study	Evaluation; Findings
Bottled water - motivations and perceived environmental consequences. ***Ballantine, Ozanne, & Bayfield (2019)***	*Evaluated:* *Small study identifying (N = 16) five main themes as to why people purchase bottled water emerged, including:* • *Health, comprising personal health (keeping hydrated) and cleanliness (fear of germs from other sources of water),* • *the bottle (bought because the bottle looks 'cool'),* • *convenience,* • *taste,* • *self-image* <u>Findings:</u> Perceived Environmental Consequences: • Overall, limited understanding of the environmental consequences of purchasing bottled water; • Neutralisation techniques (e.g. "as long as they're recycled properly, then I think it's alright") were used to justify behaviour when thinking of the environmental impacts of bottled water. Suggestions for ways to reduce the purchase of bottled water: • Focus messaging on the cleanliness of municipal water supplies and a frequent level of testing to protect consumer health that exceeds that required for bottled water. • Ensure availability of sources of water enabling consumers to refill bottles, provide the convenience they desire; provide cold water. • Provide consumers with the opportunity to recycle plastic bottles, even away from the home. • Activate social-norms, coupled with persuasive information: van der Linden (2015) found that this combination elicited the greatest reduction in intention to purchase bottled water. *Note: As indicated above, this is a very small study and further research would be desirable.*

There has been no comprehensive analysis or quantification of the behavioural aspect of plastic pollution to date. Reviews on plastic-related behaviour change (e.g. Heidbreder et al., 2019) suffer from a paucity of studies that focus on plastic-specific behaviours, instead drawing on recycling behaviour studies, which are far more numerous. This may limit the comparability of studies and the conclusions that can be drawn from them. However, waste management analysis and analysis of items found during environmental monitoring and beach cleans can provide an evidence-based starting point, by identifying which items and materials to target (e.g. plastic bottles, black plastic (SAPEA, 2019, p79; EarthWatch, 2019).

Table 9. Assessing Interventions on Consumption of Single Use Plastic

Examples of Behaviour Change and Academic Study	**Evaluation; Findings**
Factors influencing plastic bag use in South Africa - O'Brien & Thondhlana (2019):	*Evaluated:* *plastic bag use practices and factors influencing use in South Africa. The paper outlines which interventions might be most effective in achieving pro-environmental actions.* Findings: • Most respondents perceived there was a plastic bag use problem in the country but still used plastic bags because it was convenient (51%). Other motivations included the ease of availability (40%) and affordability (20%). 42% purchased plastic bags because they could use them again (e.g. as bin liners); • High-spending consumers were likely to consume more plastic bags despite high education levels, challenging the underlying assumption that high education and income will likely result in pro-environmental behaviour; • Respondents indicated that alternative 'environmental-friendly' bags that were cheap and reusable would reduce uptake of shopping plastic bags; • Interventions for reducing plastic bag use in South Africa have centred on fines and levying of taxes, but this hasn't been particularly successful. As implementing and monitoring such interventions are costly, behaviour change interventions were suggested as being more user-driven, cheaper and sustainable over a longer period; • As life cycle assessment evidence suggests there is a low environmental impact of plastic bags, relative to alternatives, they suggest that resistance to interventions like outright bans of plastic bag production may grow.

A waste hierarchy is also important for prioritising actions, but there is a dearth of research on waste reduction currently. Distinguishing impact vs. intent-oriented behaviours is also helpful to define the most effective behaviour change (Stern, 2000). Impact-oriented behaviours are defined as those with the greatest impact on the environment, such as purchasing items with less packaging, whereas intent-oriented behaviours are defined as behaviours undertaken explicitly for environmental reasons.

These different motivations can identify novel pathways for change: for example, people may avoid plastic packaging due to health concerns about additives (SAPEA, 2019, p. 80).

Further initiatives and emerging work from grey literature can be found in the Appendix, most notably a report by the charity Earthwatch (Earthwatch, 2019) that analyses and prioritises behaviours based on waste analysis. Finally, WRAP (www.wrap.org.uk) has a programme of work on communication and behaviour change and should be consulted.

8.6 Conclusions

There is a considerable influence of media and politics in parallel to scientific communication on the public discourse regarding plastics and micro-plastics.

This influence is governed by risk perception principles, as presented by scientists and the media interpreting science, and through the visual images through film, TV and shared by social media.

The evidence suggests that (for other pollutants) visual images and elite sources may attract more attention and topics are intensified by social media peer-to-peer sharing.

Communicating transparently about the uncertainties in scientific evidence is a safer approach than assuming and communicating a lack of risk, especially in sensitive domains such as food and human health.

Differences between technical or scientific assessment of risk and risk perception processes are governed by different values and judgemental factors.

There is a feeling of co-responsibility in the public and a willingness to make change where they feel it is possible; some citizen and stakeholder initiatives are actively engaged in campaigns and projects. This momentum could be harnessed to co-create widely acceptable solutions.

There appears to be consensus between different societal actors – to date there has been little indication of plastic pollution deniers.

Research is needed that identifies and quantifies behaviours and analyses feasibility, acceptability and impact.

Behaviour change programmes can be faster and more cost-effective at achieving changes in motivation and awareness than policy tools. But policy measures are important to reduce situational barriers, otherwise motivational change may not lead to behavioural change, and the desired environmental outcome. Communication and labelling according to best-practice is an important element of making interventions work.

While littering is only one source of materials and items escaping into the natural environment, it is worth including but may be more difficult to address successfully, due to the social undesirability of the behaviour and lack of engagement with interventions by 'litterers' and also difficulties in enforcement.

Research on public knowledge and awareness has so far focused on macro-plastics rather than micro- and nanoplastics and we know very little about perceptions of pathways and impacts other than on wildlife (e.g., human health).

Policies such as the plastic bag charge may catalyse wider awareness of plastic waste and lead to policy 'spill over,' i.e. greater support for other waste-reduction policies. Potential behavioural side effects (e.g. in terms of health) and trade-offs (e.g., in terms of carbon emissions) of alternatives ought to be evaluated systematically.

Close interdisciplinary collaboration is desirable between the natural, technical and social/behavioural sciences to address the complex issue of plastic waste and pollution, and any capacity gaps should be addressed urgently. This capacity will help to move forward with solutions to other environmental challenges beyond plastic.

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Annex 1 Additional "grey literature" Commentary on Behaviour Change

These reports have been provided as context for the issue although not directly shaping the review presented in Chapter 8, recognising that wider sources of information are also available and will continue to be moving forward. Whilst these are not all from the peer-reviewed literature, some refer to such literature. Some initiatives are also at a very early stage and could be pursued to results stage.

Earthwatch Europe

Earthwatch Europe have recently completed a study investigating the actions that are frequently recommended to the general public, examining the potential of these actions for positive environmental impact. This report was jointly funded by Plastic Oceans UK (https://earthwatch.org.uk/images/plastic/PlasticRiversReport.pdf).

Earthwatch Europe has also been working with businesses to explore the issue of plastic pollution from microplastics (their report "Microplastics: How should business respond?", produced in partnership with Eunomia, was released on 4th March 2019, https://earthwatch.org.uk/microplastics). Approaching the problem sector by sector, they offer an assessment tool for five microplastic sources. The report focuses on the main risks to business and includes recommendations and further research opportunities for businesses.

Commonseas: Plastic Drawdown Project

Commonseas have been working on a 'wedges' model, similar to what has been used in the energy context. This concentrates on policy analysis and offers a toolkit to address plastic pollution. The most effective policies to reduce plastic pollution in the natural environment are identified. The model investigates plastic leakage from land into rivers and the Ocean and aims to identify opportunities for plastic reduction at different timescales. It aims to highlight the impact different actions may have, including the lag between implementation and results. Current country models include the United Kingdom, Greece, Indonesia and the Maldives.
(https://commonseas.com/)

Hubbub

https://www.hubbub.org.uk/blog/cutting-plastic-waste-hubbubs-five-step-plan

Three Impact Reports are available, including one on the Starbucks Cup Charge Trial.

Hubbub worked with Starbucks to measure whether a 5p charge would encourage people to switch to reusables. Following trials across 35 stores, reusable cup used with hot drinks increased from 2.2% to 5.8%. Results support Poortinga et al. findings that charging for disposable cups has a bigger effect than offering discounts.
(https://www.hubbub.org.uk/blog/cutting-plastic-waste-hubbubs-five-step-plan).

Resource London Report on improving recycling in flats (Knightly et al., 2019)
This ethnographic research highlighted three factors – motivation, ease and knowledge – are all necessary conditions for improving recycling rates in flats, but that these are not always addressed by those delivering waste services (see above on the role of knowledge). The report suggests that, while many people living in flats and on estates are keen to recycle, they do not always feel that it is easy or that they have the right knowledge to recycle effectively. Flats present a range of recycling challenges, including space constraints in people's homes, the state and location of communal bins on estates, and continuing confusion about what residents can and cannot recycle where they live. Taking place on 12 housing estates across six inner London boroughs, the project is testing different recycling interventions so that the successful initiatives can be replicated in other urban locations across the UK.
The interventions being tested and the barriers they aim to overcome are:

- *Tenant recycling packs* – provided by landlords to explain what items they expect their tenants to recycle and what happens to their recycling; aiming to address the fact that many residents don't feel responsible for recycling and properly disposing of their waste
- *Emotive messaging around communal areas* – large poster signage to help residents feel more responsibility and motivation for recycling
- *More, smaller recycling bins* – conveniently located smaller bins around the estate, to make recycling more accessible and convenient
- *Feedback mechanisms* – to show residents that their recycling efforts are appreciated, that everyone has a contribution to make, and provide updates on recycling rates and what is being achieved
- *In-home storage solutions* – a space-saving hook and bag system to help residents find space in the home to store recycling, and make it cleaner and easier to recycle

Initial results from the pilots, which began in September 2018, are said to be showing positive impacts, with the overall recycling and capture rates appearing to improve and contamination decreasing. A full waste composition analysis at the end of the project will provide more definitive results and recommendations, which will then be published and shared more widely. Following on from of initial results, Resource London is launching a communications toolkit for other waste authorities considering improvements to their flats service.

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The above authors suggest that solutions to plastic pollution problems are likely to involve a combination of the following (p. 11):

- "Improved product design, taking in mind various stages of reuse, recycling and end of life;
- Campaigns to promote marine conservation and clean ups though public education and promotion of ethical consumerism;
- Easy access to recycling and other responsible waste disposal alternatives;
- Increased infrastructure to capture plastic items at source;
- Research and development propositions at the material design level;
- Technological innovations to keep post-consumer plastics in a circular economy loop;
- Regulation, including bans on certain products where appropriate and economic incentives for many different actors in the supply, use and disposal chain;
- Commitment of plastics producers and distributors to adopt end-of-life waste management practices".
- Setting of achievable policy targets relevant to marine plastic pollution.

van Sebille et al. (2016) conclude by emphasising that "NGO communities, the private sector and a wide range of policy makers should coordinate with other relevant actors in this space and align initiatives accordingly".

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Annex 2 Workshop Attendees

Name	Organisation
Dr Margrethe Aanesen	The Arctic University, Norway
Dr Tenaw Abate	Arctic Technology Innovation, Industry and Regional Development Climate and Environment, Tromso,
Tasqeen Ahmed	Defra
Dr Adil Bakir	CEFAS
Dr Nicola Beaumont	Plymouth Marine Laboratory
Dr Geoff Brighty	ICE blue
James Brown	Defra
Jessica Churchill-Bissett	Marine Management Organisation
Dr Matthew Cole	Plymouth Marine Laboratory
Dr Deborah Cracknell	University of Plymouth
Prof. Linda Godfrey	Council for Scientific and Industrial Research (CSIR), South Africa
Dr Daniel Gonzalez	Cadiz University
Bethany Graves	JNCC
Dr Chris Green	Defra
Dr Dannielle Green	Anglia Ruskin University
Dr Denise Hardesty	CSIRO, Oceans and Atmosphere
Dr Lesley Henderson	Brunel University London
Jessica Hickie	Environment Agency
Alice Horton	CEH – Centre for Ecology & Hydrology
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Charlotte Johnson	Natural England

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Dr Ceri Lewis	University of Exeter
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Dr Olwenn Martin	Brunel University London
Calum Mitchell	Defra
Stephanie Ockenden	Defra
Dr Sabine Pahl	University of Plymouth
Anthony Parsons	ICE blue
Lesley Parsons	ICE blue
Joe Perry	Defra / CEFAS
Charlotte Pochin	Defra
Prof. Wouter Poortinga	Cardiff University
Dr Andries Richter	Wageningen University
Josie Russell	CEFAS
Hazel Selley	Natural England
Hasmitta Stewart	Defra
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Martin Wagner	Norwegian University of Science and Technology