SAPEA Evidence Review Report:

A Scientific Perspective on Microplastics in Nature and Society

About SAPEA

Spanning the disciplines of engineering, humanities, medicine, natural sciences and social sciences, SAPEA - Science Advice for Policy by European Academies – brings together outstanding knowledge and expertise from over 100 academies, young academies, and learned societies in over 40 countries across Europe.

SAPEA is part of the European Commission's Scientific Advice Mechanism (SAM), which provides independent, interdisciplinary, and evidence-based scientific advice on policy issues to the European Commission. SAPEA works closely with the European Commission Group of Chief Scientific Advisors (GCSA).

This Evidence Review Report will inform the European Commission GCSA's Scientific Opinion on the topic, which will be available in July 2019.

Funded through the EU's Horizon 2020 programme, the SAPEA consortium comprises Academia Europaea (AE), All European Academies (ALLEA), the European Academies' Science Advisory Council (EASAC), the European Council of Academies of Applied Sciences, Technologies and Engineering (Euro-CASE), and the Federation of European Academies of Medicine (FEAM).

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Forward By SAPEA

'A Scientific Perspective on Microplastics in Nature and Society' is the fourth Evidence Review Report published by the SAPEA consortium. SAPEA is an integral part of the European Scientific Advice Mechanism (SAM) and was asked to review the current evidence on health, environmental and societal impacts of nano- and microplastic pollution.

The interest, concern and uncertainties surrounding nano- and microplastics and the heightened media attention on plastic pollution, coupled with the many unknowns, make the project very timely. The broad scope and complexity of the issue make it especially challenging and the current topicality of the subject make it especially important.

SAPEA assembled a large multi-disciplinary international working group for the project, covering the natural sciences, behavioural sciences and political sciences. We were delighted with the motivation and collaboration of the experts, and their willingness to deliver this report. The working group provided specialist knowledge on subjects ranging from nano- and microplastics, polymers science, marine pollution, ecology, toxicology, risk assessment, human health, computer modeling, regulatory processes, behavioral sciences, media and communication, risk perception and attitude and behaviour research, and more. The resulting report demonstrates not only the outstanding knowledge of the experts, but also their exemplary commitment to the voluntary task of working in an interdisciplinary way and bringing the best and newest scientific knowledge into policy-making.

Thank you to the European Academies and SAPEA Networks for nominating so many excellent experts, also to the Group of Chief Scientific Advisor and the SAM Unit for the fruitful partnership. The JRC shared some knowledge about media monitoring aspects as well, for which we are very grateful. FEAM supported this project as Lead Network within SAPEA and ALLEA contributed by hosting a workshop specialising in the behavioural sciences at the Berlin Brandenburg Academy of Sciences. The Royal Netherlands Academy of Arts and Sciences and acatech's Brussels office both kindly hosted working group meetings.

This report informs the Scientific Opinion of the GCSA due in 2019. The aim is for these two reports to be used by the European Commission in planning and policy-making. Building on the success of past SAPEA projects, this rapid project establishes a new collaborative model for future SAM projects. We would like to thank everyone involved in making it a success and express our sincere gratitude to those who have worked hard on it, especially the working group members and excellent Chairs.

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Prof. George Griffen   Prof. Sierd Cloetingh

President of   Chair SAPEA Board 2019 & President of

FEAM 2019   Academia Europaea (x - y)

Forward by the Working Group Chairs

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Executive Summary

Scope and Objective

Microplastics are **plastic particles of mixed shape** that are present in air, soil, freshwater, seas, in biota, and in several components of our diet. NMPs are below 5 mm in size (Arthur, 2009) and come from **a variety of sources**, including fisheries, products and textiles (use and breakdown), agriculture, industry, waste, and others. Because of fragmentation and degradation of larger plastic items and of microplastics, it is plausible that nanoplastics will be formed. Scientists, policy-makers and the public are becoming increasingly concerned about both the ubiquity of nano- and microplastics (NMPs) and the uncertainties surrounding their impacts, hazards and risks to our environment and to human health. Heightened media attention on plastic pollution is observed. If the occurrence and concentrations of NMPs continues to rise, either from intentionally produced NMPs, or NMPs formed by the degradation of larger plastic items, what can science tell us about the risks and what sense can be made of this complex evidence base?

The scientific evidence base and policy context are being reviewed by the European Commission's Science Advice Mechanism (SAM). As part of this mechanism, this Evidence Review Report offers a scientific perspective on the state-of-the-art knowledge about the implications of NMPs **in nature and society** and highlights the unique features and complexities of the topic. In this report, a SAPEA working group rapidly reviews the current knowledge about NMPs and offer their conclusions on that knowledge as it stands today. They also highlight uncertainties and knowledge gaps in order to inform appropriate future actions.

Many agencies, groups and discussion forums are bringing together experts specializing in plastics and microplastics to share their perspectives on microplastics pollution and to look at potential policy needs. Both the scientific evidence base and the policy context is evolving quickly. What is unique about this report is that it is an interdisciplinary analysis by independent scientists, free from political institutional influences, coordinated by the European Scientific Academies. The ERR provides the first step in a 2-step process that feeds into a Scientific Opinion on the subject in 2019, which will be written by the European Commission's Group of Chief Scientific Advisors (GCSA). At current, a systematic overview on policy options and their predicted efficiency and relevance to reduce current and future risks of NMP in Europe is not available and so this is welcomed by the working group.

This report distinguishes clearly between what is known, what is partially known and what is not known where possible and the broad scope for it is outlined in a statement that was issued by the GCSA, in July 2018 (GCSA, 2018). Nano- and microplastics in the environment (as reviewed in Chapter 2) are solely the result of human activity, and it is essential to understand the contributing factors of society within the system. A unique aspect of this report is that it reviews evidence from the social and behavioural sciences (in Chapter 3) in conjunction with the natural sciences evidence, which is crucial to designing effective policies. The working group also reviews current computer modelling performed on the topic (Chapter 2) and briefly reviews plastic-related policies. In chapter 4, a review of the scientific underpinnings to current policies is given, and it is noted where they do or (as in most cases) do not include NMPs.

This report is the result of discussions at two physical meetings, held in Brussels and Amsterdam, and one workshop held in Berlin. The authors worked remotely and wrote this report within twelve weeks, from September to November 2018. For the specialized reader, the detailed evidence that underpins this report can be found within the sections of each chapter and more information can be found within the 435 references. The main conclusions reached by the working group can be found at the end of each chapter. A digest and combined summary can be found in Chapter 5, which also presents some solutions for society, as potential options derived from this scientific evidence.

Conclusions

The number of papers is growing exponentially in this field, but the knowledge is not growing at the same rate - there is some redundancy and marginality in the papers. The SAPEA working group concludes that a lot is already known about nano- and microplastics, and more knowledge is being acquired, but some of the evidence remains uncertain and it is by its nature, complex (for instance, differences in size, shape, chemical additives, concentrations, measurements, fates, unknowns, human factors, media influences, actions and behaviours, as reviewed in the report). While members of the working group have diverging interpretations of some of the evidence, they review and present their views in a non-biased way, also presenting where they found consensus.

They conclude that there is a need for improved quality and international harmonisation of the methods used to assess exposure, fates and effects of NMPs on biota and humans. We have a fair knowledge of microplastics concentrations for freshwaters and the ocean surface, but little is known about air and soil compartments and about concentrations and implications of NMPs below the ocean surface. The working group concludes from this evidence that, while ecological risks are very rare at present, there are at least some locations in coastal waters and sediments where ecological risks might currently exist. If future emissions to the environment remain constant, or increase, the ecological risks may be widespread within a century. Little is known with respect to the human health risks of nano- and microplastics, and what is known is surrounded by considerable uncertainty (Section 2.6), however the relevant conclusion of this working group is that we have no widespread risk to NMPs at present. Most micro plastics go in and out of most organisms, and as with many chemicals, 'the poison is in the dose'.

It has been demonstrated in the laboratory that at high exposure concentrations and under specific circumstances, nano- and microplastics can induce physical and chemical toxicity. This can result in physical injuries, inducing inflammation and stress, or it can result in a blockage of the gastrointestinal tract and a subsequent reduced energy intake or respiration. Sections 2.5 and 2.6 of this report review evidence of studies in several aquatic organisms, where, for example, researchers conclude that exposure to microplastics in the laboratory has a significant, negative effect on food consumption, growth, reproduction and survival, once effect thresholds are exceeded. But we have no evidence that this happens in nature.

Most these effect studies, however, are either performed using concentrations that are much higher than those currently reported in the environment, or are performed using very small microplastics, for which limited exposure data exists, or only used spherical ones which are not representative of real world types of particles or used relatively short exposure times. Currently, it is not known to what extent

these conditions apply to the natural environment. This limits the reliability of the risk assessment for nano- and microplastic.

While inflammatory evidence is seen in animal models, we don't know if this translates to humans or not. In humans, workers/occupational exposure to microplastics can lead to granulomatous lesions, causing respiratory irritation, functional abnormalities and other (such as flock workers lung). The chemicals associated with microplastics, can have additional (and difficult to assess) human health effects, such as reproductive toxicity and carcinogenicity, however, the relative contribution to chemical exposure via NMP among the mix of chemicals, is probably small at present (section 2.5.6), although the number of assessments remains limited. Therefore, the degree of this toxicity and impacts for environmental NMPs remains uncertain'.. With a sparse evidence-base for both dietary and airborne microplastics concentrations, especially concerning the inhalable size fraction, it is unclear what the human daily intake of nano- or microplastics is, yet this knowledge is essential for estimating health effects.

There is a need to understand the potential modes of toxicity for different size-shape-type NMP combinations in carefully selected human models, before robust conclusions about 'real' human risks can be made, though the occurrence and impacts are beginning to be measured. Meanwhile, very little is known about nanoplastics (as opposed to microplastics), and this should be addressed before any pertinent assessment can be made about their impacts and risks.

The currently known detail about environmental and health impacts to date, sources, occurrences, fates, hazards and risks, can be found in Chapter 2 and the full list of conclusions of the Chapter can be found in Section 2.7.

There is a considerable influence from the media and politics in parallel to the scientific communications on the public discourse of NMP. Chapter 3 of this report highlights how insights from sociology, psychology, media and communication studies and organisational studies have an important role to play in understanding the interplay between natural science insights and the planning of effective societal responses. These disciplines are necessary in the design of successful policies and interventions and in societal engagement to reduce NMP pollution (and macroplastics as contributors to NMP, although they are not the focus of this review). A conclusion of this working group is that communicating transparently about the uncertainties in the scientific evidence is a safer approach than assuming a lack of risk, especially in sensitive domains such as food and human health.

Human decision and behaviours are the reason why plastics exist in our environment. The economy drives emission to the environment, and behaviours of citizens and other stakeholders that both put them there, and which could ultimately change that. The uses of plastic posing the highest risks in the future will be those related to high volumes, high emission profiles, and/or intrinsic hazardous properties of the materials. If NMP pollution is to be reduced, societal understanding and risk perception of the issue, together with motivations and behavior change principles need to be considered for lasting change. While NMPs have hardly been addressed to date by the social and behavioural sciences, the group draws on literature from other environmental issues and puts forward

ideas about what can be inferred from them in relation to the NMP topic. Chapters 3 and 4 indicates that interventions will be accepted by the public if linked to relevant values and perceptions, with transparent communication and implementation, which then may lead to a significant reduction in the current and future risks of NMP. The authors conclude that there is consensus and momentum for action and no evidence of plastic 'denial' (as opposed to climate change denial) and see Section 3.7 for the full list of conclusions.

The evidence reviewed within Chapter 3 and 4 presents that a large array of measures is useful for addressing and reducing plastic pollution, such as fees, bans, Environmental Protection Regulations and voluntary agreements. However, it is not feasible to distinguish between NMPs and larger macroplastics when reviewing and defining regulations (with exception of those scenarios where primary microplastics are regulated). Legislation addressing plastic pollution can mainly be grouped into measures that aim to protect the marine environment (such as the EU Marine Strategy Framework Directive) and those that are focused on waste (such as the EU's Waste Directive). The scientific basis for these groups of legislation are somewhat different. Environmental legislation in particular is based on only few (albeit comprehensive) reports and monitoring studies, as reviewed in Chapter 4. Due to the lack of scientific understanding, the precautionary principle (PP) has been part of the foundation for current regulations. Notably NMPs are not mentioned explicitly, nor is monitoring required specifically for NMPs at present. The PP enables decision-makers to adopt precautionary measures when scientific evidence is uncertain, and when the possible consequences of not acting are high.

Options and Next Steps

Close interdisciplinary collaboration between the natural, social and behavioural and regulatory sciences is the way forward to address the complex issue of plastic waste and pollution. The absence of concrete evidence of microplastic risks at present does not allow us to conclude with sufficient certainty either that risk is present or that it is absent. It will thus take some time before more reliable conclusions on risks become available for the various environmental compartments and for public health assessment.

As socioeconomic developments increase, and if plastic use continues as 'business as usual' or increases further, it follows that the associated risks will concurrently increase. The working group finds that there is a need for more inquiry into these future socio-economic scenarios, as well as the environmental ones. The working group concludes from their review of the combined evidence in this report that it will be important to implement both agreements and legislation which focus on emission reduction and the use of less hazardous materials (see Chapter 4). Such agreements would protect that which society aims to protect, such as marine and surface waters, air, food products, soil and drinking waters - collectively our environment and health. In general, enforceable measures or protection levels are often laid down in legally binding texts, and these can create new markets for innovative solutions which the evidence reveals are needed. The evidence suggests that focus should be on circular economy approaches, away from linear processes and end-of-life clean-up. The working group offers more options based on the science evidence in Chapter 5 of this report.

The future work of the GCSA will bring in more dialogue with industry and other organisations and stakeholders and will review in more detail the various policy measures and legislative instruments in

place, those under development or those potentially needed. Their report will be informed by this report and will combine the scientific evidence presented here with a detailed EU, national and international policy analysis (SAM, 2018) and they will formulate recommendations for policy makers in July 2019. This joint project by the SAM is further detailed here: http://ec.europa.eu/research/sam/index.cfm?pg=pollution

and here: link to new NMP SAPEA webpage.

Chapter 1: Introduction

'Concern about the presence of microplastic particles in soil, air and water and their effect on biota and human health is increasing among scientists, policy makers and the public. This is due to steadily improving knowledge of the scale and impacts of pollution by plastic in general and by microplastics in particular, either intentionally produced, or formed by the degradation of larger plastic items. Heightened media attention to marine and land-based plastic pollution with images of floating garbage patches, littered beaches, entangled and suffocated animals, and zooplankton ingesting plastic particles is also contributing significantly to public awareness.' (Starting Consideration of the Statement by the European Commission, Group of Chief Scientific Advisors (GCSA, 2018).

The GCSA has launched work leading to scientific advice on this topic, informed by this review of scientific evidence by SAPEA. SAPEA was requested to write an Evidence Review Report (ERR) that gives a scientific perspective on the health and environmental impacts of nano- and microplastic pollution, as part of the Science Advice Mechanism (SAM) of the European Commission (EC). The ERR gives a state-of-the-art synthesis of relevant published scientific evidence and captures the different facets of the complexity of microplastics, in nature and in society.

1.1 The Complexity of Microplastics

Since the discovery of the first plastic made from synthetic components in the early 1900s (Andrady & Neal, 2009), industry has been exploring new properties and opportunities regarding plastic materials. This growing interest in a relatively cheap and malleable material resulted in vast applications. As a result, today we are surrounded by a plethora of plastic objects, ranging from everyday items such as lunch bags, to more complex products and machines composed partly or entirely of plastic material.

Contamination of the environment with plastic debris is one of today's major environmental problems that affects society (EFSA, 2016; GESAMP, 2016; Koelmans et al., 2017a; Lusher, Hollman, & Mendoza-Hill, 2017). Plastic debris is a human-created waste of solid polymer material, that has deliberately or accidentally been released in the environment. Plastic debris is an extremely diverse material, composed of many different polymers at different weathering states, and of different shapes and sizes (Browne, 2015; GESAMP, 2016). Plastic debris is a material of high societal concern, as it has been declared an unnatural stressor to a wide range of organisms, an eyesore and an unethical addition to nature. The cleaning of contaminated areas requires effort and cost, which have implications for the economy. Plastic debris can also be seen with the naked eye, which explains part of the concern of the public (Koelmans et al., 2017a).

One sub-fraction of plastic debris is that of nano- and microplastics, pragmatically defined as plastic debris particles smaller than 5 mm (NOAA definition) (GESAMP, 2016). Usually, 0.1 or 1μm is used as a lower size boundary for microplastic, and plastics lower than this size are referred to as nanoplastics. In this report, we discuss nano and microplastics separately in some cases, and in others, together as NMPs (to represent both nano and microplastics).

The cut-off at 5 mm is to some extent arbitrary, as there is no crucial difference in environmental behaviour compared to that of somewhat larger particles. The aforementioned size cut-offs are habits that have grown in the plastic debris community, yet a consensus definition has not yet been reached.

As a result of the broad range of applications and uses of plastics, various sources of nano and micro plastics exist. Generally, microplastics are classified into two groups, primary microplastics and secondary microplastics (GESAMP, 2016). **Primary nano and microplastics** are small microscopic pieces of plastic that are purposefully manufactured for specific applications, e.g. pellets for industrial production and microbeads. **Secondary nano and microplastics** are produced indirectly, from the breakdown of larger plastic waste or debris, both at sea and on land. The diversity and complexity of sources is reflected in the diversity of nano- and microplastic particle scale characteristics (shape, size, density, polymer type), its transport and fate characteristics, its effect thresholds and effects on biota, and in its risk characteristics. The adsorption of environmental organic contaminants to nano- and microplastic, as well as the presence of residual additive chemicals native to the original polymer, further adds to this complexity. Chemical mixture toxicity is complex in itself. The co-occurrence of nano- and microplastic and chemicals in the same environmental substance, or 'compartment of nature', has been shown to lead to context-dependent interactions of further extended complexity.

The microplastics debate cannot be fully separated from the wider debate on plastic production, consumption and pollution, because most originate from the breakdown of macroplastic items, yet this report has nano and microplastics as its primary focus. The main aspect in which nano- and microplastics contrast to larger plastic debris in general, is the fact that it is **virtually invisible** when dispersed in the environment. This aspect, together with a higher chance of ingestion by a larger range of species, has contributed to the perception that nano- and microplastics may constitute a risk to humans and the environment. Fragmentation and weathering may proceed until the nanoscale (i.e., < 0.1 or 1 µm) (Koelmans, Besseling, & Shim, 2015), a scale at which nano- and microplastic occurrence, behaviour and effects are highly uncertain, further contributes to societal concern.

To assess the exposure, ecological and human health effects of nano- and microplastic is highly complex. Microplastics have been detected in air, soils, freshwaters, drinking water, the oceans and in food products such as seafood, table salt, and potentially beer and honey (see Chapter 2). The presence of nanoplastics in nature is generally considered highly plausible, however there is very limited evidence from measurements, as adequate analytical methodology is still lacking. This relates to the inherent complexity of them, as well as on the inherent complexity of food webs and ecosystems (Scheffer, 2009).

1.2 Societal Responses to the Problem of Plastic Debris

Plastic pollution (whether at the macro- or microplastic level) is attracting considerable public attention and has triggered calls for policy action. Increasingly, the consensus is that one scientific discipline alone cannot solve complex environmental issues, such as plastic pollution (Backhaus & Wagner, 2018; Vegter et al., 2014). For example, eco-toxicologists and marine biologists might collaborate to understand how microplastics affect marine organisms. The social and behavioural sciences become relevant in the interplay between natural science insights and societal causes, perceptions and responses. Chapter 3 of

this report selects insights from media and organisational studies, risk perception and communication, and attitude and behaviour research, that may help engage society in reducing macro- and microplastic pollution and to design successful policies and interventions. In summary, answering questions about how plastic moves from the economy into the environment, and where opportunities for changed awareness, action and behaviour might exist, require a causal linking of information from different scientific fields, as illustrated in Figure 1 (and as later discussed in Figure 3).

In Chapter 4, SAPEA introduces existing, emerging and potential future regulatory and legal frameworks of relevance to microplastics, covering hard legislation and soft policy and ecosystem-focused measures. This brief overview is to set the scene for a political legal science analyses of these issues, and critique of the rationale for applying or not the precautionary principle in the face of uncertainty, as is very pertinent to the topic of microplastics. A detailed policy context review was performed in parallel by the SAM Unit of the European Commission, who shared that work with the working group to support their work (SAM, 2018).

1.3 Aims and Scope of the Evidence Review Report

The present SAPEA scientific evidence review report (ERR) covers the full extent of current scientific knowledge about nano- and microplastics (NMPs) and existing knowledge gaps in order to help inform future actions and policy measures and with the aim for protection against adverse environmental and human health effects.

The SAPEA ERR aims to be presented in a way to promote a more informed public and policy debate (GCSA, 2018) and will feed into the Scientific Opinion paper, which will be written by the GCSA in Spring 2019.

As well as providing an overview of evidence-based scientific knowledge, the report's structure is designed to distinguish clearly between what is known, what is partially known and what is not known. It will look at the social and behavioural sciences, along with overviewing the state-of-the-art of the natural sciences and provide some policy context to the microplastics debate. These three main scientific fields each are covered in a separate chapter, whereas links between them (Figure 1) are covered in each of them, and in Chapter 5. The working group also reviews what has been learned from current computer modelling performed on the topic.

The aims of the report are to provide:

1) A rapid evidence review and summary of the existing natural sciences reviews and overview reports covering exposure, (eco)toxicology, environmental and human health risks and incorporating the most recent primary literature not covered by existing reviews (**Chapter 2**), (also see Annex 6 for details of the systematic literature review strategy that was performed to support the project).

2) An analysis of the social and behavioural sciences, covering issues such as media influences, risk perception by citizens, the behaviour of stakeholders, the political economy and psychology of the microplastic debate (**Chapter 3**).

3)   A political and legal analysis of various national and international legislative, regulatory, policy (LRP) frameworks of relevance (**Chapter 4**).

4)   The main conclusions of the SAPEA Working Group are listed at the end of each chapter.

5)   In Chapter 5, the working group provide a synthesis of the information provided in the whole report, addressing

   a.   a reflection on the adequacy of current regulatory frameworks given the latest scientific evidence;

   b.   summary of main conclusions from preceding chapters;

   c.   a presentation of options for consideration by the GCSA in their preparation of a Scientific Opinion (**Chapter 5**).
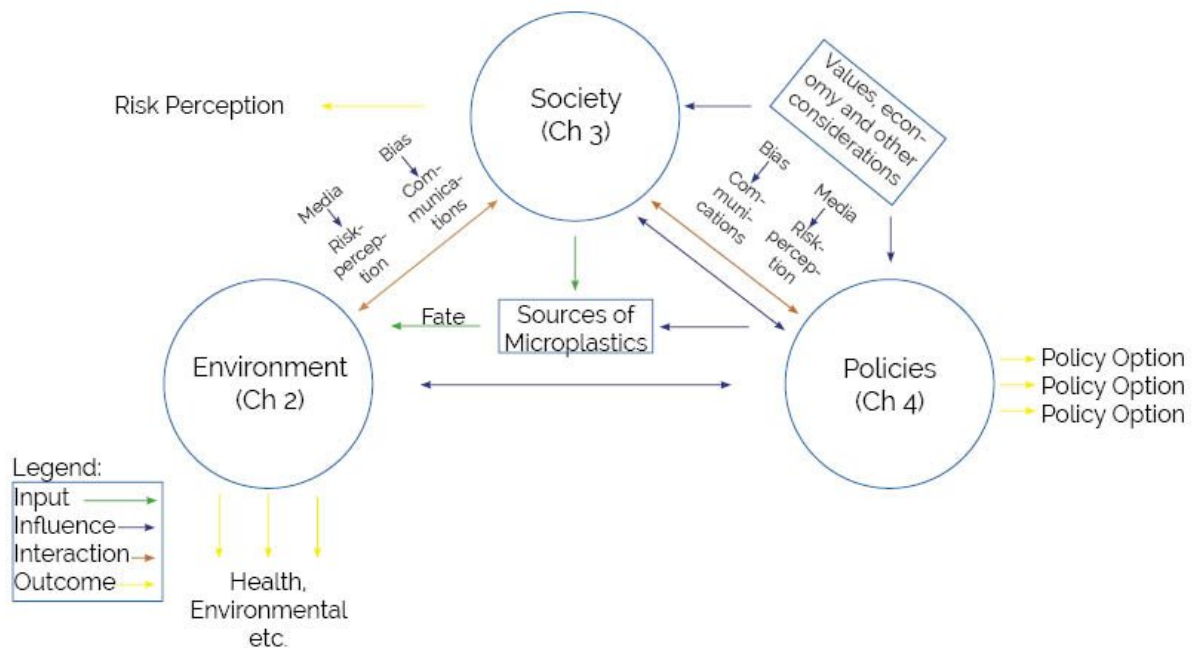
Figure 1: This figure summarises what this ERR aims to review, i.e. the evidence base for what is known about nano and microplastics in nature (Chapter 2), in society (Ch3) and in policies (Ch4). It reviews the inputs, influences, interactions, interplay and outcomes of media and policy activities with society and with the environment.

Chapter 2: The Natural Science Perspectives

2.1 Introduction

In recent decades, pollution of the environment with plastic debris has received increasing attention in society due to the visibility of plastic debris, because of ethical and aesthetical considerations and because of concerns with both respect to ecological harm, and more recently to human health (GESAMP, 2016). This Chapter aims to provide an overview of the existing evidence and the proporties of plastic and plastic debris, its occurrence and concentration in the environment, exposure, its hazards and effects on organisms, communities and food webs, and finally the probability of risks for the environment and human health. We also review models that have been used for scenario studies with respect to the problem of plastics debris.

Risk in the context of chemical assessment can be defined from the perspective of natural sciences as "the probability of an adverse effect on man or the environment occurring as a result of a given exposure to a chemical or mixture"(Vermeire & van Leeuwen, 2007). Risk assessments often use simple risk characterization ratios (RCRs), whereby a risk is characterized as the ratio of actual or predicted exposures to the maximum acceptable concentration of a given chemical or particle in a given environment. An RCR exceeding 1 is usually interpreted by policymakers as an unacceptable situation that warrants further study and/or risk mitigation measures. For the risk assessment of microplastics, risk metrics have also been suggested that consider the likelihood of risk exceedance, as well as impact severity (Mahon et al., 2017; UN, 2016). A risk is the chance (high or low) that any hazard will actually cause harm. Risk exceedance simply means the likelihood of being exposed to the hazard at some given level, or higher.

Expected and actual exposure levels differ vastly between environmental compartments and sites. Furthermore, maximum acceptable concentrations (e.g. Predicted No Effect Concentrations (PNECs), Derived No Effect Levels (DNELs), Acceptable Daily Intakes (ADIs) and similar estimates) have to be determined in relation to the most sensitive (eco)toxicologically relevant endpoint (i.e. reproduction, growth or mortality) and the species/ecological communities present in a given compartment, which can be detailed to each and every microplastic particle type of interest. This renders any chemical risk assessment highly complex and data demanding. This issue is even more challenging for microplastics than for 'ordinary' chemicals, because their overall risk might be driven by a combination of at least four interlinked processes: physical effects of the particles, food limitation caused by particle exposure, chemical toxicity from associated chemicals and the unintentional distribution of associated (micro)biota, and the interactions between these factors (see (Engler, 2012; Reisser et al., 2014; Syberg et al., 2015). Real world exposure is not to one well-defined particle type, but to a complex mixture of particles of different polymers, sizes, shapes, surface characteristics and chemical composition (Lambert, Scherer, & Wagner, 2017). In principle, this would demand for an individual risk assessment for each class of nano- and microplastics, for instance for each individual polymer and size class (Koelmans et al., 2017). This is practically not feasible at the moment because exposure and hazard data would be needed for each particle class. Whether and how this complexity can be simplified into a single RCR (or at least to a small set of distinct RCRs) is currently unclear. Koelmans et al. (2017) provided a first

template, employing adverse outcome pathways and tiered hazard assessment strategies to systematize the issues at hand, but practical experiences are still missing.

This chapter is structured following the main components of this classical risk assessment framework. After providing basic definitions and an introduction to polymer science in the context of plastic debris, we discuss exposure, hazard assessment, and finally risk characterization.

As requested by the GCSA, for each section, the information is separated in what is known, what is unknown, and a category in between, representing what is 'partially known', to roughly indicate the level of certainty associated with current knowledge. We emphasize that this information represents a continuous scale and that allocation into these three categories to some extent is subjective, despite the fact that this has been performed by subject experts, following a thorough literature review. We report the conclusions of the working group based on the current evidence as a whole and their interpretations of the robustness of the evidence (even where research is at an early stage), so that diverging, and consensus opinions are reported. The bars along the side of the page indicate these categories, i.e. Dark blue for known, blue for partially known and pale blue for unknown.

We have described the NMP complexity above, which is linked with uncertainty. Uncertainty and partial knowledge may affect policy and decision making and later in the report this will be dealt with (Chapter 4). There, we consider evidence about the policy relevance and challenge of the combination of this uncertainty with the system complexity, whereby interventions are devised in situations of partial knowledge (see Chapter 2, Section 2.6 and Chapter 3, Section 3.3.3). The question whether decisions can be taken based on scientific evidence about NMPs in the environment, while there is only partial information is challenging, and will be covered by the GCSA in their subsequent Scientific Opinion in more detail.

2.2 Basics, Definitions, Polymer Introductions.

A scientific understanding of the environmental impacts of microplastics requires a good material science view on the fate and degradation processes of plastic products under environmental conditions. Therefore, it is important to have a basic knowledge of polymer science. The term 'plastic' refers to material consisting of organic polymers and additives. A polymer is a molecule of high molar mass, the structure of which comprises the multiple repetition of units derived from molecules of low molar mass (monomers) (International Union of Pure and Applied Chemistry).

Thermoplastic polymers are produced at high volumes, and it follows that they occur most frequently in the environment and therefore attract the greatest attention. This group of polymers comprises polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethyleneterephtalate (PET) and polyurethane (PUR), including their foam variants. Less frequent polymers with the potential ability to create microscopic residues in the environment are based on copolymers (polymer structures polymerized from two or more monomers), polymer blends and multilayer structures with specific properties, e.g. barrier materials in food packaging. Other types of polymers, such as fibre-forming polymers used for synthetic textiles (e.g. polyamides, polyacrylonitrile), glass fibre (diameter 5-15 μm)-reinforced unsaturated polyesters and also rubbers, can become

components of microplastics. Newly developed bio-based (e.g. polylactide acid, PLA) and biodegradable (e.g. oxo-degradable polyolefins) plastics may contribute to plastic debris as well, because they are not fully degraded under natural conditions (Lambert & Wagner, 2017).

Almost all plastic products contain additives for the purpose of enhancement of specific properties, typically UV stabilizers, antioxidants, plasticizers, colorants, fillers, etc (Murphy, 2003). These various additives modify the kinetics of degradation. Time dependent leaching of additives and non-intentionally added substances, for example residues of polymerization initiators, or monomers and oligomers can influence the time course of polymer degradation. The presence of recyclates (if processed in a waste recycling plant), can also influence degradation of plastic products, and it depends on the quality and percentage content of recyclate. Advanced polymer nanocomposites contain intentionally-added inorganic nanoparticles, e.g. organoclays, carbon nanotubes, or nano-titanium oxide (Koo, 2006). These variables add another complication layer to the complex task of assessing the 'real' environmental exposures and risks of microplastics. *In this Chapter, we discuss nano and microplastics separately in some cases, and in others, together as NMPs (to represent both nano and microplastics).

2.3 Exposure

2.3.1 Sources

What is known

Environmental factors acting on large pieces of plastic debris, generating secondary microplastics, are among the most common sources of nano and micro plastic pollution (Boucher & Friot, 2017; Law & Thompson, 2014). Due to harsh solar radiation and exposure to wind and waves, bulk plastic objects break down to form smaller particles (Andrady, 2011; Song et al., 2017). The degradation cycle continues and eventually forms micro and nano particles. While environmental action is the most common pathway for micro and nano plastic formation, other pathways have been identified (Boucher & Friot, 2017). For example, small plastic particles are often produced (within the microplastics size range) and find application in the cosmetic industry and are called microbeads (Beckwith & Fuentes, 2018). They are added, for example, to shower gel and facial scrub products, to increase the abrasive effect and improve exfoliation and cleaning properties of the treatment (Juliano & Magrini, 2017). Since microbeads are microscopic, they find their way into water systems and later into natural waterways (Cole, Lindeque, Halsband, & Galloway, 2011).

Synthetic textiles and clothing are a large source of microplastic pollution (Napper & Thompson, 2016). Abrasion during laundry as well as exposure to chemicals and detergents, cause the breakdown of synthetic fibres into smaller microfibres (Browne et al., 2015). Like microbeads, the microscopic size of the fibres allows them to find their way into the air, rivers, lakes and larger water bodies. City dust resulting from weathering, environmental abrasion and spills is another source of microplastic pollution, often mentioned together with abrasion of car tyres from driving (Boucher & Friot, 2017).

Plastic coatings are an effective, protective material and used to prevent oxidation of metal components, or as a thermal insulator. Some other sources of microplastics that are often mentioned in the literature are such coatings and paints (Gallo et al., 2018; Kroon, Motti, Talbot, Sobral, & Puotinen,

2018) and pollution coming from abrasion of the recreational fishing and marine vessels (Boucher & Friot, 2017). Effectively, these protective plastic layers are exposed to the environmental impacts that they are trying to protect from, and eventually they break down into smaller particles. The marine industry relies heavily on such lightweight plastic material. However, their long-term weathering, abrasion and degradation are sources of secondary microplastics, that directly enter the marine environment (Brandon, Goldstein, & Ohman, 2016; Duis & Coors, 2016). Also in the marine environment, abandoned, lost and discarded fishing gear (ALDFG) are considered a relevant source of plastic debris (Gillman, Chopin, Suuronen, & Kuemlangan, 2016), which due to fragmentation may contribute to the occurrence of microplastics in the oceans).

Abrasion from car tyres is considered a large source of micro- and possibly nanoplastics (Kole, Lohr, Van Belleghem, & Ragas, 2017; Wagner et al., 2018).Tyre wear particles (TWP) released from car tyres, and old tyre tread particles used as infill in artificial turfs are considered important sources for micronized rubber particles in the environment.

Apart from products and materials as sources, sometimes certain environmental entry pathways are referred to as sources in the literature. For example, atmospheric deposition can be considered as an entry pathway of NMP for land, freshwaters and the oceans, and export from rivers can imply an input to marine systems. Likewise, sewage treatment plants are sometimes considered a source or entry pathway of microplastics for freshwaters (Mason et al., 2016; Talvitie et al., 2015). As such, microplastics have been detected in both the primary and secondary sewage treatment stages (Carr, Liu, & Tesoro, 2016; Talvitie et al., 2015). Installation of post-filtration (tertiary treatment) removes up to 97% of microplastic particles, if applied (Mintenig, Int-Veen, Loder, Primpke, & Gerdts, 2017). Despite the relatively high removal efficiencies by sewage treatment, sewage effluents are still considered a major contributor to the presence of microplastics in surface waters.

Siegfried et al. (Siegfried, Koelmans, Besseling, & Kroeze, 2017) assessed the relative importance of these sources for export from river catchments in Europe to sea and found that most of the modelled microplastics exported by rivers to seas are synthetic polymers from car tyres (42%) and plastic-based textiles abraded during laundry (29%) Smaller sources are synthetic polymers and plastic fibres in household dust (19%) and microbeads in personal care products (10%).

What is Not Well Known
There are gaps in knowledge on the actual sources and entry pathways in quantitative terms. Furthermore, currently no reliable method exists for tracing and tracking the origin, source, transport or manufacturer of microplastics found in environmental samples. There are no specific markers that could be used in forensic microplastic studies. However, there have been (unpublished) attempts to trace the origin of plastic pollutants based on the dyes used to colour the material. Other attempts focused on precise comparison of insignificant differences in the composition. This method however is not yet reliable and would require the development of a large background database. In addition, because environmental factors such as abrasion, erosion and weathering affect the sample's matrix, the composition changes over time.

Unknown

In wastewaters too, nanoplastics are an unknown and while we think they are generated due to larger plastics aging, we cannot be sure, because the mechanism is unknown, and we cannot measure them.

2.3.2 Fate

What is Known

As outlined in the previous section, microplastics are known to be emitted directly into the environment as primary plastics (predominantly macroplastics), and when microplastics are used as manufactured products (GESAMP, 2016). Once in the environment, such plastic debris degrade and are the source of secondary plastics, smaller particles that progressively form due to embrittlement, abrasion or degradation of the primary plastics (GESAMP, 2016; Koelmans, Kooi, Lavender Law, & van Sebille, 2017b). Emissions occur to all environmental compartments, including: air, soil, freshwater and marine. Subsequent transport processes can redistribute emitted plastics among compartments of media, generally causing a flow from land to rivers and to sea (Kooi, Besseling, Kroeze, van Wezel, & Koelmans, 2018). Plastics litter will also move from sea to land, e.g. by beaching. Depending on their size, density and shape, microplastics settle in riverine sediments, or flow downstream and eventually reach the marine environment.

Transport is affected by particle size, density and shape as well as processes such as fouling and aggregation-sedimentation. Transport is also influenced by wind as well as water movement (Kooi et al., 2018). Furthermore, the transport at sea can also be influenced by the state of the sea. Turbulent mixing can transport positively buoyant plastic down for tens of meters (Hardesty et al., 2017; Kooi et al., 2016). Currents and waves, on scales from meters to thousands of kilometres, can transport plastic horizontally (Reisser et al., 2015). Microplastics can also be transported vertically down through the water column and have been found on the ocean floor (Van Cauwenberghe, Vanreusel, Mees, & Janssen, 2013; Woodall et al., 2014) and inside marine organisms residing at various depths (Hermsen, Mintenig, Besseling, & Koelmans, 2018b).

What is Not Well Known

With respect to the sources of NMP, we do not fully understand their whole life cycle fate 'from cradle to grave', and all of the disintegration steps of a product. Although some first attempts have been made (Koelmans et al., 2017b) there is currently insufficient information to quantify the mass or number concentrations of NMP across environmental media, based on product or polymer mass production volumes.

Within freshwaters, we know about the transport processes qualitatively and quantitatively from first principles. However, there is very little validation of these principles, if any. We know more about the fates and processes of some particle shapes, e.g. spheres (Kooi et al., 2018), but much less about the environmental fate of some others, such as films or fibres.

The main processes and timescales that cause fragmentation of larger plastic into NMP are not well known in any environment, but it is clear that ambient environmental conditions (e.g. sea surface, beaches, deep-sea) including temperature, UV and oxygen availability can all influence rates of

degradation. *How does plastic lose buoyancy to start sinking to the ocean floor* (generally assumed to be biofouling and weathering), and *to what extent NMPs reside suspended in the water column*, are unanswered questions that are important if we are to assess exposure and risk of NMP.

What is Unknown

The atmosphere and soil are important source media for surface waters and eventually the marine environment. However, we know virtually nothing about NMP transport mechanisms and mass flows in/from atmosphere and soil.

In freshwaters we do not know to what extent peak events such as flooding influence NMP transport and to what extent this transport is dynamic in time.

Although we know that mechanisms for biodegradation of some polymers exist (e.g (Albertsson, Andersson, & Karlsson, 1987; Austin et al., 2018; Awet et al., 2018; Bandopadhyay, Martin-Closas, Pelacho, & DeBruyn, 2018; Briassoulis, Babou, Hiskakis, & Kyrikou, 2015; Huerta Lwanga et al., 2018; Ong et al., 2018; Yang et al., 2018a; Yang et al., 2018; Yoshida et al., 2016), there are also major unanswered questions, such as: to what extent can microbes degrade NMP in the various compartments of the environment, and if that happens, then what are its end-products and especially: what are the time scales of this process? What is the role of biota in mass transport of NMPs? If considerable fractions of microplastics reside in biota (Hermsen et al., 2018b) then biota may drive substantial mass flows, however the role of ingestion-migration-egestion in the plastic debris budget is unknown.

One of the major unknowns across all environmental compartments relates to the question: through which mechanisms, at which time scales and where, do plastic debris progressively fragment to eventually reach the scale of nanomaterials. Are coastlines and beaches an important place for fragmentation? It is also not known how the occurrence of NMP in the atmosphere, soil, fresh- and marine waters and biota will evolve in the future, as a result of the current and future plastic emissions, product development and use and ongoing fragmentation.

2.4 Occurrence

2.4.1 Marine and Coastal Environment

What is Known:

Microplastics have been observed in many different domains of the marine system, including near the surface, in the so-called garbage patches in the subtropical gyres, and also in other hotspots (e.g. the Barents Sea and Mediterranean) (Cózar et al., 2014; Eriksen et al., 2014; van Sebille et al., 2015). Furthermore, microplastics have also been found in sediment samples from near-shore areas and the abyssal ocean (Woodall et al., 2014).

On the coastline, NMP have been quantified on sandy beaches at local and regional scales, worldwide (and in remote beaches), where they accumulate mostly within the drift lines on the surface of the sandy beaches (Browne et al., 2011; Lots, Behrens, Vijver, Horton, & Bosker, 2017; Lusher, 2015). There is also some evidence that microplastics can be found in the vertical profile of beach sediments (Turra et al., 2014).

While the large-scale (>100km) patterns of accumulation of microplastics are well known, the variability of distribution on smaller scales (e.g. eddies) is less well understood (Brach et al., 2018). It is also not well known what the total amount of microplastic on the ocean surface is: estimates vary by orders of magnitude and almost never include plastic < 0.3mm. This is partly related to the fact that most sampling has been done by trawling, using nets with > 0.3 mm mesh. In addition, there are limited methodologies for analysing plastic fibres in samples, and also because of the lack of understanding of the processes by which plastics fragment and sink. The lack of knowledge on particles < 0.3 mm is important since we need that information for the ERA. Furthermore, it is unclear how sources and accumulation areas are related, and how NMP are transported from rivers to the open ocean, thereby confounding which plastics ends up where (Hardesty et al., 2017) .

At the coastline, there is little information on the levels of NMP on non-beach sediments (e.g., mangroves, tidal marshes or rocky shores), nor about the 3-dimensional distribution of NMP in the body of sandy beaches, including the influence of oceanographic conditions and anthropogenic loads of NMP to sandy beaches (Browne et al., 2011; Chubarenko, Esiukova, Bagaev, Bagaeva, & Grave, 2018; Zhang, 2017).

What is Unknown:

In the open ocean, it is completely unknown how much microplastic is neutrally buoyant and thus resides just below the ocean surface (in the water column). It is also unknown whether there are processes by which plastic on the seafloor can resurface.

On coastlines, it is unknown what the inputs are of microplastics from both terrestrial and marine to coastlines (beaches), which processes deposit NMP on sandy beaches and even less is known about how much NMP is recaptured in the ocean from coastlines.

For all compartments there is a lack of globally standardized data on the *amount of* NMP.

2.4.2 Freshwater Environment and Estuaries

What is Known:

Recent studies have demonstrated that microplastics are widely distributed in freshwater bodies in concentrations at least similar to marine systems. They have been found on the water surface, in the water column and in sediments of lakes, rivers and estuaries (Eerkes-Medrano, Thompson, & Aldridge, 2015a; Li, Liu, & Paul Chen, 2018). The reported concentrations of microplastics in freshwaters vary among locations, from a few particles up to thousands of particles/m3 (Horton, Walton, Spurgeon, Lahive, & Svendsen, 2017; Rezania et al., 2018). Similarly, the concentrations of microplastics in freshwater sediments are very variable and can reach several thousand particles/kg of sediment (Hurley, Woodward, & Rothwell, 2018; Rezania et al., 2018). A number of studies have indicated the spatial association between microplastics in freshwaters and human activities (Eerkes-Medrano, Thompson, & Aldridge, 2015b; Li et al., 2018; Rezania et al., 2018).

There is very limited information about very small microplastics, i.e., smaller than 0.3mm/300 µm. Although much work has been done on method development, as we discuss in various places, there is no generally agreed method to analyse microplastics. These methodologies presented here therefore still have to 'score' as only partially known. More specifically, sampling location, sampling time as well as methodology, including sampling style, sample preparation and polymer identification are crucial for a reliable evaluation of the occurrence of microplastics in freshwaters, (as in other compartments) (Li et al., 2018). A plethora of sampling and detection methods are applied, resulting in concentration data that are not easily comparable (Eerkes-Medrano et al., 2015b). For instance, sampling with nets of 80 µm instead of 330 µm mesh size, results in 250 times higher concentrations (Dris et al., 2015). Likewise, sample preparation (such as separation with liquids of different densities, digestion of organic material using peroxide or enzymes) and the plastics identification (visual, spectroscopic or spectrometric) will determine the quality of the quantification of microplastics in a sample. Sample contamination (e.g., by airborne particles such as such as synthetic textile fibres) is a serious issue that needs to be also addressed add ref. Considering the whole set of studies of occurrence of microplastics in freshwater, there is a clear need for the further standardization of sampling and detection methods, which has to include a specification of measures for quality assurance (Koelmans et al., submitted).

Another gap of knowledge relates to the geographic representation of sampling locations. Although large Asian rivers are considered the major contributors to the microplastics pollution in the oceans (Lebreton et al., 2017; Schmidt, Krauth, & Wagner, 2017) only 16% of the monitoring studies were conducted in Asia, mostly in China. Likewise, Africa (4% of available studies) and South America (12%) are neglected regions (Blettler, Abrial, Khan, Sivri, & Espinola, 2018).

What is Unknown:

Sampling and analysis methods of nanoplastics are not yet established and, therefore, information on their occurrence in freshwaters is currently unavailable.

2.4.3 Wastewater

What is Known:

Municipal wastewaters are considerably polluted by microplastics, with effluent concentrations ranging between $10 - 10^7$ particles m^{-3} (Koelmans et al., Submitted). Microplastics are directly entering sewer systems from domestic sources, and here mainly consist of synthetic textile fibres, cosmetic microbeads and disintegrated parts of larger consumer products that are flushed down the toilet (Mourgkogiannis, Kalavrouziotis, & Karapanagioti, 2018; Murphy, Ewins, Carbonnier, & Quinn, 2016; Prata, 2018). Wastewater treatment plants (WWTP) are considered an important entry point for microplastics to the aquatic environment. Although treated effluents sometimes contain only few microplastics per litre (Carr et al., 2016; Ziajahromi, Neale, Rintoul, & Leusch, 2017), the total load of microplastics can still be high, due to the large volume of treated wastewater and the higher concentrations of microplastics that have been reported in rivers and streams downstream of WWTPs, in comparison to upstream (Estahbanati & Fahrenfeld, 2016; McCormick, Hoellein, Mason, Schluep, & Kelly, 2014).

As described in the earlier section about freshwaters, various sampling, sample preparation and plastic identification methods are used (Ziajahromi, Neale, & Leusch, 2016) without standardization for wastewaters too. The results of studies on wastewaters therefore, are also often inconsistent and difficult to compare.

Sewer systems transport microplastics into WWTPs, which are highly efficient barriers preventing microplastics from entering aquatic ecosystems. They are designed to remove particulate matter. The latest studies demonstrate that WWTPs retain 87–99% of the microplastics load (Rezania et al., 2018). The removal efficiency will depend on the specific treatment technology, and the differences in removal efficiencies between various technologies are still understudied.

Plastic and other particulate matter are removed from the liquid waste stream via sedimentation and end up in sewage sludge. Because sewage sludge is used as a fertilizer in many EU member states (Kacprzak et al., 2017), microplastics can thereafter be spread on agricultural lands and, thus, re-emitted to terrestrial ecosystems (Horton et al., 2017) (see the next section on soils). However, the magnitude of these inputs is only partially known.

Non-domestic effluent sources may contain a high number of microplastics, especially when they are generated directly by the plastics industry (e.g. plastic pellets, styrofoam used for filling, dust from drilling and cutting plastics). Industrial effluents may be treated by separate industrial wastewater treatment plants, or are indirectly discharged to the surface waters via sewage treatment plants (Prata, 2018). However, the contribution of industrial effluents to the overall concentration of microplastics in wastewaters has not been yet investigated (van Wezel et al., 2018). What is known, is that the percentage of industrial effluent compared to the total effluent treated varies highly between sewage treatment plants, for e.g. the Dutch CBS data (van Wezel et al., 2018).

Microplastics will enter aquatic systems via sewage storm water overflows, which release untreated wastewater in cases of extreme precipitation (Bhattacharya, 2016). This pathway may be more relevant than wastewater discharge but is insufficiently investigated. The same holds true for untreated wastewater discharges which on a global scale represent 80% of all wastewater (WWAP, 2018).

What is Unknown:

Due to the lack of a feasible technology, nanoplastics have not yet been detected in wastewater and thus information about their sources, occurrence and fate is unavailable.

2.4.4 Soils

What is Known:

Although knowledge of microplastics in soils is still limited (Rillig, 2012), they have been detected in a variety of terrestrial ecosystems. Microplastics have been reported in agricultural fields in North America (around 1 fibre g^{-1} soil) (Zubris & Richards, 2005), and in several riparian soils in Switzerland (up to 55.5 mg kg^{-1} and up to 593 particles kg^{-1} soil), which is (in part), far removed from direct human influence (Scheurer & Bigalke, 2018). Particles have also been found in soils in China (Zhang et al., 2018) and Australia (Fuller & Gautam, 2016).

Sources of microplastics found in terrestrial ecosystems are not well known. However, it is very likely that sewage sludge (Zubris & Richards, 2005) and animal manure (Nizzetto, Langaas, & Futter, 2016b) used as fertilizers in agriculture, introduce an important amount of microplastics into soils. Lessons learned from the analysis of microplastics in water or biota samples apply only to a limited extent to soils and analytical methods for the detection of microplastic in soils, are currently being developed, (also as per other environmental compartments) (Blasing & Amelung, 2018). There is no consensus yet, and it seems unlikely that currently available methods cover all forms of microplastics. The major challenge is that soil is a particle-rich substrate of extreme chemical complexity (de Souza Machado et al., 2018).

Methods for microplastic detection include: (1) water extraction and examination of fibres using polarized light microscopy; (Zubris & Richards, 2005) (2) heat-treating water-extracted particles and using image analysis to detect melted particles; (Zhang et al., 2018); (3) pressurized fluid extraction, a method that loses information on particle form and size (Fuller & Gautam, 2016); (4) density separation and oxidation of organic matter, followed by FT-IR identification (Scheurer & Bigalke, 2018) and use of Fenton's reagent to eliminate soil organic matter (Hurley, Lusher, Olsen, & Nizzetto, 2018).

What is Unknown:

It follows from the previous paragraphs that many gaps exist with respect to coverage of microplastics in terrestrial ecosystem types, especially forests, and in terms of continents, for example Africa. Similar to the other environmental compartments, there are no analytical methods for nanoplastics in soils, and thus there is no information on the occurrence of nanoplastic in soil.

2.4.5 Air

What is Known:

Microplastics have been reported in both indoor (Dris et al., 2017) and outdoor air (Cai et al., 2017; Dris, Gasperi, Saad, Mirande, & Tassin, 2016); total atmospheric deposition is two orders of magnitude greater indoors at 11,000 microplastics/m^2/d (Dris et al., 2017). A study of atmospheric fallout conducted on the rooftops of Paris reported predominantly microplastic fibres within a size range of 7-15 μm – 100-500 μm. The atmospheric fallout was calculated to be 2 to 355 particles/m^2/day, with higher rates at urban sites compared to suburban sites and associated with rainfall (though probably not significant). The quantity of fallout was estimated at 3-10 tonnes for an area the size of Paris (2500km^2) every year (Dris et al., 2016).

Tyre wear particles are an additional source of microplastics in air, and tyre wear particles can make up a significant component of ambient particulate matter (PM). Though, Harrison et al (Harrison, Jones, Gietl, Yin, & Green, 2012) reported tyre wear to contribute to only 10% of vehicle emissions. Studies conducted in Japan, Europe and the USA report tyre particulates and road wear particles to make up 0.05-0.70 mg/m^3 of the PM_{10} fraction (Panko, Chu, Kreider, & Unice, 2013). Microplastic pollution in deposited urban dust in Tehran was reported as 88 -605 microplastic particles/ 30 g dust (3 - 20 particles

/ dust), with particles ranging in size from 250 to 500 μm. The calculated human exposure to this material resulting from outdoor activity was a mean of 3223 and 1063 microplastic particles ingested/year for children and adults, respectively (Dehghani, Moore, & Akhbarizadeh, 2017)..

Occupational monitoring of indoor air has provided reports of high concentrations of airborne polyvinylchloride (PVC) microfibres of 7mg/m³ in manufacturing settings (Burkhart, Piacitelli, Schwegler-Berry, & Jones, 1999), whilst polyester fibres at a concentration of 1 x10⁶ particles/m³ can occur during particular processing activities (Bahners, 1994).

What Is Not Well Known:
The origins of microplastics in the atmosphere are not well understood, neither are the processes that may influence how airborne microplastics can move and behave, e.g. interactions with wind or rain. As textile fibres dominate, it is the origin of the non-fibrosis micro and nano-plastics which is not well understood. As proposed by Wright and Kelly (Wright & Kelly, 2017) there are a number of viable routes by which NMPs may reach the atmosphere and present a route of exposure through inhalation.

Sea salt aerosol formation, which typically produces particles of a mean size range <50 μm, provides a potential pathway for low density plastic particles to be transported into the air by onshore wind action (Athanasopoulou, Tombrou, Pandis, & Russell, 2008). Transport of plastic particles to air derived from dried sewage sludge onto agricultural soils has also been postulated, supported by the finding that synthetic clothing fibres persisted in soils up to 15 years after being applied (Zubris & Richards, 2005). Additional potential sources of plastic fibres to the air include clothes drying, air conditioning units, agricultural plastic sheeting, road traffic and urban dust.

What is Unknown:
There have been no estimates yet of the global extent of airborne microplastic pollution.

There are no studies describing atmospheric nanoplastic pollution (nor nanoplastic pollution in any other environmental compartment), again largely because the technology to perform such measurements is not yet established. (Despite this, some evidence presented above from the occupational exposure field in relation to manufactured nanomaterials, confirms inhalation as likely a major route for human exposure (SCENIHR, 2006). (Impacts outside of such occupational situations are unknown at present).

2.4.6 Biota

What is Known:
Field studies have demonstrated that a wide range of organisms across multiple trophic levels (or 'position in the food chain', from zooplankton to megafauna) and habitats contain microplastics, including those targeted by fisheries (De Sá, Oliveira, Ribeiro, Rocha, & Futter, 2018; Desforges, Galbraith, & Ross, 2015; Foekema et al., 2013; GESAMP, 2016 ; Hermsen et al., 2018b; Kühn, Bravo Rebolledo, & van Franeker, 2015; Lusher, 2015; Lusher et al., 2017). Consequently, ingestion is considered the most frequent interaction between microplastics and biota (GESAMP, 2016 ; Hermsen et al., 2018b; Kühn et al., 2015; Lusher, 2015). (This will be discussed further in Section 2.5.3 where hazards

are reviewed). The incidence of ingestion of microplastics by biota reported is highly variable, which is due to ecological, geographical and methodological differences (Hermsen et al., 2018b; Kühn et al., 2015). Filter feeders, deposit feeders and planktonic suspension organisms have been considered the most susceptible to microplastic ingestion, due to the relatively unselective nature of their feeding strategies (GESAMP, 2016 ; Lusher, 2015).

As in other environmental compartments/matrices discussed above, there is a wide variety of analytical methodologies and uncertainty about their reliability to detect microplastics in aquatic biota samples, despite the fact that here, the first steps towards standardization are being made (Hermsen, Mintenig, Besseling, & Koelmans, 2018a; Vandermeersch et al., 2015; Wesch, Bredimus, Paulus, & Klein, 2016). Laboratory-based studies have increased the number of aquatic taxa for which ingestion has been demonstrated, for instance for invertebrates (Browne, Dissanayake, Galloway, Lowe, & Thompson, 2008; Redondo-Hasselerharm, Falahudin, Peeters, & Koelmans, 2018; von Moos, Burkhardt-Holm, & Kohler, 2012), such as lugworms (Besseling, Wegner, Foekema, van den Heuvel-Greve, & Koelmans, 2013), zooplankton (Cole et al., 2013; Cole et al., 2016), and earthworms and vertebrates such as fish (de Sa, Luis, & Guilhermino, 2015; Huerta Lwanga et al., 2016; Ory, Gallardo, Lenz, & Thiel, 2018). For a limited number of organisms (daphnids, mussels, crabs, fish) the uptake and translocation of NMPs has been assessed in the laboratory (Browne et al., 2008; Mattsson et al., 2017). However, it is not clear whether this also occurs in other species and whether it occurs in nature.

What is Partially Known:
Although the occurrence of microplastics in terms of species, polymer types and number concentrations have been demonstrated, the mechanisms that lead to and determine the observed occurrences are not fully understood. The pathways of ingestion of microplastics by aquatic organisms in nature (i.e., directly or via contaminated prey) are variable and have not been fully tested. Microplastics may be able to spread through the food web by means of trophic transfer (i.e. movement through the food chain), a phenomenon that is expected based on theory (Diepens & Koelmans, 2018) and has also been suggested based on observations (Nelms, Galloway, Godley, Jarvis, & Lindeque, 2018; Setala, Fleming-Lehtinen, & Lehtiniemi, 2014). However, the number of studies reporting trophic transfer remain limited. For many species that are known to ingest and egest microplastics, the gut retention time is either not known, or is poorly known. Gut retention times are relevant as they define duration of internal exposure, and for digestive fragmentation. Digestive fragmentation has been shown for a planktonic species, (Dawson et al., 2018) but may occur for others as well. Within terrestrial food chains, there is recent field evidence of the transfer of microplastics (Huerta Lwanga et al., 2017), however the lack of data on terrestrial species, is much larger than that for aquatic food chains.

What is Unknown:
Due to the observed occurrence of microplastics in biota, biota is considered a (temporal) reservoir for NMP in the marine environment (Cozar et al., 2014). However, it is unknown what fraction of the total mass budget of NMP reside in biota and how this compares to other compartments such as the water column or the seabed.

As reported in other sections, currently there are no methods available for the detection and quantification of environmental nanoplastics within organisms. Consequently, there is no information on the occurrence of nanoplastics in biota in the field.

2.4.7 Drinking Water and Food

What is Known:

Microplastics have been detected in bottled and tap drinking water (Kosuth, Mason, & Wattenberg, 2018; Mason, Welch, & Neratko, 2018; Mintenig, Loder, Primpke, & Gerdts, 2019; Schymanski, Goldbeck, Humpf, & Furst, 2018) in concentrations ranging from several to 10^6 particles/L. These studies often target smaller microplastics (< 300 μm) compared to the many surface water studies, which means the measured concentrations are notably higher. Common polymer types, as well as shapes have been found, for example: PP, nylon, PS, PE, PEST, and shapes: fragments film, fibre, foam and pellet (Kosuth et al., 2018; Mason et al., 2018; Mintenig et al., 2019; Schymanski et al., 2018), similar to those found in surface waters. Microplastics also have been found in beer, sea salt, and seafood (EFSA, 2016; Kosuth et al., 2018; Lusher et al., 2017).

What is Partially Known:

There is sufficient published evidence to say that microplastics occur in bottled water and food stuff. Still, the number of human diet components, as well as the number of studies per diet component covered in the literature, is still very limited. Furthermore, the quality of studies that detected NMP in biota or drinking water is limited, which makes it difficult to draw conclusions. Collectively, this means that we have no full and balanced view about the occurrence of microplastics in food and drinking water.

What is Unknown:

Our knowledge of the occurrence of microplastics in components of the human diet varies across regions. As for nanoplastics in drinking water and food, there is no information at all. This means that currently there is insufficient data to assess exposure for humans, let alone to assess the human health risks of NMPs in drinking water and food. Furthermore, currently it is not well known to what level the materials used in drinking water production and distribution processes contribute to the occurrence of NMP in drinking water, and to what extent materials used in food production and packaging contribute to occurrence of MNP in food.

2.5 Hazards of Micro and Nanoplastic Particles

2.5.1 Ecotoxicity: Freshwater Species

What is Known:

It has been demonstrated that nano- and microplastics can induce physical and chemical toxicity (Bergmann, Gutow, Klages, & 2015; Wagner & Lambert, 2018) . The former occurs when the particles attach to the outer or inner surfaces of an organism. This can result in physical injuries, inducing inflammation and stress, or it can result in a blockage of absorptive surfaces (e.g., gut blockage) and a subsequent reduced energy intake or respiration. Physical toxicity can also manifest after tissue translocation of plastic particles, that is, a transfer from the outside (gut lumen) of the body into tissues.

In addition to physical impacts, nano- and microplastics can induce chemical toxicity. A discussion on these mechanisms is provided in section 2.5.5.

Considering the effect of sizes only (Foley, Feiner, Malinich, & Hook, 2018), concluded that exposure to microplastics has a significant, negative effect on food consumption, growth, reproduction and survival across all population groups.[1] Here, zooplankton, non-mollusk macroinvertebrates and juvenile fish appear to be especially sensitive. However, the study also reported an absence of effects for a range of species or endpoints and did not consider microplastics concentrations as the most important factor driving toxicity. More recent studies did find a clear dose-effect relationship, from which for instance EC_{10} (Effect Concentration for 10% of the population tested) values could be derived (Gerdes, Hermann, Ogonowski, & Gorokhova, 2018; Redondo-Hasselerharm et al., 2018). In summary, microplastics can have negative effects on the food consumption, growth, reproduction and survival of a range of species, once effect thresholds are exceeded.

What is Partially Known:
Limited data is available on the actual exposure of freshwater species to microplastics in the field. A range of studies report that nanoplastics and very small microplastics will pass biological barriers (e.g., the gut epithelium) and enter the body (Triebskorn et al., 2018). However, it remains unknown which proportion of particles actually passes epithelia (and what the rate of uptake is). In zebrafish, this is only observed when fish are exposed to high particle concentrations (Batel, Linti, Scherer, Erdinger, & Braunbeck, 2016). However, the tissue transfer of nanoplastics might be more relevant, as recently reported in fish (Mattsson et al., 2017). Galloway et al (Galloway et al., 2017) also reported the translocation of 70nm nanoplastic (nano acrylic ester copolymer particles) across the gut epithelium and into the liver in embryo zebrafish, fed with a diet containing 0.01% nanoplastics.

A major shortcoming of most effect studies, is that they are either performed using concentrations that are much higher than those currently reported in the environment, or that they are performed using very small microplastics, for which limited exposure data exists (Lenz, Enders, & Nielsen, 2016). In addition, most data is available for spherical polystyrene microplastics, which are not representative of the plastics found in the environment (Lambert et al., 2017). Another relevant question is, whether or not the experimental approaches developed for dissolved chemicals are adequate for assessing particle toxicity.

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[1] The meta-analysis does include data from marine and freshwater taxa.

A few studies investigated impacts on algae and aquatic higher plants. Microplastics can affect the root growth of floating duckweed (Kalčíková, Žgajnar Gotvajn, Kladnik, & Jemec, 2017) and nanoplastics hinder algal photosynthesis (Bhattacharya, Lin, Turner, & Ke, 2010). In both these cases, it is assumed that adsorption of particles induces physical toxicity, but the current knowledge about the mechanism of toxicity and ecological implications is limited (only one study on that exists). Impacts of nano and microplastics on the growth of sediment-rooted macrophytes have also been observed, but here also the knowledge is limited (i.e. effects only at very high concentrations), (van Weert, Redondo-Hasselerharm, Diepens, & Koelmans, 2019). The long-term, ecological impacts of nano- and microplastics in freshwaters remain unknown.

2.5.2 Ecotoxicity: Marine Species

What is Known

Laboratory experiments with different marine species have been conducted to investigate ingestion, translocation, excretion and toxicity of microplastics (Besseling et al., 2013; Cole, Lindeque, Fileman, Halsband, & Galloway, 2015; Farrell & Nelson, 2013; GESAMP, 2016 ; Lusher, McHugh, & Thompson, 2013; Watts, Urbina, Corr, Lewis, & Galloway, 2015). The majority of ecotoxicological studies have used marine organisms as model species, including small crustaceans, molluscs, worms and fish (Lusher et al., 2013; Wright, Rowe, Thompson, & Galloway, 2013). There is also evidence that microplastics are ingested by a wide range of organisms in the natural environment (Lusher et al., 2013).

Most laboratory studies have assessed the effects of microplastics on individuals rather than cells, organs or populations and at high concentrations. Among the biological effects identified in organisms exposed to microplastics, most studies to date focused on physiology impacts and particular traits of the exposed organisms (such as feeding rate, oxygen consumption, growth development, mortality, as well as behavioural responses (Wright et al., 2013).

A reduction of feeding efficiency due to ingestion of microplastics was documented for zooplankton, lugworms and fish and a reduction in oxygen consumption was also evident for lugworms and crabs, exposed to different sizes and types of microplastics (Cole et al., 2015; Farrell & Nelson, 2013; GESAMP, 2016 ; Sussarellu et al., 2016).

Microplastics have also been demonstrated to have negative impacts on early stage development of marine biota, with evidence of negative effects on the growth and body condition of sea urchins

and on the growth and photosynthesis of microalgae (Rochman et al., 2014), under lab conditions (Martinez-Gomez, Leon, Calles, Gomariz-Olcina, & Vethaak, 2017; Zhang, Chen, Wang, & Tan, 2017; (Rochman, Hoh, Kurobe, & Teh, 2013)).

In addition, toxic effects related to immune response, oxidative stress and neurotoxicity have been reported for molluscs (Browne, Niven, Galloway, Rowland, & Thompson, 2013) , and these have been translated into increased mortality rates for copepods (GESAMP, 2016).

It is noteworthy that while the working group consider these as 'knowns', most of these studies have been conducted using different bioassay protocols, that in many cases used concentrations of microplastics considerably higher than found in the environment for larger MP. For smaller MP, the environmental concentrations remain to be determined. For instance, a limited relevance for bioaccumulation of microplastics under likely environmental conditions was detected for lugworms (Teuten, Rowland, Galloway, & Thompson, 2007). Acute experiments also showed no toxic effects of microplastics on marine zooplankton (Tanaka et al., 2013).

What is Partially Known:

The environmental relevance of such laboratory studies is not clear, since the majority of studies has employed particle sizes that are smaller, or concentrations that are greater, than those that are typically reported for the environment (Connors, Dyer, & Belanger, 2017). However, it is important to note that our understanding of environmental concentrations is incomplete and is limited by sampling methods and ability to identify particles. Hence, our current knowledge of environmental concentrations is regarded by many to be an underestimate of the actual concentration and this is particularly the case for very small particles. In addition, numerous studies have been conducted using homogenous, PE or PS particles that do not represent the heterogeneity of particles found in the environment. Polypropylene, polyester and polyamide particles are under-represented in laboratory studies. However, it should be recognised that there are uncertainties about what are realistic environmental concentrations too, because the ability to isolate and quantify particles from environmental media is methodologically constrained, especially for smaller particles.

NMP can pass through the digestive system of organisms and can be excreted (Wright et al., 2013) and it is also clear that some particles can transfer from the gut to the circulatory system (Browne et al., 2008); however, little is known about how this varies between organisms and particle sizes. It has been suggested that smaller particles are potentially more hazardous, equally it may be possible that very small particles in the nano size range may pass into and out of organism with relative ease. More work is needed to understand the differential retention and effects of particle size.

What is Unknown:

Little is known about the effects of microplastics across a wider range of organisms (other than the model species commonly used in ecotoxicological studies, such as fish, crustaceans and molluscs), and little from all trophic levels within marine food webs.

Most laboratory experiments have exposed organisms to relatively short-term *acute* exposures and little is known about chronic effects. In addition, little is known about the long-term effects of particles that are retained by organisms. Finally, the majority of experimental evidence is at the organismal or sub-organismal level and there is limited evidence about how to scale up to higher levels of organisation (populations, assemblages) (Browne et al., 2015).

2.5.3 Ecotoxicity: Soil Species

What is Known:

There are very few experimental studies on soil biota. The most investigated group of organisms is earthworms and some studies showed an impact of PE beads (looking at the earthworm's mortality) (Huerta Lwanga et al., 2016), ,but, others did not observe negative effects using a similar experimental system and the same earthworm species. Microplastics did not affect feeding behaviour in isopods (crustaceans in soil) (Jemec Kokalj, Horvat, Skalar, & Krzan, 2018). Effects of microplastics on terrestrial plants have not yet been systematically studied, however there is one study where negative effects on wheat root growth were observed (Qi et al., 2018). There is one report providing field evidence for transfer of plastic debris along a terrestrial food chain (Huerta Lwanga et al., 2017); here micro- and macroplastic in soil, earthworm casts, chicken faeces, crops and gizzards (used for human consumption) were assessed.

What is Partially Known:

Key soil physical variables, including reduced soil aggregation, lower bulk density and increased water-holding capacity can be affected by different microplastic types (especially fibres) (de Souza Machado et al., 2018). Such effects are likely to have ripple-on effects on many soil microbial groups and perhaps root growth.

What is Unknown:

At present, there are no studies of nanoplastic effects in soil. There are also no studies on the effects of nanoplastics on plants and how NMP can affect the crop yield and consequently food production.

2.5.4 Field and Ecological Effects

What is Known:

The occurrence of NMPs in biota and 'the field' have been reviewed in earlier sections. Regarding their toxicity, compared with the increasing body of knowledge relating to sublethal toxicological effects at the level of individual organisms, much less is known to quantify ecological and community-level effects of microplastics, especially in the field (see Figure 2). Despite this, several mechanisms of effect at the ecological level of organisation, have been suggested or investigated by various authors. These include those related to the physical presence of plastics as an alternative environmental matrix, such as shading effects, alterations in porosity or texture of sediments, alterations in the buoyancy of organic material and its transfer through the water column, as well as the transfer of pathogens and invasive species on buoyant debris (see (Galgani, Hanke, Werner, & De Vrees, 2013; Galloway, Cole, & Lewis, 2017; Wright et al., 2013; Zarfl et al., 2011).

Kleinteich et al (Kleinteich, Seidensticker, Marggrander, & Zarfl, 2018) applied genetic fingerprinting techniques to test the sensitivity of natural freshwater sediment bacterial communities to the presence of microplastics. Whilst the microplastics affected the bacterial community composition in sediments from an uncontaminated riverbed, those from a polluted river section were resistant to change. Here, the microplastics had a *protective effect*, in reducing the bioavailability of the hydrophobic contaminants.

Goldstein et al (Goldstein, Rosenberg, & Cheng, 2012) investigated the potential for microplastics to act as a novel hard substrate in the North Pacific Subtropical Gyre and found that its presence was correlated with enhanced oviposition by the endemic insect *Halobates sericeu.* The increase in egg densities offered a potential route for enhancing the transfer of energy and nutrients between assemblages associated with pelagic and substrate zones.

The potential for microplastics to influence carbon and nutrient cycling has been proposed through alterations to the biological pump that transports atmospheric carbon to the deeper ocean. Ingestion of microplastics altered the sinking rates of zooplankton faecal pellets and facilitated their ingestion through trophic levels, enhancing food web trophic transfer (Cole et al., 2016). The potential for transfer of contaminants associated with NMP through trophic levels has been further modelled by Diepens and Koelmans (2018), noting subtle differences in the dynamics of transport for pollutants of varying physicochemical character (e.g. polybrominated biphenyls and polyaromatic hydrocarbons).

Ingestion of plastics as a replacement for nutritious food, resulting in reduced energy allocation for growth, reproduction and other bodily functions has been noted in a number of experimental contexts (Galloway and Lewis (Galloway et al., 2017). For example, culturing worms in sediments contaminated with concentrations of microscopic PVC of 1%, led to a decrease storage amounts of lipid, of up to 30% (Wright et al., 2013). They calculated that based on the current densities of worms in coastal mudflats of 85 worms per m^2, and with each worm processing 400 cm^3 annually, 33 m^3 of microplastic would be taken into the food web and the decrease in feeding activity would cause an annual decrease of bioturbation of 130×10^6 m^3 of sediment. Additionally, alterations in patterns of behaviour, including changed responses to feeding cues in birds (Savoca, Wohlfeil, Ebeler, & Nevitt, 2016) and changes in anti-predator behaviour in arthropods (such as jumping behaviours), have been reported (Tosetto, 2016).

There are currently a few studies that have quantified effects on ecological functioning. Effects on the ecological functioning of bivalve (mollusc) dominated habitats when contaminated with biodegradable or non-biodegradable microplastics were reported (Green, 2016). Outdoor experimental systems called 'mesocosms' were used to conduct experiments using mussels and oysters. There were no effects seen for mussels when measuring filtration rates, nitrogen cycling or primary productivity of the sediments. However, for oysters, significant increases in filtration rates were seen, with subsequent changes to the distribution of sediment-dwelling biota. This illustrates how subtle effects can be species specific. Outdoor mesocosms (experimental systems that examine the natural environment under controlled conditions) containing oysters were similarly used to show that repeat exposure to relatively high concentrations of microplastics led to reductions in the diversity of associated benthic assemblages, including reductions in gastropods and arthropods, with both of these examples presumably due to differences in the distribution of nutrients (Green, 2016).

Some ecologically relevant studies address trophic transfer rather than population effects or ecological functioning. As mentioned in Section 2.4.6, trophic transfer has been demonstrated for a range of species, including from mussels to crabs (Farrell & Nelson, 2013; Watts et al., 2015) between planktonic trophic levels (Setala et al., 2014) and between herring and captive seals (Nelms et al., 2018). When the

microplastic content of herring used as feed, was compared with that found in the faecal matter of seals fed with the same herring, differences were found in the size and shape distribution of the plastics, suggesting that longer fibrous shapes were being retained in the gut of the seals, or that routes of exposure other than through food (e.g. inhalation of airborne particles) were going on.

A four-species model of a freshwater food web (with algae, waterflea, primary and secondary consumer fish) was used to explore the uptake and distribution of nanoplastics of <100nm. It showed that nanopolystyrene was widely distributed throughout the algal cells and tissues of exposed animals. It was adhering to the external body wall and appendages and even penetrating the embryo wall and yolk sac of hatched juvenile fish, albeit at relatively high exposure concentrations of 50 mg L^{-1} (Mattsson et al., 2017). There were some negative impacts observed, with alterations in fish motility, most notably the distance traveled and area covered, with evidence of histopathological alterations in the livers of fish that were exposed to nanoplastics directly (Chae & An, 2018).

What is Partially Known:
Larger scale ecological effects are widely postulated, but to date are largely unexplored. A systematic review in 2016 highlighted that of 366 perceived threats to marine life due to debris, 296 had been tested, of which 83% were found to be substantiated. These were almost all at the sub organismal level (Figure 2), and whilst evidence was available to support affects at the level of individual organisms and assemblages, most of these were from larger items of litter. This reveals the lack of data and urgent need for more study to document ecological impacts for microplastics (Rochman et al., 2016).

Recently, the need to bring ecological relevance to chemical effect assessments for microplastics has been addressed by using species sensitivity distributions (SSDs), in higher tiers of effect assessments, although the generally sublethal levels of the effects attributed to NMPs and lack of data generally has hindered a comprehensive assessment (Besseling, Redondo-Hasselerharm, Foekema, & Koelmans, 2018

)
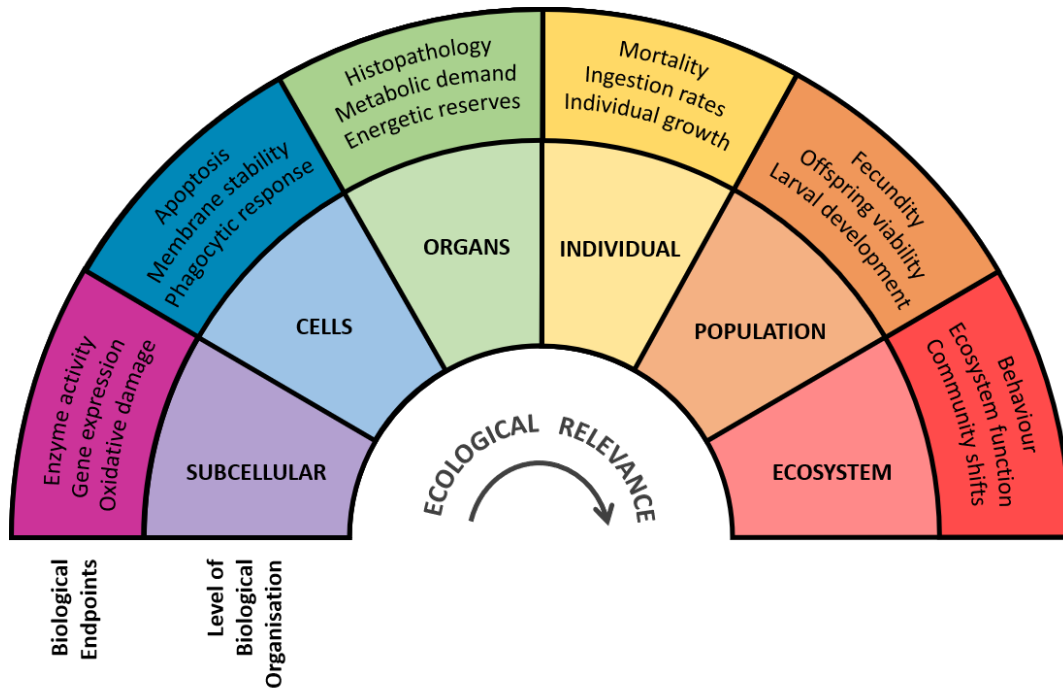
Figure. 2 Impacts of NMP on biota reported at various levels of biological organization. (A biological endpoint is a marker of disease progression). Most studies have been at sub-organismal levels and studies at a community or ecological level are relatively sparse.

2.5.4 Impacts on Human Health

What is Known:

We have discussed that microplastics have been documented in both marine (Yang et al., 2015) and freshwater (Ossmann et al., 2018; Wagner & Lambert, 2018) and dietary sources. However, exposure via ingestion of atmospheric deposition also represents a substantial pathway (68,415 microplastics/person/yr, and (Catarino, Macchia, Sanderson, Thompson, & Henry, 2018)) microplastics have been reported in both indoor and outdoor air (Section 2.4.5) (Dris et al., 2017) and (Cai et al., 2017; Dris et al., 2016). Exposure via inhalation is dictated by aerodynamic diameter (<10 μm aerodynamic diameter deposit in the airway) (Carvalho, Peters, & Williams, 2011). In the gut, particle uptake (<10 μm) can occur via endocytosis and phagocytosis (Eldridge, Meulbroek, Staas, Tice, & Gilley, 1989), in the Peyer's patches of the ileum, or via persorption for larger particles (up to 130 μm) (Volkheimer, 1993).

Occupational exposure to plastic microfibres leads to granulomatous lesions, postulated to contain acrylic, polyester, and/or nylon dust (Pimentel, Avila, & Lourenço, 1975). This causes a higher prevalence of respiratory irritation (Warheit et al., 2001). Flock worker's lung is a rare interstitial lung disease which

establishes in nylon textile workers exposed to respirable-sized fibre dust (Boag et al., 1999; Eschenbacher et al., 1999; Kremer, Pal, Boleij, Schouten, & Rijcken, 1994). Workers also present chronic respiratory symptoms and restrictive pulmonary function abnormalities.

Plastic fibres are extremely durable in synthetic lung fluid (Law, Bunn, & Hesterberg, 1990). Stemmer et al. (Stemmer, Bingham, & Barkley, 1975) found that inhaled polyurethane foam dust caused inflammation and eventually tissue scarring in guinea pigs. Additives, dyes and pigments are often incorporated in plastic products, many of which have additional human health effects, including reproductive toxicity, carcinogenicity and mutagenicity (Fromme, Hilger, Kopp, Miserok, & Völkel, 2014; Linares, Bellés, & Domingo, 2015; Lithner, Larsson, & Dave, 2011).

What is Partially Known:
Evidence on airborne microplastics is sparse. However, a predominance of airborne microplastic fibre diameters between 7 and 15 µm has been reported (Dris et al., 2017), thus entry into the airway is plausible, but this is yet unmeasured. Plastic fibres have been reported once in pulmonary tissue (Pauly et al., 1998). In the deep lung, very small microplastics may be taken up by macrophages and epithelial cells (Geiser et al., 2005), and potentially translocate into systemic circulation, as observed for titanium dioxide (Husain et al., 2015). Larger microplastics could be cleared to the gut or evade clearance mechanisms.

There is very little evidence quantifying dietary exposure, and to date, this has only focused on seafood exposure pathways (Lusher et al., 2017). In the gut, the mucus layer presents a barrier; latex microbeads (500 nm) exhibit restricted diffusion through it (Bajka, Rigby, Cross, Macierzanka, & Mackie, 2015), although this hasn't been studied for environmental microplastics.

An additional potential impact may be caused by the inhalation of microplastics carrying microbial colonisation (Kirstein et al., 2016; Zettler, Mincer, & Amaral-Zettler, 2013). In addition to the risks associated with pathogenic species infections, inhaled microplastics could cause a shift in the microbial community structure of microbes colonising the lung. Co-contamination with organic contaminants could lead to their microbial metabolism and activation of oxidative stress pathways.

What is Unknown:
With a sparse evidence-base for both dietary and airborne microplastics exposures, especially concerning the inhalable size fraction, it is unclear what the human daily intake of nano- or microplastics is, yet this knowledge is essential for estimating health effects. Little to nothing is known of the kinetics and biodistribution of microplastics post-exposure. The *in vivo* persistence of microplastics in different physiological environments is also unknown. Whilst evidence exists for the inflammatory effects of plastic dust in animal models, information on whether these studies translate to humans is lacking.

How translational the evidence on inflammatory effects of occupational exposure to plastic fibres is, to a low-dose exposure over a life course is not known. Chemical effects in the lung or gut could occur following the desorption or leaching of chemicals, but there is a lack of information on the remaining burden of chemicals or monomers in environmental microplastics. The role of shape – fibrous and non-

fibrous – in toxicity is also unknown for microplastics. There is a concern that, if small enough, fibres may cause effects similar to those of asbestos.

2.5.6 Interactions with Chemical Pollutants

What is Known:

Several recent reviews have summarized our current understanding of the interactions between microplastics and chemical pollutants, and the implications of this interaction for chemical exposure and risk (GESAMP, 2016; Koelmans, Bakir, Burton, & Janssen, 2016a; Wang et al., 2018; Ziccardi, Edgington, Hentz, Kulacki, & Kane Driscoll, 2016). Microplastics are known to contain organic chemicals from manufacture (additives, monomers, catalysts, reaction by-products), chemicals that can leach out of the plastic once microplastics are released in the environment (GESAMP, 2016 ; Hermabessiere et al., 2017). At the same time they also take up other hydrophobic organic chemicals from the environment, just as organic matter or lipid phases in sediment or organisms do (GESAMP, 2016; Koelmans, Bakir, Burton, & Janssen, 2016b; Ziccardi et al., 2016). This renders the bioavailability of microplastic-associated chemicals highly variable and context dependent.

For instance, if organisms are relatively clean compared to microplastics and the plastic is the only or the dominant chemical source, microplastic ingestion leads to extra bioaccumulation of chemicals (Koelmans et al., 2016b). Such increased chemical bioaccumulation due to microplastic ingestion only leads to adverse effects if chemical effect thresholds are exceeded. However, if chemical concentrations are high enough, microplastic ingestion can cause adverse chemical effects. The latter scenario has been dealt with in several laboratory studies, that showed adverse effects at high chemical and microplastic concentrations (GESAMP, 2016 ; Koelmans et al., 2016b).

Chemicals are also taken up by other uptake pathways, that is, from food, prey or ambient water, and recent experimental work has demonstrated that in more ecologically-relevant situations, this far exceeds the uptake of chemicals via plastics (Beckingham & Ghosh, 2017; Devriese, De Witte, Vethaak, Hostens, & Leslie, 2017; GESAMP, 2016 ; Horton et al., 2018; Koelmans et al., 2016b; Lohmann, 2017; Rehse, Kloas, & Zarfl, 2018). Alongside those organisms tested, this has also been argued with respect to exposure to microplastic-associated chemicals in humans. EFSA (EFSA, 2016) estimated that the consumption of 225 g mussels (~1 portion) would, at maximum, cause the ingestion of 7 µg microplastics. This would, even under worst case assumptions, contribute less than 0.2% to the dietary exposure of Bisphenol A, and even less for PCBs and PAHs.

Furthermore, the bioavailability of plastic-associated chemicals has been demonstrated to be less than that of natural food items, which are more easily digested (Beckingham & Ghosh, 2017). For these reasons, effects of microplastic ingestion on chemical bioaccumulation (i.e. uptake by the organism) generally will be minor in nature. Still, in hot spot locations, or when microplastic concentrations in the environment would increase, some extra bioaccumulation is to be expected for such chemicals (Chen et al., 2018; Diepens & Koelmans, 2018).

Under reversed conditions, that is, if organisms or their prey are more contaminated than ingested microplastics, the situation is the other way around and plastic ingestion leads to less chemical bioaccumulation (GESAMP, 2016 ; Koelmans et al., 2016b; Scopetani et al., 2018).

What is Partially Known:

Although the mechanisms behind the interactions between chemical pollutants and microplastics are reasonably understood, their interaction remains difficult to predict in nature. This is because it is not clear what the chemical concentrations are on plastics and in water, and how these chemical concentrations change over space and time. Furthermore, we know little about the effects of particle aging and fragmentation on the interaction between chemicals and microplastics (Jahnke et al., 2017). Finally, actual exposure of organisms to microplastics, chemical exchange rates to/from plastics under gut fluid conditions (i.e., inside the gut of organisms, including humans), and actual risk characterisations due to this exposure across a variety of habitats are only known to a limited extent.

What is Unknown:

One major unknown is the chemical composition of plastics, which varies from product to product even for the same polymer type. Often, additives remain unknown, which hinders an effective assessment of the risks associated with leaching of such chemicals. Furthermore, there are previously described general knowledge gaps that also specifically limit our understanding of risks due to plastic-associated chemicals. For instance, there is no reliable information about what the range of future concentrations of microplastics in the oceans will be. This causes high levels of uncertainty with respect to the chemical risks associated with the microplastic. For nanoplastics, the information gap is even larger. As the nature and concentrations of nanoplastics in the environment have not been measured yet, we do not know anything about the importance of nanoplastics for the total chemical risks posed by fragmenting microplastic (Koelmans et al., 2015).

2.6. Risks

What is Known:

Little is known with respect to the ecological and human health risks of NMPs, and what is known is surrounded by considerable uncertainty. The conclusions drawn from this information are uncertain, and this uncertainty was assessed in part via a formal expert elicitation procedure which time did not permit the working group to complete, but which helped clarify the language used to write these conclusions, and the degree to which the group found consensus or not to these conclusions on risk. Expert elicitation for policy advice should built on and use the best available research and analysis and be undertaken only when, given those, the state of knowledge is insufficient to support timely informed assessment and decision making (Morgan, 2014). Therefore, the procedure has been suggested earlier as a way to deal with the uncertainties associated with knowledge on NMPs (EFSA, 2014; Koelmans et al., 2017a).

A range of reports, books and reviews from academics (Bergmann et al., 2015; Koelmans et al., 2017a; Wagner & Lambert, 2018), governmental and international bodies (GESAMP, 2015, GESAMP, 2016, US EPA, 2016) and various scientific publications, discuss microplastic risks for the environment (Avio, Gorbi, & Regoli, 2017; Chae & An, 2017; Chae & An, 2018; da Costa, 2018; Syberg et al., 2015) or human

health (Lusher et al., 2017; Smith, Love, Rochman, & Neff, 2018). These papers reflect on approaches to assess risks of microplastics in a general sense, but they do not aim to provide a quantitative characterization of risk (RCR) that could serve as a reliable basis for the implementation of risk management measures.

Three recent peer reviewed articles do aim to provide quantitative risk estimates for microplastics, based on comparison of measured (MEC) or predicted exposure concentrations (PEC) and predicted no effect concentration (PNEC) data (Besseling et al., 2018 ; Burns & Boxall, 2018; Everaert et al., 2018).

Everaert et al (2018) analysed the risk for the marine environment. The authors estimated a maximum acceptable concentration of 6650 buoyant particles per m-3 using a species-sensitivity distribution (SSD). They compare this effect threshold with an estimated average concentration at the ocean surface of 0.2 – 0.9 particles per m3 for 2010. This means that a risk was not expected based on these average ocean data. However, based on published high MECs for specific locations, they concluded that 'adverse effects could potentially occur'. They presented similar analyses for the seafloor and beached microplastics, also showing effect thresholds being orders of magnitude higher than present measured concentrations. However, using a model to estimate future predicted environmental concentrations (PECs), it was concluded that adverse effects of sedimented and beached plastics are expected around 2060. The first type of assessment is colloquially referred to as a retrospective assessment, whereas the latter is an example of prospective risk assessment (Maltby, 2006) . Although both are associated with considerable uncertainty, this is more the case for the prospective assessment, as it relies on a very uncertain prediction of future concentrations in the oceans.

Besseling et al (2018) analysed risks of microplastics for the aquatic environment. They estimated an HC_5 (Hazardous Concentration for 5% of the species) of 113×10^3 particles m^{-3} using an SSD. They compared this threshold with the highest reported MECs (102×10^3 particles m^{-3} on a coastal water location) and concluded that ecological risk could exist in coastal waters, because of the similar particle number concentrations reported there. For freshwater and the ocean surface however, MECs were three and five orders of magnitude lower than this HC_5 value, respectively.

Burns and Boxall (2018) reviewed risks of microplastics for the aquatic environment and showed that, on average, MECs are several orders of magnitude lower than effect thresholds obtained from laboratory studies. They also constructed an SSD and calculated a HC_5 value of 6.4×10^7 particles m^{-3}, which was 3 orders of magnitude greater than the 95% MEC of 8.5×10^3 particles, which, based on current data, indicates that risks are limited. However, as in case of the above assessments, the margin of safety between highly polluted areas and sensitive species is low indicating that there may be some habitats in which risks can occur.

The effect data used in the hazard assessment, as well as the MEC data used to assess exposure, differ considerably among these studies and so do the resulting risk characterizations. Notably, all of these studies emphasize the provisional nature of their assessments because of the limitations in the data that were used. The studies relied on concentration data that are uncertain, due to incomplete sampling of compartments considered and due to the often-limited reliability of analytical methodologies used (Connors et al., 2017). Another limitation is that the exposure assessment is based on data for large

microplastics whereas the hazard assessment used data for smaller microplastics. The concentrations of the latter in the environment remain largely unknown but are expected to be higher than the concentrations of larger particles. Accordingly, the exposure assessment might underestimate the actual environmental concentrations of small microplastics. Estimated HC_5 or acceptable concentrations vary by 5 orders of magnitude. The SSDs must be considered provisional as well, as they contained:

- a limited number of data points;
- were not fully representative of all relevant functional groups;
- not all incorporated data points have a population relevance;
- and they included data obtained for a diverse variety of tested microplastic types (shape, size, polymer, associated chemicals);
- which however do not necessarily match those that are present in the environment.

The latter implies that the risk characterization is uncertain. Nevertheless, and while acknowledging such uncertainties, the three studies share the observation that exposure concentrations are on average *orders of magnitude* lower than concentrations where effects are expected to occur, but that this may be different for very specific locations or in the future.

The above evidence summarizes what is known about the ecological risks of microplastics based on the literature. As mentioned, this information is considered provisional and the number of studies addressing such risks quantitatively, is small (n=3). Therefore, the issue remains how this information should be interpreted, and what it tells us about the *true* current and future risks of microplastics. The working group has thus formulated conclusions with respect to the risks of microplastics that still are uncertain and the likeliness of the conclusions to be true is evaluated differently among experts. As part of the process, the differences were made explicit by using an expert elicitation procedure where experts with expertise relevant to risk assessment, assigned a certain level of likeliness to the formulated conclusions.

What is Partially Known

In many academic papers and reports, the concentration-dependency of risks has received little attention (also true for other types of societal reporting media, as reviewed in Chapter 3). The scarce data from academia on dose-response relationships have allowed for provisional examples of characterizations of risks only for the aquatic compartment. There are very limited dose-effect data for benthic organisms and terrestrial organisms, however insufficient for systematic risk characterizations based on single species test effect thresholds, let alone for the construction of SSDs. The same holds for exposure data, where especially for soils the data gap is huge. This implies that the information is fragmentary and that a systematic risk assessment based on dose response relationships for species across compartments is not yet possible.

What is Unknown

Risk assessment combines a hazard and exposure evaluation. The quality of any risk assessment is determined by its weakest piece of evidence. Therefore, the risk assessment process is limited by all the knowledge gaps listed in the previous chapters on exposure and hazard assessment. For microplastics,

quantitative assessments are currently lacking for other environmental compartments than water, and in relation to risks for human health. Human health risk assessment for NMP, has therefore not yet been done.

No risk assessments have been published for nanoplastics. It is yet unknown what are the concentrations of nanoplastics in environmental compartments or components of the human diet. Therefore, exposure cannot yet be assessed. As for effects, there is limited data, however, most of the experimental designs did not allow for constructing a dose-effect relationship. Furthermore, the limited studies use synthesized nanoparticles, most often nano-sized polystyrene and it is unknown how well these represent nanoplastics that occur in the environment (Gigault et al., 2018).

2.7 Modelling

What is Known

Numerical modelling is one of the tools with which we can gain insight into the fate and transport of plastic debris, including microplastics and its associated chemicals, across environmental compartments. It is a widely applied technique to tackle complex geological problems by computational simulation of scenarios. Over the past decade, a series of models of various complexity have been constructed that specifically target plastic debris or microplastics. These models have been applied to various aspects of the wider problem of plastic debris, such as:

- the emission of plastics, plastic debris, nano- or microplastics, to countries (Kawecki, Scheeder, & Nowack, 2018).
- transport in rivers and river catchments on various scales (Kooi et al., 2018).
- export to the oceans (Siegfried et al., 2017).
- transport and circulation in the oceans (Hardesty et al., 2017).
- predicting the mass of plastic debris in the ocean from plastic production data (Koelmans et al., 2017b).
- vertical transport in the ocean (Kooi, Nes, Scheffer, & Koelmans, 2017).
- transfer of microplastics in aquatic food webs (Diepens & Koelmans, 2018); and
- the role of plastic as a vector for chemicals to organisms (Koelmans et al., 2016a).

Here we provide an overview of relevant modelling approaches and of any potential to shed light on some of the more complex aspects of microplastics including future 'what if?' and 'under which conditions?' scenarios.

Emission and transport on land and in rivers

Kawecki et al (2018) presented a static probabilistic material flow analysis of seven polymers for Europe and Switzerland to provide a basis for exposure assessments of polymer-related impacts. This necessitates that the plastic flows from production to use and finally to waste management are well-understood. The results may serve as a basis for more refined assessments of exposure pathways of plastics (or their additives) in the environment or exposure of additives on human health. As such, they also inform risk assessment of NMPs, which may form from the materials assessed in the study.

An example of a more refined microplastic transport and exposure model was provided by Nizzetto et al (Nizzetto, Bussi, Futter, Butterfield, & Whitehead, 2016a). They presented a spatiotemporally explicit model that was applied to the Thames River catchment. The model is based on an existing hydrobiogeochemical multimedia model, INCA (Integrated Catchment) contaminants, with a rainfall-runoff module, a sediment transport module and the possibility to add direct effluent inputs from for instance, WWTPs.

This model showed that the transport of microplastics is related to flow regime, especially for the larger (> 0.2 mm) particles. It did not include biofouling, aggregation, or fragmentation, and did not include nanoplastics.

Besseling et al (2017) also presented scenario studies on the fate and transport of NMP with a spatiotemporally resolved hydrological model, accounting for advective transport, homo- and heteroaggregation, sedimentation-resuspension, presence of biofilm, polymer degradation and burial. This model did include nanoplastics and simulations provided retention of NMP in a river stretch, concentration profiles in the water column and concentration hot spots in the sediment. A similar study was published recently for car tyre dust particles, however in this case the model was implemented on a much wider i.e. river catchment scale (Unice et al., 2018).

What was learned? The relevance of the 3 above studies (Besseling et al., 2018

; Nizzetto et al., 2016a; Unice et al., 2018) is that they showed how particle characteristics and river hydrodynamics affect the transport of microplastics, and how this affects exposure in freshwaters and export to marine systems.

Lebreton (Lebreton et al., 2017) provided an empirical model, in which data on mismanaged plastic and run off in catchments were correlated to measured microplastics concentrations in 13 rivers, which then was extrapolated to all rivers in the world to estimate microplastics export from river to sea. Whereas significant correlation (n=13) was demonstrated, applicability of the empirical model beyond the calibration data set remains uncertain. Schmidt (Schmidt et al., 2017) provided a similar global compilation of data on plastic debris in the water column across a wide range of river sizes and found that loads of micro- and macroplastic are positively related to mismanaged plastic generated in the river catchments. The 10 top-ranked rivers transport 88–95% of the global load into the sea.

What was learned: Using mismanaged plastic as a predictor, the global plastic debris inputs from rivers into the sea could be estimated (1.15 – 2.41 million tonnes, Lebreton et al, 2017; 0.41 – 4 million tonnes Schmidt et al, 2017).

Siegfried et al (Siegfried et al., 2017) presented an alternative, more deterministic (global) scale modelling approach to analyse the composition and quantity of point-source microplastic fluxes from European rivers to the sea. The model accounted for different types (personal care products, laundry, household dust and tyre and road wear particles (TRWP)) and sources of microplastics entering river systems via point sources, for sewage treatment efficiency and for plastic retention during river transport. Microplastic export differed among the rivers, as a result of differences in socio-economic development and technological status of sewage treatment facilities.

What was learned: Siegfried's model was used to explore future trends up to the year 2050, suggesting that in the future, river export of microplastics may increase in some river basins, but decrease in others. For many basins, a reduction in river export of microplastics from point-sources was foreseen, mainly due to anticipated improvements in sewage treatment.

Fate and transport in marine systems

Numerical modelling also has been shown to be a valuable tool in the analysis of microplastics in the marine realm (Hardesty et al., 2017). When combined with observational data it has helped to answer questions that wouldn't be possible to answer otherwise. More specifically, modelling has helped to 'inpaint' regions of the ocean surface where observations are not available (e.g. (Lebreton et al., 2018; van Sebille et al., 2015). In these uses, the patterns from modelled distributions can be regressed against observations, to provide a method to interpolate based on ocean circulation.

What was learned: The recent results obtained by Lebreton et al (Lebreton et al., 2018) suggested that ocean plastic pollution within the Great Pacific Garbage Patch is increasing exponentially and at a faster rate than in surrounding waters. The world-ocean maps provided by circulation models can be used to identify regions where microplastic concentrations are expected to be high, information which is relevant for ecological risk assessment.

Modeling also has helped to provide further mechanistic understanding of the role of circulation features in the transport of microplastics. Examples include submesoscale features (Maes, Blanke, & Martinez, 2016), wave effects (Iwasaki, Isobe, Kako, Uchida, & Tokai, 2017) and upper-ocean mixing (DiBenedetto, Ouellette, & Koseff, 2018). Finally, modeling also has been used to elucidate where microplastics found in an area could have originated from, by backtracking simulations e.g. (Cózar et al., 2017; Peeken et al., 2018).

Besides for mapping microplastic abundance at the ocean surface, models have provided scenario-based projections of how certain mitigation measures would affect the amount and distribution of marine microplastics e.g. (Koelmans et al., 2017b; Sherman & van Sebille, 2016). Koelmans et al (2017) developed a 'whole ocean' mass balance model that combines plastic production data, surface area-normalized plastic fragmentation rates, estimated concentrations in the ocean surface layer (OSL), and removal from the OSL by sinking. The model was used to simulate known plastic abundances in the OSL and below, over time.

What was learned: Simulations suggested that 99.8% of the plastic that had entered the ocean since 1950 had settled below the OSL by 2016, with an additional 9.4 million tons settling per year.

The relevance of such models is that they complement the current spatially explicit ocean circulation models and allow simulations over time. Furthermore, it helps in testing hypotheses on fragmentation and vertical transport processes of oceanic plastic, which to date are poorly understood.

The role of vertical transport in the abundance of NMP in the OSL also is poorly understood. Kooi et al (Kooi et al., 2017) developed a model for vertical transport of microplastics in the oceans. The model is based on settling, biofilm growth (biofouling), and ocean depth profiles for light, temperature, water

density, salinity, and viscosity. The model provided depth profiles for individual microplastic particles over time, and predicted that the particles either float, sink to the ocean floor, or oscillate vertically, depending on the size and density of the particle. The predicted size-dependent vertical movement of microplastic particles resulted in the highest concentration to be at intermediate depths.

What was learned: Therefore, relatively low abundances of small particles are predicted at the ocean surface, while at the same time, these small particles may never reach the ocean floor. The relevance of the modeling study is that the simulations provided hypotheses on the fate of 'lost' plastic in the ocean. Furthermore, the concentration depth profiles could be helpful for predicting risks of exposure to microplastics for potentially vulnerable marine organisms living at these depths.

Fate and bioavailability of plastic-associated chemicals.

Simulation models have been used to assess the role of microplastics in the fate and bioavailability of plastic associated chemicals (such as additives, persistent organic pollutants (POPs), polybutylene terephthalate (PTBs)) in aquatic systems, food webs and ecosystems. This phenomenon has often been referred to as the 'vector effect' of microplastics.

What was learned: The models have helped to translate laboratory findings to chemical behavior and risks on the (eco-)system scale, which helps to evaluate the environmental relevance of the laboratory findings.

Gouin et al (Gouin, Roche, Lohmann, & Hodges, 2011) provided a mechanistic analysis of chemical behavior on the system scale, using a thermodynamic approach. Results suggested that only chemicals with $logK_{OW}$> 5 have the potential to partition >1% to polyethylene. Food-web model results suggested that the relative importance of microplastic as a vector of PBT substances to biological organisms is likely of limited importance, relative to other exposure pathways. These results have later been confirmed by other, more detailed modeling studies, i.e. by Koelmans et al (Koelmans, Besseling, & Foekema, 2014; Koelmans, Besseling, Wegner, & Foekema, 2013).
 (2013, 2014) who included full kinetics of the processes including scenarios for additives and used Monte Carlo modeling to account for uncertainty, by Bakir et al (Bakir, O'Connor, Rowland, Hendriks, & Thompson, 2016) and Herzke et al (Herzke et al., 2016) for a wider range of species (lugworm, fish and seabirds), and by Koelmans et al (Koelmans et al., 2016a) where a model-guided synthesis of laboratory, field and modeling data available in the literature thus far was provided.

What was learned: The latter synthesis also provided a validation of the model outcomes against results obtained in laboratory experiments.

Whereas the previous models mainly addressed the effect of microplastics ingestion on the uptake of chemicals that are at equilibrium on the level of single species, a recent model provided a more comprehensive analysis of the vector effect, also for chemical non-equilibrium scenarios (comparing equilibrated vs non-equilibrium additive or environmentally sorbing chemicals), metabolizable versus non-metabolizable chemicals, on the level of entire marine food webs (Diepens & Koelmans, 2018). The presented model simulates the transfer of microplastic as well as its associated chemicals across any food web. It was implemented for an Arctic case comprised of nine species including Atlantic cod and polar bear as top predator.

What was learned: The analysis suggested that microplastics would not biomagnify in the food web (Biological magnification is the increasing concentration of a substance, in the tissues of tolerant organisms at successively higher levels in a food chain). It confirmed earlier model analysis that ingested microplastics can increase or decrease uptake of organic chemicals, dependent on polymer type, species properties, chemical characteristics (hydrophobicity and persistence) and equilibrium state, and thus that the vector effect, if any, is very context dependent.

The relevance of the general models is that they can be implemented for specific conditions, i.e. habitats, organisms or classes of chemicals, to evaluate the relevance of microplastic for chemical uptake by and effects on organisms. The effect of microplastics on chemical uptake are likely to be small for most habitats, at the present microplastic exposure levels. However, they can be larger in locations where abundances of plastic debris are high e.g. (Chen et al., 2018), or in the future - when plastic abundances increase (Everaert et al., 2018).

What is Partially known

At present, the models described above are typical research tools, in that they evolve continuously when new data or insights about NMP behaviour becomes available. Currently all models are provisional and lack validation. Here, validation is defined following Rykiel (Rykiel, 1996): '*Validation is establishing the truth of a model in the sense of (a) consistency with data, (b) accordance with current knowledge, (c) conformance with design criteria*'. Earlier sections in this chapter have identified the quality and quantity of microplastic occurrence data in air, soil and water as a major knowledge gap. This means that comparisons of modeled scenarios against this data have occurred only to a very limited extent too, and thus that validity at this point (criterion a) is poorly known. This seems especially the case for the fate and transport models, and less for the chemical uptake models reviewed here.

Most published models seem in accordance with current knowledge (Rykiel's criterion b), but that does not imply that they can accommodate the full spectrum of NMP behaviour in environmental systems. Many models for instance, assume microplastics to be (near-) spherical and in a virgin state, which means they are less well equipped to simulate non-spherical particles, (such as for instance fibres, weathered particles, or particles that form agglomerates due to biofilm formation and attachment to other particular matter). The NMP transport models for freshwaters do not necessarily capture all possible system behaviours and often make assumptions, (such as steady state, average flow, retention or weather conditions), or neglect inputs or processes (such as diffuse inputs, sediment bed load transport or aggregation of small microplastics).

Similarly, models of marine NMP fate and transport are only as good as the hydrodynamic data that underpins them. Much effort is being made to create and validate better, finer-scale hydrodynamic datasets, including in Europe within the Copernicus Marine Environmental Monitoring Service (CMEMS). Yet, the finest-resolution hydrodynamic data available there on a global scale has resolutions of around 5-8 km, which is not nearly fine enough to explicitly resolve all scales relevant to plastic transport. Furthermore, these models are often more accurate in the open ocean than near coastlines, while plastic transported from rivers to the open ocean necessarily must move through the coastal zone. The

modelling of marine MNP in this coast-ocean-coast system was therefore highlighted as one of the major knowledge gaps in the Hardesty et al (2017) review paper.

Another knowledge gap is the transport of marine NMP near the ocean floor. Most global scale models have vertical resolutions of tens to hundreds of meters in the deep ocean, meaning that the bathymetry (the study of underwater depth of ocean floors) in many regions is very complicated to model, and hence deep flows are poorly simulated. While in a regional setup, it is more customary to use terrain-following coordinates, this is not yet widespread on basin or global scales.

Finally, modelling of marine NMP would benefit greatly from better understanding and data on key processes that affect plastic particles in the open ocean, including fragmentation, biofouling, sinking, and beaching. The present state-of-the-art is to model marine NMP as passive particles that simply follow the ocean currents, even though there is evidence that particles change density while at sea e.g. (Kooi et al., 2017).

All published model papers seem to recognize their limitations, provide limitations of the approaches and disclaimers, which renders them valid with respect to Rykiel's criterion (c).

What have we learned: In short, models have been successful in answering some questions about sources, transport and fate of NMP, but could be even more useful if they become more realistic.

What is Unknown

Similar to the earlier sections of this chapter, the largest knowledge gaps within the modelling evidence relate to the smallest NMP size fractions, especially those at the submicron scale. One model exists that addresses 100 nm nanoplastics (Besseling et al, 2017), but it remains highly speculative, given the lack of concentration data that would be required for validation of the model.

Other unknowns relate to transport, fate and exposure modeling of NMP in the soil and the air compartments.

2.7 Chapter 2 Conclusions

Here we provide the main conclusions based on the evidence provided in the preceding sections.

1. Microplastics are present in virtually all environmental compartments, including in biota.
2. In order to be able to understand the fate of NMP and to build models for prospective risk assessment, there is a need to develop methods to assess the relationships between polymer structural characteristics and the formation of smaller plastic particles (NMP) in nature, due to embrittlement, fragmentation or degradation.
3. There is a need to develop markers and/or approaches to causally link plastic that one can find in nature, to its origin, source or manufacturer.
4. Some knowledge of microplastic concentrations exist for the ocean surface and to a lesser extent for freshwaters, however, hardly anything is known about air and soil compartments and about concentrations and implications of NMP below the ocean surface.

5. Hardly any information is available on measurement methods, fate, effects, and risks with respect to nanoplastics.
6. There is a need to improve NMP measurement methods, to standardize and internationally harmonize them, to obtain agreement on them internationally, such that they can be applied on a comparable routine basis in a regulatory context.
7. There is a need to develop adequate NMP risk assessment methods, including those involving NMP interactions with other stressors (chemicals, climate change, eutrophication (a dense growth of plant life), acidification) to standardize and internationally harmonize them and to obtain agreement on them internationally, such that they can be applied on a routine basis in a regulatory context.
8. There is a limited number of promising theoretical models that simulate the fate and transport of NMP in environmental compartments, including food web transfer, that are potentially relevant for prospective risk assessment with respect to nano- and microplastics. However, validation is lacking.
9. There is a need to understand fate, exposure and risk for those NMPs that are most relevant to sensitive receptors across all environmental compartments, based on specific protection goals set. (Risk assessment always has a different protection goal in different contexts).
10. There is a need to understand the abundances of NMP in the human diet, drinking water and air, specifically down to sizes <10 µm, in order to be able to start assessing risks for human health.
11. There is a need to understand the potential modes of toxicity for different sizes, shapes and types of NMP in human models.
12. For microplastics, the working group has formulated three conclusions with respect to ecological risks: one concerning present local risks (13A), one concerning present widespread risks (13B) and one concerning the likeliness of ecological risks in the future (13C). These conclusions are:
    A. 'There may at present be at least some locations where the predicted or measured environmental concentration exceeds the predicted no-effect level (PEC/PNEC>1).'
    B. Given the current generally large differences between known measured environmental concentrations (MEC) and predicted no-effect levels (PNEC), it is more likely than not that ecological risks of microplastics are rare (no widespread occurrences of locations where PEC/PNEC>1).
    C. If microplastic emissions to the environment will remain the same, the ecological risks of microplastics may be widespread within a century (widespread occurrence of locations where PEC/PNEC>1).'
13. The evidence described above in Chapter 2, and later in Chapter 3 and Chapter 4, supports that even though 'high quality' risk assessment is not yet feasible, action to reduce, prevent and mitigate pollution with NMP is suggested to be needed. At the same time, developing and using risk assessment approaches for NMP are important to be able to prioritize these actions, and to plan where and when to apply them.

2.7.1 Outlook

Given the paucity of agreed methods for exposure and hazard characterization and the fact that only few quantitative data are of sufficient quality, the absence of evidence of microplastic risks currently does not allow one to conclude that risk is neither present, nor absent, with sufficient certainty. Substantial method development and validation will be required before more systematic and reliable empirical studies can be implemented on a broader scale. Experimental designs also need improvement (Backhaus & Wagner, 2018; Koelmans et al., 2017a; Ogonowski, Gerdes, & Gorokhova, 2018) It will thus take some time before more reliable conclusions on risks become available for the various environmental compartments and for public health assessment.

Chapter 3: Social and Behavioural Sciences Perspectives

3.1. Introduction

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.

Chapter 3 highlights how insights from media and communication studies, sociology, psychology, organisational studies, risk perception and attitude and behaviour research have an important role to play in understanding the interplay between natural science insights and societal responses. These disciplines in turn help in the design of successful policies and interventions and in societal engagement in reducing macro- and microplastic pollution.

Figure 3, from GRID/Arendal by Maphoto (Pravettoni, 2018) depicts how plastic moves from the economy to the environment. The many steps in this picture are areas where human decisions and behaviours occur and have an effect. These same steps are areas where altered actions and behaviours could alter the effect of how plastic enters the environment. Plastic litter, like other waste or pollution problems, is linked to the market, to producer offer as well as consumer demand and behaviour. As Grid/Arendal report, the price of plastic products does not reflect the true cost of disposal and the cost of recycling and disposal are not borne by the producer or consumer directly, but by society (Newman, Watkins, Farmer, Brink, & Schweitzer, 2015). This flaw in our system allows for the production and consumption of large amounts of plastic at very low prices. Waste management is done 'out of sight' from the consumer, hindering awareness of the actual cost of a product throughout its life. We will discuss some of these points in further detail in the following sections, starting with the media.

The social/behavioural literature on NMP specifically is in its infancy. We report this where we can (and discuss nano and microplastics together as NMPs, as in the preceding chapter). But we also draw on other evidence and principles from the broader literature where these are likely to affect societal dynamics and responses to NMPs. We use research on plastic pollution more broadly because large items of plastic litter fragment into secondary microplastics, and we also draw on the relevant wider literature on media communications, risk perception and communication, and attitude and behaviour change.

How plastic moves from the economy to the environment
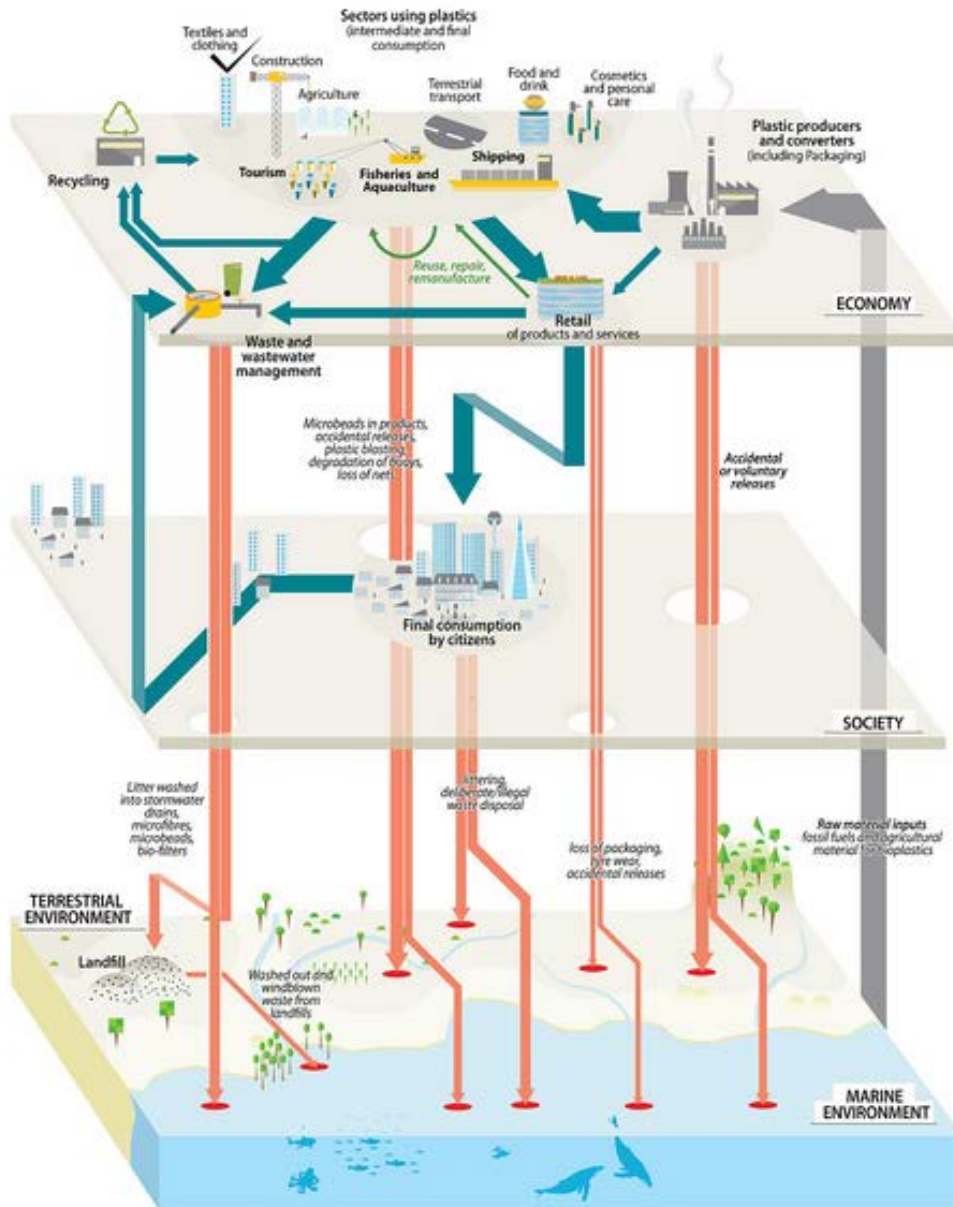
Figure 3: How plastic moves from the economy into the environment and where opportunities for changed awareness, decisions and behavior might exist.

3.2. The Changing Role of the Media

Media play a vital role in communicating global threats and environmental crises constituting public issues, by shaping discourses, public awareness, political action and public responses (Cottle, 2009; Hansen, 2018; van der Wurff, 2012) . High profile media attention has arguably propelled the issue of plastics pollution and microplastics up the public and policy agenda (Kramm, Volker, & Wagner, 2018; Völker et al., 2017) building on decades of activism by environmental NGOs and communities. In 2017,

David Attenborough's BBC documentary series 'Blue Planet II' highlighted the quantity of plastic waste in the ocean. This was described by the Head of the UN Environment Programme, Erik Solheim, as having "helped spur a wave of action" internationally. The so-called 'Blue Planet effect' was associated with announcements calling for legislation to reduce single use plastics (e.g. UK Secretary of State for Environment, Food and Rural Affairs, Michael Gove).

While many of the risks to the environment, organisms and human health from microplastics remain unknown (see Section 2.6), the issue of microplastics is being depicted in public discourse as urgent and pressing. News reports, social media campaigns and popular media, including films and documentaries, communicate and frame the issue in a certain way for the public and policy makers. There is evidence that scientific and media reporting of microplastics has increased rapidly over recent years (GESAMP reports; Figure 4 and 5 and Annex 6). Thus, it clearly is an issue that the public have been exposed to and that receives increasing attention. While it is difficult to know exactly how these media reports translate into public perception and action, it is reasonable to assume a link to an emerging social norm, critical of plastics use, and bottom-up, as well as top-down calls for policy, for example for phasing out microbeads in cosmetics. Further media analysis of microplastics is missing in the published literature, but in the remaining sections of the report, we can build on a rich literature concerning politically contested scientific issues from the past and ongoing, including climate change, genetically modified foods, BSE, and other 'scares'.

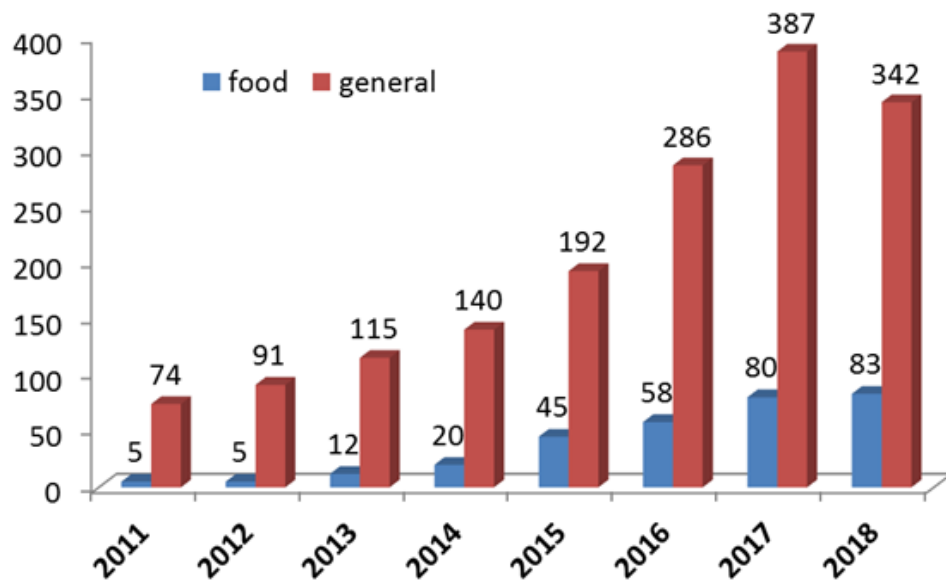Figure 4: Scientific publications (including articles, reviews and conference proceedings) on the topic of microplastics generally (red bars) and microplastics in food (blue bars) has been increasing since 2011 (Scopus only). *JRC, personal communication and applying their Europe Media Monitor (EMM) and the Tool for Innovation Monitoring (TIM). For more, see also the graphs and report in Annex 6 from the*

literature search performed to support this project for an analysis of the number and type of scientific publications on NMPs found using a wider set of databases.
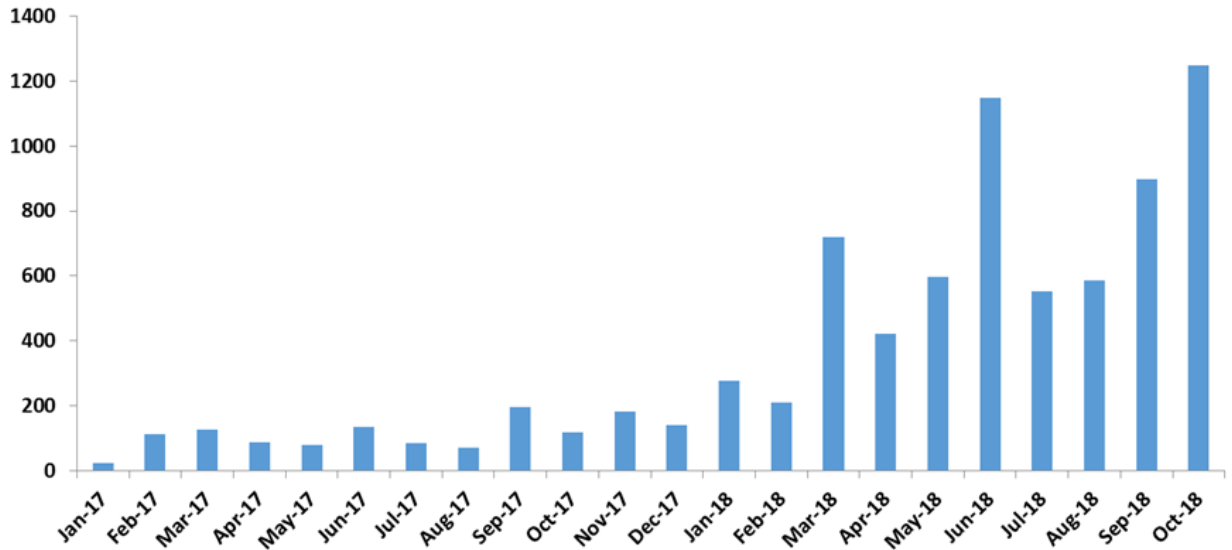
Figure 5: Monthly number of news items extracted from EMM since January 2017 (*JRC, personal communication*). News published in over 70 languages in traditional or social media on microplastics were monitored with the EMM. A total of 6433 media news items were collected on microplastics between January 2017 and July 2018 demonstrating increased coverage of the topic, starting in January 2018 (clear peaks in March, June and September/October are potentially related to specific news stories as indicated in the textboxes).

Peak	Topic
March 2018	Microplastics found in bottled drinking water (published)?
June 2018	World Environment Day / WWF report
October 2018	Microplastics found in human faeces and table sea salt (unpublished)

The role of media in constructing scientific problems

We know that the media play an integral role in constructing social problems (Hilgartner & Bosk, 1988; Schoenfeld, Meier, & Griffin, 1979). Previous studies show how media can define a problem, offering causal interpretation and moral evaluation, providing audiences with a 'story line' in which complex

topics are simplified in terms of responsibility and consequences (Entman, 1993; Gamson & Modigliani, 1989; McCombs, 1997). The newsworthiness of certain risk factors has important consequences for how the public engages with and understands messages (Friedman, Dunwoody, & Rogers, 1999; Henderson & Kitzinger, 1999; Karpf, 1988; Nelkin, 1995; Peters, 1995; Wilkie, 1991). Under certain circumstances, media can transform 'straight science' stories covered by science specialists into political stories. For example, during the 1990's, genetically modified (GM) foods became a populist campaign cause in the UK, fuelled by intense competition between different sections of the press (Allan, 2002: Chapter 7). Public mistrust of GM technology as risky and 'against nature' increased. This came in the wake of the BSE crisis (mad cow disease) during which the beef market collapsed, when the UK Government admitted after years of denial that there was in fact a probable link between BSE and variant Creutzfeldt-Jacob disease (Allan, 2002). These events highlight the dangers of presenting a 'no-risk' message to the public before firm scientific knowledge has been gathered (POST, 2000). NMP is a similar issue in that there are considerable scientific uncertainties over its impact currently? This complexity and uncertainty and question about what action is appropriate is relevant for the topic of NMPs at present.

News values create hierarchies of environmental issues, prioritising 'event-centred reporting' of natural and human-made disasters (such as droughts, floods, chemical and oil spillages), over hazards such as pesticides in farming, climate change, air pollution or 'slow-burning problems of the poor', which are ignored or marginalised within the global public view (Nelkin, 1995; Nixon, 2011; Solman & Henderson). Moreover, the conventions of news reporting help to create a common sense hierarchy of credibility, with some voices being presented as 'naturally' more legitimate than others (Allan, 1999; Gitlin, 1980). Issues of representation and balance of sources have been debated around the coverage of climate change (Painter, 2013) and we do not yet know if there are similar patterns with reporting of nano and microplastics.

Battles over environmental issues do not of course only concern the communication of expert scientific advice, but are aimed at winning hearts and minds (Hansen, 2011). NGO's (non-governmental organizations), some scientists and activist organisations target media and seek to become regular sources and creators of emotive and engaging messages. Compelling visual images are vital to ensuring media coverage for pressure groups (Doyle, 2009). Recent research finds that Millennials (defined as those born from the mid-1980s to present) derive 68% of their news from social media (Pew Research Centre, 2018). There is evidence that learning about immoral acts online triggers far stronger feelings of outrage than when the same acts are reported on television or in newspapers (Hofmann, Wisneski, Brandt, & Skitka, 2014). Strong emotional impact heavily influences social media sharing, with moral-emotive language significantly increasing the diffusion of political content across social media, especially within groups who old the same ideological views (Brady, Wills, Jost, Tucker, & Van Bavel, 2017). However, information shared may be inaccurate or sensationalised. Media reflects the social resonance of events, but not the actual events. This raises questions about appropriate proactive preparation (e.g. clarifying the unknowns). Vosoughi, Roy and Aral (Vosoughi, Roy, & Aral, 2018) found that false news (about politics, science, natural disasters) diffused more quickly on Twitter than actual news did, probably motivated by emotions of surprise or disgust. We discussed above that there is increased

reporting of NMPs, so it follows from this evidence that with this growing public awareness of microplastics, it is likely that much of this will diffuse across social media.Media audiences, powerful interests and scientific literacy

It is important to question issues of legitimacy and how certain definitions come to dominate the public sphere, and in whose interests (Hansen, 2016). For example, environmental pressure groups can catalyse public debate about plastics pollution through creating media friendly 'spectacular' events. Environmental stories or 'spectacular environmentalisms' function through visual grammar and are framed in ways that rouse emotions- to get us to feel and act in certain circumscribed ways (Goodman, Littler, Brockington, & Boykoff, 2016). The quantity of coverage does not necessarily equate with authority or sustained change. Celebrity and elite activism concerning global issues and humanitarian crises is on the rise (Turner, 2016) .This so-called 'celanthropy' (King, 2013) can increase the profile of an issue but does not necessarily bring about behaviour change (Jeffreys, 2016).

Analysis of climate change reporting identifies the success of corporate public relations in exploiting news conventions of balance and impartiality to create the misleading impression that the science on the issue was uncertain or evenly divided (Boykoff & Boykoff, 2004; Oreskes & Conway, 2010).This strategic construction of climate change as scientifically contested may undermine societal engagement with the issue and personal behaviour change (Happer & Philo, 2015). Various stakeholders may also seek to present evidence and arguments for or against specific policy initiatives that are in line with their interests and deliberately engage with the media to influence the political climate and promote positive public perceptions of their activities to advance their business goals (Henderson & Hilton, 2018). Strategies include making 'their' industry goals appear to be 'our' universal goals, which are in everyone's interests (Williams & Nestle, 2015), or public relations strategies that aim to represent commercial decisions by organisations as instead guided by sustainable goals – 'greenwashing' (Signitzer & Prexl, 2007).

Specialist science writing and environmental journalism is in decline across Europe and beyond, with changing media landscapes resulting in increased pressures and new journalistic practices (Curran, 2010). There is an increase in desk-based journalism, a decline in using official sources, lack of separation between reporting and opinion and the emergence of non- professional citizen journalists, all of which has implications for reporting practices and the nature of media representation (Van Witsen & Takahashi, 2018). Traditional media, which has tended to attract high levels of trust, is challenged by an array of new outlets; audiences change how they consume and engage with messages regarding emerging scientific issues. Media and scientific literacy remain key concerns given the current debates about 'fake news' and the proliferation of 'opinion', (mis)represented as scientific facts.

Yet it is important not to fall into rehashing debates about the public 'deficit' model. This assumes a link between public 'lack of knowledge' or science literacy and public scepticism or hostility and has long been discredited within public understanding of science e.g (Irwin & Wynne, 1996; Wynne, 1992). Indeed, following the BSE crisis, a new model emerged which acknowledged that rather than experts

communicating 'certainty' about `objective facts', there was a need for discussion involving openness, transparency and stating uncertainties around scientific knowledge (see also section 3.3.2 and Chapter 4, section 3.3.3, where evidence about such complex risk communication is reviewed). It is largely accepted that public understanding of science is better framed as 'public engagement with science', an acknowledgement that there is no deficit in knowledge, but rather any emerging risk information is made sense of and possibly actively ignored in ways that are responsive to experience, trust in authority and a surfeit of information (Carter, 2016).

The decline in trust in the political classes and shifting dynamics in terms of the role of scientific experts are also important factors here. For example, new media techniques - including big data - facilitate innovative citizen-expert alliances, and environmental justice activists are adopting citizen science techniques such as crowd sourced data on pollution (Gabrys, Pritchard, & Barratt, 2016). These might not have the same authority and credibility necessary to gain scientific and political traction (Kinchy & Perry, 2012) but can induce powerful social dynamics, because they include experiential learning. Political action is also required to bring about societal change (Mah, 2017).

While there is often an oversimplified view of the link between media and effects on attitudes or behaviour, we do know that media provide a repertoire of images, meanings and definitions to make sense of emerging environmental problems (Hansen, 2018). In this respect, nano and microplastics may represent an interesting dilemma. Evocative images of charismatic animals entangled in plastics are likely to be familiar to audiences, however the problem of microplastics as opposed to macroplastics can present greater challenges in terms of how the public understands the scale of the issue and the connection between their everyday actions and the problem.

Media reflects the social resonance of events, but not the actual events. This selective power reinforces the plurality of information, conflict perception and moralizing of topics. Recipients therefore often feel overwhelmed by the plurality of possible interpretations and thus, in order to avoid cognitive dissonance, allocate highest importance to the information that resonates most with their own opinion. This effect is intensified even more by the increasing use of the internet and social media as source of information, which also supports the propensity to justify preexisting opinions (Renn, 2018).

Given that the scientific evidence is still emerging on NMP, and that their risks are not fully known at this point (see section 2.6), there may be greater opportunity for interest groups to define the issue. In other words, this is an issue that could be driven more by media and politics than by the current science.

3.3 Knowledge and Risk Perception

Research on society's knowledge and awareness related to NMPs is limited, and there are gaps in particular regarding the perception of different types, sources and final-destinations of NMPs (e.g., in food, from tyres and fabrics, atmospheric, and primary versus secondary NMPs), and regarding nanoplastics overall. However, some research exists concerning perceptions of microplastics in personal care products and food and drinking water. US and UK data from 2015 and 2016 showed that the majority of participants were still unaware of plastic particles in cosmetics (Chang, 2015; Greenpeace, 2016). In a small-scale qualitative study (Anderson, Grose, Pahl, Thompson, & Wyles, 2016) showed that

only environmentalists were aware of the environmental effects of microplastics; but that after handling samples representing the amount of microbeads in cosmetics, beauticians and students also expressed concern about the potential negative environmental impact of microplastic and perceived the use of microbeads as 'unnatural and unnecessary'. A representative survey in Germany showed that the majority of the population feels strongly (39%) or moderately (23%) contaminated by plastic particles in food and drinking water (BMUB/UBA, 2016).

More research has been conducted on perceptions of marine litter (Gelcich et al., 2014) and marine threats (Lotze, Guest, O'Leary, Tuda, & Wallace, 2018) more broadly. A survey across 16 European countries found that participants judged marine litter to be an important problem and were concerned about it (Hartley et al., 2018). While age and gender were not important predictors of concern in this study, level of education, visiting the coast, noticing litter, values, and social norms were. The role of seeing litter is noteworthy here and suggests that direct experience of polluted environments could be an important factor in motivating people to take action, in line with Anderson et al (2016) and linked to experiential learning in education. However, in other contexts seeing littered environments can lead to more littering because it conveys a negative social norm, see section on social norms below (Clayton, Schultz, & Kaiser, 2012).

Some studies have investigated the influence of specific policy instruments and activities on awareness. Specifically, a plastic carrier bag tax in Portugal, while significantly reducing the use of plastic bags, had no impact on individuals' awareness of marine litter and its impact on the environment and on human health (Martinho, Balaia, & Pires, 2017). However, Poortinga et al (Poortinga & Whitaker, 2018) found that the English plastic bag charge helped catalyse awareness in the general public. A school video competition increased European students' concern about marine litter (Hartley et al., 2018) suggesting that creative educational programs harnessing young people's imagination can raise awareness of marine pollution.

Overall, research on public knowledge and awareness has so far focused on certain sources of microplastics, such as microbeads and marine litter, but has omitted others, such as car tyres or synthetic fabrics. Perceptions of microplastic concentrations related to environmental compartments other than marine, such as freshwater, air, and soil, have hardly yet been investigated (with the exception of the BMBA/UBA survey on drinking water and food, see above), but could potentially yield higher public concern, because they are closer to people's daily experience and thus potentially perceived as more threatening. The perceived health risks of plastic pollution have not been systematically studied (2.5.5), although there have already been several media stories on the topic (some presenting unpublished work). The media appear to have covered mainly the ecological / environmental impacts of marine pollution, e.g., wildlife becoming entangled, and this aspect features most highly in the perception studies so far (Hartley et al., 2018).

We can learn from the broader risk perception literature (Kraus, Malmfors, & Slovic, 1992; Marteau et al., 1991; Ueland et al., 2012).Public risk perceptions typically differ from experts' assessments of risks. Notably, experts tend to conceptualise risks in a formal way, based on the likelihood and seriousness of potential negative consequences, while the general public tends to consider many other aspects, such as

the degree of disagreement in the scientific community, effects on future generations, ecosystems and non-human life, and whether risks and benefits are fairly distributed (Vlek, 2004; Vlek & Keren, 1992). Affective reactions also play a large role in non-expert's risk perceptions e.g (Finucane, Alhakami, Slovic, & Johnson, 2000). Kasperson et al. (Kasperson et al., 1988) provide a systematic framework for the 'social amplification' of risk, which considers both technical and socio-cultural processes that may explain why public responses to risks can become amplified or attenuated (Pidgeon, Kasperson, & Slovic, 2003). More recently, Vijaykumar and Nowak (Vijaykumar, Jin, & Nowak, 2015) have integrated the role of the media into this process. It is clear that societal and scientific appraisals of risk differ because different criteria are used. This does not mean one type of assessment is more valid than the other; it means there needs to be a societal discussion on risks and appropriate responses that should be based on scientific evidence as well as moral and social considerations.

Research within the psychometric paradigm of risk perception suggests that people perceive (environmental) hazards as less risky and more acceptable the larger the related benefits of the item to humans are, the more they pose a delayed or gradual risk over time, and the less observable or tangible (Slovic, 1987). While many of the sources of and actions that cause microplastic pollution contain clear and immediate benefits (there are positive uses of the plastics with useful products & applications), their negative impacts are often not visible and delayed (see GESAMP analysis). Water quality is assessed by the general public on the basis of visual and olfactory factors only (Jones, Aslan, Trivedi, Olivas, & Hoffmann, 2018), suggesting that the negative impacts of microplastics on water quality might not be noticed and therefore be underestimated by the public. If society cannot obviously see a problem, i.e. if they cannot assess it for themselves, they have to turn to other sources, such as experts or the media, to form an opinion. In that case, how those experts make decision under uncertainty and trust in communication sources becomes vitally important (discussed above and in (White & Eiser, 2006). In the plastic context, large items of litter are visible and can be assessed by non-expert-observers, but they cannot easily judge NMP for themselves.

Visibility of risks is also related to the psychological distance of risks – a subjective feeling of the issue being disconnected and remote from daily life. Construal level theory (Trope & Liberman, 2010) and research on climate change (Spence, Poortinga, & Pidgeon, 2012) suggest that objects or events that are uncertain, and temporarily, socially, and geographically distant are evaluated as less risky and elicit less concern. With regard to microplastic pollution, psychological distance might be experienced to be high because public awareness is mainly related to marine pollution (which is geographically distant for many people living inland) and severe pollution may only be seen in distant places outside of Europe (social distance; but see below). Further, impacts on human health are currently unknown which could cause psychological distance due to uncertainty. However, more research is becoming available and is being discussed in the media (about negative impacts of microplastics in certain environmental compartments and on potential human health threats), that might lead to decreases in psychological distance and increases in perceived risks of NMP. Also, research within the psychometric paradigm of risk perception revealed that perceived impacts on humans, as well as impacts on other species are associated with higher perceived environmental risks (McDaniels, Axelrod, & Slovic, 1995).

3.3.1 Values

Perceptions of (environmental) risks also depend on individuals' values. Four types of values are particularly important to understand environmental risk perceptions and behaviour:

- 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, Perlaviciute, van der Werff, & Lurvink, 2012).

The research has shown that altruistic and particularly biospheric values are positively associated with greater perceptions of global environmental risks. In contrast, people's hedonic and egoistic values are negatively associated with these risk perceptions (Steg, Perlaviciute, & van der Werff, 2015; Whitfield, Rosa, Dan, & Dietz, 2009). To date, no research has examined how values may affect risk perceptions related to microplastics. Yet, in line with previous studies, we would expect strong biospheric and altruistic values to be related to perceiving higher environmental risks. There is some initial evidence that supports this assumption: In the Hartley et al., study (Hartley et al., 2018) perceiving the marine environment as having altruistic-biospheric value, positively predicted concern, whereas perceiving the marine environment as having egoistic value did not. Additionally, it can be expected that strong altruistic values are related to higher perceived risk for public health, while strong egoistic values may be associated with perceiving higher risks for one's personal health. It could be expected that strong hedonic values are associated with perceiving lower risks for health and the environment. Individuals with strong hedonic values might perceive behaviours causing microplastics pollution as beneficial, because these behaviours are potentially linked with comfort and pleasure (e.g., car driving, beauty products, synthetic textiles) and thus support hedonic values. Based on the psychometric paradigm of risk perception, it can be assumed that due to such perceived benefits, they may perceive microplastics pollution as less risky (McDaniels et al., 1995).

Values may not only affect to what extent people evaluate microplastics as risky and of concern, but also affect the motivational potential of perceptions of environmental and health risks, that is, the extent to which perceptions of these risks affect behaviour (change) and the acceptability of policy to reduce the negative impacts of microplastics (Bolderdijk, Gorsira, Keizer, & Steg, 2013; van den Broek, Bolderdijk, & Steg, 2017). For people with strong biospheric values, perceived environmental risks are likely to be particularly motivating. People with strong altruistic values are likely to be most strongly motivated by perceived environmental risks that may have negative implications for other people, and particularly by perceived public health risks. Next, for people with strong egoistic values, particularly perceived (personal) health risks are likely to be motivating.

Finally, the extent to which people accept risks related to microplastics depends on the type of moral reasoning they engage in. Specifically, some individuals may apply a consequentialist reasoning and perceive the risks as acceptable and actions are morally right - when the benefits of actions causing these risks are believed to be higher than the costs and risks associated with it. On the other hand, individuals may apply a deontological reasoning, in which they base risk assessment on the inherent

rightness or wrongness of actions *per se*, rather than on the consequences of actions. In such cases, actions may be evaluated as morally wrong, irrespective of the benefits associated with it (Böhm & Tanner, 2012).

3.3.2 Communicating Risk and Uncertainty

Scientists communicate their findings and scientific findings are often characterised by a degree of uncertainty (see also section 3.3.3 below) and uncertainty about the presence of risks, as is the case for NMPs (see Chapter 2). Understanding these risks and uncertainties is very important for informed decision making among the public and policy makers alike, but research shows that people are generally averse to uncertainty (Keren & Gerritsen, 1999); they prefer certain findings and clear outcomes. Scientific communications are also often based on very complex relationship and specific definitions that do not easily translate into non-expert understanding. Some research has investigated how expert risk terms are interpreted by non-experts, for example in the context of climate change risks. Research has shown that verbal probability terms agreed by the IPCC to communicate uncertainty were interpreted very differently and with great variability by non-expert audiences, and the discrepancy was worse for more extreme probabilities - in both a US sample (Budescu, Broomell, & Por, 2009) and in an international sample spanning 24 countries (Budescu, Por, Broomell, & Smithson, 2014).

The science of science communication has taught us that there is rarely a one-size-fits-all way of communicating science and uncertainty. What we need are customised communication strategies for different audiences (Fischhoff, 2013; Fischhoff & Davis, 2014). First, the target group needs to be identified (do we want to address political leaders, industry, retailers, environmental agencies or NGOs, the media or consumers?), then their interests and values need to be considered (Renn, 2005). According to Renn et al. (2005), communication consists of four key elements: Documentation (in order to ensure transparency), information (serves to enlighten), a mutual dialogue (for two-way learning) and participation in risk management and risk analysis, so that the concerns of all stakeholders are represented.

Even 23 years after Fischhoff's (Fischhoff, 1995) seminal paper summarising developmental stages in risk management, participation and co-creation is not ubiquitous. Some scientists appear to be stuck in the early stages described by Fischhoff (e.g., "All we have to do is get the numbers right" or "All we have to do is tell them the numbers"), when many socio-technical risks enter a societal process of sense making, potential controversy, ethical and moral considerations that goes way beyond the numbers. Communication is emphatically not an ethically neutral business. If, for example, what we say is misunderstood, decisions with unwanted consequences may result. How then do we determine what to say and what not to say? Detailed protocols promoting good science and uncertainty communication describe how this can be done (Fischhoff & Davis, 2014a). To make sense of science, we do not require new communication tools and procedures. We can use the tools and techniques we already possess.

There is a risk that science and uncertainty will lead to distrust, especially in the post-expert society, and uncertainty may also be associated with inaction. We know that "distrust, once initiated, tends to reinforce and perpetuate distrust" (Slovic, 1999) and there is a saying "trust arrives on foot and leaves on horseback". Both emphasise the great fragility of trust in decision makers. There is evidence that

more cautious decision making, and more transparency, is associated with greater trust (White & Eiser, 2006) and that people rely on social trust when they cannot assess the risks and benefits of an issue for themselves (Siegrist & Cvetkovich, 2000).Decision-making and risk management both involve two equally important components: information (knowledge) and preferences (values), and scientists, policy makers and the public engage in a discourse between these aspects to ideally come to a consensus.

3.3.3 Assessing Uncertainty

Good governance and decision-making require information both on the scientific evidence and the associated uncertainty. Scientific evaluation should therefore include assessment of uncertainty, as stated in the European Commission's Communication on the Precautionary Principle (Commission, 2000). In most scientific advice, uncertainties are characterized qualitatively, if at all. The impact of the uncertainty is usually expressed by using words such as 'likely', 'unlikely', 'possible' to qualify scientific conclusions. Multiple studies have demonstrated that such verbal expressions are ambiguous and interpreted in different ways by different people (Theil, 2002). The fact that precisely quantified information on the environmental effects of microplastics is only partially available, makes policy and decision-making based on the partial information difficult, but the sciences can provide some information on microplastics in the environment.

The Intergovernmental Panel on Climate Change (IPCC) has developed approaches aimed at improving the expression of uncertainty in their assessments. They reduce ambiguity by expressing the likelihood that scientific conclusions are correct using verbal terms which are defined quantitatively, in terms of probability. For example, (Mastrandrea, 2010) conclude that "Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate", where 'likely' is defined as corresponding to 66-100% probability.

Mastrandrea et al (2010) do not provide any explicit advice on how experts should make the probability judgements required by their likelihood scale, or how the cognitive biases known to affect such judgements can be mitigated (Kahneman, Slovic, & Tversky, 1982). Such advice is included in guidance for uncertainty analysis published recently by the European Food Safety Authority (EFSA), which also proposes a modified version of the IPCC scale (EFSA, 2018a, 2018b).

It is essential to acknowledge when quantitative expression of uncertainty is not possible, as is emphasised in many publications on scientific uncertainty (Sahlin, 2012; Stirling, 2010). This is recognised in the Codex (2018) Working Principles for Risk Analysis, which call for quantification "to the extent that is scientifically achievable", and also in the guidance of both IPCC (Mastrandrea et al. 2010) and EFSA (2018 a, b). When assessors feel unable to give probabilities, or even ranges of probabilities, the report suggests that they should describe the cause and nature of the uncertainties involved and report that the assessment is inconclusive (EFSA, 2018a).

The approaches outlined above can be applied to any type of scientific assessment, including urgent assessments (EFSA 2018a), and those where assessors have to weigh multiple, potentially conflicting, lines of evidence (EFSA, 2017). When applied well, they should improve the rigour of uncertainty assessment and reduce ambiguity in expressing uncertainty and hence provide a more useful

contribution to decision-making processes, including application of the precautionary principle when appropriate.

There are other methods of knowledge quality assessment too (cf. www.nusap.net) which can be used to boost policies with a more robust knowledge basis. The framework of *post-normal science* (Funtowicz & Ravetz, 1993) depicts most science-for-policy as inherently characterized by high system uncertainties, high stakes, debated values, and decision urgency, characteristics which all seem appropriate for microplastics. Three comments need to follow here. First, one needs to realize that the values at stake most often are not restricted to economic values, and do not always refer to the values embedded in national constitutions or EU law. They can be intangible values like the beauty of a beach and the integrity of an ecosystem (Kaiser, 2015). Secondly, evidence of people's (i.e. citizens') values could be considered a relevant input into evidence-informed policies the same way natural science evidence is relevant (as reviewed in Chapter 3). Thirdly, the so-called *Sustainable Development Goals* (SDGs) supplement the value base on which to design our policies, and in relation to microplastics several of the SDGs come explicitly into play.

3.3.4 Disgust, Unnaturalness and Absolute Opposition

Emotions towards microplastics might affect people's reactions and policy preferences in several ways. Research revealed that absolute opponents of genetically modified (GM) food, i.e. people who agree that GM food should be prohibited no matter the risks and benefits, were more disgust sensitive in general and disgusted by the consumption of GM food than were non-absolute opponents or supporters (Scott, Inbar, & Rozin, 2016). Similarly, general disgust sensitivity predicted absolute opposition to recycled drinking water, which some people rejected because they perceived it as contaminated, even if it was purer than drinking or bottled water according to chemical analysis (Rozin, Haddad, Nemeroff, & Slovic, 2015). Psychological aspects of the rejection of recycled water; contamination, purification and disgust, again indicating a difference in risks as assessed by experts vs. risk perception by non-experts. Similar 'moral' opposition was found with regard to artificial as compared to natural items, especially in the food domain (Rozin et al., 2004). If future scientific evidence indicates that microplastics enter the food chain, people might be more likely to take an absolute stand related to microplastics, because they might feel disgusted and experience a violation of purity due to the perceived unnaturalness (see early evidence from BMBF/UBA survey in Germany on concern). Indeed, there is already evidence to suggest that people oppose microbeads due to their unnaturalness (Anderson et al., 2016).

3.4. Decisions and Behaviour

As there is no natural variation of plastics in the environment, all plastic pollution has to result from human decisions and behaviour, whether of manufacturers, retailers, or consumers (Pahl & Wyles, 2016; Wyles, Pahl, Holland, & Thompson, 2017). It is therefore useful to review what we know about the determinants and dynamics of behaviour in a range of stakeholders. These insights will help to define options for and increase the effectiveness of future policy action.

3.4.1 Actors and Stakeholders

Because plastic materials are used widely and for many different purposes in modern society, any change in the plastic use system will affect a wide range of societal groups and stakeholders, including

manufacturers, retailers, consumers, various levels of government, waste and recycling companies, as well as professional users of the coast and seas and environmental organisations (Andrady, 2011; Terlau & Hirsch, 2015). We know of no systematic stakeholder analysis e.g (Reed et al., 2009) for NMP, but will illustrate some relevant actors in the following:

- **Manufacturers** may be guided by considerations of reputation, consumer demand, cost and availability of technology, as well as by corporate social responsibility. Anecdotally, some companies have reduced plastics use because highly motivated individuals within the organisation have persisted with changes. In these examples, a single trailblazer can be responsible for triggering substantial reductions in plastic (e.g., https://www.surfdome.com/lifestyle_blog/less-plastic-infographic/).

- **Retailers, especially food retailers** can offer low-plastic options for products and services, and support customers who want to use refillable containers. Retailers also have opportunities to change their delivery options to customers and influence suppliers. Such leadership and social norm setting can have powerful effects in the relevant sphere of influence and can be supported by policies.

- Motivated and informed **consumers** may avoid plastic products and reject single-use packaging, given suitable choice and clear labelling, and they may demand the reduction of plastics from government and producers. Consumers also influence change via acceptance (or not) of new options and systems, and these need to be built around existing practices and carefully piloted to ensure success.

- **Citizens, environmental organisations** and **scientists** may collaborate on citizen science projects that can raise awareness (Hidalgo-Ruz & Thiel, 2013) and have a range of benefits to participants (Wyles et al., 2017) and trigger social change (Dauvergne, 2018), e.g., the 'Beat the microbead' campaign (http://www.beatthemicrobead.org/). Moreover, citizen beach clean events have seen a substantial increase in participants recently. For example, the Great British Beach Clean organised by the environmental charity Marine Conservation Society (MCS), which saw a doubling of numbers from 2017 to 2018 (from 6,944 to 14,527 for the UK) (MCS, 2018).

- Notably, such collaborations appear more common around marine litter and plastic pollution than around other socio-technical challenges such as nuclear power or GM foods.

- Some specific stakeholders, such as **fishers**, experience the plastic that is polluting the marine environment directly and see the consequences on their livelihoods. Programmes such as Fishing for Litter can integrate such professional users of the coast in reducing plastic pollution and give a positive signal to actors further removed from the ocean (Wyles et al., under review). Even in the absence of organised programmes some bottom-up initiatives are addressing the problem head-on (Geographic, 2018).

- In many cases, changes will only work if different actors are aligned. For example, reducing the emerging problem of microplastic pollution from tyre abrasion in the future will probably depend on technical alternatives that provide similar levels of safety and comfort, but also on consumers choosing these alternatives, and on policy makers enacting new regulation, or incentives. Professional standards, certifications and product labelling can motivate action, the

evidence suggests they might work better if widely publicised and aligned with consumer demand (e.g. marketing fish from certified fishing for litter boats).

In a Europe-wide study, Hartley et al. (Hartley et al., 2018) asked members of the public how responsible they thought different actors were for marine litter, broadly defined. Retailers, industry and government were perceived as most responsible, but also least motivated and competent with regard to reducing marine litter, whereas independent scientists and environmental groups were perceived as least responsible, but most motivated and competent. This suggests that the public see certain actors as responsible - but do not necessarily trust the same actors to solve the issue.

3.4.2. Identifying Behaviours

In addition to understanding the roles of multiple stakeholders, it is also important to identify the specific behaviours that contribute to plastic pollution and those that support solutions. For example, a number of decisions and behaviours can result in a single-use plastic bottle ending up in the natural environment, such as a consumer buying a bottle of water instead of refilling a bottle, disposal of the bottle as waste, instead of reuse or recycling, to introduce certain waste disposal options that may be vulnerable to items being lost before reaching landfill, the bottle not being picked up by anyone before it reaches the ocean and so on. As well as looking at plastics produced at large volume, and the high risk plastics (as reviewed in Chapter 4), in order to understand and reduce the amount of NMP in the natural environment, it is necessary to also identify the most relevant behaviours to target. The focus here is mostly on behaviours by the general public. Dietz et al.(Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009) argue that large behaviour change programmes could yield rapid environmental benefit whereas policies take longer to implement, and Benartzi et al. (Benartzi et al., 2017) estimate that behavioural nudging interventions can be more cost-effective than policy tools including incentives.

When determining the most relevant behaviours to target, the '**plasticity'** or potential of change in that behaviour, as well as the '**elasticity'** or effectiveness of the change in addressing the problem are two key factors (Dietz et al., 2009). In other words, 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 and found that insulating homes would have the most impact and carpooling the least. This type of analysis is currently lacking for plastics pollution, but of crucial importance to identify the most effective and acceptable actions for behaviour change programmes.

Current knowledge is incomplete, as there has been no comprehensive analysis or quantification of the behavioural aspect of plastic pollution and potential points of change. Some inferences can be made from waste management analysis and analysis of items found during environmental surveys and beach cleans. These can identify which items and materials to target (e.g., plastic bottles, black/coloured plastic). However, it is less clear what behaviours to target to reduce microplastic pollution because plastic fragments emerge from a wide range of sources that cannot be traced currently (see Section 2.3.1). Bertling et al (2018) have recently estimated that traffic, infrastructure and buildings are major emitters of primary microplastics. Further analysis tracing sources could potentially help to identify relevant associated behaviours.

There are other starting points for prioritising behaviours. According to the waste management hierarchy, the reduction of waste and reuse of products should be considered before recycling and disposal behaviour (http://ec.europa.eu/environment/waste/legislation/a.htm). In Europe, 62% of all plastic waste is generated by packaging (Andrady, 2015), so a behavioural backlash against packaging could be very effective. For example, in Germany in the 1980s consumers started unpacking products in shops and leaving the packaging behind, and similar initiatives are coming back now, for example in Ireland (https://www.irishtimes.com/news/environment/shoppers-urged-to-leave-packaging-in-supermarkets-as-part-of-campaign-1.3435666). Waste prevention behaviours range from one-off behaviours, e.g. purchasing durable, long-lasting products and avoiding single-use products, to habitual behaviours, e.g. re-using items (such as shopping bags or refillable packaging), avoiding over-packaged goods, and sharing or renting items (such as appliances or equipment). Beyond this generic approach, there may be specific behavioural solutions for emerging issues. To reduce microplastics pollution from textile fibres, consumers may decide to buy washing machines with fibre filters and/or washing nets for textiles. For such technical solutions to work optimally, however, consumers will also need to clean filters and dispose of the fibres in a responsible manner.

Behavioural research investigates what drives specific behaviours, distinguishing between impact-oriented or intent-oriented analysis (Stern, 2000) .Impact-oriented research explicitly looks at the behaviours with the greatest impact on the environmental issue, such as purchasing items with less packaging (see above), whereas intent-oriented research examines behaviours undertaken explicitly for environmental reasons. Exploring different motivations for specific behaviours can highlight novel pathways to change, e.g. some people may avoid plastic packaging due to health concerns about additives. These two approaches complement one another to help explain what drives action and to demonstrate the effectiveness of different interventions.

3.4.3. Determinants of Behaviour

A multitude of social, personal and situational factors shape environmental attitudes and behaviour relevant to reducing plastic pollution. These factors enable and motivate people to act and can be used to design interventions to change behaviour (Steg & Vlek, 2009). Similarly, they can be barriers to change. In particular, **concern, perceived behavioural control, identity, values, attitudes, emotions and personal and social norms,** as well as **knowledge and awareness,** have been identified as predictors of intentions and behaviour (Pahl & Wyles, 2016). In terms of personal factors, **knowledge** in itself is typically not sufficient to motivate pro-environmental behaviour by individuals (Abrahamse & Steg, 2013; Hornsey, Harris, Bain, & Fielding, 2016; Ünal, Steg, & Gorsira, 2018) or by organisations (Anderson and Newell, 2004). Knowledge is related to awareness and concern regarding environmental problems caused by human behaviour, but these relationships are not always strong (Ünal et al., 2018). However, a lack of knowledge may undermine behavioural action to address the issue. Research within the health domain (Fisher & Fisher, 1992; Nisbet & Glick, 2008) has shown that behaviour change requires, at a minimum, a motivation to change (motivation) and practical know how (skills), in addition to knowledge. For example, knowing about plastic harming wild animals may not lead to behaviour change in the absence of motivation (*why* should I do something about this? Do I care?) or practical skills (*how* can I reduce my plastic footprint at the practical level?)

Beyond specific knowledge, overall problem **awareness** and **concern** are predictors of behaviour (see (Bamberg & Möser, 2007; Lindenberg & Steg, 2007; Steg, 2016) for reviews on environmental behaviour). Research has found high levels of public concern about marine litter and a willingness to take action, and that concern was associated with behavioural intentions to mitigate the problem(e.g., (Hartley et al., 2018). Research suggests that problem awareness translates into behaviour via **outcome efficacy** (sometimes labelled **response efficacy**) and **personal norms**, provided that people feel capable of change. Specifically, higher problem awareness is associated with a stronger belief that one's own actions will help to reduce the problems (outcome efficacy), which in turn strengthens feelings of moral obligation and responsibility to reduce the problems (personal norms). Individuals are motivated to act in line with their personal norms, particularly when the relevant behaviour is not too costly (Steg, 2016; Steg & Vlek, 2009).

Personal factors work together with **situational factors** facilitating or inhibiting pro-environmental behaviours. Examples of relevant situational factors include **economic constraints, social pressures, and opportunities for alternative actions (Kollmuss & Agyeman, 2002)**. An empirical example of research on personal and situational factors related to littering was conducted by Schultz et al. (Schultz, Bator, Large, Bruni, & Tabanico, 2013). Observing nearly 10,000 people in 130 outdoor locations, they established a littering rate of 17% for larger items and 65% for cigarette butts. Older people littered less, and littering behaviour reduced when bins were presented, and when the site was less littered. This observational approach generates objective and quantitative data on littering behaviour.

Recycling is one of the most-studied waste-relevant behaviours, although it is lower priority in the waste hierarchy (see above). The provision of facilities and curb side collection schemes has helped to increase recycling rates (Guagnano, Stern, & Dietz, 1995) and made recycling one of the most commonly reported environmental behaviours, in particular in the Western world (Whitmarsh, Capstick, & Nash, 2017). Recycling can reduce the risk of plastic waste entering the environment as secondary NMPs, e.g., from landfill leaks and it supports circular economy approaches. The opportunity to recycle may have unintended consequences, in that it may 'license' increased consumption of resources (Catlin & Wang, 2013). For example, Germany is often lauded for its recycling system but is actually significantly above the European average for per capita waste (https://www.destatis.de/Europa/EN/Topic/EnvironmentEnergy/Waste.html).

Less is known about the drivers of waste abatement or reduction behaviours (Nash et al., 2017). Factors underlying self-reported waste reduction, reuse, and recycling behaviours appear to differ significantly, with reduction and reuse behaviours being more strongly associated with environmental values and concern (Barr, 2007; Whitmarsh et al., 2017) found that reduction behaviours are far less common than recycling, and that they are predicted by both socio-demographic and psychological factors, including education, pro-social values, a green identity and intrinsic motivation.

Many behaviours are **habitual**, meaning that they are less open to reasoned thought and deliberation than assumed by most psychological models of behaviour and behaviour change. Purely reasoned approaches of human behaviour have been challenged in recent years by considering some behaviour and decision making as automatic and habitual, and thus separate from reasoned action. A prominent

view separates decision making into two types of information processing: automatic, quick and heuristic-driven cognition (Type 1), and conscious, slower, and reasoned cognition (Type 2), where the two types may contrast or conflict with each other (Evans & Stanovich, 2013). Motivational factors are less predictive of habitual behaviour (Ouellette & Wood, 1998) and individuals are less likely to attend to information (Verplanken, Aarts, & Van Knippenberg, 1997) when behaviours are habitual. Habits may however be amenable to change when a situation changes (Bamberg, 2006; Verplanken, Walker, Davis, & Jurasek, 2008) or when the automaticity of a behaviour is disrupted (Poortinga, Sautkina, Thomas, & Wolstenholme, 2016).

In summary, a large literature on predictors of behaviour has demonstrated that there are many different factors that determine action. These factors can be employed in communications and interventions aimed to change behaviour. The literature distinguishes reasoned, slow processes where people think carefully about their choices and actions, and impulse-driven, fast processes that are minimal in cognitive analysis and effort.

3.4.4. Behaviour change interventions

Several strategies are available to change attitudes and behaviours in relation to plastic pollution. Steg and Vlek (Steg & Vlek, 2009) distinguish between informational and structural approaches, which reflect interventions aimed at motivating and enabling behaviour change respectively. Interventions should be informed by theory and research on the determinants of relevant intentions and behavior; theory-based research was found to have larger effect sizes in health interventions (Bartholomew Eldredge et al., 2016). Public participation and social marketing approaches can help to make interventions more acceptable and effective (McKenzie-Mohr, 2002; Timlett & Williams, 2008). Interventions can range from more or less sophisticated communication campaigns to behaviour change interventions at community, regional and national levels and may include structural changes, such as charges, bans and legislation. As mentioned above, people are likely to change their behaviour if there is sufficient motivation, a feasible alternative and/or a supportive infrastructure. For example, in terms of infrastructure placement of bins (DiGiacomo et al., 2018) and signage (Wu et al., 2018) can substantially improve disposal behaviour. The most common conclusion from research of behaviour change is to combine a variety of different interventions and approaches, tackling a wide range of behavioural determinants both psychological and situational. In this section we review a selection of interventions with a focus on their social and behavioural effects.

Policies can intervene at different stages of a product's life to prevent plastic ending up in the environment (Willis, Maureaud, Wilcox, & Hardesty, 2018). Many policies have focused on specific behaviours or products involving single-use plastics and packaging (Chapter 4) (Xanthos & Walker, 2017). However, little research has been conducted evaluating how successful these policies and campaigns have been.

Information campaigns with the aim to change behaviour have been around since the earliest days of the environmental movement, but these have been met with varied success, in line with our discussion of the role of knowledge above (Clayton et al., 2012).This has led to a shift towards more theory-based interventions, for example **social norm interventions**. Cialdini et al (Cialdini, Reno, & Kallgren, 1990)

showed that social norms (both in the form of existing litter and in the form of messages) influence littering behaviour. Schultz (Schultz, 1999) demonstrated that personal and social norm feedback increased observed recycling rates. Keizer et al (Keizer, Lindenberg, & Steg, 2008) extended this by showing norm effects even when the norm that is violated is in a different domain, e.g., undesired graffiti was linked to more littering behaviour. Dupre and Meineri (Dupré & Meineri, 2016) showed that social comparison feedback improved recycling behaviours in French university cafeterias. A recent meta-analysis across 70 interventions confirmed that social modelling (e.g., via training block leaders) and changes to the environment (e.g. changing bin proximity or appearance) were most effective in improving household recycling (Varotto & Spagnolli, 2017).

Many countries around the world have introduced **legislation** relating to single-use carrier bags (Clapp & Swanston, 2009). Research has shown that charges are highly effective at reducing the use single-use bags (Convery, McDonnell, & Ferreira, 2007; Poortinga, Whitmarsh, & Suffolk, 2013; Thomas, Poortinga, & Sautkina, 2016). While charges are usually understood as an economic instrument (Dikgang, Leiman, & Visser, 2012), even small charges can reduce the use of single-use bags (McElearney & Warmington, 2015) potentially acting as a prompt that makes the use of plastic salient. The broad population-wide effects of the charge suggest that it works by disrupting a habitual behaviour, and potentially giving people an ostensible reason for change when they may have been ready to act for some time (Poortinga et al., 2016). A similar reasoning underlies the use of defaults. Johnson and Goldstein (Johnson & Goldstein, 2003) argued, in the context of organ donation, that defaults are interpreted as an implicit recommendation, or norm, that this is the best course of action. Accepting a default is also effortless as people do not need to make a decision. Before the plastic bag charge was introduced, the default was getting free bags every time people went shopping and avoiding this involved undesirable cognitive effort.

There is some evidence that pricing instruments are more effective in reducing the use of single-use carrier bags than are voluntary measures. The introduction of bags for life by UK supermarkets in the early-2000s was accompanied by a moderate reduction in the use of single-use carrier bags (WRAP, 2014). This suggests that the provision of more sustainable alternatives may help, but that further incentives are needed for more widespread behaviour change. Field experiments in which supermarket shoppers received prompts or persuasive normative messages also showed reductions in plastic bag usage, if to a much smaller extent (de Groot, Abrahamse, & Jones, 2013; Ohtomo & Ohnuma, 2014). However, with increasing awareness and concern about plastic effects on wildlife, it is possible that intrinsic motivations may become more powerful compared to extrinsic drivers such as pricing (Pahl, Wyles, & Thompson, 2017).

In line with this recent research, there has been combined incentives with environmental messages and structural changes to encourage the use of reusable coffee cups. In a field experiment, Poortinga and Whitaker (Poortinga & Whitaker, 2018) found that particularly combinations of different measures were effective. The study found that a discount on reusable cups was less effective than a charge on disposable cups. This may be because consumers are generally less sensitive to a gain than to a loss (Kahneman & Tversky, 2012) or because the use of a reusable cups has become more common and therefore normative (Cialdini & Goldstein, 2004).

Policies and interventions may not only change the targeted behaviour but may also have a range of side effects and unintended consequences, both positive and negative. The acceptability of environmental policies appears to increase after they have been implemented (Nilsson, Schuitema, Jakobsson Bergstad, Martinsson, & Thorson, 2016; Poortinga et al., 2016; Poortinga et al., 2013) possibly indicating an initial general reluctance against any change, and there is evidence that policies, such as the plastic bag charge, may catalyse wider awareness of plastic waste and lead to 'policy spillover,' i.e. greater support for other waste-reduction policies (Thomas et al., 2016).

Spillover to other environmental behaviours may occur when people engage in environmental behaviours, although these effects are likely to be small (Austin, 2011) and may only happen when the behaviour is seen as diagnostic of an internal disposition (e.g. values or identity). Thomas and colleagues (Thomas et al., 2016) found that spill over to other environmental behaviours is more like happen when behaviour change is internally motivated than when it is externally motivated by a charge. It may however be advisory to forego the secondary behavioural spillover effects in favour of larger primary effects of behaviour change (Evans, 2013; Steinhorst, Klöckner, & Matthies, 2015; Steinhorst & Matthies, 2016) , if rapid change is desired.

Spillover effects may also be negative when people feel they have 'done their bit'. By taking a single action, individuals may justify not taking further action or even license less sustainable behaviours (Thøgersen & Crompton, 2009). Little research on these topics has been conducted in the area of waste and litter-related behaviours. Another important factor that determines the potential spillover of an intervention is framing, e.g. the motive it is communicated with. Studies have shown that monetary framing, compared to environmental framing of a pro-environmental behavior can limit a positive spillover effect on other pro-environmental behaviors (Evans et al., 2013; Steinhorst et al., 2015) or the acceptability of related political measures (Steinhorst & Matthies, 2016). Therefore, if broader change is desired, interventions should appeal to environmental rather than monetary appeals. Monetary incentives could be explained as a way to overcome behavioral barriers in order to 'do good for the environment'. This is an important addition to traditional research on incentives because it demonstrates the potential risks inherent in a strong focus on personal financial gain when communicating about pro-environmental behaviour change.

Replacement behaviours and products may have other negative effects. The introduction of a plastic bag charge in England was associated with an increase in the use of more durable reusable plastic bags ('bags for life'). Life Cycle Analysis (LCA) show that these bags need to be used multiple times to provide environmental benefits over the single use. There is however evidence that bags for life are accumulating in households, suggesting that these types of bags are not used optimally (Poortinga et al., 2016). Little is known about the trade-offs, between environmental indicators such as plastic vs. carbon footprint, but also between wider important implications such as, for example healthy eating, affordability, wastage in the case of food packaging e.g (White, 2018).

Policies to change waste-relevant behaviours do not necessarily prevent plastics and other waste products ending up in the environment. They also need to address littering and other waste disposal practices that may contribute to plastic pollution. Research by Willis and colleagues (Willis et al., 2018)

suggests that integrated solutions, concurrently targeting recycling, littering and illegal dumping are the best at reducing coastal waste loads in Australia.

3.4.5. Outlook

If possible, the evidence presented above supports that interventions should provide preferable, sustainable alternatives that are feasible and most attractive for consumers in a specific situation and address a variety of motives for the consumer. Refillable packaging combined with deposit return schemes is already available in some European countries for some products, such as beverages, milk or yoghurt containers. Current situational barriers, however, prevent people from using these solutions for a wide range of products, such as food or beverages consumed on the go. There is little evidence of consumer perceptions on refillable packaging systems. However, a survey study in the UK investigated the drivers and barriers of refillable packaging systems from a consumer and industry perspective (Lofthouse, Bhamra, & Trimingham, 2009). A Europe-wide refillable packaging system for to go products, for example, could become the more attractive alternative to single-use packaging. If refillable containers were easily available (pre-packed to go products) and widely returnable (e.g. reverse vending machines), were free of charge, but available for a reasonable deposit and would be made of materials with a good environmental footprint, this solution would address a range of motivations (financial, health, environmental) and remove situational barriers (time, mobility, comfort). Life cycle assessment and a systematic circular economy analysis would be required to understand the implications in terms of carbon footprint, material flow and feasibility. Shopping and consumption patterns are already changing substantially, with increased online purchasing, sophisticated deals to steer purchases, new service design e.g. through delivery services e.g. 'last-mile' delivery, and with marketing and consumer demand increasingly focusing on experiences/image rather than physical product features or ownership (Twitchen, 2017). This offers important additional opportunities for shifting consumer behaviour towards a circular economy.

3.5. What is Unknown

There are a range of unknowns in the social and behavioural sciences applied to NMP. Perceptions and attitudes towards nanoplastics are unknown, and there are major gaps in our understanding of perceptions of microplastics. We do not know whether people are concerned about microplastics in environmental compartments other than marine, and even research on perception of marine microplastics is limited. We do not know people's perceptions of microplastics from a range of recently established sources such as fabrics and tyres. Because perception research typically precedes behaviour research, there is no research on behavioural interventions that directly address NMP either. There is a also gap in our knowledge about the unwanted consequences and side effects of legal and economic interventions.

3.6. Chapter 3 Conclusions

Here we provide the main conclusions of the working group, based on the evidence provided in the preceding sections:

1. There is a considerable influence of media and politics in parallel to scientific communication on the public discourse regarding NMP.
2. This influence is governed by risk perception principles, e.g., the evidence suggests that visual images and elite sources may attract more attention and are intensified by social media peer-to-peer sharing.
3. Communicating transparently about the uncertainties in scientific evidence is a safer approach than assuming a lack of risk, especially in sensitive domains such as food and human health.
4. Differences between technical / scientific assessment of risk and risk perception processes are governed by different values and judgmental factors.
5. There is a feeling of co-responsibility in the public and a willingness to make change where they feel it is possible; some members of the public are actively engaged in campaigns.
6. Overall there appears to be consensus between different societal actors – to date there has been little indication of plastic deniers.
7. Human decisions and behaviour are the sole cause of plastic pollution - there is no natural variation of plastics in the environment.
8. The evidence supports that societal actors and stakeholders and their interrelationships should be mapped systematically to inform interventions, (if they are needed and are to work).
9. Behaviours should be identified and quantified to target behaviour change campaigns.
10. Knowledge / information on its own is NOT a key predictor of behaviour but is useful to facilitate change.
11. Behaviour change programmes can be faster and more cost-effective at achieving change than policy tools.
12. Incentives and charges vary in effectiveness in different contexts and are not equally acceptable. Different tools / instruments are needed for different actors and different behaviours.
13. It is important to go beyond incentives and charges, because such an exclusive economic focus has substantial risks. Where possible, interventions should consider intrinsic motivations and values to encourage spillover effects that can achieve broader, longer-term changes.
14. There should be rigorous evaluation of measures and interventions to understand unintended consequences and side effects of alternatives, including trade-offs with other important outcomes such as carbon footprint and health.
15. Research on public knowledge and awareness has so far focused on certain sources of microplastics, such as microbeads and marine litter, but others are closer to people's daily experience and thus potentially perceived as more threatening.
16. Policies, such as the plastic bag charge, may catalyse wider awareness of plastic waste and lead to 'policy spillover,' i.e. greater support for other waste-reduction policies.
17. Close interdisciplinary collaboration is desirable between the natural, technical and social/behavioural sciences to address the complex issue of plastic waste and pollution.
18. Capacity building and training is needed to form a new generation of scientists that think interdisciplinarily, which the evidence shows is needed to find solutions to such environmental issues

Chapter 4: Regulatory and Legislative Aspects

4.1 Introduction

In this chapter, we overview existing, emerging and potential future regulatory and legal frameworks of relevance to microplastics. The purpose is not to provide a comprehensive description on them all per se, but to introduce them and make a digest of academic work and expert knowledge, commenting on relevant aspects of them, and in this context provide some overview analysis and insights. A more detailed policy context document has been prepared as part of this project (SAM, 2018). We also review the three governing principles that govern EU legislation concerning environmental protection, the scientific underpinnings that have guided the legislations, and finally, we make reference to implementation, enforcement, voluntary measures and governance (evidence of success, which is also reviewed in Chapter 3).

4.2 The Current Policy Landscape

Historically, plastic pollution has been part of the wider waste management policy landscape's development and implementation. The Waste Framework Directive (2018/851/EC, formerly 2008/98/EC, and 2006/12/EC, and originally 75/442/EEC), is intended to provide a basis for coherent Member State action to address the challenge of waste management. The latest revision of the Directive requires Member States to coordinate with other obligations under international and EU water legislation. The Directive is the central coordinating measure for EU waste laws, acting as a framework Directive under which other waste laws sit.

Within the amended Waste Framework Directive, marine litter, in particular plastic waste, is explicitly mentioned in articles 9, 33 and 35. It is recognized that its origin stems to a large extent from land-based activities, mainly by poor solid waste management, littering by citizens and a lack of public awareness. Therefore, specific measures are requested to be laid down in waste prevention programmes and management plans. Strategies and measures should be updated every six years, and reporting is obligatory from 2018 on.

Plastic pollution is further addressed under two other legislative areas: Environmental legislations (with emphasizes on marine protection) and those legislations that address products and packaging of products. Finally, plastic pollution is addressed on an overall policy level in the European plastic strategy (COM/2018/028) and the European action plan for the Circular Economy, Closing the loop (COM/2015/0614). Table 4.1. provides an overview of the relevant legislations under these areas, notably within most of them, micro and especially nano plastics are not explicitly mentioned.

4.3 The Three Governing Principles

Apart from the categorization of legislation, there are furthermore three overarching principles that govern EU legislation concerning environmental protection. These are the precautionary principle (PP), the proportionality principle (PrP) and the polluter pays principle (PPP).

The precautionary principle: is mentioned in Article 191 of the European Treaty concerning protecting of the environment and human health. This implies that all environmental legislations with a mandate in the treaty must consider the PP. Legislations with legal mandate in other Articles of the treaty must

have the PP written in explicitly, to provide the same obligation, a relevant example is the chemicals regulation, REACH. The principle enables decision-makers to adopt precautionary measures when scientific evidence is uncertain, and when the possible consequences of not acting are high.

The European Commission published a communication on how the PP should applied in 2000 European Commission (2000). Communication from the Commission on the precautionary principle. (Commission, 2000). The Commission states that the PP should be applied in a structured approach to address risk, especially concerning risk management. Use of the PP is therefore linked to assessment of risk including inherent uncertainties, and measures taken based on PP should be:

- *Proportional*;
- *non-discriminatory*;
- *consistent with comparable measures*;
- *based on an examination of the potential benefits and costs of action or lack of action;*
- *subject to review;* and
- *capable of assigning responsibility for producing the missing scientific evidence.*

The Precautionary Principle (PP) is designed to guide action in cases where there is a lack of full scientific certainty, though its precise formulations in various legal and other contexts vary (COMEST, 2005). It is part of a suite of environmental principles to respond to possible harms (de Sadeleer, 2002). Since the EU Treaty of Nice (2000), it is a binding principle in EU law. However, the principle continues to be disputed. In the international arena, some States (including the USA) dispute its very existence (Trindade, 2015) and even where precautionary language is clearly inscribed into international agreements, its application is contested (Gruszczynski, 2013). In the EU, too, parts of industry continue to question both the principle itself, and /or its roll-out (Scott, 2018).

There is a rhetoric that the PP is inhibiting innovation, and efforts are made by industry to promote a principle of innovation (Garnett, Van Calster, & Reins, 2018). However, defendants of the PP claim that the effect of the principle is innovation-friendly (UNESCO/COMEST 2005), and in line with wider development objectives safeguarding consumer and environmental protection and supporting the principles of circular economy.

The proportionality principle (PrP) is written into Article 5 of the European Treaty. It states that: *the content and form of Union action shall not exceed what is necessary to achieve the objectives of the Treaties.* Any proposal put forward by the Commission, including actions based on the PP, must therefore also be weighed against what is deemed necessary to prevent the possible risk to the environment and/or human health.

The polluter pays-principle (PPP) is written in the Article 191(2) of the European Treaty. The PPP entails that the polluter should bear the cost of measures needed to reduce the pollution that exceeds acceptable levels. The extended producer responsibility (Monier et al., 2014) is an application of the PPP, which is implemented in the Waste Framework Directive among other regulations. According to the OECD definition (OECD, 2001), EPR is an environmental policy approach in which a producer's

responsibility for a product is extended to the post-consumer stage of a product's life cycle. EPR provides an incentive for producers to take into account environmental considerations along the products' whole life, from the design phase to their end-of-life. The life cycle assessments (see below), thus, play a crucial role as scientific foundation for application of the PPP.

In many environmental legislations, a hazard analysis and critical control points (HACCP) or cycle safety planning approach is used as framework (van Wezel, Mons, & van Delft, 2010). Points of compliance are then to be specified, and further in-depth risk assessment and risk management are only needed in situations of non-compliance.

Table 4.1. – Overview of EU Legislation and Policies on (Micro-)Plastics

Legislation	Date[a]	Status & Milestones	Concerned Environmental Compartment	MP[$] Explicitly Targeted?
Product legislation – market introduction and approved use				
REACH (EC **1907/2006) Oxo-degradable plastics and Intentionally added microplastics**	Implemen-tation in discussion	ECHA will propose a restriction on market introduction or use of microplastics per January 2019, **when** it is the most appropriate Union-wide measure, is targeted at effects or exposures that cause the risks identified, is capable of reducing these risks to an acceptable level within a reasonable period of time and proportional while being practical and monitorable. Oxo-degradable plastics contain additives which promote the oxidation of the material	Soil/Water	Yes
Single Use Plastics (SUPs) and Fishing Gear (COM(2018)340)	May 2018	Legislative process ongoing	Water (Marine)	Yes

Packaging and Packaging Waste (94/62/EC)	May 2018	Revised version to transpose	Soil/Water	No
Food Contact Materials (1935/2004) and Regulation (EU) No 10/2011 on plastic materials and articles	Aug 2016	Evolving amendments	Soil/Water	No
Waste legislation and Emissions to the environment				
Industrial Emission Directive (2010/75/EU)	Nov 2010	Ongoing BAT BREFs*	Soil/Water	No
Waste Framework Directive (2008/98/EC)	May 2018	Revised version to transpose	Soil/Water/Air	No
Packaging and Packaging Waste (94/62/EC)	May 2018	Revised version to transpose	Soil/Water	No
Landfill Directive (1999/31/EC)	May 2018	Revised version to transpose	Soil/Water/Air	No
Port Reception Facilities (proposal)	Jan 2018	Legislative process ongoing	Water (Marine)	No
Urban Waste Water Treatment Directive (91/271/EEC)	May 1991	Ongoing review, pos. rev. 2019	Fresh Water	No
Environmental legislation, quality of receiving environment				
Drinking Water Directive (98/83/EC)	Dec 2017	Review process ongoing	Freshwater	No (but mentioned in proposal for revision)
Water Framework Directive (2000/60/EC)	Dec 2000	Ongoing review, pos. rev. 2019	Fresh Water	No
The Marine Strategy Framework Directive (2008/56/EC) and the amending Directive 2017/845/EC and Commission Decision 2017/848/EC	Jun 2008	Ongoing implementation	Water (Marine)	Yes (marine microsized litter)
Ambient Air Quality Directive (2008/50/EC)	Aug 2015	Ongoing review, pos. rev. 2020	Air	No
Strategies (non-binding)				

The EU Plastics Strategy (COM/2018/028)	Jan 2018	Soil/Water/Air	**Yes**
European action plan for the Circular Economy, Closing the loop (COM/2015/0614)	Dec 2015	Soil/Water/Air	**No**

ªThe date of the most recent relevant official document referred to in the text above (such as proposal date or adoption date or launch date, etc. as applicable); $^\$$MP – **Microplastic**; #tbd **– to be discussed**,*BAT BREFs - Best Available Technique (BAT) Reference Document

4.4 Scientific Underpinning of Current Legislation

To review the current policy measures, it is important to assess the scientific underpinning that has guided their development to this point, and to relate the scientific understanding to the protection goals aimed at in the policy. Environmental and human health protection goals differ fundamentally, because environmental protection aims at protecting populations and ecosystem functions, whereas human health protection focus on the individual.

4.4.1. Scientific Underpinning for Product Legislation

In May 2018, the European Commission proposed the 'Single Use Plastics Ban', which was approved by the European Parliament in October 2018. The Directive aims at reducing pollution from the ten most commonly found single use plastic (SUP) items found on European beaches, as well certain fishing gear (COM, 2018). The scientific foundation for this directive is based on environmental monitoring data concerning beach litter (Addamo, Laroche, & Hanke, 2017). The Directive argues that plastic is highly persistent, often has harmful properties and undergoes transboundary environmental transport, properties which are comparable to those of persistent organic pollutants under the UN Stockholm Convention (UN, 2004). In a study for the European Commission by Amec Foster Wheeler, a first attempt was made to assess PECs (predicted environmental concentrations) and PNECs (no-effect concentration) for intentionally added microplastics (Scudo et al., 2017).

Since the publication of that report, the European Commission has requested ECHA (the European Chemical Agency) to assesses the hazard and risks of microplastics, and the need for a restriction on market introduction and use of microplastics under REACH (Table 4.1.), and to review the socio-economic impacts of such a restriction. The outcome of ECHA's assessment is expected in January 2019. According to our interpretation of the evidence, such a restriction might be proposed only if it is considered:

i. the most appropriate Union-wide measure;
ii. is targeted at effects or exposures that cause the risks identified;
iii. is capable of reducing these risks to an acceptable level within a reasonable period of time and

iv.   proportional, while being v) practical and vi) monitorable. A decision on whether a restriction is needed, should take place by the end of 2020.

If the restriction has to rely on these points, it may lag behind, as the scientific evidence presented in Chapter 2 concludes that methods for exposure and hazard identification are insufficient.

It is already clear that at the very practical level even of macroplastics, there are considerable information gaps which obstruct optimal recycling (De Romph & van Calster, 2018). In view of the current scientific uncertainties in both the hazard and the exposures to nano and microplastics (see chapter 2), probably the aforementioned six conditions for a restriction cannot be met with certainty. Therefore, the precautionary principle would come into play, although this principle is not mentioned explicitly in ECHA's proposal for a possible restriction for market introduction and use of microplastics.

In November 2014, Members of the European Parliament proposed a ban on 'oxo-degradable' plastics within the EU. This measure was blocked, however an amendment to the Packaging and Packaging Waste Directive, adopted in May 2015, committed the Commission to examine the impact of the use of oxo-degradable plastic on the environment. This report (Hann, Ettlinger, Gibbs, Hogg, & Ledingham, 2017), confirms and rejects various hypotheses with regards to biodegradation, littering and recycling of pro-oxidant additive containing plastics. With regard to the Directive (94/62/EC), and (1935/2004) and Regulation (EU) No 10/2011 on plastic materials and articles, no specific scientific underpinning is available with regard to NMPs.

4.4.2 Scientific Underpinning for Waste Legislations and Emissions to the Environment
The scientific foundation for the waste legislations is largely built upon life cycle assessments (LCAs). To make LCA workable, a good understanding of the risks that a good or material poses during its whole life cycle, and of the measures by which these risks can be diminished (such as lowering emissions, preventing exposures, or using less hazardous alternatives) is needed.

Based on the consensus among this working group and contributors, measures that have proved successful may include technological measures, leading to lower plastic emissions both at the production site, during use, or at the end-of-life, for which technology add-ons at sewage treatment plants are an example (Section 2.3.1 and 2.4.3). However, measures might also include the use of alternative materials legislation, safe or circular design of products, or different consumer behaviour (van Wezel et al., 2017). These measures can be stimulated by a series of voluntary agreements, (financial) stimuli or be enforced by law.

Effective interventions are those measures that will be accepted and lead to a significant reduction in the current and future risks of NMP. Measures should thus be focused on those uses of plastic posing the highest risks for ecosystems and humans. This will be related to the volume and type of plastics which can be attributed to the various uses, their emission profiles and the resulting exposures, and the intrinsic hazardous properties of the materials in the various uses. Work to probabilistically assess plastic material flow in the European context are available (Kawecki et al., 2018). However, more work is needed related to release factors and further environmental pathways

It can be expected that the packaging industry is one of the main sectors where implementation of emission reduction measures can have large benefits, as this sector uses 38% of the produced plastics (Rabnawaz, Wyman, Auras, & Cheng, 2017). Other factors to consider in the choice for appropriate measures, is feasibility, enforcement possibilities and public acceptance (the evidence based for this as related to other pollutants, are reviewed in Chapter 3). At present, a systematic overview on policy options and their predicted efficiency and relevance to reduce current and future risks of NMP is not available.

4.4.1. Scientific Underpinning for Environmental Legislations

As mentioned above, the Marine Strategy Framework Directive (MSFD) provides the legal framework for environmental protection of European marine waters. The aim of the MSFD is to ensure good ecological status (GES) in these waters by 2020. Several protection goals mentioned in the Directive specify the criteria for GES. Relevant for plastic pollution is Descriptor 10 on "Marine litter" and Descriptor 8 on "Contaminants". Descriptor 10 states that: "…properties and quantities of marine litter do not cause harm to the coastal and marine environment". This is relevant for plastic litter, including micro- and nanoplastics.

According to the Directive, Member States must ensure that the levels of micro litter, including microplastics on the water surface in the water column, in sediment and in marine organisms, do not cause harm to the coastal and marine environment Commission Decision (EU) 2017/ 848 of 17 May 2017. Laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU. Additional scientific and technical progress is still required to support further development of some threshold values COMMISSION DECISION (EU) 2017/848 Recital 20, as also highlighted in Chapter 2. Member States have taken some action on primary and secondary microplastics through their MSFD programmes of measures, and in domestic policy initiatives (actions), including agreements with industry, supporting citizen initiatives and legislative prohibition of some products with intentionally added primary microplastics (France, Ireland, Italy, Sweden, UK). Non-legislative policy options are covered in some of the proposals between industry and the market and administrations (certification schemes for aquaculture, fisheries, plastic production) which are mostly local or national arrangements).

Currently specific legislative risk-based criteria have not yet been established for nano and microplastics, although first scientific attempts to derive ecological thresholds are being published (see chapter 2). As reviewed in Chapter 2, briefly, the impact is determined based on prevalence in biota and in surface waters. There is limited monitoring coverage of marine litter in biota, but the stomach content of Northern Fulmars (Fulmarus glacialis) and Leatherback Turtles (Dermochelys coriacea) is used as an indicator for floating marine litter, including plastic pollution. The Water Framework Directive (WFD) has protection goals, similar to those found in MSFD, but does currently not mention litter specifically and neither nano nor microplastics are among the priority substances in WFD.

Reviews:

1) Arguably the most comprehensive review of the legislations to date, has been UNEP's 2017 study which focussed on marine plastic litter and microplastics (Raubenheimmer, Nilufer, Oral, & McIllgorm, 2017) which summarily reviews existing laws and initiatives in 130 pages, at the international as well as regional and voluntary level. It suggests concrete steps towards improvement. It also signals that authorities worldwide, are best advised to ensure the co-ordination of their actions. This having been said, the EU's regulatory 'trading-up' impact is well documented and in plastics, too, the EU may want to heed international co-operation yet lead by example.

2) The EU's Joint Research Center (JRC) have provided more in-depth analysis of impacts that serve as scientific foundation for measures on marine litter, including plastic pollution. In the report 'Harm caused by Marine Litter', (which does not mention nano or microplastics specifically), Descriptor 10 of the MSFD is addressed, and harm is distinguished into three different categories: i) harm to marine life and habitats, ii) direct or indirect risk to humans and iii) socioeconomic impacts. Harm to marine life is predominantly through entanglement, ingestion and vector effects (i.e. the transfer of chemicals by the plastics). The report states that 817 marine species have been demonstrated to be impacted by marine litter by 2016, and 120 of these species are on the IUCN red list. Ingestion has been documented in 331 marine species. At least 40% of the world's seabird species, all turtle species and 50% of marine mammals are currently known to have ingested plastic marine debris. For smaller animals at the bottom of the food chain, there is less knowledge, but ingestion has been reported in benthic worms, shrimps, shellfish and zooplankton (see 2.4.6). The report further states that indirect effects are most likely to impact at a population level, and that such effects are very difficult to prove.

3) Another document that specifically reviews the scientific foundation for regulation of marine litter is the UN GESAMP report 'Sources, Fate and Effects of Microplastics in the Marine Environment'. The impact of microplastics is addressed in this report, which explains that out of 175 reported impacts of micro litter, 78% of the impacts were from microplastics. The impacts were typically observed at organism or sub-organismal level, with few studies designed to assess impacts on higher levels, or biological organisation (such as population or ecosystem level (See 2.5.3)). The JRC and GESAMP reports illustrate what scientific foundation existing marine protection regulations is based upon. As reviewed in Chapter 2, there is numerous documentations of prevalence of marine plastic litter (including microplastics) in water, sediment and biota. Effects of macro plastics are well documented, whereas effects of microplastics mainly relate to levels of biological organisations below those in focus in the environmental protection goals.

Entanglement and ingestion have been demonstrated to occur in nature, the vector effect however has not. It is not clear what is meant in the JRC report with 'impacted' and 'harm', these terms are ambiguous, also in the underlying reports. Ingestion does not as such imply impact or harm, especially not for microplastic. At present, the recognition of dose-response approaches as a prerequisite to assess risk or harm has grown (Ch2), but the reports do not reflect the relevance of critical effect thresholds. Also, the GESAMP report does not clearly specify what is meant with 'impact', but it appears to include any effect, regardless of exposure concentration considered environmentally relevant. This does not

match with the increasing recognition of risk-based approaches in assessing harm or impact of microplastics.

4.5 Current Directives/Conventions

The regulatory follow-up to nano and microplastics follows the 'incremental' approach' (Reins, 2017) which is now common to the regulation of new technologies, as well as the regulation of newly perceived risks. The approach entails that upon the discovery of a new risk or the development of a genuine new technology, as well as in the event of societal calls for the (re)regulation of incumbent technologies, the existing regulatory framework is scanned for its suitability towards the regulatory target at issue. An assessment, depending upon the outcome of this regulatory assessment, the regulator involved may:

- conclude that no action is required, meaning that the regulatory concern is properly addressed by existing law; or
- might propose that the regulatory field be prepared for potential future action, should further scientific insight show cause for concern, in particular by inserting 'hooks' into the laws and regulations, upon which any future action may be anchored; or finally
- might propose (in the event that an initiative needs to take the form of legislative intervention) or straightforwardly implement (where the change may be affected by implementing regulation) immediate changes to the regulation, to address perceived shortcomings. The piecemeal European initiatives highlighted in this chapter (e.g. the proposed ban on select single-use plastics) are an example of this approach.

In the case of the EU, the decision (between the 3 options presented above) is heavily influenced by the precautionary principle, discussed above. Seminal publications which guide the European Commission's approach include the European Environment Agency's *Late Lessons from Early Warnings (EEA, 2013).* Because of the scale of NMP presence in the production and consumption phases, a holistic assessment along the incremental lines suggested above, to date has been neither completed nor, arguably, initiated. Table 4.1 lists, (in non-exhaustive manner), a number of laws at the EU level, in which NMPs have or have not been specifically addressed, however it cannot be argued (nor has it been claimed by the European Institutions) that there is currently a comprehensive framework in place.

The working group's review of the evidence supports that it will be important to implement both agreements and legislations which are focused on emission reduction and the use of less hazardous material, as agreements that set protections levels in the environmental compartments that society aims to protect, such as: marine and surface waters, air, food products and drinking waters. In general, measures or protection levels that can be enforced are often laid down in legally binding texts, and these can create new markets for innovative solutions (to help develop better methods, solutions).

4.6 Implementation and Enforcement

Implementation of Directives and Conventions takes place in a nested fashion, from the national level through to the global. There is an interlinkage and a dependency between the levels, with strong overlaps in the scope and modality of implementation (Existing OSPAR measures in support of MSFD

programmes of measures- OSPAR aquis 2015). For example, the monitoring of marine litter takes place at the Regional Seas Convention level, but the monitoring is used to fulfil the obligations of the EU MSFD. Similarly, the programmes of measures for MSFD rely on the regional work of the sea conventions, under their regional action plans on marine litter (OSPAR, 2015). At the level of the regional seas conventions and within their competence to reduce pollution levels actions, monitoring and assessments are carried out periodically. In the period 2009-2014 there is evidence of all sizes of litter within the environment, but no indication of a trend in abundance (OSPAR, 2017).

The implementation of the rules-based EU environmental acquis is carried out by the member states and the European Commission. To ensure that the implementation is uniform, the primary Directives are supported by common implementation strategies and common understanding documents supporting the Implementation. This approach ensures that there is a level of consistency that allows for oversight and comparison of the national implementations. The participation of sectoral and NGO observers affords a level of oversight and accountability to the process.

In the wider macro-regional approach, such as a regional seas convention or political groupings such as the G20, marine litter action plans have been in place for several years. These action plans take greater cognisance of the uncertainty and lack of knowledge around this type of pressure. The plans seek to take different modes of action from awareness raising, education and behavioural change, improved monitoring, reducing the sources and types of marine litter and developing a better understanding of the scientific understanding of harm levels, to be established before taking directed actions(OSPAR Regional Action Plan on Marine Litter 2014.)

EU Implementation follows a timeline set out in the Directives, and has different phases of action. These range from scientific assessments and development of environmental monitoring systems, to the delivery of management measures and actions designed to address the pollution pressure. Legislation includes an oversight role for the European Commission to assess the effectiveness of the actions of the Member States during the implementation cycle.

The implementation and effectiveness of the Marine Strategy Framework Directive, as the only EU code that seeks to set environmental targets for marine litter, including micro plastics, is worth considering. The environmental targets reported to the EU Commission in 2012 for marine litter show that no Member State was assessed as defining adequate targets for marine litter (EU, 2008). Only two Member States set quantitative targets for microplastics based on existing work at a regional seas convention macro-regional level. Notwithstanding the lack of adequate environmental targets, the Directive requires the implementation of management measures to address pressures and maintain or achieve good environmental status. In July 2018 the European Commission's assessment of the national measures highlighted strengths, weaknesses and recommendations (EU, 2008). In summary:

Strengths
- Measures cover both the reduction of litter inputs and the removal of existing litter, but measures are mainly directed to macro-litter (not NMPs).

- There is transboundary coordination by member states and an acknowledgement of the transboundary impacts of marine litter. They link their measures to wider macro-regional actions and they coordinate these through their relevant Regional Seas Conventions.
- Awareness raising around the problem of marine litter is a measure adopted by most Member states.
- All Member States are aware of the problem of marine litter, including micro-litter such as NMPs, and most Member States have a good understanding of the main sources contributing to this problem.

Weaknesses
- Very few Member States report direct measures on micro-litter, such as NMPs. Some report indirect measures to address knowledge gaps for this type of litter, which while not yet fully addressing the problem, will positively contribute to better characterising the pressure and its potential impact on fauna. Similarly, there are no direct measures in place to tackle degradation products.
- Due to the lack of knowledge and reporting on the effects of marine litter and NMPs on biota, it is often unclear how Member States will interpret the issue of 'not causing damage on the marine environment' or 'significant impacts on the marine ecosystem', even though these aspects have been included in many of the GES definitions or in specific targets.
- At a macro-regional level, it is too early to say if any changes are occurring in the presence of litter in the marine environment (OSPAR, 2017).
- These findings relating to implementation and effectiveness are largely consistent with the state of knowledge about the scale of harm to the marine environment from macro and micro litter such as NMPs. The absence of convergent scientific evidence or advice about reference levels and baselines and the effects of marine litter can give rise to diverging approaches to implementation of measures. The dynamic between adequate understandings of risks - in order to take action, and the invoking of the precautionary principle as justification to take action, can give rise to tension in the pace, ambition and effectiveness of the implementation process between the various institutions and administrations.
- Regarding enforcement, policy measures that aim to regulate specific production and use are specifically targeted. Upon release of reports describing damaging nature of microbeads to the environment and advocacy by conservation groups, a number of countries introduced a full ban on microbeads, these include the US, Canada, France and New Zealand. On the other hand, some countries introduced partial manufacture and import ban to limit the pollution. A number of countries are currently working on their own microbeads legislations. In the end, a producer can only be held responsible for his share to the total environmental burden. As plastics are so abundantly used in our society, environmental exposures are the results of a plethora of different uses which are related to various producers. As microbeads a smaller source (by volume) and as covered in section 2.3.1, tracing is not possible. Therefore, it will be difficult to really hold any single or specific producer responsible for environmental or human health risks (De Jong, 2018).

4.7 Voluntary Arrangements

Voluntary arrangements form an important component in the overall governance framework (UNEP 2017). It can be more efficient to pursue voluntary agreements than legally binding instruments, which tend to take many years to negotiate. In addition, the existence of legislation does not in itself guarantee that a practice will cease. For example, the IMO MARPOL Convention, Annex V, forbids the disposal of all plastic waste from ships. Unfortunately, implementation and compliance are very difficult on the high seas, and anecdotal evidence suggests the practice remains widespread (although there have been some successful high-profile cases against cruise companies in the Caribbean).

As detailed in chapter 2, the fisheries and aquaculture sectors represent a substantial source of plastic marine litter. Some of the most obvious impacts are due to derelict fishing gear, commonly referred to as Abandoned Lost or Otherwise Discarded Fishing Gear (ALDFG), also reviewed in sources section 2.3.1. The Food and Agricultural Organisation of the United Nations (FAO) has put into place a voluntary Code of Conduct for Responsible Fisheries, that is global in scope 2018 (UN, 2018). It contains a series of provisions and standards covering topics such as adequate port-reception facilities, storage of garbage on board and the reduction of ALDFG, which should help to reduce the quantity of plastics entering the ocean from this industry. In 2018, the 33rd session of the Committee on Fisheries approved voluntary guidelines for the marking of fishing gear. This is regarded as an important step towards reducing the generation of ALDFG, as well as targeting illegal and unregulated fishing. This is as an example of the international community reaching a voluntary agreement. It can some time to reach agreement in this way but can be less problematic than agreeing on legislation, in the form of a Convention.

Also regarding ALDFG, the European Maritime and Fisheries Fund (EMFF) supports local initiatives on this issue (EU, 2017). These initiatives do use EU funds to encourage the behavioural change but are non-binding. It is interesting to note the end of that report they detail the challenges in evaluating effectiveness. There is also a 2017 report published by UN Environment Programme on marine litter and oceans governance (part of the UNEA process (UN, 2017)).

4.8 Governance

Governance is the process of steering multi-faceted issues and problems with potentially conflicting interests and values in an organized society or group. In the EU context, it is widely recognized that governance ought to be inclusive, i.e. involve relevant actors and stakeholders such as scientific expertise, industry, regulatory and political agencies, and civil society. Scientific knowledge and evidence constitute but one of several relevant considerations in this context (Gluckman, 2014) balancing is left to upstream engagement processes and dialogues between all stakeholders and parties.

Governance of issues characterized by uncertainty and complexity may lead to 'harder' or 'softer' measures to steer an issue in a positive direction, the harder being regulatory measures, while the softer being instruments of soft law such as (ethical) guidelines, internal (self-) control schemes, revised innovation goals, adaptive management schemes etc. Regarding microplastics, based on what we know from the evidence (see Chapter 3), it seems reasonable to assume that a combination of hard and soft law might easily emerge.

Ethics and human rights have a role in policies to govern microplastics, for example microplastics left to enter the food chain particularly because of the absence of reliable risk information (cf. also the report of the Council of Europe, on nanotechnologies (though it may be still too early to say). Ethics may appeal to the individual actors' social responsibility, as e.g. fishermen's responsibility for their gear, or market actors' and consumers' responsibility for choices of food and drinks' packaging and recycling. Awareness campaigns and other engagement activities might also be the outcome of wide governance activities (see also Chapter 3). Good governance addresses not only powerful and important stakeholders but aims at engaging broader segments of society. If we expect widespread compliance to legal measures and if we expect behaviour change where needed, our knowledge base suggests that European policies should be accompanied by engagement campaigns and dialogues (see chapter 3 section on behaviour change 3.4.4).

4.8 Chapter 4 Conclusions

1. Legislations addressing plastic pollution can be grouped into those that are aimed at market authorization for materials and products and influence NMPs downstream of macroplastics, those that aim to protect the marine environment (such as MSFD), and those that are focused on waste (such as the Waste Directive).
2. In the current relevant legislations for these 3 groups, in general NMPs are not mentioned explicitly, nor is monitoring required specific risks for NMPs.
3. Specific legislative risk-based criteria have not yet been established for micro- and nanoplastics.
4. The scientific foundation for these groups of legislations are somewhat different, and especially the foundation for the environmental legislations are based on only a few, but comprehensive reports and monitoring studies.
5. Due to the lack of scientific understanding the precautionary principle has been part of the foundation for current regulation (in accordance with the Treaty).
6. Extended producer responsibility can be viewed as an implementation of the polluter pay principle.
7. A large array of measures has proven to be useful for addressing plastic pollution, such as fees, bans, EPR and voluntary agreements. All have pros and cons (also reviewed in Chapter 3).
8. This suggests that effective interventions will be accepted and lead to a significant reduction in the current and future risks of NMP. The uses of plastic posing the highest will be related to high *volumes*, high *emission profiles*, and/or intrinsic *hazardous* properties of the materials.
9. At current, a systematic overview on policy options and their predicted efficiency and relevance to reduce current and future risks of NMP is not available.
10. It will be important to implement both agreements and legislations which are focused on emission reduction and the use of less hazardous materials, as agreements that set protections levels in the environmental compartments that society aims to protect, such as marine and surface waters, air, food products and drinking waters. In general, measures or protection levels that can be enforced are often laid down in legally binding texts, and these can create new markets for innovative solutions.

11. As socioeconomic developments increase, in a business as usual scenario-use of plastics will increase and problems increase. There is a need for more work to look at these socio-economic scenarios, more research on consumers and less on producers / industrial processes.

5. Chapter 5: Conclusions and Options

This Rapid Evidence Review Report establishes that microplastic particles are present in air, soil and sediment, freshwaters, coastal waters, seas and oceans, in biota, and in several components of the human diet (see Chapter 2). The news media are covering NMPs and there is some societal awareness and concern about the issue and some perception of risk, embedded in a broader debate on general plastic pollution (see Chapter 3). A limited range of policies exist that address NMPs either directly or indirectly (see Chapter 4) and are based on only a few scientific studies.

The SAPEA working group concludes that a lot is already known about nano- and microplastics, and more knowledge is being acquired, but some of the evidence remains uncertain and it is by its nature, complex (for instance, differences in size, shape, chemical additives, concentrations, measurements, fates, unknowns, human factors, media influences, actions and behaviours, and there is some redundancy and marginality in the papers, as reviewed in the report). While members of the working group have diverging interpretations of some of the evidence, they review and present their views in a non-biased way, also presenting where they found consensus.

SAPEA Process

The motivation for this project, as reviewed in Chapter 1, is that among scientists, policy makers and the public, there appears to be growing concern about the presence of microplastics, and there is incomplete knowledge about NMP effects on biota and human health, both currently and in terms of future trends (GCSA, 2018). Much less is known about nanoplastic than about microplastic particles.

The report considered the available evidence against a range of questions. Is there sufficient risk, and if so, what could affect the drivers of the NMP risk and alleviate the problem? What conclusions, solutions and options does the current scientific evidence offer towards answering these questions? What are the relevant EU-level, and national policies and measures that have proven to be successful, or are in place to address this issue, and what future measures could potentially address this – does the current science say anything about them? What would be the outcome of a 'no change', business as usual scenario? As with many societal challenges, both the issue and solutions are complex and require many disciplines and evidence sources to resolve.

A multidisciplinary SAPEA Working Group here took 12 weeks to review the evidence from the natural, the social/behavioural and political sciences as they relate to NMPs and summarized their conclusions at the end of each of the 3 preceding chapters. The GCSA will write a subsequent paper with rationale and recommendations for policy, based on this evidence. At present, a systematic overview on policy options and their predicted efficiency and relevance to reduce current and future risks of NMP is not available, though work has begun (SAM, 2018).

Conclusions

The SAPEA Working Group have concluded that there is room for improved quality of methods and a need for international harmonization of the methods that are used to measure and assess NMP concentrations and exposure (see Chapter 2). We need more knowledge about what the exposure means and what its effects on biota and humans are. Clarity on what 'what we know' and what 'we do not know' about NMPs, their actual risks and how interdisciplinary science can help underpin evidence-based solutions, to build awareness and help make good policy decisions is needed.

Little is known with respect to the ecological and human health risks of NMPs, and what is known is surrounded by considerable uncertainty (Section 2.6), however the relevant conclusion of this working group is that we have no widespread risk at present. For microplastics, the working group has formulated three conclusions with respect to ecological risks: one concerning present local risks (13A), one concerning present widespread risks (13B) and one concerning the likeliness of ecological risks in the future (13C). These conclusions are:

- There may at present be at least some locations where the predicted or measured environmental concentration exceeds the predicted no-effect level (PEC/PNEC>1).
- Given the current generally large differences between known measured environmental concentrations (MEC) and predicted no-effect levels (PNEC), it is more likely than not that ecological risks of microplastics are rare (no widespread occurrences of locations where PEC/PNEC>1).
- If microplastic emissions to the environment remain the same, the ecological risks of microplastics may be widespread within a century (widespread occurrence of locations where PEC/PNEC>1).

Most micro plastics go in and out of most organisms, and is the case with many chemicals, 'the poison is in the dose'. It has been demonstrated in the laboratory that at high exposure concentrations and under specific circumstances nano- and microplastics can induce physical and chemical toxicity. This can result in physical injuries, inducing inflammation and stress, or it can result in a blockage of the gastrointestinal tract (e.g., gut blockage) and a subsequent reduced energy intake or respiration. Sections 2.5 and 2.6 of this report review evidence of studies in several aquatic organisms, where, for example, researchers conclude that exposure to microplastics in the laboratory has a significant, negative effect on food consumption, growth, reproduction and survival, once effect thresholds are exceeded. But we have no evidence that this happens in nature.

Most of these effect studies are performed using concentrations that are much higher than those currently reported in the environment, or are performed using very small microplastics, for which limited exposure data exists, or only used spherical microplastics, which are not representative of real world particles, or they used relatively short exposure times. Currently, it is not known to what extent these artificial conditions apply to the natural environment. This limits the reliability of the risk assessment for nano- and microplastics.

While inflammatory evidence is seen in animal models, we don't know if this translates to humans or not. In humans, workers/occupational exposure to microplastics can lead to granulomatous lesions, causing respiratory irritation, functional abnormalities and other (such as flock workers lung). The chemicals associated with microplastics, can have additional (and difficult to assess) human health effects, such as reproductive toxicity and carcinogenicity, however,the relative contribution to chemical exposure via NMP among the mix of chemicals is probably small at present (section 2.5.6), although the number of assessments remains limited. Therefore, the degree of this toxicity and impacts for environmental NMPs remains uncertain . With a sparse evidence-base for both dietary and airborne microplastics concentrations, especially concerning the inhalable size fraction, it is unclear what the human daily intake of nano- or microplastics is, yet this knowledge is essential for estimating health effects. There is a need to understand the potential modes of toxicity for different size-shape-type NMP combinations in carefully-selected human models.

Solutions to address these conclusions begin with the further development of risk assessment approaches for NMPs and their application. If improved methods are realised, the quality of quantitative ecological or human health risk assessments could be increased.

- For the exposure assessment, this would imply the development of better measurement methods and the application of these to a variety of environmental compartments (such as air, water, soil, sediment);
- For the hazard assessment, this would imply improvement of the realism of the experimental approaches, such as implementing designs towards assessment of dose-response relationships, assessment of particle shape- specific influences on hazards, chronic endpoints and better controls.
- International agreement and standardization on the technical aspects of these improvements is considered crucial for such an improved risk assessment.

In turn, better methods would then enable us to:

- more accurately foresee the degree of harm (for human health and the environment);
- prioritize measures and actions by Member States;
- and to plan where and when to apply actions (for example Member States could develop efforts to prevent, identify and tackle the pollution risk hot spots, (such as where ecological risks exist).

It was reviewed in Chapter 4 that legislations addressing plastic pollution can be grouped into those that aim to protect the marine environment (such as the EU MSFD) and those that are focused on waste (such as the Waste Directive and RSC Action Plans on Marine Litter). The scientific foundation for these two groups of legislations are somewhat different, and in particular the foundation for the environmental legislations are based on only a few, but comprehensive reports and monitoring studies. Other legislations influence microplastics downstream of macroplastics, but do not specifically mention them. Additionally, a large and mixed array of measures is useful for addressing plastic pollution, including fees, bans, EPR and voluntary agreements (reviewed in Chapters 3 and 4), however it is not feasible to distinguish between NMPs and larger plastics when accessing the regulations (with exception

of those scenarios where primary microplastics are regulated). Due to the lack of scientific understanding, the precautionary principle has been part of the foundation for current regulations (in accordance with the Treaty).

The current focus in policies that are under development on single use plastics (SUPs) and intentionally added microplastics might not be the most effective. But which policy interventions could be taken by the European Commission and Member States and which areas would benefit from increased cooperation at EU level? The evidence as reviewed in this report, implies that Member States could address microplastics better, through direct measures, in addition to indirect measures (as described in Chapter 4), and in line with recommendations of The EU Technical Group on Marine Litter, to ensure coherence of approaches. More clarity could come on the relevance of policy actions focusing on:

- plastic production in general;
- more measures specifically relevant for microplastics;
- short-living plastic products (i.e. < 6 months);
- single use plastics (SUP);
- intentionally added microplastics; and or
- oxo-degradable plastics;
- more measure that are enforceable;

A systematic evaluation of actions should be undertaken, using process and outcome evaluation, which includes environmental and social outcomes.

NMP products cannot be re-used in the circular economy. The uses of plastic posing the highest risk are those related to high volumes, high emission profiles, and/or intrinsic hazardous properties of the materials (e.g. fibers, textiles and tyre wear particles). In order to influence and to ensure that NMP levels in the environment are directly addressed, the working group's conclusions suggest future policy decisions support a reduction of emissions to the environment and facilitate a transition towards a more circular and sustainable plastic economy. For example, such options might include looking to the high volume of plastics used in packaging, and probably the packaging directive would give options for severe emission reduction.

Time horizons, and socio-economic developments (population growth, GDP growth, etc.) and important technological as well as societal developments, such as the internet and social media, by themselves are bringing about large changes in society. Breakthrough innovations (3D printing for example, packaging (see Chapter 3)) will change plastics use, public behaviour and policy needs and future needs to address pollution and should be considered in future planning (and baseline business as usual actions).

The possibility and feasibility of non-plastic alternatives could be made more mandatorily evaluated in product legislation, especially for uses with high volumes and/or high emission profiles. However, as listed above, caution is needed when promoting non-plastic alternatives on a generic level, because comparably, we don't know which the more sustainable solution is. But a mandatory assessment of

sustainability and a push towards more circularity of materials used is surely needed (e.g. reusable container deposit schemes).

If the objective is to reduce plastics and sources of microplastics, banning certain products or types of plastic is a measure that has been shown to be effective to reduce emissions, though this may have little support and/or face opposition and potential side effects of promoting other unsustainable products should be considered. Also, notably, as above, certain types of plastics and combinations of materials are considered more problematic than others (such as PVCs and possibly also oxo-degradable polymers). A phase out of problematic polymers (those that are small, light and easily fragmented) by issuing bans would be a strong and effective step towards a more sustainable and circular plastic economy. Bans can also be used to facilitate transition away from high volume/high exposure products, such as those meant to be targeted in the new SUP legislation. In this context, there is a need to develop markers and/or approaches to causally link plastic that one can find in nature, to its origin, source or manufacturer.

It is however important to emphasize that the current scientific foundation for assessment of environmental impact is still in its infancy for the majority of the plastic pollution and it is advisable to consider environmental impact of alternatives too, while developing measures to reduce impact of plastic pollution. There are still significant uncertainties related to the impact of plastic pollution – especially microplastics, and even more for nanoplastic, and it is important to find the right balance between waiting for sufficient scientific foundation and avoiding 'paralysis by analysis' (Ch 2 conclusions and uncertainty section Chapter 3.3). In value chains where high consumption/high exposure and/or high risk are relevant, it is therefore an option to invoke the precautionary principle, in accordance with the European Treaty.

As mentioned in Chapter 4, the European Commission has requested ECHA to assess the hazard and risks of microplastics, and the need for a restriction on market introduction and use of microplastics under REACH (Table 4.1.). Based on our interpretation of the evidence base, and in view of the current uncertainties in both the hazard and the exposures to NMPs, the six conditions (as listed in Chapter 4) for a restriction cannot be met with certainty. Thus, the precautionary principle would come into play, although this principle is not mentioned explicitly in ECHA's proposal for a possible restriction for market introduction and use of microplastics. (The principle enables decision-makers to adopt precautionary measures when scientific evidence is uncertain, and when the possible consequences of not acting are high).

Aside from banning, and even though 'high quality' risk assessment is not feasible yet, the evidence suggests that other action to prevent and mitigate NMP pollution might still be taken now. While 'high quality' risk assessment is being developed coordinated monitoring efforts could be taken, (comparable to the existing WATCHLIST procedure under the Water Framework Directive), for NMP in surface waters, waste water, drinking water, air, sediment and soil to gain better insight into exposure and variability of exposure. In this monitoring, a typology of NMP should be used related to polymer type and size, so a connection to emission profiles can be made.

- Subsequent to these monitoring efforts, the topic of NMP could, when considered relevant, be taken up more explicitly, in for example the water framework directive, air quality directive, industrial emission directive and drinking water directive.
- Another benefit would be to facilitate more awareness of NMPs and informed debate by generating a publicly assessable overview of these measures and data that have been collected in relation to the monitoring programs.
- This could ensure a coordinated effort among the member states and thus optimize monitoring efforts.
- By ensuring transparency of such a database/watch list, this work would further enhance the foundation of inclusion of relevant stakeholders, thereby increasing the awareness and inclusion of these stakeholders in accordance with the principle of good governance.
- A systematic effort is advised to be made on opinions and motivations of different stakeholder groups beyond the general public, in order to tailor future actions.

This evidence (as presented in Chapter 3) supports that for policy and other stakeholder responses and measures, the focus should not be solely on technical solutions, but should consider the societal dynamics of technology acceptance and potential risks when people do not agree with, culture and the potential of social dynamics and behaviour change. Microplastics in the environment are solely the result of human decisions and actions, and we need to better understand these contributing factors in the system (see Figure 3), in order to design effective policies. This includes societal understanding and risk perception and communication of the issue in the context of uncertainty over some impacts, motivations for actions that reduce NMP spillover and potential for system change, that is accepted widely. If we do not consider and integrate the 'human factor' in planned policy actions, there is a risk of unintended consequences and policy failure (as reviewed in Chapter 3).

What could influence societal responses and behaviours in a manner that would address the problem and help achieve the policy objectives? How could we apply the influence of media and politics in parallel to the scientific insights described in this paper with communication on the public discourse of NMP? How do we resolve the discrepancy between the outcomes of scientific assessments of risk and the outcomes of risk perception processes? Options for solutions that apply this behavioural science knowledge and these conclusions, include:

- To monitor media coverage and societal perceptions of microplastic impacts, in order to allow for timely responses to changes in public opinion;
- Behavioural factors should be quantified and addressed in measures (policy actions and voluntary agreements), wherever possible;
- Systematic communications to motivate behaviour change and policy support, based on the literature about scientific behaviour change, could accompany actions, going beyond mere information and education on facts, linking to values and norms that are important to society;
- A systematic effort is advised to be made on opinions and motivations of different stakeholder groups beyond the general public, in order to tailor actions.

- In order to have incentives that work, different incentives might be needed for different groups (the pay more versus discount scenario motivating for consumers for example).
- Of the many measures that are useful and trying to address plastic pollution, there is a need for clearer options to consumers which link to their everyday social practices, and better product labelling (such as the blue angel), (on occasion it is not accurate, not effective). These could take into account the potential situational barriers at the point of sale.
- The evidence suggests that communicating transparently about the uncertainties in scientific evidence is a safer approach than assuming a lack of risk, especially in sensitive domains such as food and human health.

To address this societal issue and concern, the evidence and conclusions as summarized in this report, also support that measures should be taken to address the capacity gap in rigorous interdisciplinary, problem-focused scientific collaboration between natural, technical, social and behavioural sciences.

Given the insufficient status of standardised methods for exposure and hazard characterization and the fact that only few quantitative data are of sufficient quality currently, the absence of evidence of microplastic risks currently does not allow one to conclude that risk is neither present, nor absent, with sufficient certainty. It will thus take some time before more reliable conclusions on risks become available for the various environmental compartments and for public health assessment and better methods alone will not solve the problem.

The high level of public interest in protecting marine environments could be harnessed and connected to changes in the use and capture of plastic further upstream from NMPs, e.g., via citizen science programmes or product labelling and other sustainably tailored behavioral options. The evidence reviewed in this report suggests that with improved methodology and more honest and transparent knowledge, that effective interventions will be accepted by citizens and coordinated efforts can lead to a significant reduction in the current and future risks of NMP.

Annex 1: Working Group Members

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Annex 2: External Contributing Experts and Workshop Participants

To gather further expert input and complement the expertise of the members of the Working Group, a one-day workshop specifically dedicated to social and behavioural sciences took place on the 05th October 2018, in Berlin. Experts particularly discussed (1) perceptions and understandings of the NMP debate, and both their positive and negative implications for policy-making; (2) Public behaviour regarding NMPs and implications for policy-making; and (3) policy initiatives and regulatory frameworks that could help harness the NMP issue for public good. Drawing on the outcomes of the discussions, the external experts provided input into the Evidence Review Report which was incorporated by the working group. A special thanks to these contributing experts is hereby given.

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Annex 3: Glossary of Terms

Term	Definition
Acceptable Daily Intakes	An estimate of the amount of a substance in food or drinking water that can be consumed over a lifetime without presenting an appreciable risk to health. It is usually expressed as milligrams of the substance per kilogram of body weight and applies to chemical substances such as food additives, pesticide residues and veterinary drugs.
Advection	The transport of a substance by bulk motion.
Aggregation-sedimentation	
Arthropods	Any member of the phylum Arthropoda, the largest phylum in the animal kingdom, which includes such familiar forms as lobsters, crabs, spiders, mites, insects, centipedes, and millipedes.
Asbestos (paradigm)	Name given to six minerals that occur naturally in the environment as bundles of fibre that can be separated into thin, durable threads for use in commercial and industrial applications. These fibres are resistant to heat, fire, and chemicals and do not conduct electricity. For these reasons, asbestos has been used

	widely in many industries, but has subsequently determined to be a carcinogen and therefore not desirable.
Attitude-Behaviour-Context Model	Integrated model of environmentally significant behaviour, with the assumption that behaviour is a function of the organism and its environment. "Attitude" variables can include beliefs, norms, values or 'pre-dispositions' to act in certain ways. Contextual factors can include financial incentives and costs, physical capabilities and constraints, institutional and legal factors, public policy support, etc. (from
Benthic	Refers to anything associated with or occurring on the bottom of a body of water. The animals and plants that live on or in the bottom are known as the benthos.
Bioaccumulation	The increase in concentration of a substance in an organism over time.
Bioassay	An analytical method to determine concentration or potency of a substance by its effect on living cells or tissues. Bioassays were used to estimate the potency of agents by observing their effects on living animals (in vivo) or tissues (in vitro).
Bioavailability	Term used to describe the proportion of a nutrient in food that is utilized for normal body functions.
Bisphenol A (BPA)	A chemical that is mainly used in combination with other chemicals to manufacture plastics and resins. BPA can migrate in small amounts into food and beverages stored in materials containing the substance.
Celanthropy	Celebrity philanthropy, term used to describe celebrities who use media to raise awareness about certain issues.
Derived No Effect Levels	Level of exposure above which humans should not be exposed.
Dose-effect	The relationship between the dose of harm-producing substances or factors and the severity of their effect on exposed organisms or matter
Ecotoxicology	Discipline concerned with the toxic effects of chemical and physical agents on living organisms, especially on populations and communities within defined ecosystems, and includes the transfer pathways of those agents and their integration with the environment.
Eddy	A small-scale circular current of water.
Elasticity	Effectiveness of the change in addressing a problem.
Endocytosis	The invagination of the cell surface to form an intracellular membrane-bounded vesicle containing extracellular fluid
Endpoint	A biological endpoint is a direct marker of disease progression - e.g. disease symptoms or death - used to describe a health effect

	(or a probability of that health effect) resulting from exposure to a chemical.
Epithelia	Continuous sheets of cells (one or more layers thick) that cover the exterior surfaces of the body, line internal closed cavities and body tubes that communicate with the outside environment (the alimentary, respiratory and genitourinary tracts), make up the secretory portions of glands and their ducts, and are found in the sensory receptive regions of certain sensory organs (e.g. ear & nose).
Extended Producer Responsibility	Environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle.
Fate	Destiny of a chemical or biological pollutant after release into the natural environment.
Fenton's reagent	A solution of hydrogen peroxide with ferrous iron as a catalyst that is a suitable method for treating wastewater that is resistant to biological treatment or toxic to the microorganisms
Fouling-sedimentation	The accumulation of unwanted material on solid surfaces to the detriment of function. The fouling materials can consist of either living organisms (biofouling) or a non-living substance (inorganic and/or organic).
FT-IR	Fourier Transform Infrared Spectroscopy, method that is most often used for bacterial detection and identification is Fourier transform infrared spectroscopy (FTIR). It enables biochemical scans of whole bacterial cells or parts thereof at infrared frequencies.
Gastropods	Large class of molluscs which includes snails, slugs, whelks, and all terrestrial kinds.
Gut retention	Holding back within the gut of matter that is normally eliminated.
Hazard	A potential adverse effect of an agent or circumstance.
HC5	Hazardous Concentration for 5% of the species
Ileum	The final and longest segment of the small intestine. It is specifically responsible for the absorption of vitamin B_{12} and the reabsorption of conjugated bile salts.
Macrophage	Large (10–20 μm diameter) amoeboid and phagocytic cell found in many tissues, especially in areas of inflammation, derived from blood monocytes and playing an important role in host defense mechanisms.
Microbeads	A tiny sphere of plastic usually used in beauty products.
Microplastics	Plastic debris particles of a size ranging from 0,1 mm to 5 mm.
Motivation-Opportunity-Ability model	Model that aims at understanding decision-making, by taking into account the motivation of consumers (i.e. social norms, beliefs),

	the opportunities in place (i.e. situational conditions) and the ability of consumers (i.e. habits, task knowledge).
Nanoplastics	Plastic debris particles of a size inferior to 0,1 mm.
Nylon	A tough, lightweight, elastic synthetic polymer with a protein-like chemical structure, able to be produced as filaments, sheets, or moulded objects.
Outcome efficacy (or response efficacy)	Efficacy refers to the message cues or actions to avoid a threat. Response efficacy refers to a person's beliefs as to whether the recommended actions will avoid the threat.
Oviposition	Term used to describe laying of eggs.
Pellet	A small hard ball or tube-shaped piece of any substance.
Phagocytosis	Phagocytosis, or 'cell eating', is the process by which a cell engulfs a particle and digests it.
Plastic	Material consisting of organic polymer and additives.
Plasticity of behaviour	Potential of change in that behaviour
Polymer	Molecule of high molar mass, the structure of which comprises multiple repetition of units derived from molecules of lower molar mass (monomers).
Polystyrene	A hard, stiff, brilliantly transparent synthetic resin produced by the polymerization of styrene. It is widely employed in the food-service industry as rigid trays and containers, disposable eating utensils, and foamed cups, plates, and bowls. Polystyrene is also copolymerized, or blended with other polymers, lending hardness and rigidity to a number of important plastic and rubber products.
Post-normal science	Concept developed in the early 1990s in response to the new conditions of science in its social context, with increasing uncertainty. It enables science to engage with uncertainties, high-stake decisions, disputed values and urgent decisions.
Predicted Exposure Concentrations	Measured or calculated amount or mass concentration of a substance to which an organism is likely to be exposed, considering exposure by all sources and routes.
Predicted No Effect Concentrations	Concentration that is expected to cause no adverse effect to any naturally occurring population in an environment at risk from exposure to a given substance.
Psychometric paradigm of risk perception	Paradigm that aims at explaining lay perceptions of the risks of technological and health hazards, which were found to differ from the risk estimates of experts who generally based their assessments on the relative frequency of negative outcomes such as death or disability. The primary question underlying this

	research agenda was why some hazards with low probability of negative outcomes were perceived as riskier than others that carried a much higher probability.
Public deficit model	A model that assumes a link between public lack of knowledge or science literacy, and public scepticism or hostility.
Recyclates	Material that is recyclable.
Risk	The probability of an adverse effect on man or the environment occurring as a result of a given exposure to a chemical or mixture
Risk Characterisation Ratio	Risk characterised as the ratio of actual or predicted exposures to the no effect concentration of a given chemical or particle in a given environment.
Sensitive receptors	Sensitive receptors are people or other organisms that may have a significantly increased sensitivity or exposure to contaminants by virtue of their age and health, status (e.g. sensitive or endangered species), proximity to the contamination, dwelling construction or the facilities they use. The location of sensitive receptors must be identified in order to evaluate the potential impact of the contamination on public health and the environment.
Shading effects	Effects of covering something.
Situational factors	Situation factors, taken more broadly, may refer to (a) situation cues (objective physical stimuli in an environment), (b) psychological situation characteristics (subjective meanings and interpretations of situations), and (c) situation classes (types or groups of entire situations with similar cues or similar levels or profiles of characteristics).
Species Sensitivity Distribution (SSD)	Cumulative probability distributions of toxicity values for multiple species. For environmental risk assessment, the chemical concentration that may be used as a hazard level can be extrapolated from an SSD using a specified percentile of the distribution.
Stoke's Law	Mathematical equation that expresses the settling velocities of small spherical particles in a fluid medium. Stokes's law finds application in several areas, particularly with regard to the settling of sediment in fresh water and in measurements of the viscosity of fluids. (https://www.britannica.com/science/Stokess-law)
Subtropical gyre	an area of anticyclonic ocean circulation that sits beneath a region of subtropical high pressure. The movement of ocean water within the Ekman layer of these gyres forces surface water to sink, giving rise to the subtropical convergence near 20°–30° latitude. (https://www.britannica.com/science/subtropical-gyre)
Taxon	A word used to group or name species of living organisms.

Theory of Interpersonal Behaviour	Theory in which behaviour in any situation is a function partly of the intention (influenced by social and affective factors as well as by rational deliberations), partly of the habitual responses, and partly of the situational constraints and conditions. Behaviour is influenced by moral beliefs, but the impact of these is moderated both by emotional drives and cognitive limitations.
Theory of Planned Behaviour	Theory which predicts deliberate behaviour, because behaviour can be deliberative and planned. The theory holds that only specific attitudes toward the behaviour in question can be expected to predict that behaviour. In addition to measuring *attitudes* toward the behaviour, we also need to measure people's *subjective norms*. Finally, *perceived behavioural control* influences intentions. This refers to people's perceptions of their ability to perform a given behaviour.
Translocation	The movement of materials from leaves to other tissues throughout the plant.
Water column	A vertical section of water from the surface to the bottom of the sea, a lake, a river, etc.

Annex 4: List of Abbreviations

ABC	Attitude-Behaviour-Context
ADI	Acceptable Daily Intakes
ALDFG	Abandoned Lost or Otherwise Discarded Fishing Gear
BBC	British Broadcasting Corporation
BSE	Bovine Spongiform Encephalopathy
COFI	Committee of Fisheries of the FAO
DNEL	Derived No Effect Levels
EFSA	European Food Safety Authority
EMFF	European Maritime and Fisheries Fund
EPR	Extended Producer Responsibility
ERR	Evidence Review Report
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FT-IR	Fourier Transform Infrared Spectroscopy
GCSA	Group of Chief Scientific Advisers
GES	Good Ecological Status

GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
IMO / MARPOL	International Maritime Organization / International Convention for the Prevention of Pollution from Ships
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
JRC EMM	JRC Europe Media Monitor
JRC TIM	JRC Tool for Innovation Monitoring
MEC	Measured Exposure Concentrations
MOA	Motivation-Opportunity-Ability
MSFD	Marine Strategy Framework Directive
NMP	Nano-Microplastics
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenil
PE	Polyethylene
PEC	Predicted Exposure Concentrations
PEST	Polyester
PNEC	Predicted No Effect Concentrations
PP	Polypropylene
PS	Polystyrene
PVC	Polvynilchloride
RCR	Risk Characterisation Ratio
SAPEA	Science Advice for Policy by European Academies
SDGs	Sustainable Development Goals
SSD	Species Sensitivity Distribution
TIB	Theory of Interpersonal Behaviour
TPB	Theory of Planned Behaviour
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
VBN	Value-Belief-Norm
WHO	World Health Organization
WWTP	Wastewater Treatment Plants

Annex 5: Acknowledgements

SAPEA wishes to thank the following people for their valued contribution and support to the production of this report.

Scopus, PatStat and Cordis, respectively. Both tools perform text mining and analysis of their content.

The items resulting are depending on the parameters of the searches. In the case of the publications, the searches were done to match those of the news, (so it needed to contain one of the following keywords (in the title, abstract or keywords sections). (microplastics OR "micro-plastics" OR "micro plastics" OR nanoplastics OR "nano-plastics" OR "nano plastics").

Literature Review

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Annex 6: Systematic Literature Search Method Report

6.1 Objectives

The objective was to collect and collate published and grey literature relating to microplastic pollution in the natural sciences, and in the social and behavioural sciences and humanities, (and all other microplastics-associated papers retrievable with the search term), in order to support an Evidence Review Report on Microplastics for SAPEA, as part of the Science Advice Mechanism of the European Commission.

6.2 Scope

All retrieved studies were assessed for relevance **at title/abstract** using the following inclusion criteria:

- *Relevant subjects:* For natural sciences: source, transport, incidence and impact. For social and behavioural sciences: perception, policy and economic studies.
- *Relevant types of study:* Primary research and reviews. Relevant reviews were collated and listed in a separate appendix.
- *Geographical limits:* Global, except Asia and the Southern Hemisphere, which were excluded in all but 'Impact' studies.
- *Language*: Studies with abstracts published in the English language.
- *Date of Publication*: Primary research was included from 2017. No date restrictions were applied for reviews.

6.3 Method

The literature was collated following guidelines for systematic reviews to produce Quick Scoping Reviews and Rapid Evidence Assessments (Collins, Coughlin, Miller, & Kirk, 2015), (Collaboration for Environmental Evidence 2018). Table 2 shows the keywords used in searches. A wildcard (*) was used where appropriate, and accepted by the database/search engine, to pick up multiple word endings. Searching using

microplastic as a single word *and* hyphenated was more efficient compared with long, complex search strings. Table 3 lists the databases searched, together with dates of searches and any date limits applied.

Table 2. Search terms used for database searches

Search Term, Where Accepted by Database	Search Conditions, Where Accepted by Database
microplastic* OR micro-plastic*	2017-2019
nanoplastic* OR nano-plastic*	2017-2019
"plastic debris"	2017-2019
micro-plastic* AND review	1970-2019
microplastic* AND review	1970-2019
nano-plastic* AND review	1970-2019
nanoplastic* AND review	1970-2019
"plastic debris" AND review	1970-2019

Table 3. Online sources searched to identify relevant literature with dates of searches (in bold), and date limits for searches.

Search strategy	Search conditions
Web of Science (31/07/18):	
microplastic* OR micro-plastic*	(2017-18)
nanoplastic* OR nano-plastic*	(2017-18)
TS="plastic debris"	(2017-18)
TS=(micro-plastic* AND review)	(1970-2018)
TS=(microplastic* AND review)	(1970-2018)
TS=(nano-plastic* AND review)	(1970-2018)
TS=(nanoplastic* AND review)	(1970-2018)
TS=("plastic debris" AND review)	(1970-2018)
CAB (31/07/18):	
microplastic* OR micro-plastic*	(2017-19)
nanoplastic* OR nano-plastic*	(2017-19)
"plastic debris" (2017-19)	(2017-19)
micro-plastic* AND review	(1993-2019)
microplastic* AND review	(1993-2019)
nano-plastic* AND review	(1993-2019)
nanoplastic* AND review	(1993-2019)
"plastic debris" AND review	(1993-2019)
Science Direct (02/08/18)[1]:	
microplastic*	(2017-19)
nanoplastic*	(2017-19)
"plastic debris"	(2017-19)
microplastic* AND review	(Prior to 2016)[2]
nanoplastic* AND review	(Prior to 2016)
"plastic debris" AND review	(Prior to 2016)

[1] *Could not search micro-plastic* or nano-plastic* as the hyphen allowed words, for example, nano and plastic to be in separate sentences.*
[2] *Searching prior to 2016 avoided duplicates of those found in 2017-2019 searches above*

Searches were also carried out on the following organizational websites:

- Department for Food Environment and Rural Affairs (UK) [https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs]
- Natural Environment Research Council open archive (UK) [https://nora.nerc.ac.uk/]

- Environment & Natural Resources Canada
  [ttps://www.canada.ca/en/services/environment.html]
- European Environment Agency [http://www.eea.europa.eu/]
- Umweltbundesamt (Germany) [https://www.umweltbundesamt.de/en]
- United Nations Environment Programme [http://web.unep.org/]
- United Nations Environment Programme Mediterranean Action Plan
  [http://web.unep.org/unepmap/]
- United States Environment Protection Agency [https://www.epa.gov/]
- World Health Organization [http://www.who.int/en/]

The results of each search were imported into EndNote Web, and then retrieved references were combined in a final folder and duplicates removed. The included research was grouped and summarised in an Excel spreadsheet which was delivered to the Working group. The Endnote files were also shared with the SAM Unit for combination within one large NMP-related library to support this project.

6.4 Results

Table 4 displays the results yielded from the databases. Database searches yielded 4,826 articles, reviews, editorials or books. The organisational searches identified further studies of potential interest. Of the 3,369 studies following automated duplicate removal, **838 studies passed the relevant study inclusion criteria applied during abstract screening, and a further 11 studies were added from the organizational searches.** Primary literature (n=638) was the dominant study type, followed by review papers (n=185). Books made up a small number of the studies, and editorial, even less so (Figure 5).

Table 4. Number of results derived following automated duplicate removal and application of study inclusion criteria

Database	No. of Results	No. of Results After Automated Duplicate Removal
Web of Science	1389	949
CAB	344	137
Science Direct	3093	2283
Total	4837	3369
Total studies following application of inclusion criteria (including 11 additional studies from organisational searches)	**849**	

The most common themes were impact (n=364) and incidence (n=280), followed by transport (n=94) and source (n=71), respectively. Significantly less articles were of relevance to political (n=20), perception (n=18) and economic (n=2) themes. Where the articles covered more than one theme, they were categorised under the primary theme.

Some studies that were excluded from the primary scope, could still be of potential interest to the reporting team (e.g. methodology studies, articles with no abstract, studies from the wrong geographical area or the wrong date range). These were listed in an Appendix, and no further action was taken with them.
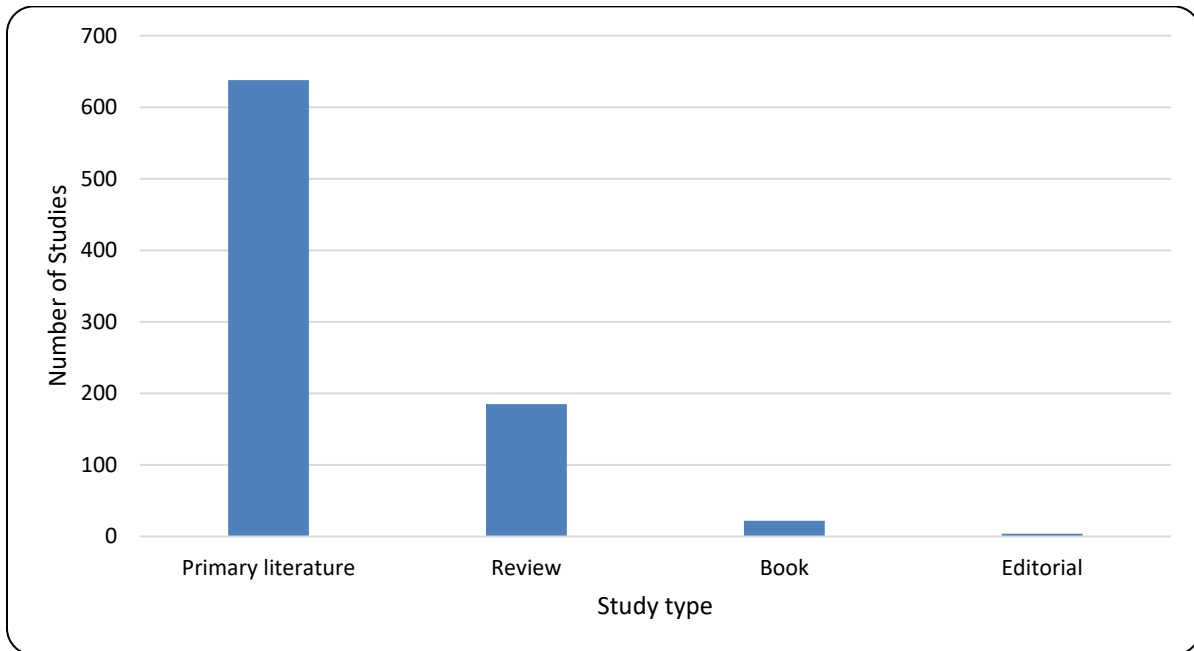

Figure 5. The number of studies per study type in the systematic map database.

Figure 6 illustrates the themes in relation to study type. Impact (n=237) and incidence (n=231) themes were addressed almost equally, and most frequently, in primary literature. In review papers, there was a significantly greater focus upon impact (n=114), almost three times more studies than incidence (n=35).
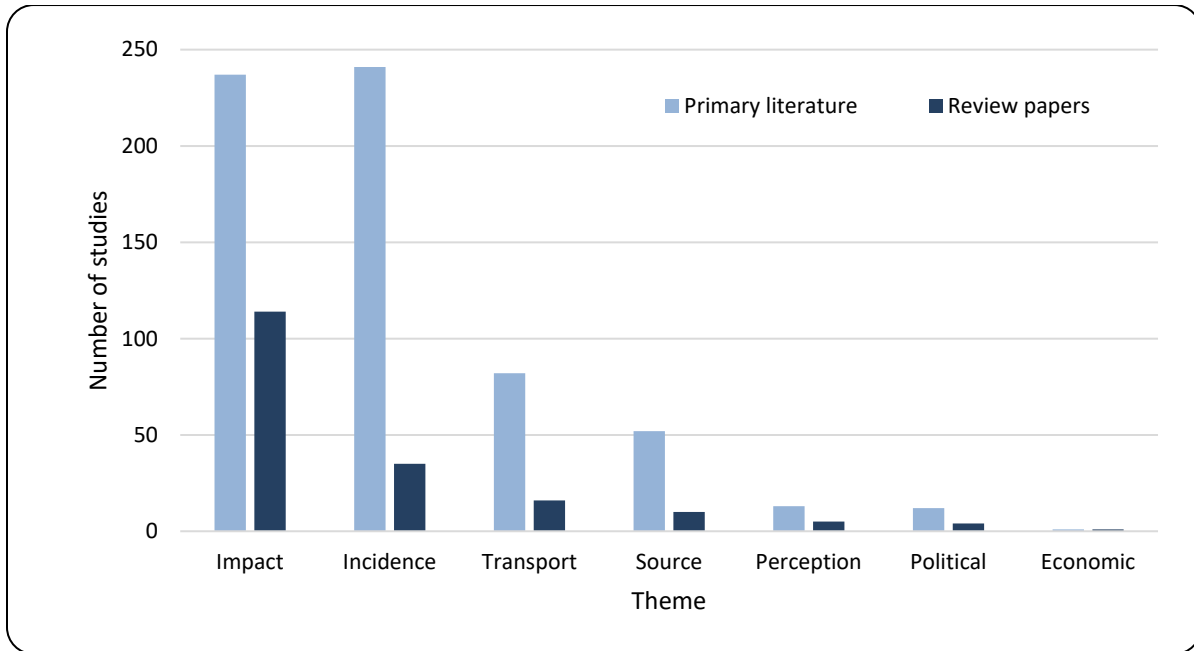

Figure 6. The number of studies within each theme for primary literature and review papers in the systematic map database.

Figure 7 displays the number of relevant review papers published per year. A total of 184 review papers were identified through screening. Prior to 2015 there was no year where the number of review papers exceeded six. In the period 2015-17 there was consistency in the number of review papers published per year (n=~30), a figure which doubled in 2018 (n=60). One article from 2019 was also collected as an 'early view' paper.
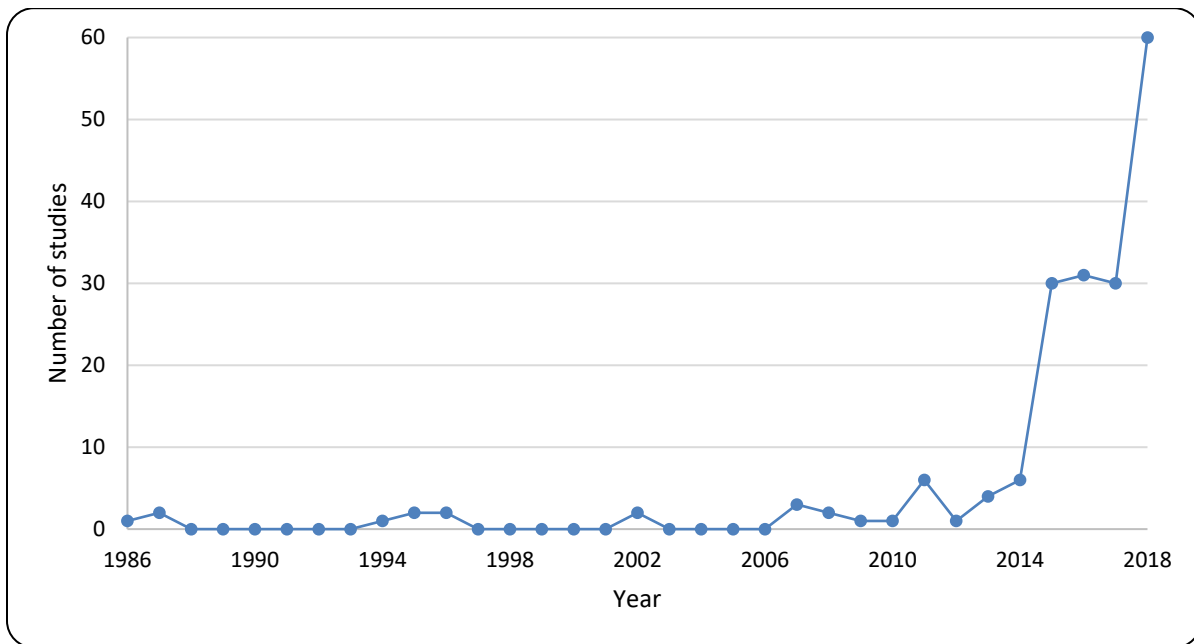

Figure 7. The number of review papers published per year (1986-2018) in the systematic map database.

Within themes (incidence, impact etc.), individual studies often considered multiple factors (for example impacts could be discussed for both 'Marine' and 'Fish' studies). In these cases, all relevant fields were recorded in the summary Excel file delivered to the Working group.

6.5 Incidence

Across the 280 studies categorized as incidence studies, the location of plastic incidence was most commonly investigated in the marine environment (n=210). This was almost five times the number of studies than the second most common location of incidence, freshwater (n=43). There is a noticeably lower focus upon terrestrial incidences, and soil or sediment, food or drink product, land, and air all the focus of n<30 studies (Figure 8). Studies most commonly investigated the incidence of plastics in fish and birds, with a noticeably lower focus across studies upon terrestrial organisms.
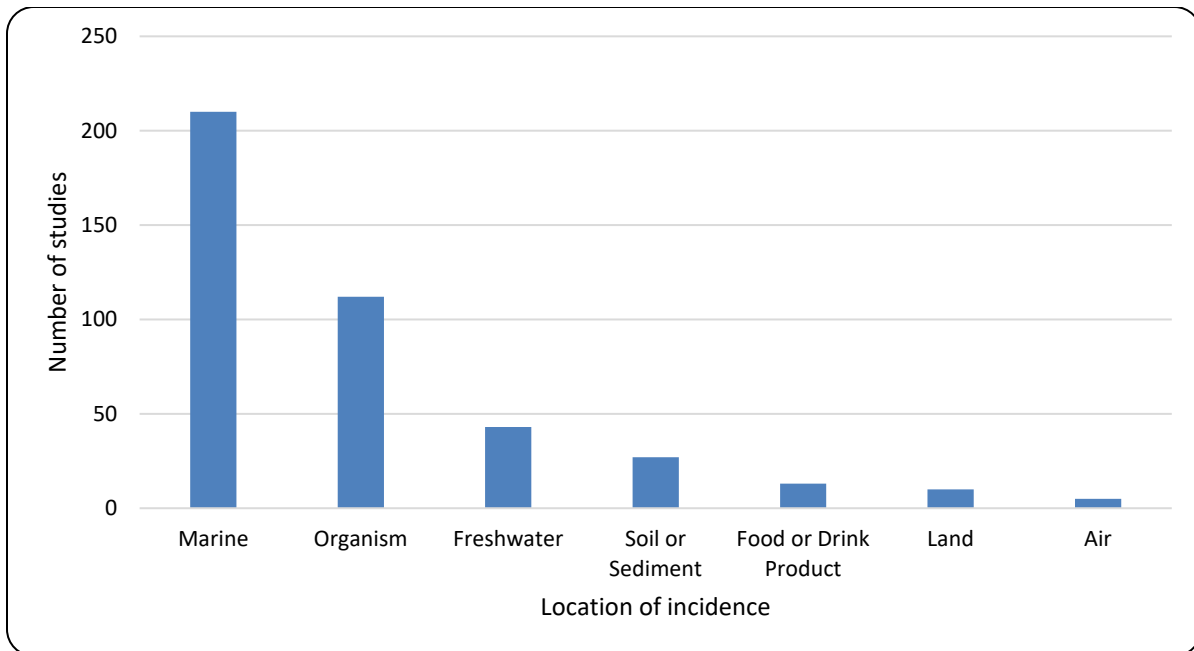
Figure 8. The number of studies per location of plastic incidence. N.B. Studies categorized as 'soil or sediments' include terrestrial studies and marine/freshwater sediments.

6.6 Impact

Of the 364 impact-themed studies, there was a focus upon investigation of plastics within the marine environment, and organisms found within. There were 171 studies investigating the impacts of plastics upon marine or coastal areas, three times as many as the second most common impact type, freshwater (n=55). Human impact, soil or sediment, and biological pollution and availability studies were all comparatively low (Figure 9).

Fish (n=50) were the most frequently investigated organism in relation to the impact of plastics, reflecting the marine or coast focus of many investigations (Figure 10), followed by studies on crustaceans and barnacles (n=37). Studies on molluscs, mammals, reptiles, plants and birds were all noticeably lower, with a particularly low frequency of studies on terrestrial organisms. Bacteria, fungi and annelids were among the organisms categorized in the 'other' group (n=29).
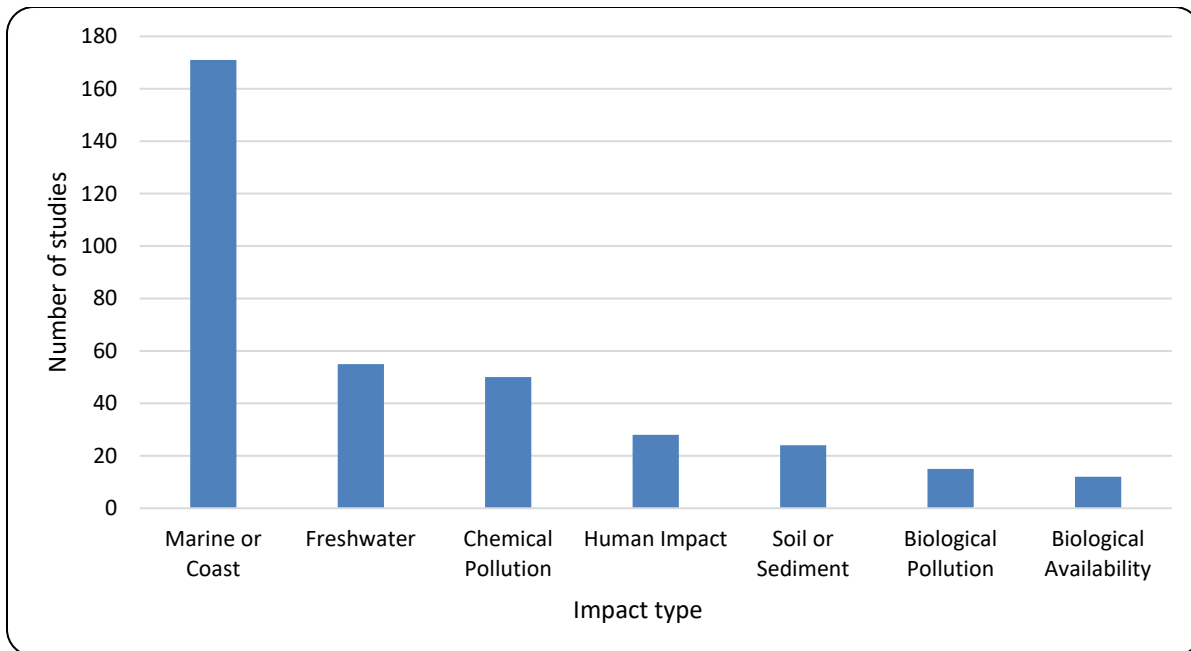
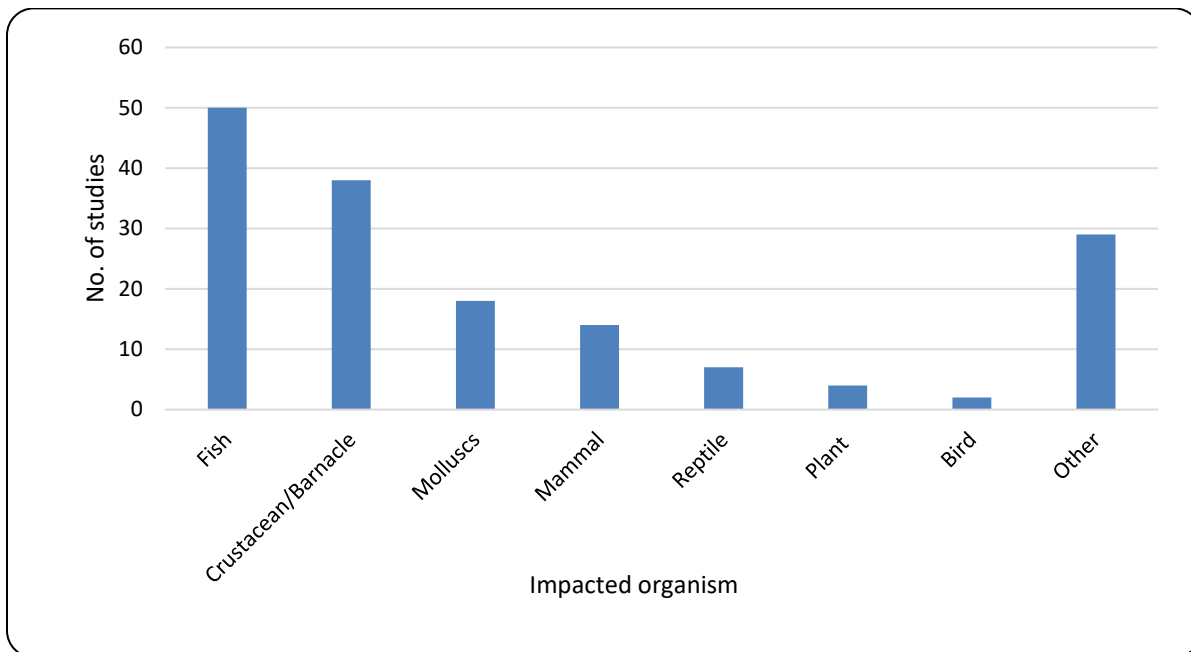Figure 9. The number of studies related to the impact type of plastic.

Figure 10. The number of studies related to the impact of plastic on organism type.

6.7 Transport

A total of 82 studies were identified within the transport theme. Water (n=41) and organism/within organism (n=40) were the most commonly studied method of plastic transport. Air and anthropogenic plastic transport studies were comparatively few in total (Figure 11).
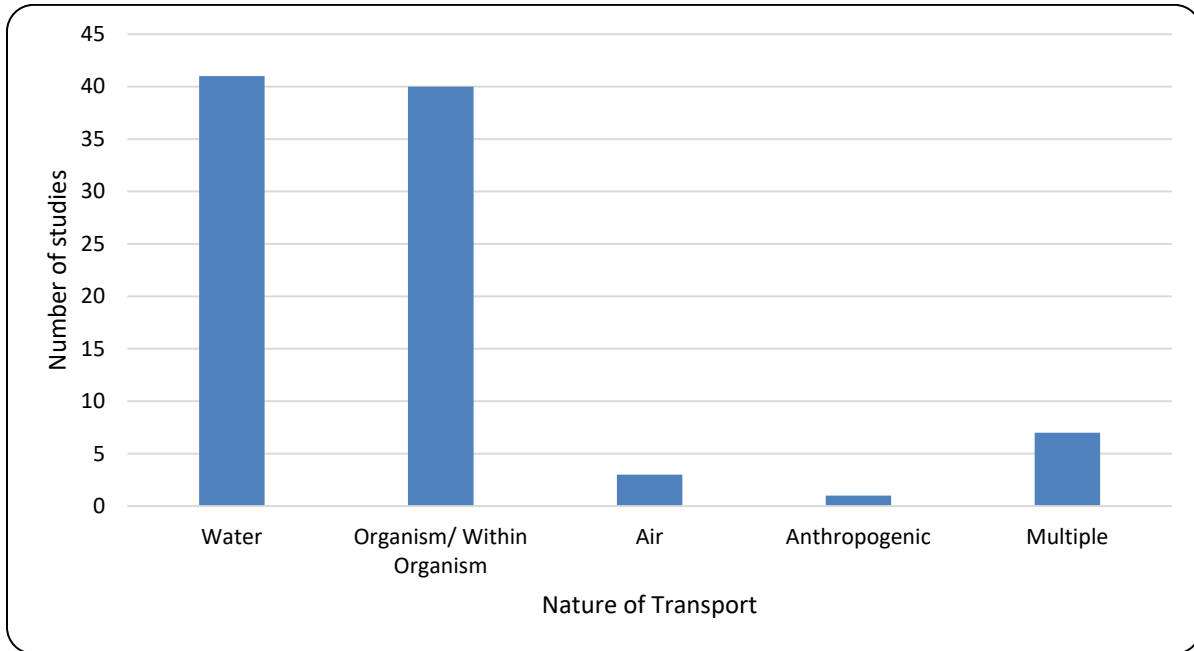
Figure 11. The number of studies per nature of plastic transport.

6.8 Source

Figure 12 summarises the distribution of the 71 studies primarily investigating the source of plastics. Litter (n=21) was most commonly investigated, followed by textiles, and washing of (n=14), and water/wastewater (n=12). Micro-beads were commonly studied in the cosmetics and personal products studies. Bio-fouling and the degradation of plastics by organisms appear to be an area of emerging interest.

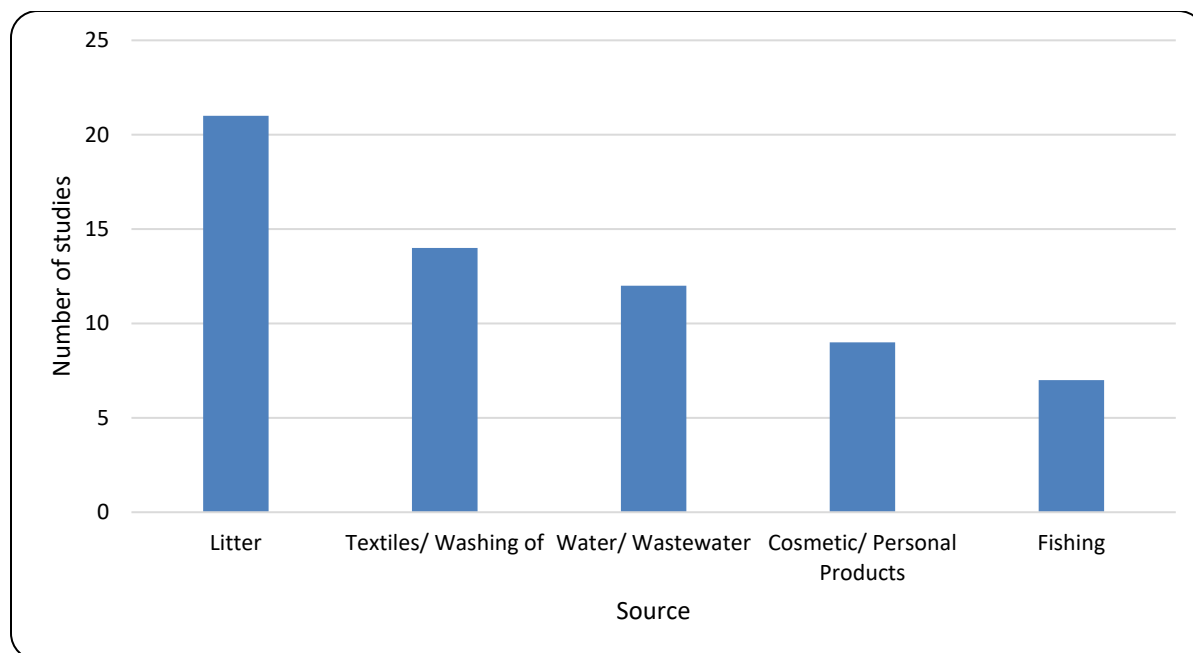Figure 12. The number of studies per plastic source.

6.9 The Social and Behavioral Sciences and Humanities

There were fewer studies found that related to the social sciences than those found for the natural sciences. Studies categorized as 'perception' (n=18) were often concerned with the behaviour change of consumers, and this was partly mirrored in the political theme (n=20), as ways to deal with plastic waste was evident among investigations. There were only two studies categorized as 'Economic'.

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