A Trash Free Waters Report on Priority Microplastics Research Needs: Update to the 2017 Microplastics Expert Workshop

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LIST OF ACRONYMS

EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
MEW	Microplastics Expert Workshop (EPA 2017)
MICRO	MICRO2020 International Conference
Mt	million metric tonnes
MDP	NOAA Marine Debris Program
NAS	National Academies of Sciences, Engineering, and Medicine
NOAA	National Oceanic and Atmospheric Administration
QA/QC	Quality Assurance / Quality Control
SCCWRP	Southern California Coastal Water Research Project
SETAC	Society of Environmental Toxicology and Chemistry
SME	Subject Matter Expert
UN	United Nations
WHO	World Health Organization

GLOSSARY

Bioavailability	The ability of a substance to be absorbed and used by the body.
Biotransformation	The process by which a substance changes through a chemical reaction within the body.
Built environment	Man-made structures, features, and facilities viewed collectively as an environment in which people live and work.
Characterization	The process of identifying a polymer based on chemical and physical attributes.
Dose-response	The relationship between the exposure to a substance and the resulting changes in body function or health.
Effluent	Treated liquid waste discharged from a wastewater treatment plant or untreated waste or sewage discharged directly into receiving waters, such as a river or sea.
Egestion	The act of excreting unusable or undigested material.
Environmental matrix	The external surroundings and location in which a substance is found (e.g., air, soil, surface water, sediment, groundwater, tissue).
Gut dysbiosis	The imbalance of microorganisms within the intestines, often caused by the ingestion of a substance that disrupts the natural microbiota.
Immunotoxicity	The adverse effects on the structure or functioning of the immune system, or on other systems as a result of immune system dysfunction, caused by exposure to a toxic substance.
Leachate	Liquid, usually water, that has moved through a solid and extracted soluble or suspended solids (e.g., liquid generated from water moving through a solid waste disposal site and accumulating contaminants).
Limnetic snow	The macroscopic organic material that forms as aggregates in a lake or pond.
Microplastics	Solid polymeric materials to which chemical additives or other substances may have been added, which are particles with at least three dimensions that are greater than 1 nm and less than 5,000 micrometers (µm) (CA State Water Resources Control Board 2020).
Microfiber	A synthetic fiber in the micro-scale that is characterized by a thin, fibrous shape.

Mesocosm	An experimental setup that examines the natural environment under controlled conditions, providing a link between field surveys and laboratory experiments.
Nanoplastics	Solid polymeric materials to which chemical additives or other substances may have been added, which are particles with all dimensions in the nano-size range (1-100 nm).
Nonpoint source	A diffuse source of pollution not included in the definition of "point source" in Section 502.14 of the Clean Water Act.
Point Source	A discrete source of pollution that meets the definition of “point source” as defined in Section 502.14 of the Clean Water Act (e.g., a pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel).
Polymer	A substance with a molecular structure of many similar units bonded together (e.g., synthetic organic materials used as plastics and resins).
Recovery rate	The amount of a substance quantified within an environmental sample as compared to the total amount of that substance within the sample.
Scleractinian coral	Coral that produce a rigid internal skeleton made of calcium carbonate.
Source water	Sources of water (such as rivers, streams, lakes, reservoirs, springs, and groundwater) that provide water to public drinking water supplies and private wells.
Sorption	The adherence of one substance onto (adsorption) or within (absorption) another substance.
Sludge	The residual, semi-solid material that is produced as a by-product during sewage treatment of industrial or municipal wastewater.
Toxicokinetics	The rate at which a chemical enters the body and the processes involved in excretion and metabolism of the chemical once it is inside the body.
Toxicodynamics	The dynamic interactions of a chemical with its biological target (e.g., a tissue) and the subsequent biological effects (e.g., molecular, cellular, organ-level).

EXECUTIVE SUMMARY

As part of its ongoing national program to prevent trash from entering waterways, the Environmental Protection Agency (EPA) Trash Free Waters Program convened an expert workshop in June 2017 to identify and prioritize the scientific information needed to understand the risks posed by microplastics. Workshop participants utilized a risk assessment approach to develop conceptual models that describe, among other topics, exposure pathways and potential impacts of microplastics to environmental and human health. This report updates the information contained in the expert workshop report (EPA 2017) to assist the scientific research and funding communities with identifying information gaps and emerging areas of interest within microplastics research.

To prepare this update, with the technical support of Industrial Economics, Inc. (IEc), EPA contacted 11 subject matter experts (SMEs) in analytical method development; sources, transport, and fate of microplastics; ecological assessments; and human health assessments. During our discussions with these SMEs, we explored current advances in microplastics research, including their insights into recent peer-reviewed publications and/or white papers that have expanded the fundamental knowledge base within their field of expertise. The SMEs provided additional perspectives on the conceptual models developed in the workshop report (EPA 2017) and suggested revisions based on their knowledge of the current state of the science. In addition, a targeted literature review and cited reference searches relevant to these priority research topics were conducted. Information on conferences, workshops, and journals to better contextualize the state of the science, information gaps, and emerging areas of interest were also compiled.

Findings from the discussions with SMEs and literature review indicate that each of the priority research topics identified by the workshop participants in 2017 certainly remain relevant in 2021. Priority research needs are highlighted in Exhibit ES-1. The recent studies identified through discussions with SMEs and the literature review are prime examples of how multiple research communities work together to drive microplastics and nanoplastics research.

The body of scientific literature is increasing, with peer-reviewed papers published weekly. New conferences and journals highlighting microplastics and nanoplastics research are enabling even more inter-disciplinary approaches. In addition to original, primary research, external drivers such as the Save Our Seas 2.0 Act, the U.S. Federal Strategy for Addressing the Global Issues of Marine Litter, and a current state of the science report published jointly by Environment and Climate Change Canada and Health Canada have identified research gaps and priorities. By considering and highlighting research gaps and emerging areas of interest, this report aims to spur momentum toward solutions that reduce and prevent microplastics and nanoplastics at their source.

EXHIBIT ES-1 PRIORITY RESEARCH NEEDS IN MICROPLASTICS/NANOPLASTICS RESEARCH

TOPIC	PRIORITY RESEARCH NEEDS
Analytical Methods	❖ Methods tailored to size range, plastic type, matrix, and research question. ❖ Quality control measures to enable cross-study comparisons. ❖ Methods to isolate, characterize, and measure nanoplastics.
Sources, Transport, and Fate	❖ Primary data collection and modeling exercises to investigate sources of microplastics and nanoplastics and their movement throughout the environment. ❖ Solutions to address the upstream sources of microplastics and nanoplastics. ❖ Processes that influence movement of microplastics, such as flow, deposition, and degradation.
Environmental Assessments	❖ High-quality laboratory toxicity studies using environmentally relevant concentrations and conditions. ❖ Exposure to and bioaccumulation of chemicals in tissues. ❖ Characterization and impact assessment of microfibers.
Human Health Assessments	❖ Development of reproducible methods to measure microplastics and nanoplastics. ❖ Quantification of microplastics and nanoplastics in relevant matrices, such as drinking water, air, dust, and food. ❖ Studies that quantify routes of exposure and relative risk to better characterize human health impacts.

INTRODUCTION

In June 2017, the U.S. Environmental Protection Agency (EPA) Trash Free Waters Program convened a workshop that brought together SMEs in the fields of environmental monitoring, waste management, toxicology, ecological assessments, and human health assessments to discuss and summarize the risks posed by microplastics[1] to ecological and human health (EPA 2017). The resulting workshop report outlined priority scientific information needs within four broad categories of research, including the following:

- **Methods of Microplastics Collection, Extraction, Characterization, and Quantification**. Participants identified a goal to "establish reproducible, representative, accurate, precise methods for microplastics analysis that include appropriate quality assurance/quality control (QA/QC)" (EPA 2017).
- **Sources, Transport, and Fate of Microplastic**. Participants articulated the need to conduct "research on the sources, transport, fate, and distribution of microplastics in the environment to be used for exposure characterization in risk assessment of human and ecological health impacts." They emphasized that this research should focus on how use and wear of consumer products, as well as agricultural and waste management practices, contribute to microplastics in the environment and how particle characteristics (e.g., size, shape, color, density) affect the ways in which microplastics behave and move in the environment (EPA 2017).
- **Ecological Assessments of Microplastics**. Participants thought it important to create "standardized toxicity tests for microplastics in … ecologically representative organisms and systems," consider bioavailability of microplastics and their associated chemicals (e.g., how much is absorbed), and develop relationships to understand whether and how the amount of exposure to microplastics influences the impact on human and ecological health (EPA 2017).
- **Human Health Assessments of Microplastics**. Participants identified broader goals for human health risk assessment of microplastics, a field that is just being established, such as "create(ing) methods and conduct(ing) research to

[1] Consistent with the definition of 'microplastics in drinking water' as adopted by the state of California (CA State Water Resources Control Board 2020), this report defines microplastics as "solid polymeric materials to which chemical additives or other substances may have been added, which are particles which have at least three dimensions that are greater than 1 nm and less than 5,000 micrometers (µm)." Microplastics and nanoplastics, or particles 1-100 nm, do not have universally accepted definitions. Where relevant, this report specifies particle size ranges targeted within the literature cited.

characterize human exposure to and impacts from microplastics in drinking water (including source water), seafood, freshwater fish and indoor/outdoor dust" (EPA 2017).

To build on the momentum in the 2017 Microplastics Expert Workshop (MEW), the EPA Trash Free Waters Program is releasing this report to assist the scientific research and funding communities in identifying information gaps and emerging areas of interest within microplastics research. This report is structured to update each of the four categories listed above (field and analytical methods; sources, transport, and fate; ecological assessments; and human health assessments). Each report section includes a status update on the state of the science, informed by conversations with SMEs and a targeted review of the peer-reviewed literature.

To develop the content of this report, EPA, with IEc's technical support, developed a list of relevant SMEs by reviewing the 2017 MEW participant list and recent peer-reviewed literature on microplastics and nanoplastics, ensuring representation in each of the four research categories. IEc and EPA held discussions with 11 SMEs to gain their perspectives on current advances in their field, critical peer-reviewed publications and/or white papers, and the continued relevance of the scientific information needs identified in the 2017 MEW report. The list of SMEs contacted is included in Appendix A.

The information collected during these discussions was used to conduct a targeted literature review and formulate descriptions of information gaps and emerging areas of interest in the sections of this report. In addition, a targeted cited reference literature search was conducted, based on critical peer-reviewed publications, identified through discussions with the SMEs, relevance to particular sections of the report, and professional judgement. The results of the literature review and cited reference search are summarized in Appendix B. Related documents and white papers, such as the 2020 U.S. Federal Strategy on Marine Litter (EPA et al. 2020), the recent Save Our Seas 2.0 Act, and information related to Federal working groups on microplastics and nanoplastics, were considered in contextualizing the findings based on the current funding environment and high-level priorities set by Federal government agencies and the U.S. Congress.

The sections of this report are:

- Section 2: Analytical Methods,
- Section 3: Microplastic Sources, Transport, and Fate,
- Section 4: Ecological Assessments,
- Section 5: Human Health Assessments,
- Section 6: State of the Science,
- References, and
- Appendices.

Analytical methods to collect, extract, characterize, and quantify microplastics and nanoplastics are evolving to address more complex scientific questions. This section provides an overview of the findings from the 2017 MEW, a brief review of the current peer-reviewed literature on analytical method development, and an updated assessment of the state of the science since the 2017 workshop.

2017 MEW

The participants in the 2017 MEW focused on the basic elements of experimental design when discussing methods for field collection and sampling; laboratory processes, including extraction, separation, and cleanup; and analysis of laboratory findings, including quantification and characterization of microplastic particles (see Table 1 in EPA 2017; Exhibit 2-1). The research question, purpose, and cost all factor into a decision-making process for determining an acceptable methodological approach, along with the limitations and uncertainties associated with the methods. The report resulting from the 2017 MEW summarized a set of considerations for field sampling, laboratory analysis, and subsequent quantification and/or characterization of microplastic particles. The participants stressed the importance of utilizing methods that meet the goal of the research. For example, research proposals should determine what sample volume and how many samples would be necessary to achieve a representative sampling program, and then tailor the method to ensure high-quality measurements that answer the research question within the available budget. In addition, the participants discussed harmonization of terminology, especially related to shapes and characteristics of microplastics, as well as harmonization of methodology, including the need for robust QA/QC at the field sampling, laboratory analysis, and quantification and/or characterization stages of a given project (see Table 2 in EPA 2017; Exhibit 2-2). Harmonized terms and methods make it easier for researchers and practitioners to speak the same language and come to a common understanding about which methods are most appropriate for certain types of studies. Lastly, workshop participants identified QA/QC needs, including certified standard reference materials for microplastics in environmental media, use of field and laboratory blanks, and improving image libraries used to conduct checks of polymer type.

EXHIBIT 2-1 CONSIDERATIONS IN PLANNING SAMPLING AND ANALYSIS (REPRODUCED TABLE 1, EPA 2017)

Table 1. Considerations when planning microplastics sampling and analysis.

Microplastics Field Sampling	Microplastics Extraction, Separation and Cleanup	Microplastics Quantification and Characterization
▪ Which sample type/matrix is relevant? ▪ What size range is relevant? ▪ Which particle/polymer types are relevant? ▪ How many samples are needed? ▪ Will samples be kept discrete, homogenized or pooled for analysis, and what does this mean for interpretation of the results? ▪ Which sampling method is appropriate? ▪ What sample volume is needed to get a representative sample? ▪ What quality assurance/ quality control (QA/QC) methods are needed? ▪ Which units will be used for the final results and what does that mean for the comparability of data? ▪ What are the detection limits of the methods used?	▪ What QA/QC methods can be used (e.g., to determine procedural recoveries or to prevent background contamination)? ▪ What are the impacts of the chosen method on the final result? Will artifacts be introduced? ▪ How can sorbed contaminants and microbes be accounted for? ▪ Which polymers/particle types are accounted for, recognizing that some particle types such as microfibers can be challenging to extract and may be lost? ▪ What are the detection limits of the methods used?	▪ What are the limitations of the methods used? ▪ Which polymers/particle types are accounted for? ▪ What are the detection limits of the methods used?

EXHIBIT 2-2 QA/QC NEEDS FOR SAMPLING AND ANALYSIS (REPRODUCED TABLE 2, EPA 2017)

Table 2. QA/QC needs for microplastics sampling and analysis.

Microplastics Field Sampling	Microplastics Extraction, Separation and Cleanup	Microplastics Quantification and Characterization
▪ Methods to ensure the statistical representativeness of samples ▪ Consideration of the implications of bulk sampling versus pre-filtration/screening ▪ Use of appropriate blanks (field and lab blanks) to assess background contamination ▪ Use of appropriate methods to reduce procedural contamination in samples	▪ Standard reference materials for microplastics in various environmental media ▪ Analytical standards for microplastics ▪ Use of appropriate blanks (matrix and spikes) ▪ Use of aged particles rather than pristine particles for QA/QC, taking into account relevant time scales of environmental exposure for the matrix being analyzed ▪ Use of individual versus homogenized/pooled samples	▪ Instrumental library accuracy, including pristine and weathered microplastics ▪ Identifying and accounting for analytical confounders ▪ Shape standard terms to describe microplastics types

LITERATURE REVIEW

Laboratory methods to isolate and extract microplastics from an environmental sample have improved since 2017. Recent papers show the development of new and refined methods that can measure particles in the nano-scale size range and help investigate the risk these particles pose to humans and wildlife. For example, Caputo et al. (2021) published a review of nine laboratory techniques that measure particle size distribution and concentrations of small microplastics and large nanoplastics (60 nm to 2 µm polystyrene). In addition to testing the performance of each method,[2] the authors review gaps in methodologies and characterize three distinct analytical goals, including preparation of a sample by isolation and/or fractionation, physical characterization, and chemical identification of polymers and other compounds. For each tested laboratory method, the results summarize the applicable size range, ability to measure total concentrations, cost, technical expertise required, and other relevant parameters for researchers who need to choose one or more analytical method to answer a specific research question. Given the focus on measuring particle sizes and concentrations, the methods summarized in Caputo et al. are not likely to be sufficient to address all research questions (e.g., a research question involving chemical composition or particle degradation). The authors suggest that researchers may need to use multiple complementary methods; for example, more than one method may be necessary to

[2] Authors test the following methods: dynamic light scattering and multi-angle dynamic light scattering, transmission electron microscopy, nanoparticle tracking analysis, static light scattering, tunable resisting pulse sensing, field flow fractionation, centrifugal liquid sedimentation, flow cytometry, and nano flow cytometry.

specifically measure different particle size classes while also measuring the size and shape of the particles (Caputo et al. 2021).

Similarly, Cashman et al. 2020 tested five methods for extracting microplastics (40-710 µm) from marine sediments.[3] The authors state that a wide variety of extraction techniques have been developed to address sediment properties (e.g., grain size, organic matter content) and plastic polymers, and it is difficult to compare recovery rates (i.e., number of plastic particles measured per sample) across studies. The study was structured to have real-world relevance to United States coastal environments, including beaches and subtidal silty sediments. The authors found the recovery of microplastics varied based on the type of sediment and the polymer tested. Recovery was statistically greater than 70% (meaning the method 'found' more than 70 percent of the total number of particles) for only two of the combinations tested, polyvinylchloride in Narragansett Bay sediment as measured by the Coppock et al. 2017 method and polypropylene in Narraganset Bay sediment as measured by the Fries et al. 2013 method. No single method consistently recovered more than 70% of each polymer. Authors recommend that researchers define the size range of plastic and any considerations related to type of sediment for the extraction before deciding on a method. They also suggest including an 'internal standard' to better estimate recovery rates by ensuring a known quantity of particles added to each sample as a reference (Cashman et al. 2020).

This echoes the 2017 MEW focus on evolving QA/QC methods to allow more cross-study comparison. To move toward that eventual goal, the Southern California Coastal Water Research Project (SCCWRP)[4] held a workshop on April 4, 2019, to discuss the standardization of laboratory methods for measuring microplastics in the environment. SCCWRP subsequently launched an inter-laboratory calibration study involving more than 35 research groups in Fall 2019 to evaluate measurement methods that the State of California could use to monitor microplastics in drinking water and the environment (Rochman 2020).[5] The California State Water Board is required by Senate Bill No. 1422 to adopt by July 2021 a standard methodology to test drinking water for microplastics and accredit qualified labs.

UPDATE TO 2017 WORKSHOP

Increasingly, researchers include suggestions for enhanced harmonization across field and laboratory methods, and there is an emerging focus on QA/QC measures. In conversations with SMEs, it became clear that researchers do not expect to use a single accepted field collection method or analytical method to isolate, extract, quantify, and/or

[3] Authors tested different methods utilizing four density separation approaches (e.g., sodium chloride, calcium chloride, sodium iodide, zinc chloride) followed by some form of filtration and visual inspection under microscopy. One method used a density separation with zinc chloride followed by an oxidation step prior to filtration and visual inspection.

[4] More information on SCCWRP's work is available at the following link: https://www.sccwrp.org/about/research-areas/additional-research-areas/trash-pollution/microplastics-health-effects-webinar-series/history-california-microplastics-legislation/

[5] More information on the State of California's action on microplastics in drinking water is available at the following link: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html

characterize microplastic (and nanoplastic) particles. Rather, researchers are more likely to use methods tailored to a specific research question of interest, focusing on a particular size range, shape, polymer type, and environmental matrix (e.g., air, water, sediment, or biologic tissues).

Looking ahead, it will be essential to create a range of methods that can be used to answer different questions related to environmental and human health. In addition, as noted in both Caputo et al. 2021 and Cashman et al. 2020, more sensitive methods are needed to measure smaller microplastics and nanoplastics. Without such methods, human and ecological health risk assessments will be stalled, given the difficulty in developing accurate and precise methods to quantify nanoplastics (considered the particle size most likely to affect human health) (Al-Abed 2021).

The analytical toolbox also should include methods appropriate to different users. For example, citizen scientists and state governments have unique reasons for engaging in microplastics research and differing levels of access to analytical equipment, chemicals, and other tools necessary to collect and analyze microplastics (Baldwin and Fisher 2021). Therefore, a suite of methods that vary in sensitivity and ease of use is necessary. Simple methods that can be used in citizen science efforts and by laboratories with limited equipment could expand long-term monitoring datasets and engage the public. Developing more sophisticated methods and subsequent inter-laboratory comparisons will promote cross-pollination in academia, government, and private laboratories that conduct microplastics and nanoplastics research (Al-Abed 2021, Baldwin and Fisher 2021).

These findings are broadly consistent with those of the 2017 MEW participants, shown in Exhibits 2-1 and 2-2 above. The scientific community continues to create and evaluate methods to collect, isolate, quantify, and characterize microplastics. Recent literature and conversations with SMEs highlight the importance of continued investigation and cooperation on analytical techniques and quality control measures that enable researchers to make confident estimates of the amount and type of microplastics in the environment.

Summary | Recent Advances in Analytical Methods for Microplastics and Nanoplastics

- New techniques are being developed to measure nano-scale particles to address ecological and human health impacts and risk, though reliability has been a challenge.
- An emerging focus on quality control measures has enabled more comparisons across studies.
- New methods continue to be published, tailored to research questions and specific user groups.

Research to better understand the sources, transport, and fate of microplastics and nanoplastics provides critical linkages to document the magnitude of the issue and develop lasting solutions. This section provides an overview of the findings from the 2017 MEW, a brief review of the current peer-reviewed literature on sources, transport, and fate, and an updated assessment of the state of the science since the 2017 workshop.

2017 MEW

Participants in the 2017 MEW held an in-depth discussion on the sources, transport, and fate of microplastics, and prepared a conceptual model to describe how they move throughout different parts of the environment (e.g., soils, groundwater, wetlands, freshwaters, intertidal habitats, and marine waters). The workshop report refers to two comprehensive publications by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP 2015, 2016) in addition to other reports on the sources of microplastics (e.g., mismanaged waste, wastewater effluents, sewage, wear and tear of products) and processes involved in their movement and fate in the environment (e.g., flow, deposition, degradation, and bio-transformation). The participants organized information on microplastics sources, transport, and fate based on how much information was available in the literature and the reliability of that information (Model I, EPA 2017). At that time, participants agreed there was little information on microplastics sources such as landfill leachate, product use and wear, agricultural plastics, litter and illegal dumping, industrial wastewater, combustion, and human aquatic activities. Participants also agreed that there was little information on the processes that govern transport, including flow, deposition, degradation, and bio-transformation; as well as the occurrence of microplastics throughout the environment (e.g., air, soil, sediment, and wetland organisms, limnetic snow in freshwaters, groundwater, and deep seawater (Model I, EPA 2017)). Importantly, participants found no available data from the U.S. on microplastics in air or groundwater, both of which have implications for human health.

LITERATURE REVIEW

Sources, transport, and fate of microplastics are frequently discussed within the peer-reviewed literature. Knowledge concerning the extent of environmental contamination from microplastic and nanoplastic particles continues to expand, with new reports of particles that were collected from remote locations. This section focuses on studies published since the MEW that were mentioned in discussions with SMEs and/or have broader application to advances in the field. For example, Barrett et al. (2020) identified microplastics ranging between 5 mm and 50 µm in size from deep-sea sediment cores collected at the Great Australian Bight. Samples ranged from 0 to 13.6 fragments per gram of dry sediment, which the authors scaled up to a global approximation of microplastics contained as “standing stock” in ocean sediment. Crossman et al. (2020) measured microplastics in biosolids applied to agricultural fields in Ontario (ranging 8.7×10^3 – 1.4×10^4 per kg), and discussed the high potential for microplastics to move from soil to aquatic systems through runoff. In a study to investigate the sources and pathways of microplastic particles found in local waterbodies, Grbić et al. (2020) measured and characterized microplastics and other particles in the surface waters of Lake Ontario (0.8 particles per liter) and its source waters such as stormwater runoff (15.4 particles per liter), agricultural runoff (0.9 particles per liter), and wastewater effluent (13.3 particles per liter). The authors found proximity to urban areas was positively correlated with particle concentrations. Discrepancies between the order of magnitude of particles exported from agricultural fields in Crossman et al. and those found in surface waters in Grbić et al. indicate gaps in understanding transport pathways and the environmental fate of microplastics and nanoplastics.

Addressing the lack of information about the transport of microplastics and nanoplastics in air, Brahney et al. (2020) measured atmospheric deposition (i.e., settling of microplastics from air and precipitation to land) to 11 remote conservation areas in the United States. Brahney et al. found microplastics in 98 percent of the collected samples, ranging from 4-188 µm (particle size) and 20µm-3mm (fiber length). Wet periods were influenced by nearby population centers and the resuspension of plastics from soils. Dry periods were dominated by smaller particles that were likely moved over a longer distance as part of large-scale climate patterns. The authors suggested these patterns move plastic away from an initial source in urban centers and deposit it elsewhere due to favorable conditions such as slower air movement or a barrier such as a mountain range. Microfibers, consistent with textile fabrics, were prevalent in both wet and dry samples. Brahney et al. estimated that more than 1,000 tons of plastic are deposited annually to the 11 areas sampled in the study.

Inputs and pathways of environmental exposure were mentioned as a key information gap multiple times in discussions with SMEs. Simulation exercises can generate global estimates of microplastic in certain areas, using assumptions about sources and pathways across urban centers and habitats. For example, Gavigan et al. (2020) estimated 4.3 to 7.0 million metric tonnes (Mt) of synthetic microfibers were emitted globally from 1950 to 2016 due to washing clothing. The authors estimated that approximately half of the total fibers were generated during the last decade, and that fibers in terrestrial and landfill areas exceed fibers in waterbodies. Lau et al. (2020) developed a Plastics-to-Ocean model[6] that characterized flows for land-based sources of macroplastics and microplastics, and estimated how much plastic waste is currently in the environment. The

[6] This report was developed by The PEW Charitable Trusts. More information is available at the following link: https://www.pewtrusts.org/en/research-and-analysis/articles/2020/07/23/breaking-the-plastic-wave-top-findings

model used five scenarios to determine which interventions (e.g., focusing on collection and disposal; recycling; reducing and substitution; or systems change) could reduce plastics in the environment. The authors noted the need for more quantitative data on the key sources, rates of movement, and pathways of microplastics in the environment, in order to create better predictive models. Innovations such as reuse and refill systems, sustainable materials, waste management technology, and governmental policies were suggested as necessary steps to curb future plastic pollution.

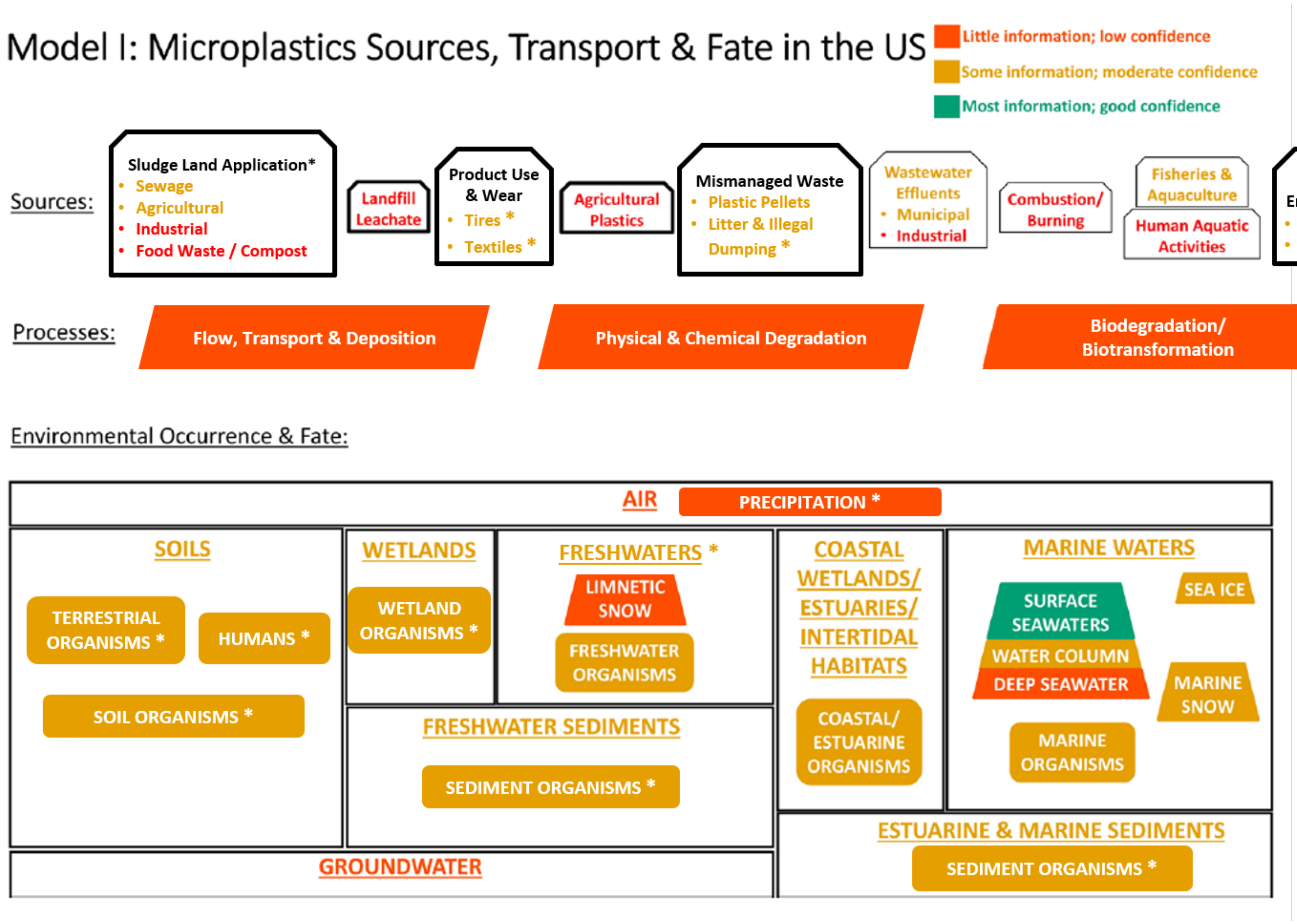
In another modeling exercise, Law et al. (2020) used solid waste assessments to assess the amount of plastic waste generated in the United States in 2016 (42.0 Mt, highest of any country in the world). They also estimated mismanaged waste resulting from domestic littering and illegal dumping, as well as inadequately managed exported plastic waste. The estimated amount of plastic waste generated in the U.S. that ended up in the coastal environment in 2016 is up to five times larger than a similar estimate for 2010 (Jambeck et al. 2015) and was among the highest of any country globally (0.51 to 1.45 Mt). The authors concluded that waste reduction focused on material, product, and packaging design would reduce environmental inputs by addressing end-of-life management of plastic products.

As these recent studies have shown, the sources, transport, and fate of microplastics and nanoplastics are a series of interrelated topics, made more complex by the knowledge gaps related to the degradation of larger plastics. Novel studies that collect new environmental data will provide more information about sources and enable scientists to understand and map the connections between the location where plastics are introduced to the environment and where they end up. Modeling exercises that use the best available information can infer pathways, environmental sinks, and the eventual fate of microplastic particles. In this way, primary data collection and modelling exercises are complimentary and work together to fill gaps in understanding microplastics' sources, transport, and fate.

UPDATE TO 2017 WORKSHOP

Research on the sources, transport, and fate of microplastics has moved forward since 2017, with most SMEs agreeing that the original conceptual model in the MEW report should be updated to reflect scientific gains in understanding the occurrence of microplastics in the environment. In addition, they suggested expanding the list of sources to reflect the built environment, including wastewater and stormwater runoff from urban areas (Exhibit 3-1). Multiple SMEs noted increased interest in identifying where microplastics are introduced to the environment as opposed to focusing on where they accumulate in marine waterbodies, which has been well documented (Jambeck 2021, Law 2020, Rochman 2020).

EXHIBIT 3-1 CONCEPTUAL MODEL I: MICROPLASTICS SOURCES TRANSPORT & FATE IN THE US (REPRODUCED AND UPDATED(*) FROM EPA 2017)



The growing interest in the sources, transport, and fate of microplastics internationally and within the United States appears to be supported by the recent Save Our Seas 2.0 Act, the scientific literature, and funding groups. For example, the NAS is conducting a study sponsored by the NOAA Marine Debris Program (MDP) to evaluate the contributions of U.S. sources to global ocean plastic waste, including where it comes from, the amount of debris in domestic waters, and the export and import of plastic waste to and from the United States. The NAS study will include the full range of plastic particle sizes. In addition, the NOAA MDP FY2021 Marine Debris Research Notice of Funding Opportunity focused on pathways, fate, and transport of marine debris from upstream to marine and freshwater coastal zones, as well as questions relevant to particle fragmentation and degradation.[7]

Also emerging is a focus on solutions that address the introduction of microplastics and nanoplastics to the environment. There is a wide range of potential solutions. For example, the World Economic Forum published a report drawing attention to and advocating for a circular economy for plastics that would require a systematic and collaborative approach that involves the packaging industry, governments, and non-governmental organizations (WEF 2016). Specifically focused on microfiber pollution, Wood and Box (2020) summarized a workshop in California on textile solutions to microfiber pollution, including statewide strategies related to microfibers, ongoing studies, and potential solutions from consumers (e.g., supplemental laundry filtration devices) and the textile industry (e.g., a Fiber Release Global Standardization test to measure fiber release and design textiles to minimize shedding). Other organizations with an on-the-ground presence, such as National Geographic, are funding scientific data collection such as the "Plastic: Sea to Source" expedition, aiming to deliver a holistic understanding of plastic pollution in a watershed.[8] These efforts, including advocacy for a circular economy, innovation in capturing microfibers from textiles, and expeditions to collect new data to map sources, pathways, and fate, demonstrate that a multi-pronged approach is needed to reduce microplastics and nanoplastics in the environment.

Summary | Recent Advances in Microplastics Sources, Transport, and Fate

- Studies have measured the occurrence of microplastics in most environments (Exhibit 3-1).
- An emerging focus is on solutions aimed at the initial point of release of microplastics into the environment.
- Stormwater and wastewater are sources of microplastics sources from the built environment, and there has been an increasing focus on microplastics generated through wear and tear of products (e.g., tires, microfibers from clothing; Exhibit 3-1).
- The NAS is conducting a broad study to evaluate the contributions of U.S. sources to global ocean plastic waste, which will provide more information on sources, transport, and fate.

[7] More information on the FY2021 NOAA Marine Debris Research funding opportunity is available at the following link: https://marinedebris.noaa.gov/sites/default/files/NOAA-NOS-ORR-2021-2006620_NOFO_Report_0.pdf

[8] More information on the expedition is available at the following link: https://www.nationalgeographic.org/projects/plastic/team/

SECTION 4 | ECOLOGICAL ASSESSMENTS

Ecological assessments include studies on the occurrence and effects of microplastics and nanoplastics, including the toxicological effects of exposure. This section provides an overview of the findings from the 2017 MEW, a brief review of the current peer-reviewed literature on ecological assessments, and an updated reflection on the state of the science since the 2017 workshop.

2017 MEW

Participants in the 2017 MEW agreed that data on the toxicity of microplastics and nanoplastics is limited, as is information from field studies on the impacts of microplastics. Therefore, the conceptual model showing the ecological occurrence and impacts of microplastics pools relevant research on species, grouping them by how they feed (e.g., detritivores, decomposers, predatory fishes, filter feeders, etc.; see Model II in EPA 2017). Participants identified a priority need for toxicity testing that generates high-quality laboratory data and the inputs necessary to conduct ecological risk assessments. Further, participants noted the importance of "reproducible, representative, accurate, precise methods for microplastics analysis" (EPA 2017). Model II expanded on Model I. It included the same environmental compartments and provided more detail on the amount of information and confidence level for the groups of organisms in each compartment (see Model II in EPA 2017). Participants identified little information on organisms that interact with soil, including humans as well as soil invertebrates, and sediment and wetland organisms. They determined that other compartments such as freshwater, marine waters, and coastal wetlands/estuaries/intertidal habitats are better studied across a range of organisms. After the workshop, a third conceptual model was constructed on the toxicokinetics/toxicodynamics of microplastics to identify uncertainties and assign confidence levels based on the available toxicological data (see Model III in EPA 2017).

Participants identified two high-priority areas for future research: (1) particle translocation within an organism (e.g., the movement of a microplastic particle from the digestive tract to another organ); and (2) exposure to and bioaccumulation of chemicals from the plastic to an organism's tissues. The workshop report described many challenges to conducting research that is environmentally relevant, and suggested that experimental designs use complex microplastic mixtures and mesocosms that "allow for multi-species and community-level assessments" to generate realistic data on species of interest.

LITERATURE REVIEW

The literature related to the ecological impacts of microplastics continues to expand, with many papers focusing on the ingestion of plastic particles by particular species in a specific location. Three original research studies, Hankins et al. (2018), Rochman et al. (2017), and Tian et al. (2021), are summarized here as examples of typical studies on the effects of microplastics. Hankins et al. (2018) exposed stony (scleractinian) coral to microbeads. They found that both species (*Montastraea cavernosa* and *Orbicella faveolata*) could expel 75 percent or more of the beads, with a majority of microbeads expelled within 48 hours. This study provided evidence about the ability of corals to select certain size ranges of plastic particles during feeding, and expel particles that were consumed. In another laboratory experiment, Rochman et al. (2017) investigated the effects of microplastic particles laced with polychlorinated biphenyls (PCBs) on freshwater prey and predators. Subtle effects were observed in clam tissues exposed to both PCBs and microplastics. Separately, Tian et al. (2021) conducted a multi-step study on the impact of synthetic tire tread particles, a potentially overlooked source of plastic particles to the environment. Tian et al. isolated a toxic chemical called 6PPD-quinone, then exposed juvenile coho salmon (*Oncorhynchus kisutch*) to a synthetic version of 6PDD-quinone and estimated a lethal concentration to salmon. The authors measured levels of 6PPD-quinone in roadway runoff and creeks on the U.S. West Coast that, based on their laboratory estimates, are toxic to salmon. By isolating this chemical in runoff, identifying its likely source (i.e., tire tread particles), and measuring it in creeks, Tian et al. documented a pathway for chemicals in worn tires to reach salmon in nearby streams.

Larger-scale reviews of impacts across groups of organisms are important contributions that aggregate individual study findings and evaluate the current state of the science. For example, Bucci et al. (2020) updated a systematic review the authors first conducted in 2016, extracting data from 139 independent laboratory and field studies across a variety of organisms and plastic types. This weight of evidence approach from Bucci et al. determined that 59 percent of the effects tested in these studies were detected; of the detected effects, 58 percent were due to exposure to microplastics and 42 percent from exposure to macroplastics. In studies with undetected effects, 94 percent were based on exposure to microplastics. Exposure to small plastic particles can create a range of effects in organisms, including no measurable effect (Bucci et al. 2020).

Specific effects caused by microplastics and nanoplastics may be difficult to detect and measure, and therefore should be studied using innovative methods and well-considered endpoints. Foley et al. (2018) conducted a meta-analysis of laboratory and mesocosm experiments investigating microplastics in fish and aquatic invertebrates and reviewed effects on consumption, growth, reproduction, and survival. The study found that effects varied and included many neutral responses, which agrees with the findings from Bucci et al. (2020). As echoed in discussions with SMEs (e.g., Rochman 2020), Bucci et al. determined that only a small number of concentrations used in studies (17%) had been found in nature and stated a need for environmentally and ecologically relevant study designs that test for differences in particle types, sizes, shapes, doses, and exposure conditions.

Focusing on ingested nanoplastics and microplastics, Hirt and Body-Malapel (2020) conducted a literature review on the effects of ingestion on gut health and immune response, using a range of species as a proxy for understanding potential impacts to humans. The authors found several studies that showed exposure leads to adverse reactions, such as impairments to gut tissues, gut dysbiosis (e.g., changes to the diversity and composition of gut microbes), and immunotoxicity (e.g., count and function of immune cells).

Gaylarde et al. (2021) reviewed the recent literature on nanoplastic particles, mostly laboratory-based studies. The authors explored the potential effects of nanoparticles on ecosystems, including the movement of organic and inorganic pollutants, and challenges such as a lack of methods that can measure environmental concentrations. The findings agreed with other studies and discussions with SMEs highlighting the lack of reproducible methods for measuring nanoparticles in the environment and their effects on organisms.

UPDATE TO 2017 WORKSHOP

Research on the ecological impacts of microplastics and nanoplastics continues to move forward. Several broad reviews organize information from dozens of studies and put the impacts into context across groups of organisms. Studies on the occurrence of microplastics in the environment continue at a faster pace than studies on the toxicological and other effects of microplastics and nanoplastics. For example, Crossman et al. noted that a risk assessment for microplastics in agricultural soils is not yet possible due to a lack of established threshold concentrations, above which effects are known to occur. Some researchers have begun considering how to piece together available data into risk assessment frameworks, though this application is in the developmental stages (see for example, Koelmans et al. 2017, OPC 2021). Effects-focused studies require more resources, including time and money, and are crucial to identifying solutions that target the most at-risk species and key pathways responsible for moving microplastics from one place to another. An important information gap identified by several SMEs is the impact of microfibers, which have not been well characterized or studied in toxicological experiments.

A revised version of the original conceptual model in the MEW report related to the ecological occurrence and impacts of microplastics (Model II, EPA 2017) is presented in Exhibit 4-1. Based on feedback gained through discussions with SMEs, we updated the model to show that many of the environmental compartments are better understood, with moderate confidence that microplastics have been documented to occur in soils, wetlands, freshwaters, marine waters, coastal wetlands, and sediments. In the future, SMEs suggested the model could be split into two diagrams to separately address the occurrence and impacts, given the latter is less well-characterized and should be based on environmentally relevant concentrations of microplastics (Law 2020, Rochman 2020). In addition, SMEs envisioned another compartment for organisms that have accumulated microplastics and therefore are a source of microplastics to the environment and other organisms.

In discussions with SMEs on the conceptual model related to toxicokinetics and toxicodynamics (Model III, EPA 2017), minor updates were suggested but not a wholesale change to the model (see Exhibit 4-2). For example, there is relatively good confidence that microplastics may be retained in organisms, and as described in the previous section, there is more evidence related to the impacts on ecological communities. There was a suggestion that future iterations of this model could separate out the physical impacts of the particle (e.g., impacts such as physical abrasion due to particle ingestion, or nutritional effects due to a false sense of satiety) from the toxicologic impacts of the chemicals that are associated with the microplastic (e.g., cellular damage cause by bioaccumulation and uptake of chemicals) (Rochman 2020). Ultimately, the model summarizes important routes of exposure and the potential impacts of that exposure, and the research in this field has not moved forward as quickly as other topics given its complicated nature.

Summary | Recent Advances in Ecological Assessments

- While studies have measured the occurrence of microplastics in most environments, studies on the impacts are still lacking (Exhibit 4-1).
- New large-scale reviews (e.g., Bucci et al. 2020) evaluate impacts to many types of organisms, and argue for more environmentally and ecologically relevant study designs across particle types, sizes, shapes, and conditions.
- Particle retention and bioavailability is better understood (Exhibit 4-2).
- Quantifying nanoparticle concentrations and exposures has been a challenge with currently available methods.

EXHIBIT 4-1 CONCEPTUAL MODEL II: ECOLOGICAL OCCURRENCE & IMPACTS OF MICROPLASTICS (REPRODUCED AND UPDATED(*) FROM EPA 2017)

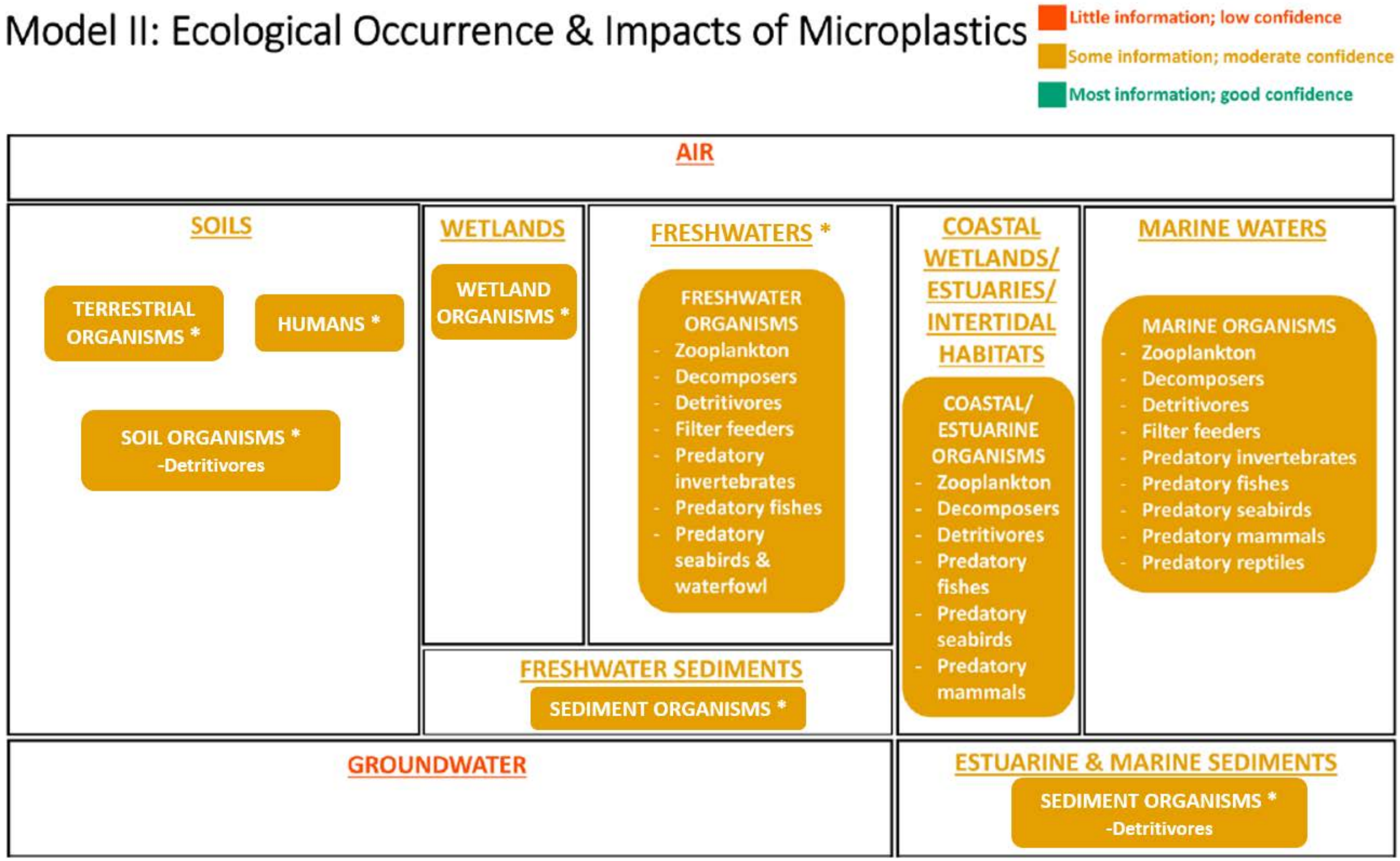
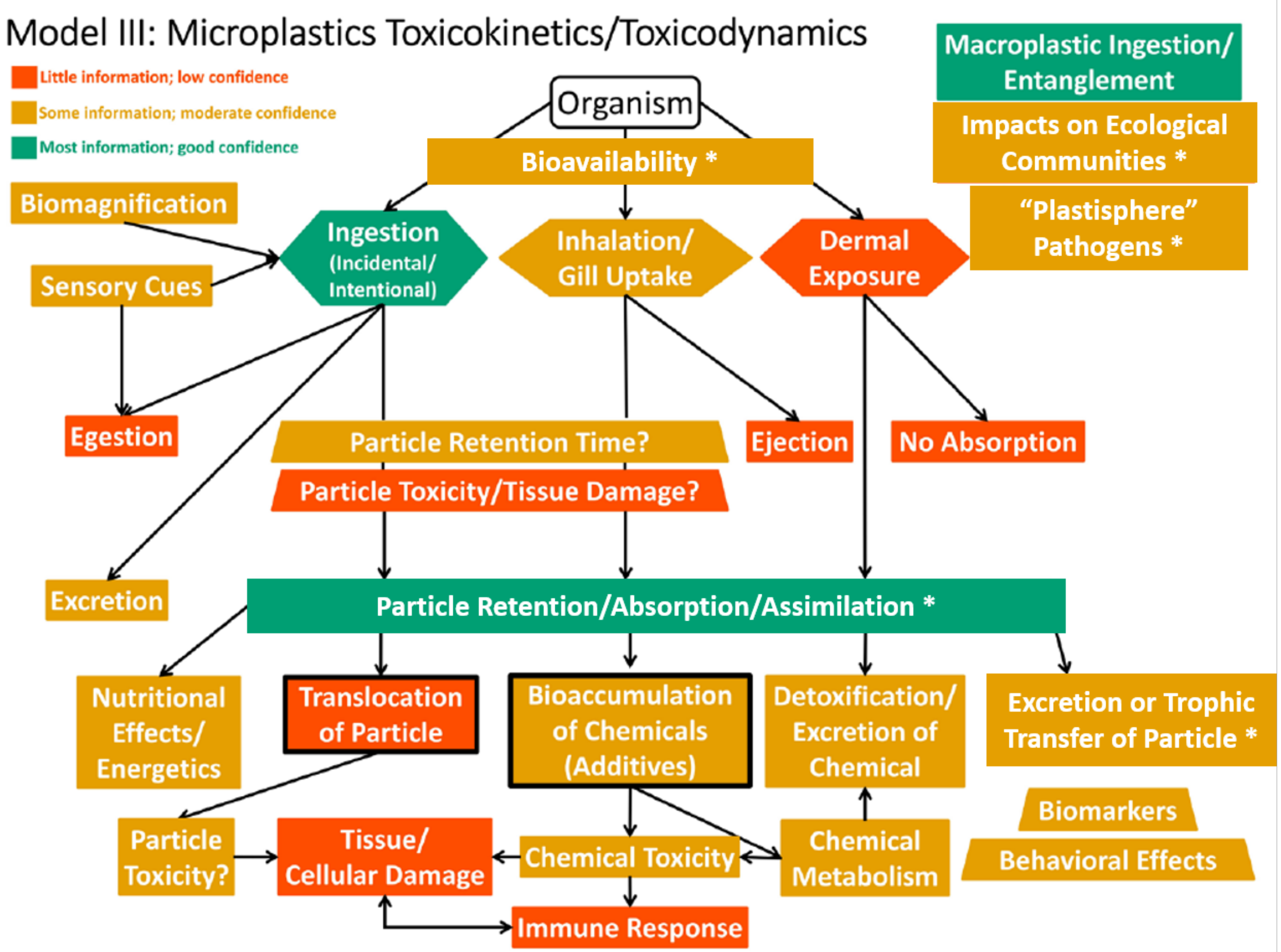


EXHIBIT 4-2 CONCEPTUAL MODEL III: MICROPLASTICS TOXICOKINETICS/TOXICODYNAMICS (REPRODUCED AND UPDATED(*) FROM EPA 2017)



Research on human exposure to microplastics and nanoplastics, and the associated risk from that exposure, is in an early stage of development. This section provides an overview of the findings from the 2017 MEW, a brief review of the current peer-reviewed literature on human health assessments, and an updated reflection on the state of the science since the 2017 workshop.

2017 MEW

Participants in the 2017 workshop discussed pathways that expose humans to microplastics, relative confidence levels for available data, and priority information needs at that time. The findings are summarized in a conceptual model (see Model IV in EPA 2017). Workshop discussions on this topic made it apparent that human health assessment of microplastics, and the underlying and necessary research, is nascent in the U.S. as well as globally. Developing a better understanding of the human health risks of microplastics requires the availability of reliable and reproducible methods, knowledge of the sources and movement of microplastics in the environment, and information on the toxicokinetics and toxicodynamics of particle uptake (i.e., how quickly plastics enter the body, and how they move and act when in the body). The information on exposure and toxicity is sourced from medical literature, focused on exposure to implanted plastic devices, and from studies of occupational exposure. Human physiological responses to small particles are well studied, though information on the amount and type of plastics in such particles is not well known. Also unknown are the risks posed by chemicals contained within a plastic particle or attached to it. Participants noted that nanoplastics are expected to be highly relevant for human exposure, and quantifying these small particles is a challenge due to background contamination and lack of reliable methods.

LITERATURE REVIEW

The literature on human health and microplastics is evolving with advances in methodologies to measure microplastics and nanoplastics in tissues and the environment. One paper mentioned by multiple SMEs, Catarino et al. 2018, examined microplastics in wild mussels (*Mytilus edulis*) from Scotland. The authors compared the number of microplastics measured in mussel tissue to plastics measured in household dust, and found that human consumption of mussels posed a minimal risk of microplastic ingestion (up to 4,620 particles per year per capita) compared to incidental human consumption of dust (13,731-68,415 particles per year per capita). Thus far, much of the literature on human microplastics exposure has focused on measuring exposure from seafood and drinking water, with less information available on exposure from terrestrial food sources and other beverages (e.g., microplastics could be introduced through mismanaged processing or fragmented packaging). However, recent studies have investigated other food items such as beer, honey, sugar, and salt (e.g., see Barboza et al. 2018 for a review of known studies). The type of information provided in Catarino et al. provided valuable information to evaluate the relative risks of distinct routes of exposure (i.e., microplastics in mussels and dust).

Several literature reviews relevant to human exposure and health impacts of microplastics were published since 2017. For example, Campanale et al. (2020) compiled information on chemicals used by the plastics industry and the effect of these chemicals on human health. The authors include sections on chemicals such as bisphenol A, a common plasticizer used in food packaging; phthalates, a class of compounds that provide flexibility, pliability, and elasticity to plastics; heavy metals, which can be added to plastics (e.g., colorants, flame retardants, fillers, and stabilizers); and flame retardants, including both inorganic and organic (e.g., brominated flame retardants) compounds. Campanale et al. reviewed multiple studies on the effects of microplastic and nanoplastic exposure on the human digestive and respiratory systems, and suggested that human exposure is occurring through ingestion, inhalation, and dermal contact, though the fate and effects in the body are not yet well characterized.

Prata 2018 and Prata et al. 2020 reviewed the human health consequences of exposure to airborne microplastic particles. The 2018 review focused on the potential for exposure to airborne microplastics and occupational diseases related to such exposure. For example, Prata 2018 surveyed the literature on occupational diseases in workers in synthetic textile, flock[9], and vinyl chloride industries that could be exposed to chronic high concentrations of airborne particles. Mechanisms of toxicity, such as the processes of buildup and clearance in lungs, oxidative stress, damage to cellular structures, and particle movement were reviewed as causes of potential respiratory diseases. Cancer from chronic inflammation or gene mutations was also reviewed as an outcome of exposure to airborne particles. Pathways of exposure and toxicity are the focus of Prata et al. 2020, which found more information on ingestion, inhalation, and dermal exposures. The authors noted that papers related to microplastic toxicity are still limited.

In addition to published papers, several recent efforts aim to better understand the human health impacts of microplastics. The World Health Organization (WHO) released a widely-circulated report on the global occurrence of microplastics in drinking water that also discussed possible human health risks, broken down by risks caused by particle, chemical, and biofilm toxicity (WHO 2019). The report included a section on treatment technologies for wastewater and drinking water, and concluded with a list of research needs, including development of standard sampling and analysis methods, studies on the occurrence and characterization of microplastics in drinking water, improved understanding of the source of microplastics in fresh water, information on the

[9] Flock is defined as a velvet-like or fleeced fabric made of cut nylon, polyester, or other synthetic material fibers.

occurrence and fate of microplastics throughout the water supply chain, data on the return and significance of treatment waste streams (including sludge), studies on the toxicological effects of microplastics to inform human health risk assessments, data on the uptake and fate of microplastics in the gastrointestinal tract, and studies focused on understanding how humans are exposed to microplastics (e.g., food, air) (WHO 2019).

The NAS held a workshop sponsored by the U.S. National Institute of Environmental Health Sciences on emerging technologies to advance research and decisions on the environmental health effects of microplastics (NAS 2020). A recurring theme of the workshop was the complexity of microplastics as a diverse mixture of materials. Participants noted challenges in the following topics:

- Characterizing the suite of different plastic types, sizes, shapes, and chemical composition,
- Describing differences between laboratory and environmental samples,
- Developing processes to recycle and up-cycle mixed plastics into other products, and
- Reducing the sources of microplastics.

Workshop participants pointed to lessons learned from previous studies in nano-pharmacology and nano-toxicology. In addition, participants discussed the importance of developing cross-disciplinary approaches to leverage partnerships with the chemical manufacturing and pharmaceuticals industries, applying their knowledge bases to answering questions about the human health impacts of microplastics and nanoplastics.

UPDATE TO 2017 WORKSHOP

Discussions with SMEs, coupled with a review of recent peer-reviewed literature and other scientific reports, made it clear that human exposure and risk assessments for microplastics are nascent compared to research on the environmental fate and effects of microplastics. Organizations such as the NAS and WHO are beginning to convene scientific experts and publish informative reviews with information on exposure routes (e.g., inhalation, ingestion), rates of exposure, and impacts that will be useful for eventually conducting such assessments (NAS 2020, WHO 2019).

In addition, the FDA is conducting a literature review to compile papers relevant to microplastics and nanoplastics in foods (Wiggins 2021). The FDA is expected to identify key information gaps and inform future efforts by U.S. Federal agencies with an interest in nanoplastics research. A common theme among these efforts is a need for reproducible methods to accurately and precisely measure microplastics and nanoplastics in the environment, food, and human tissues. Conversations with SMEs suggested that human health studies can address the lack of analytical methods by pulling from previous studies on nano-particle uptake and toxicity (Al-Abed 2021; Hahn 2020), which agrees with the conclusions of NAS workshop participants (NAS 2020).

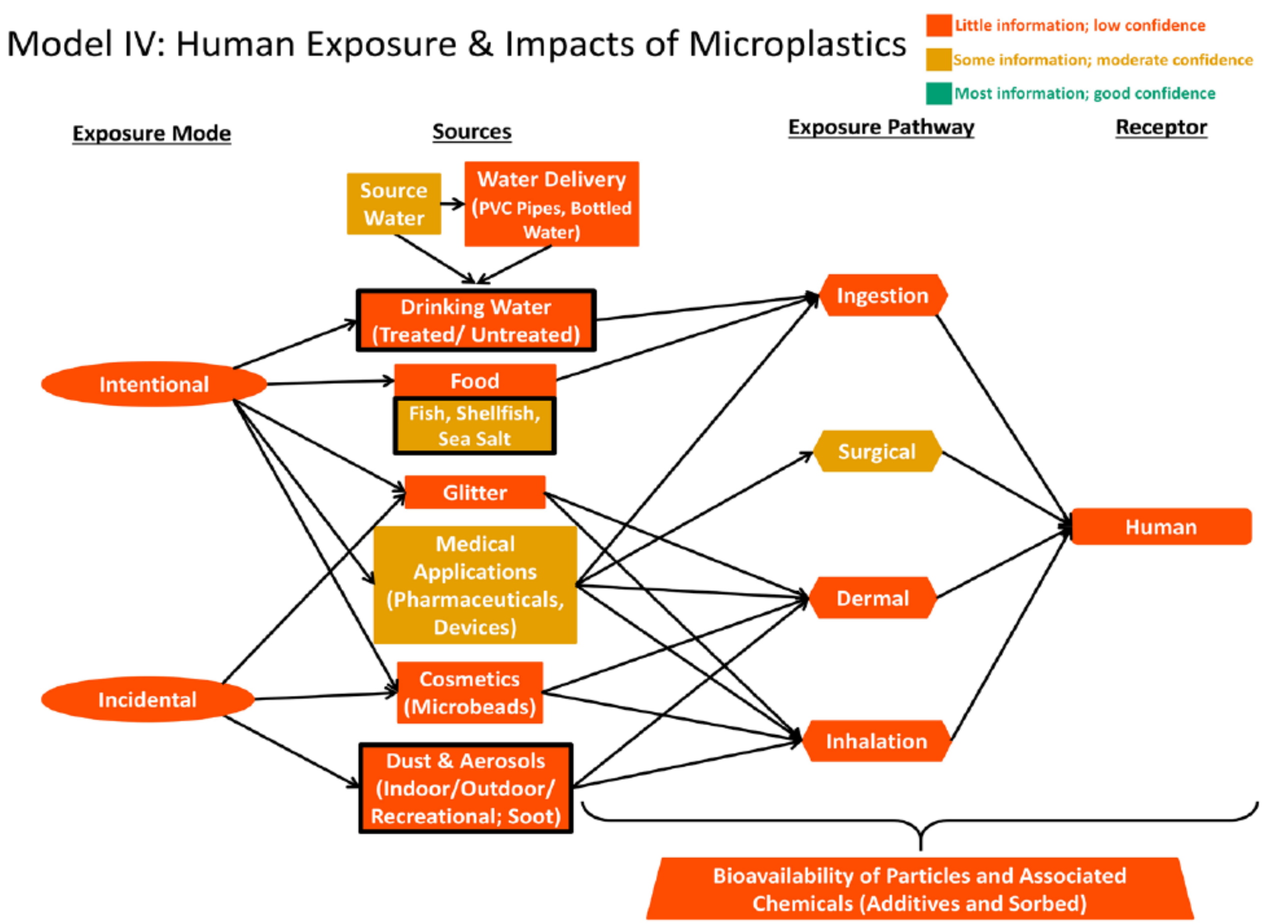
Given the relatively slow movement of studies on human exposure and health impacts of microplastics and nanoplastics, no updates were suggested to the Human Exposure &

Impacts of Microplastics conceptual model from the MEW report (Model IV, EPA 2017; reproduced here as Exhibit 5-1). The discussion with Mark Hahn highlighted the importance of understanding human exposure to nanoplastics; the current state of the science shows stronger evidence of exposure to nanoplastics but remains relatively weak in demonstrating health impacts from that exposure.

Summary | Recent Advances in Human Health Assessments

- Organizations such as NAS and WHO are turning their attention to the human health risks of microplastics and nanoplastics, but SMEs did not believe any updates to the Model on Human Exposure and Impacts of Microplastics (Exhibit 5-1) were warranted.
- An emerging global research focus is on the occurrence and amount of microplastics in drinking water (e.g., WHO 2019).
- Quantifying nanoparticle concentrations and exposures has been a challenge with currently available methods.
- Studies that quantify multiple routes of exposure provide necessary information to evaluate 'relative' risks from different sources of microplastics.

EXHIBIT 5-1 CONCEPTUAL MODEL IV: HUMAN EXPOSURE & IMPACTS OF MICROPLASTICS (REPRODUCED FROM EPA 2017 WITH NO UPDATES)



Discussions with 11 scientists with expertise in fields related to microplastics and nanoplastics research (e.g., oceanography, hydrology, toxicology, chemistry, waste management) provided additional context on the current state of the science. To better characterize interactions among and between in these related fields of research, the following section summarizes information on key workshops and conferences, major journals publishing across ecological and human health fields, and potential external drivers of research topics and questions into new and emerging focal areas.

RESEARCH COMMUNITY

Few conferences focus exclusively on microplastic pollution. However, microplastics and nanoplastics research is increasingly represented at major scientific conferences across a variety of disciplines. Discussions with SMEs identified several microplastics-specific conferences hosted in Europe and abroad (Hankins 2021, Herring and Uhrin 2021, Rochman 2020), though conferences such as the International Marine Debris Conference have been hosted in the United States. The following conferences, panels, and workshops were identified by SMEs as some of the significant events for microplastics and nanoplastics research since 2017.

CONFERENCES

- The **Society of Environmental Toxicology and Chemistry (SETAC)** is a global professional organization dedicated to the study, analysis, and solution of environmental problems, as well as management and regulation of natural resources. Geographic branches of SETAC host annual meetings designed to provide a forum for environmental experts, and many of these annual conferences attract sessions on microplastics and nanoplastics research, including microplastic toxicology and methods development. In addition, SETAC offers ongoing training courses on emerging contaminants, advances in analytical methods, and other tools used in toxicology and analytical chemistry, and publishes the journal *Environmental Toxicology and Chemistry*.
- The **International Marine Debris Conference** is a sporadic conference that has previously been hosted by NOAA and global organizations such as United Nations (U.N.) Environment. The first conference was held in 1984, while the sixth and most recent conference was held in 2018 and organized by NOAA and U.N. Environment. This conference included sessions on a wide variety of issues associated with marine plastic pollution, including effects on organisms, methods development and standardization, policy, and prevention. In discussions with

SMEs, they emphasized the importance of this conference in uniting researchers of many disciplines beneath the umbrella of microplastics research (Hankins 2020, Helm 2020).

- **MICRO** is a relatively new conference that has been held every other year since 2016. It has gained traction among the research community as a major microplastics conference since the original event (Rochman 2020). The conference was held virtually in 2020, with a focus on "Fate and Impacts of Microplastics: Knowledge and Responsibilities."
- The **Society for Risk Analysis** has hosted an annual conference since 1988 to showcase the latest global research concerning all aspects of risk assessment. In 2020, the conference included a microplastics-specific symposium titled, "Emerging risks of micro/nanoplastics: perspectives from diverse sectors."
- The **American Chemical Society** holds many meetings and expositions each year, increasingly featuring work relating to microplastic particles. SMEs found these meetings valuable in gathering the community of researchers investigating the chemical properties of microplastics in the environment (Al-Abed 2021).

WORKSHOPS

- In 2019, **Woods Hole Oceanographic Institution** hosted a workshop titled "The Science of Microplastics in the World Ocean," which featured 36 speakers from domestic and international institutions. The intent of the workshop was to identify next steps in understanding the fate, distribution, impacts, and technology development necessary to advance global scientific understanding of microplastics and nanoplastics.[10]
- The **National Academy of Sciences** hosted a workshop in 2020 titled "Emerging Technologies to Advance Research and Decisions on the Environmental Health Effects of Microplastics." The workshop resulted in a summary report in which participants collaboratively characterized the prevalence of microplastics in the environment, the effects of microplastics on human health, reducing microplastics in the environment, and new approaches to inform public health and policy decisions (NAS 2020). The workshop brought together the microplastics toxicology community and promoted research that distinguishes the health and environmental health impacts of different types of microplastics (Hahn 2020, Law 2020).
- **SETAC** hosted a microplastics seminar series in Spring 2021 entitled, "What We Know and What We Need To Know: The Analysis, Monitoring and Effects of Microplastics in Humans and the Environment." This seven-part series provided an overview of the state of the science and discussed current methodology and

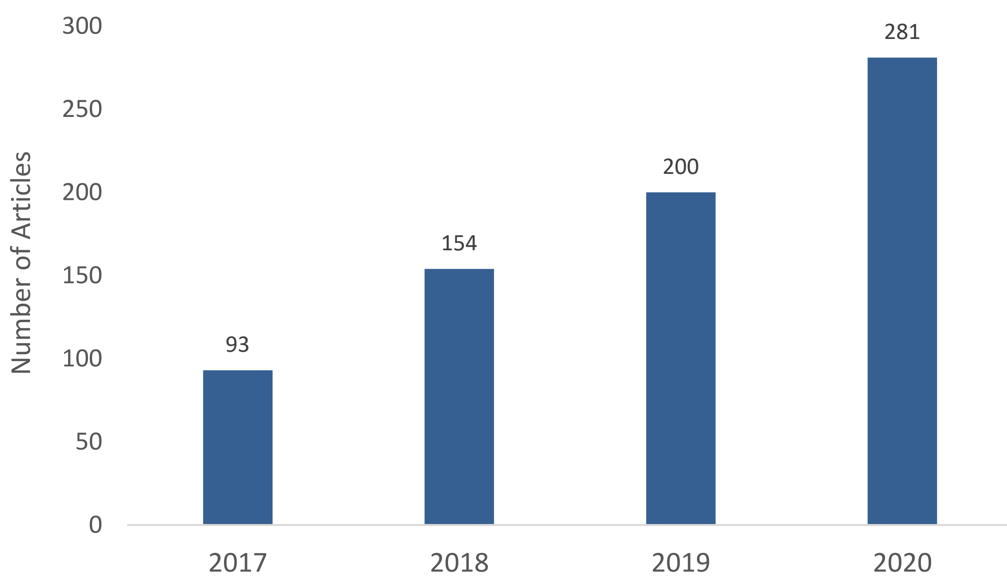
[10] More information on the conference is available at the following link: https://microplastics.whoi.edu/the-science-of-microplastics-in-the-world-ocean-international-workshop/program/.

challenges regarding the risk assessment of microplastics and nanoplastics. The seminar series included presentations from researchers on modelling and experimental approaches.[11]

GROWTH IN MICROPLASTICS RESEARCH

The number of microplastics-related manuscripts published across a wide variety of journals has continued to increase annually since 2017. A growing number of journals are publishing microplastics work, including journals focused on toxicology, spectroscopy, analytical chemistry, and physical oceanography. Based on a review of peer-reviewed articles published in *Marine Pollution Bulletin*, a well-known journal for microplastics research, the number of articles focused on microplastics has increased substantially each year since 2017 (ScienceDirect 2021; Exhibit 6-1). The number of microplastics articles published in *Marine Pollution Bulletin* increased by more than 300 percent between 2017 and 2020. The same increasing trend is clear when papers are tallied by some of the key sub-topics such as human health, ecological risk assessment, transport, methods development, and ingestion (Exhibit 6-2). More information about the increase in microplastics research is available in a bibliometric analysis of more than 2,000 articles published between 1986 and 2019, broken down by document type, research topic, author name, country, journals, and keywords (Zhang et al. 2020).

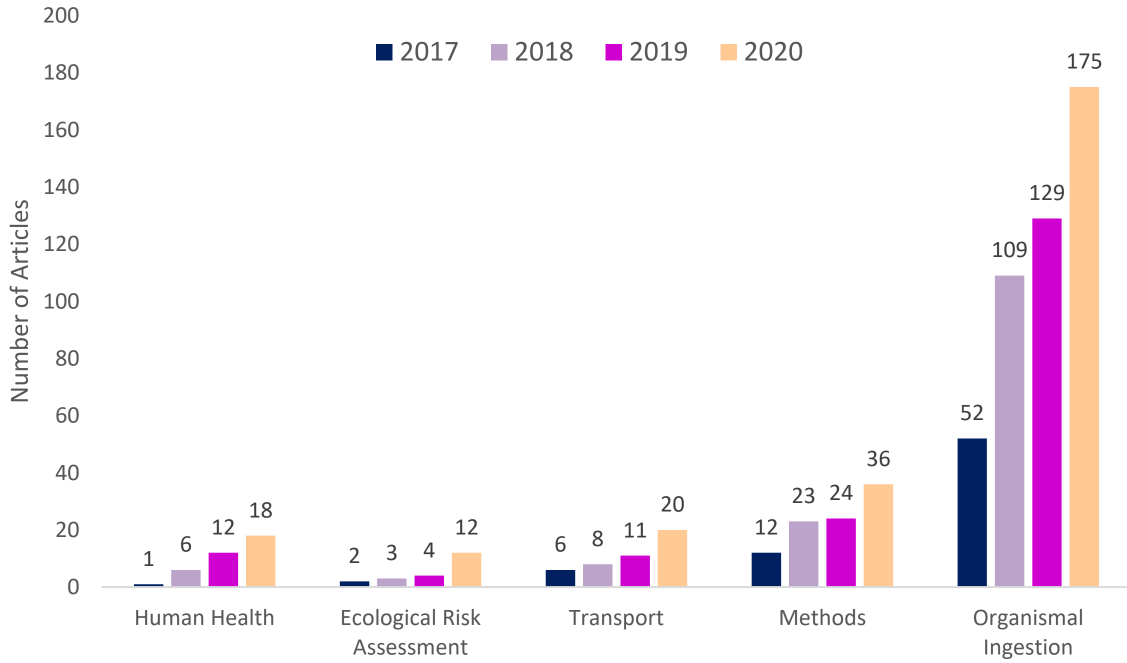
EXHIBIT 6-1 PEER-REVIEWED JOURNAL ARTICLES ON "MICROPLASTIC" PUBLISHED IN *MARINE POLLUTION BULLETIN*, 2017-2020



Source: ScienceDirect 2021

[11] More information on the SETAC virtual seminar series is available at the following link: https://seminars.setac.org/programme/background-and-scope/.

EXHIBIT 6-2 PEER-REVIEWED JOURNAL ARTICLES ON "MICROPLASTIC" PUBLISHED IN MARINE POLLUTION BULLETIN, 2017-2020, BY SUB-TOPIC[12]



Source: ScienceDirect 2021

JOURNALS

The following journals were highlighted in discussions with SMEs across ecological and human health disciplines for their strong record of publishing studies related to microplastics and nanoplastics research. Many of these journals are represented in the literature review conducted for this report (see Appendix B).

- *Marine Pollution Bulletin* was highlighted by SMEs as a pivotal platform for the latest marine microplastics research, with a broad and deep reach across disciplines.
- Multiple SMEs mentioned the high quality of journal articles published in *Environmental Science and Technology*, many of which involve microplastics characterization and risk assessment.
- *Microplastics and Nanoplastics*, the first journal focused exclusively on these topics, is a new open-access, interdisciplinary journal publishing research that provides a quantitative and mechanistic understanding of factors that drive emissions, fate, effects, risks, and societal responses to the presence of plastic debris. The journal accepts manuscripts on a wide range of topics including plastic

[12] We reviewed four significant sub-topics, including connections between microplastics and human health, ecological risk, fate and transport, and laboratory/field methods development. The sums represent articles with these topics as part of the article title or identified by the paper's author.

quantification and characterization, transport and fate, waste management, human health, social and behavioral perspectives and policy, and biodegradable and sustainable materials.

- Broader scientific journals, including *Science*, *Science Advances*, *Nature*, and *Scientific Reports*, publish significant microplastics papers relating to human health, although such papers are rare due to the competitive nature of these journals.
- *Environmental Toxicology and Chemistry* publishes microplastics papers relating to environmental and human health. The majority of microplastics papers investigate organismal health rather than human health effects. The *Journal of Environmental Research and Public Health* also publishes research on microplastics and human health.
- Papers on research that further advances methods development may be found in *Analytical Methods*, *Environmental Toxicology and Chemistry*, and the *Journal of Hazardous Materials*.
- *Science of the Total Environment* and *Environmental Pollution* publishes robust environmental microplastics studies across a range of disciplines.
- The following journals publish research on environmental fate and transport as well as ecological risk assessment: *Chemosphere*, *Ecological Risk Assessment*, *Frontiers in Environmental Science*, and *Environmental Pollution*.
- *Water Research* publishes research on freshwater, groundwater, soil, and atmospheric cycling of plastics in the environment, as well as water treatment options.

EXTERNAL DRIVERS

Public and private organizations with an interest in scientific research, as well as governments and organizations looking to coordinate resources across expertise and locations serve as external drivers of research topics related to microplastics. Three recent examples include the state of the science report from Health Canada, the U.S. Federal Strategy for Addressing the Global Issue of Marine Litter (EPA 2020), and the Save Our Seas 2.0 Act. Two Canadian government agencies, Environment and Climate Change Canada and Health Canada, jointly published a report in 2020 to summarize the current state of the science on plastics pollution (including microplastics), with sections on impacts to the environment and human health, as well as sources, occurrence, and fate. The report concluded that additional research in many of the areas outlined in the MEW workshop report was needed (see also Helm 2020), including research on standardized methods, human exposure, ecotoxicological effects, human health effects, as well as expanded soil monitoring.

The U.S. Federal Strategy published in 2020 outlined four pillars for addressing plastics in the context of marine litter, including:

- Building capacity through locally led development to provide skill development, training, and providing critical resources for success.
- Incentivizing the global recycling market in partnership with the private sector.
- Promoting research, development and application of innovative approaches and technology.
- Promoting marine litter removal, including through litter capture systems in rivers and inland waterways.

By identifying these pillars, the Federal Strategy may be used as a springboard for new research into recycling and materials reuse, innovations in product design that leads to fewer sources and leaks of plastics into the environment and improved waste management practices.

The Save Our Seas 2.0 Act, signed into law in December 2020, includes multiple provisions that may specifically catalyze research on marine debris and microplastics. For example, the legislation provides for a genius prize for innovation and new research, enhanced global engagement, and funding to improve domestic infrastructure, including research on waste management and mitigation. The Act also tasks agencies with preparing reports on innovative uses of plastic waste as well as microfiber pollution (i.e., defining ‘microfiber,’ conducting an assessment of the sources, prevalence, and causes of microfiber pollution, developing recommendations for measuring, estimating, and reducing microfiber pollution, and planning for engagement by Federal agencies), and conducting studies on plastic pollution in the U.S. and mass balance methods to certify circular polymers (i.e., polymers that can be reused multiple times or converted into a new product).

CONCLUSIONS

Microplastics and nanoplastics are topics that have catalyzed research across wide-ranging areas of scientific expertise, such as ecological processes, toxicology, oceanography, risk assessment, human health, and many more. Original, primary research continues to expand the state of the science, conducted by principal investigators in the field and laboratory as well as by research teams formed to better understand the full scope of this important environmental issue and potential solutions to prevent microplastics at their source(s). Scientists pursing microplastics research apply their specialized backgrounds to answer questions involving field and analytical methods development; sources, transport, and fate; ecological occurrence and assessments; and human health impacts. For each of these topics, emerging areas of interest and research gaps are summarized below.

- **Analytical Methods**. During the workshop, participants stressed the importance of utilizing analytical methods that meet the goal of the research as well as advancing quality control measures to enable robust measurement and estimates of precision and accuracy. Discussions with SMEs echoed the same concepts and emphasized the importance of using methods tailored to a particular particle size range, plastic type, environmental matrix (e.g., water, soil), and research question of interest. The recent literature focuses on quality control and quality assurance protocols. One research gap identified across the board is analytical methods that can isolate and measure nanoplastic particles.

- **Sources, Transport, and Fate**. Workshop participants categorized much of the available information on fate of microplastics (e.g., in waterbodies and marine waters). However, sources of microplastics and their movement throughout the environment were mentioned as key information gaps multiple times in discussions with SMEs. These gaps are illustrated by studies such as Gavigan et al. (2020), Lau et al. (2020), and Law et al. (2020) that conducted modeling exercises to estimate U.S. and/or global contributions based on a variety of assumptions. New information has been published recently that measures microplastics and nanoplastics in the air (Brahney et al. 2020). Subject matter experts agreed that primary data collection and modeling exercises are necessary to fill knowledge gaps on the sources, transport, and fate of microplastics, emphasizing the importance of field studies that collect information on potential upstream sources of larger plastic particles that may become microplastics and nanoplastics. An emerging focal area is on solutions that address these upstream sources of microplastic and nanoplastic particles to the environment.
- **Environmental Assessments**. Workshop participants identified a need for more toxicity testing in general, including high-quality laboratory data that would provide the information needed for ecological risk assessments. They specifically noted information gaps related to particle movement in tissues as well as exposure to and bioaccumulation of chemicals in tissues. Discussions with SMEs and recent literature stated a need for environmentally and ecologically relevant study designs that test for differences in types, sizes, and shapes of microplastics and microfibers, as well as doses and exposure conditions. Several review papers have contextualized the impacts of microplastics exposure across groups of organisms, showing a range of effects. An ongoing research gap is the availability of information that describes the toxicological and other impacts of microplastics and nanoplastics.
- **Human Health Assessments**. Workshop discussions made it apparent that human health assessments are an emerging topic in the U.S. The literature on human health and microplastics is evolving along with advances in analytical methods to measure small microplastics and nanoplastics. Several recent efforts aim to better understand the human health impacts of exposure to microplastics, particularly microplastics in drinking water (e.g., WHO 2019). A common theme with SMEs and the literature review is a need for reproducible methods to accurately and precisely measure microplastics and nanoplastics in environmental samples, food, and human tissues.

External drivers have galvanized new research in microplastics and nanoplastics. The priorities identified in the three examples of external drivers noted above (i.e., Environment and Climate Change Canada and Health Canada 2020; the U.S. Federal Strategy for Addressing the Global Issue of Marine Litter (EPA 2020); and the Save Our Seas 2.0 Act) dovetail with information gathered from discussions with SMEs, many of whom mentioned an increasing interest in focusing on upstream solutions in addition to continued exploration of downstream particle fate in rivers and oceans (e.g., Herring and Uhrin 2021, Jambeck 2021, Law 2020). Funding from public agencies and private foundations, and the focused intent of grant competitions, provides a stimulus for studies on specific topics and information gaps.

New conferences and journals are emerging to better connect and share scientific discoveries across the multi-disciplinary fields involved in understanding the extent of plastics in the environment, the environmental and human health impacts, and long-term solutions. As more fields of expertise become involved in microplastics and nanoplastics research, it is clear that sustained movement along multiple fronts is likely. There is continued value in gathering SMEs together to identify the most pressing information gaps that need to be addressed to advance our understanding of the ecological and human health impacts of microplastics and nanoplastics and develop solutions to reduce and prevent their introduction to the environment.

REFERENCES

Al-Abed, S. 2021. Personal Communication as part of SME Discussion. March 11.

Baldwin, A. and Fisher, S. 2021. Personal Communication as part of SME Discussion. March 4.

Barboza, L.G.A., Vethaak, A.D., Lavorante, B.R.B.O., Lundebye, A.K., and Guilhermino, L. 2018. Marine microplastic debris: An emerging issue for food security, food safety and human health. *Marine Pollution Bulletin* 133:336-348. DOI: https://doi.org/10.1016/j.marpolbul.2018.05.047

Barrett, J., Chase, Z., Zhang, J., Banaszak Holl, M.M., Willis, K., Williams, A., Hardesty, B.D., and Wilcox, C. 2020. Microplastic Pollution in Deep-Sea Sediments from the Great Australian Bight. *Frontiers in Marine Science* 7:576170. DOI: 10.3389/fmars.2020.576170

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., and Sukumaran, S. 2020. Plastic rain in protected areas of the United States. *Science* 386(6496):1257-1260. DOI: https://doi.org/10.1126/science.aaz5819

Bucci, K., Tulio, M., and Rochman, C.M. 2020. What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecological Applications* 30(2):02044. DOI: https://doi.org/10.1002/eap.2044

California State Water Resources Control Board. 2020. Adopted Definition of 'Microplastics in Drinking Water'. California Water Boards. 3 p. Accessed at: https://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2020/rs2020_0021.pdf

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., and Uricchio, V.F. 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. *International Journal of Environmental Research and Public Health* 17:1212. DOI: https://doi.org/10.3390/ijerph17041212

Caputo, F., Vogel, R., Savage, J., Vella, G., Law, A., Camera, G.D., Hannon, G., Peacock, B., Mehn, D., Ponti, J., Geiss, O., Aubert, D., Prina-Mello, A., and Calzolai, L. 2021. Measuring particle size distribution and mass concentration of nanoplastics and microplastics: addressing some analytical challenges in the sub-micron size range. *Journal of Colloid and Interface Science* 588: 401-417. DOI: https://doi.org/10.1016/j.jcis.2020.12.039

Cashman, M.A., Ho, K.T., Boving, T.B., Russo, S., Robinson, S., and Burgess, R.M. 2020. Comparison of microplastic isolation and extraction procedures from marine sediments. *Marine Pollution Bulletin* 159:111507. DOI: https://doi.org/10.1016/j.marpolbul.2020.111507

Catarino, A.I., Macchia, V., Sanderson, W.G., Thompson, R.C., and Henry, T.B. 2018. Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environmental Pollution* 237:675-684. DOI: https://doi.org/10.1016/j.envpol.2018.02.069

Coppock, R.L., Cole, M., Lindeque, P.K., Queirós, A.M., and Galloway, T.S. 2017. A smallscale, portable method for extracting microplastics from marine sediments. *Environmental Pollution* 230:829–837. DOI: https://doi.org/10.1016/j.envpol.2017.07/017

Crossman, J., Hurley, R.R., Futter, M., and Nizzetto, L. 2020. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Science of the Total Environment* 724: 138334. DOI: https://doi.org/10.1016/j.scitotenv.2020.138334

Environment and Climate Change Canada and Health Canada. 2020. Draft Science Assessment of Plastic Pollution. 153 p. January.

EPA (U. S. Environmental Protection Agency). 2017. Microplastics Expert Workshop Report. EPA Office of Wetlands, Oceans and Watersheds. 37p. Accessed at: https://www.epa.gov/sites/production/files/2018-03/documents/microplastics_expert_workshop_report_final_12-4-17.pdf.

EPA, U.S. Department of State, U.S. Department of Energy, U.S. Agency for International Development, U.S. Department of Commerce, and the National Oceanic and Atmospheric Administration. 2020. The United States Federal Strategy for Addressing the Global Issue of Marine Litter. EPA Publication Number 160K20001. October. 24 p.

Foley, C.J., Feiner, Z.S., Malinich, T.D., and Höök, T.O. 2018. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. *Science of the Total Environment* 631-632:550-559. DOI: https://doi.org/10.1016/j.scitotenv.2018.03.046

Fries, E., Dekiff, J.H., Willmeyer, J., Nuelle, M.-T., Ebert, M., and Remy, D. 2013. Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy. *Environmental Science: Processes & Impacts* 15(10):1949–1956. DOI: https://doi.org/10.1039/c3em00214d

Gavigan, J., Kefela, T., Macadam-Somer, I., Suh, S., and Geyer, R. 2020. Synthetic microfiber emissions to land rival those to waterbodies and are growing. *PLoS ONE* 15(9): e0237839. DOI: https://doi.org/10.1371/journal.pone.0237839

Gaylarde, C.C., Baptista Neto, J.A., and Monteiro da Fonseca, E. 2021. Nanoplastics in aquatic systems – are they more hazardous than microplastics? *Environmental Pollution* 272: 115950. DOI: https://doi.org/10.1016/j.envpol.2020.115950

GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 2015. Sources, fate and effects of microplastics in the marine environment: a global assessment (Kershaw, P. J., ed.). Rep. Stud. GESAMP No. 90. 96 p. Accessed at: https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/GESAMP_microplastics%20full%20study.pdf

GESAMP. 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment (Kershaw, P.J., and Rochman, C.M., eds). Rep. Stud. GESAMP No. 93. 220 p. Accessed at: http://www.gesamp.org/site/assets/files/1275/sources-fate-and-effects-of-microplastics-in-the-marine-environment-part-2-of-a-global-assessment-en.pdf

Grbić, J., Helm, P., Athey, S., and Rochman, C.M. 2020. Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. *Water Research* 174: 115623. DOI: https://doi.org/10.1016/j.watres.2020.115623

Hahn, M. 2020. Personal Communication as part of SME Discussion. December 11.

Hankins, C. 2020. Personal Communication as part of SME Discussion. December 10.

Hankins, C., Duffy, A., and Drisco, K. 2018. Scleractinian coral microplastic ingestion: Potential calcification effects, size limits, and retention. *Marine Pollution Bulletin* 135:587-593. DOI: https://doi.org/10.1016.j.marpolbul.2018.07.067

Helm, P. 2020. Personal Communication as part of SME Discussion. December 18.

Herring, C. and Uhrin, A. 2021. Personal Communication as part of SME Discussion. April 14.

Hirt, N. and Body-Malapel, M. 2020. Immunotoxicity and intestinal effects of nano- and microplastics: a review of the literature. *Particle and Fibre Toxicology* 17:57. DOI: https://doi.org/10.1186/s12989-020-00387-7

Jambeck, J. 2021. Personal Communication as part of SME Discussion. January 6.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L. 2015. Plastic waste inputs from land into the ocean. *Science* 347: 768-771.

Koelmans, A.A., Besseling, E., Foekema, E., Kooi, M., Mintenig, S., Ossendorp, B.C., Redondo-Hasselerharm, P.E., Verschoor, A., van Wezel, A.P., and Scheffer, M. 2017. Risks of plastic debris: Unravelling fact, opinion, perception, and belief. *Environmental Science and Technology* 51: 11513-11519. DOI: https://doi.org/10.1021/acs.est.7b02219

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., et al., and Palardy, J.E. 2020. Evaluating scenarios toward zero plastic pollution. *Science* 369(6510):1455-1461. DOI: https://doi.org/10.1126/science.aba9475

Law, K. 2020. Personal Communication as part of SME Discussion. December 11.

Law, K., Starr, N., Siegler, T.R., Jambeck, J.R., Mallos, N.J., and Leonard, G.H. 2020. The United States' contribution of plastic waste to land and ocean. *Science Advances* 6(44): eabd0288. DOI: 10.1126/sciadv.abd0288

NAS (National Academies of Sciences, Engineering, and Medicine). 2020. Emerging Technologies to Advance Research and Decisions on the Environmental Health Effects of Microplastics: Proceedings of a Workshop—in Brief. Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/25862

OPC (California Ocean Protection Council). 2021. Announcement: Microplastics Risk Report and Trash Methods Playbook Available. Available at: https://www.opc.ca.gov/2021/05/announcement-microplastics-and-trash-methods-report-available/

Prata, J.C. 2018. Airborne microplastics: Consequences to human health? *Environmental Pollution* 234:115-126. DOI: https://doi.org/10.1016/j.envpol.2017.11.043

Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C., and Rocha-Santos, T. 2020. Environmental exposure to microplastics: An overview on possible human health effects. *Science of the Total Environment* 702: 134455. DOI: https://doi.org/10.1016/j.scitotenv.2019.134455

Rochman, C.M., Parnis, J.M., Browne, M.A., Serrato, S., Reiner, E.J., Robson, M., Young, T., Diamond, M.L., and Teh, S.J. 2017. Direct and indirect effects of different types of microplastics on freshwater prey (Corbicula fluminea) and their predator (Acipenser transmontanus). *PLoS ONE* 12(11): e0187664. DOI: https://doi.org/10.1371/journal.pone.0187664

Rochman, C. 2020. Personal Communication as part of SME Discussion. December 15.

Save Our Seas 2.0 Act. 2020. Public Law 116-224. 116th Congress. Available at: https://www.congress.gov/bill/116th-congress/senate-bill/1982/text.

ScienceDirect. Journal and Book Search: Microplastics. Accessed April 2021. https://www.sciencedirect.com/search?qs=Microplastics&pub=Marine%20Pollution%20Bulletin&cid=271825&date=2020&tak=risk%20assessmentd

Tian, Z., Zhao, H., Peter, K.T., Gonzalez, M., Wetzel, J., Wu, C., et al., and Kolodziej, E.P. 2021. A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. *Science* 371(6525):185-189. DOI: https://doi.org/10.1126/science.abd6951

WEF (World Economic Forum). 2016. The New Plastics Economy: Rethinking the future of plastics. 36 p.

WHO (World Health Organization). 2019. Microplastics in Drinking-Water. Geneva, Switzerland. 124 p.

Wiggins, S. 2021. Personal Communication. March.

Wood, K.M. and Box, C. 2020. California Microfiber Update: Textile Perspective. Summary of California Microfiber Workshop: Science, Innovation & Connection. 29p.

Zhang, Y., Pu, S., Lv, X., Gao, Y. and Ge, L. 2020. Global Trends and prospects in microplastics research: A bibliometric analysis. *Journal of Hazardous Materials* 400: 123110. DOI: https://doi.org/10.1016/j.jhazmat.2020.123110

APPENDICES

APPENDIX A: LIST OF SME DISCUSSIONS

NAME	AFFILIATION	EXPERTISE	DISCUSSION DATE
Souhail Al-Abed	U.S. EPA	Chemistry; Identification and Quantification of Emerging Stressors	March 11, 2021
Mark Hahn	Woods Hole Oceanographic Institution	Biochemistry; Chemical-Biological Interactions in Aquatic Animals	December 11, 2020
Cheryl Hankins	U.S. EPA	Environmental Toxicology; Anthropogenic Stressors on Coral Health	December 10, 2020
Paul Helm*	Ontario Ministry of the Environment	Environmental Chemistry; Sources and Impacts of Microplastics in Great Lakes	December 18, 2020
Jenna Jambeck*	University of Georgia	Environmental Engineering; Waste Management	January 6, 2021
Kara Lavender Law*	Sea Education Association	Oceanography; Distribution and Fate of Plastics in Ocean	December 11, 2020
Chelsea Rochman*	University of Toronto	Toxicology; Sources, Fate, and Effects of Microplastics	December 15, 2020
Austin Baldwin And Shawn Fisher	USGS, Idaho Water Science Center and New York Water Science Center	Hydrology; Water Quality and Contamination	March 4, 2021
Carlie Herring* and Amy Uhrin*	NOAA Marine Debris Program	Marine Debris and Microplastics Research (Cross-Fields)	April 14, 2021
Note (*). SME participated in the 2017 MEW.			

APPENDIX B: BIBLIOGRAPHY OF RECENT LITERATURE

The following table is a bibliography of the peer-reviewed literature cited within this report. In addition to the citation, title, and year, information is provided on the main topic(s) of the paper (to the extent possible, relating back to the priority research topics outlined in EPA 2017), the particle size focus (e.g., microplastics, nanoplastics, or both), the environment where the research took place (e.g., whether the study was conducted in a marine or freshwater habitat), and the general setting for the paper (e.g., desktop, field, or laboratory study).

CITATION	TITLE OF PAPER	YEAR	TOPIC	PARTICLE SIZE	ENVIRONMENT	SETTING
Barboza et al. 2018	Marine microplastic debris: An emerging issue for food security, food safety and human health	2018	Human Health	Micro	Marine	Desktop study
Barrett et al. 2020	Microplastic Pollution in Deep-Sea Sediments from the Great Australian Bight	2020	Microplastic Origins and Fate	Micro	Marine	Field Study (Australia)
Brahney et al. 2020	Plastic rain in protected areas of the United States	2020	Microplastic Origins and Fate	Micro	Atmosphere	Field Study (11 National Parks in the western US)

CITATION	TITLE OF PAPER	YEAR	TOPIC	PARTICLE SIZE	ENVIRONMENT	SETTING
Bucci et al. 2020	What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review	2019	Human Health; Ecological Impacts	Nano, Micro	All	Desktop study
Campanale et al. 2020	A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health	2020	Human Health	Micro	All	Desktop study
Caputo et al. 2021	Measuring particle size distribution and mass concentration of nanoplastics and microplastics: addressing some analytical challenges in the sub-micron size range	2021	Methods and Detection	Micro	All	Laboratory
Cashman et al. 2020	Comparison of microplastic isolation and extraction procedures from marine sediments	2020	Methods and Detection	Micro	Marine	Field Study (New York and Rhode Island)
Catarino et al. 2018	Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal	2018	Human Health	Micro	Marine	Field Study (Scotland)
Crossman et al. 2020	Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment	2020	Microplastic Origins and Fate	Micro	Terrestrial	Field Study (Ontario, Canada)
Environment and Climate Change Canada and Health Canada 2020	Draft Science Assessment of Plastic Pollution	2020	Microplastic Origins and Fate	All Particle Sizes	All	Desktop study

CITATION	TITLE OF PAPER	YEAR	TOPIC	PARTICLE SIZE	ENVIRONMENT	SETTING
Foley et al. 2018	A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates	2018	Freshwater Organismal Health	Micro	Freshwater	Desktop study
Gavigan et al. 2020	Synthetic microfiber emissions to land rival those to waterbodies and are growing	2020	Microplastic Origins and Fate	Micro	All	Desktop study
Gaylarde et al. 2021	Nanoplastics in aquatic systems - are they more hazardous than microplastics?	2021	Freshwater Organismal Health	Nano	Freshwater	Desktop study
Grbić et al. 2020	Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources	2020	Microplastic Origins and Fate	Micro	Freshwater	Field Study (Ontario, Canada)
Hankins et al. 2018	Scleractinian coral microplastic ingestion: Potential calcification effects, size limits, and retention	2018	Marine Organismal Health	Micro	Atmosphere	Field Study (Florida)
Hirt and Body-Malapel 2020	Immunotoxicity and intestinal effects of nano- and microplastics: a review of the literature	2020	Human Health; Ecological Impacts	Micro	Freshwater	Desktop study
Jambeck et al. 2015	Plastic waste inputs from land into the ocean	2015	Microplastic Origins and Fate	Macro	All	Desktop study

CITATION	TITLE OF PAPER	YEAR	TOPIC	PARTICLE SIZE	ENVIRONMENT	SETTING
Koelmans et al. 2017	Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Belief	2017	Risk Assessment	Micro	All	Desktop study
Lau et al. 2020	Evaluating scenarios toward zero plastic pollution	2020	Waste Management	Micro	All	Desktop study
Prata 2018	Airborne microplastics: Consequences to human health?	2018	Human Health	Micro	Atmosphere	Desktop study
Prata et al. 2020	Environmental exposure to microplastics: An overview on possible human health effects	2020	Human Health	Micro	All	Desktop study
Rochman et al. 2017	Direct and indirect effects of different types of microplastics on freshwater prey (Corbicula fluminea) and their predator (Acipenser transmontanus)	2017	Freshwater Organismal Health	Micro	Freshwater	Field Study (Canada)
Tian et al. 2021	A ubiquitous tire rubber-derived chemical induces acute mortality in coho salmon	2021	Freshwater Organismal Health	All Particle Sizes	Freshwater	Field and Laboratory Study (Washington state)
Wood and Box 2020	California Microfiber Update: Textile Perspective	2020	Waste Management	Micro	Freshwater	Field Study (California)

CITATION	TITLE OF PAPER	YEAR	TOPIC	PARTICLE SIZE	ENVIRONMENT	SETTING
World Economic Forum 2016	The New Plastics Economy: Rethinking the Future of Plastics	2016	Waste Management	All Particle Sizes	All	Desktop study
World Health Organization 2019	Microplastics in Drinking Water	2019	Human Health	Micro	Freshwater	Desktop study
Zhang et al. 2020	Global trends and prospects in microplastics research: A bibliometric analysis	2020	Microplastics Research	Micro	All	Desktop study