Microplastic Pollution in California:

A PRECAUTIONARY FRAMEWORK AND SCIENTIFIC GUIDANCE TO ASSESS AND ADDRESS RISK TO THE MARINE ENVIRONMENT

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About This Document

Responding to State legislation (S.B. 1263) to develop a Statewide Microplastics Strategy, the California Ocean Protection Council (OPC) funded the California Ocean Science Trust (OST) to convene a Working Group of scientific experts to develop a risk assessment framework for microplastic pollution in California's marine environment and provide scientific guidance to inform source reduction activities. This document represents the resulting risk assessment framework, constructed within the bounds of the current state of scientific knowledge, as well as scientific guidance for assessing and addressing microplastic pollution in California's marine environment. We thank the Policy Advisory Committee and External Advisors for their thoughtful advice and feedback throughout this process, as well as Dr. Albert Koelmans and Dr. Wayne Landis for their independent review of the full report.

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Key Recommendations

- We, the Working Group, recommend a precautionary approach to assess the risk of and manage microplastic pollution risk, based on microplastic persistence, lack of feasible cleanup options, projected rate of increased concentrations in the environment, and evidence that microplastics contaminate and may lead to adverse effects in organisms and humans.

- Managing and assessing microplastic pollution risk using a particulate approach is recommended over a toxicant approach, until California-specific data are available and the chemical effects of microplastics are fully understood.

- Future microplastic risk assessments, using the precautionary framework, should focus on the following high priority & most prevalent components:
    - **Particle Morphology:** microfibers and fragments
    - **Polymer Types:** microfibers and tire & road wear particles
    - **Fate & Transport Pathways:** stormwater runoff (urban, agricultural), aerial deposition, and wastewater
    - **Sources:** unknown in California, but international literature suggests tire & road wear, laundry & textiles, and plastic litter from aquaculture & fishing
    - **Priority Endpoints:** microplastic internalization for benthic mollusks, large crustaceans, and lower and upper trophic level fish

- Apply the risk prioritization tool, proposed here, using a weight-of-evidence approach to characterize and rank risk associated with the highest priority and most prevalent components of microplastic pollution.

- True source reduction of plastic materials may be the most effective precautionary strategy to reduce and prevent microplastic pollution, given lack of feasible microplastic cleanup strategies.

- The top research need is an inventory of the top sources of macro- and micro-plastic loading in California that investigates the contribution of agricultural sources relative to urban and industrial runoff, as well as wastewater.

- Given rapidly evolving science, we recommend revisiting this risk assessment framework in five (5) years to assess if effects data are sufficient to suggest a quantitative effects risk assessment.

Executive Summary

In 2018, the Ocean Protection Council (OPC) was tasked by state legislation (S.B. 1263) to develop a Statewide Microplastics Strategy ("the Strategy") with the goal of increasing the State's understanding of the scale and risk of microplastics (1 nm - 5 mm) on the marine environment and identifying proposed solutions to address their impacts. A key component of the Strategy is the development of a risk assessment framework for microplastic pollution in California, to be used to evaluate options, including source reduction and product stewardship techniques, barriers, costs, and benefits. The Ocean Science Trust (OST) convened an OPC Science Advisory Team (OPC SAT) Microplastic Working Group to develop the framework and provide scientific guidance to assist the State in understanding the risks microplastics pose to marine ecosystems in California.

We, the Working Group, recommend applying a precautionary approach to management of microplastic pollution. This report empowers the State to move toward source reduction and mitigation immediately, even under existing uncertainties, while concurrently addressing key knowledge gaps that will advance the precautionary framework and/or a quantitative risk assessment specific to California. While existing scientific knowledge on microplastic exposure is rapidly growing, our understanding of the effects of microplastics, as well as California-specific data on the occurrence, environmental transformations, and bioavailability of chemical constituents of microplastics, is currently limited to a few polymer types and shapes. Execution of a state-specific quantitative risk assessment is hindered without immediately available data for this complex class of pollutants. Therefore, efforts to characterize microplastics risk in the short term should focus primarily on their physical characteristics (i.e. particulate approach), as opposed to chemical (i.e. toxicant approach). A number of reliable studies were identified, demonstrating that adverse ecological effects are possible in taxa found in California marine waters with certain exposure concentrations.

We adopted a precautionary risk assessment framework, including a risk prioritization tool that focuses on assessing microplastic exposure data to characterize and rank risk to aid decision-makers with diverse expertise in prioritizing source reduction activities. The precautionary framework consists of step-wise instructions and recommendations, based on the best available science, for completing three phases in any future microplastic risk assessment:

(1) Problem Formulation:

a preliminary assessment of key factors to be considered in the risk assessment, including an examination of scientific evidence, an assessment of the feasibility, scope, and objectives of the risk assessment; a process for selecting and prioritizing endpoints based on ecological significance, susceptibility, and management relevance.

Recommendations: future microplastic risk assessments, using the precautionary framework, should focus on the following high priority & most prevalent components:

- **Particle Morphology:** microfibers and fragments
- **Polymer Types:** microfibers and tire & road wear particles
- **Fate & Transport Pathways:** stormwater runoff (i.e. urban and agricultural), aerial deposition, and wastewater
- **Sources:** unknown in California, but international literature suggests tire & road wear, laundry & textiles, and plastic litter from aquaculture & fishing
- **Priority Endpoints:** microplastic internalization in benthic mollusks, large crustaceans, and lower and upper trophic level fish

(2) Risk Characterization & Ranking:

an assessment of relevant exposure data to priority endpoints to characterize and rank the relative risk of potential adverse effects by source, polymer type, and taxon as indicated by surrogate measures of microplastic internalization and source tonnage.

Recommendations: apply the risk prioritization tool, proposed here, using a weight-of-evidence approach to characterize and rank risk associated with the highest priority and most prevalent components of microplastic pollution.

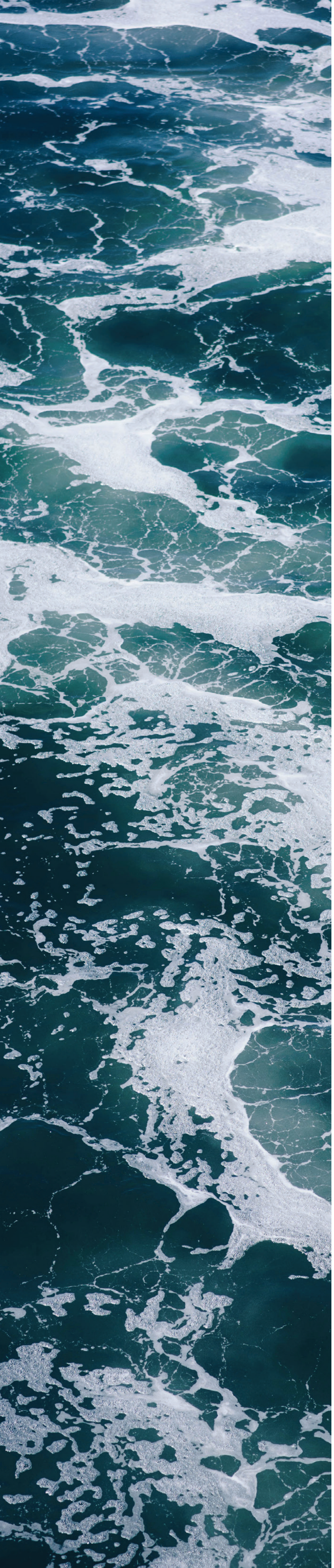
(3) Risk Evaluation & Source Reduction Prioritization:

a determination of whether characterized risk warrants State action and mitigation, and scientific guidance to aid prioritization of source reduction activities.

Recommendations: due to the complexities of the microplastic stream and uncertainties around intervention strategy efficacy, true source reduction of plastic materials, either through reducing production, safe-by-design engineering, or curbing societal use, may be the most effective precautionary strategy to reduce and prevent microplastic pollution.

We identified knowledge gaps associated with developing and implementing the precautionary framework and a quantitative effects risk assessment. The highest priority research questions to inform research and mitigation and apply the precautionary framework are: (1) What are the highest emitting sources of macro- (> 5 mm) and micro- plastic material to the marine environment in California? (2) What does monitoring reveal about trends in the concentrations of microplastic pollution within California's marine environment? And 3) How do we associate and directly link microplastic particles sampled in the marine environment to sources of concern through the development and use of new methods, technologies, and tools? Addressing these important questions will allow decision-makers to prioritize sources for reduction activities immediately, instead of waiting to act when the necessary effects data and relevant risk frameworks become available.

In five (5) years, we recommend reassessing the state of the knowledge to then support a state-specific quantitative effects risk assessment, especially considering ongoing efforts of other agencies and bridge organizations within the state. In the meantime, effects data gaps need to be filled, including a hazard analysis recognizing the multi-dimensionality of microplastics as a diverse class of contaminants is needed, followed by a risk assessment considering both current and future concentrations of microplastic mixtures in the environment.



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1. Introduction

Commercial "plastic" materials with potential ecological relevance identified in recent scientific studies have generally been considered to be articles manufactured from synthetic materials with additives, fillers, or other added materials, and can include conventional plastics, as well as textile or rubber materials. Plastic pollution is a growing environmental concern that threatens marine ecosystem health. Plastic debris has been observed across most marine habitats, including coastal and open oceans, estuaries, and benthic sediments (Barnes et al. 2009, Andrady 2011, Cole et al. 2011, GESAMP 2016). Large plastics (> 5 mm) have even been shown to negatively impact marine organisms such as impeding movement via entanglements and obstructing digestive tracts (Bucci et al. 2019).

Because of the persistent nature of plastics and their inability to degrade on meaningful ecological timescales (e.g. high density polyethylene (HDPE) bottles and pipes have a half-life of 58 and 1200 years, respectively, in the marine environment (Chamas et al. 2020)), plastic pollution is not only a current concern, but one that extends into the future. Anthropogenic mass already exceeds living biomass (Elhacham et al. 2020). By 2030, annual emissions are predicted to reach at least 20 million metric tons per year unless we fundamentally alter our plastic economy (Borrelle et al. 2020). Many plastic materials are fossil fuel-based, and with projected increased production, the associated greenhouse gas emissions (projected to account for 10–13% of the global carbon budget by 2050 (Shen et al. 2020)) have potentially significant implications for climate change and environmental justice (Zheng & Suh 2019). The U.S. produces more plastic waste than any other country, a portion of which (0.15 to 0.99 Mt in 2016) is inadequately managed through exports to other countries (Law et al. 2020). Thus, plastic pollution is not only a regional issue, but one of global importance that extends far beyond the bounds of the marine environment. Microplastic pollution will not only persist into the foreseeable future, but will be greatly magnified if unaddressed.

The scientific knowledge of large plastic debris impacts is quite advanced. Far less progress has been made on the risk characterization and management of weathered plastic particles, which fragment and degrade from large plastics to form nanometer- to millimeter-sized secondary microplastics. Microplastics have been intensely studied for a decade, and scientific understanding on their prevalence and occurrence across environmental matrices is rapidly growing. However, due to their complexity and variability in chemical and physical composition, a holistic understanding of the potential effects of both primary microplastics (which are manufactured to be small) and secondary microplastics (formed from wear, weathering, etc) has been slower to progress and more challenging to achieve.

Nevertheless, concerns over the impacts of microplastics to the environment are growing. In response to these concerns, various types of intervention strategies (e.g. plastic material reduction, collection and capture, clean up and recycling) have been implemented to prevent or reduce release into the environment. For example: (1) statewide bans prohibit sales of single-use plastics bags at large retail stores as a material reduction strategy (S.B. 270), (2) filters on washing machines trap microfibers before they're flushed (McIlwraith et al. 2019), (3) rain gardens capture microplastic particles transported in stormwater before they enter the marine environment (Gilbreath et al. 2019), and (4) technologies collect and remove macroplastics already in the marine environment, which could help to prevent further fragmentation into microplastics (Schmaltz et al. 2020). Steps have been taken in the U.S. to begin to regulate intentionally manufactured primary microplastics less than 5 mm in size, such as the Congressional Microbead-Free Waters Act of 2015 amendment to the Federal Food, Drug and Cosmetic Act (Microbead-Free Waters Act of 2015).

At the state level, California is active in microplastic pollution research and regulation. In 2015, the California state legislature prohibited the sales of personal care products containing plastic microbeads in rinse-off products (A.B. 888). In response to the California Safe Drinking Water Act: Microplastics of 2018 (S.B. 1422), the California State Water Resources Control Board (the California Waterboards) adopted the first definition for microplastics in drinking water in 2020 (State Water Resources Control Board 2020) and plans to adopt a standardized methodology for testing microplastics in drinking water in 2021. Recent and ongoing research efforts in California include an assessment by the San Francisco Estuary Institute (SFEI) and 5 Gyres Institute, which characterized microplastics and microparticles in the San Francisco Estuary (Sutton et al. 2019, Miller et al. 2021). The Ocean Protection Council (OPC) has built on this work by funding two research projects to enhance the state's understanding of microplastics in stormwater and wastewater, and how to best remove them from these pathways. Additionally, The Southern California Coastal Water Research Project (SCCWRP), along with the California Waterboards, SFEI, and the University of Toronto, hosted a webinar series on microplastics health effects in fall 2020 and are working through 2021 to develop standardized methodologies for monitoring microplastics in drinking water, as well as a toxicity database that facilitates probabilistic approaches for the assessment of risk and determination of thresholds for aquatic organisms.

In 2018, the California state legislature tasked the California Ocean Protection Council with developing a Statewide Microplastics Strategy to address and understand the scale and risk of microplastic pollution on the marine environment. A major component of the Strategy is the development of a risk assessment framework for microplastics, based on the best available information on the exposure of microplastics to marine organisms and humans through pathways that impact the marine environment. This framework will be used to evaluate options, including source reduction and product stewardship techniques, barriers, costs, and benefits (S.B. 1263).

In collaboration with the OPC, the California Ocean Science Trust (OST) convened an interdisciplinary group of expert scientists, the OPC Science Advisory Team Microplastic Working Group ("We"), to develop a risk assessment framework for microplastic pollution in California, and to provide scientific guidance to assist the State in understanding the sources, fate and transport, toxicological impacts, marine species impacts, and ecosystem and human health impacts of microplastics. Our charge was to:

- Develop a, or adapt from a pre-existing, **risk assessment framework for microplastic pollution in California** to be used by the State to understand and assess the risk of microplastic pollution, and to be incorporated into the Statewide Microplastics Strategy.
- Develop qualitative **descriptions of the various known pathways, sources, behaviors, and observed and hypothesized effects** of microplastics on the marine environment (i.e. species, habitats, ecosystems) and human health in California.
- Identify **knowledge gaps associated with** the pathways, sources, behaviors, and effects of microplastics in California.
- Develop a **list of methods, tools, and data (research questions) needed to address such knowledge gaps** and inform future research endeavors in California.

This information is critical for the State to evaluate and prioritize reduction solutions and move toward timely and well-informed action on this emerging issue. This report details our efforts, recommendations, and work to provide this information and guidance.

2. A Precautionary Risk Assessment Framework

About this Section:

We discuss our rationale for choosing a precautionary approach to assess the risk of and manage microplastic pollution. We compare particulate and toxicant management approaches and provide a rationale for recommending the former. We discuss applying and adapting the ecological risk assessment framework paradigm to microplastic pollution, and discuss how to use this framework.

Recommendations:

1. **We recommend a precautionary approach** to assess the risk of and manage microplastic pollution risk, based on microplastic persistence, lack of feasible cleanup options, projected rate of increased concentrations in the environment, and evidence that microplastics contaminate and may lead to adverse effects in organisms and humans.

2. **A particulate approach** to manage and assess risk of microplastic pollution is recommended over a toxicant approach, until California-specific data are available and the chemical effects of microplastics are fully understood.

The State will use this risk assessment framework to (1) assess the risk of marine microplastic pollution to both the marine environment and human health and (2) evaluate options, including source reduction and product stewardship techniques, barriers, costs, and benefits (S.B. 1263). This framework will primarily be used by California state resource managers, agency staff, and scientists to assess microplastic pollution risk at the entire California state-level using publicly-available data and resources. Given the framework's intended use and target audiences, we developed and recommend use of a pragmatic and scientifically sound precautionary risk assessment framework that makes use of currently available microplastic exposure data, as specified in the legislative mandate, and allows for prioritization of source reduction activities. We adapted the precautionary framework from the U.S. EPA risk assessment paradigm (Appendix 1) to include scientific guidance that informs risk prioritization and evaluation (Box 1, Fig. 1):

BOX 1:

The process (i.e. phases) for the precautionary microplastics risk assessment framework (adapted from USEPA 1992 & 1998, NRC 2009).

(1) Problem Formulation:
a preliminary assessment of key factors to be considered in the risk assessment, including an examination of scientific evidence, data gaps, policy and regulatory issues, and an assessment of the feasibility, scope, and objectives of the risk assessment

(2) Risk Characterization & Ranking*:
an assessment of relevant exposure data to priority endpoints to characterize and rank the relative risk of potential adverse effects by source, polymer type, and taxon as indicated by surrogate measures of microplastic internalization and source tonnage

(3) Risk Evaluation & Source Reduction Prioritization*:
a determination of whether characterized risk warrants State action and mitigation, and scientific guidance to aid prioritization of source reduction solutions

*Phases adapted from U.S. EPA ecological risk assessment and risk-based decision-making frameworks, specific to assessing the risk of microplastic pollution.

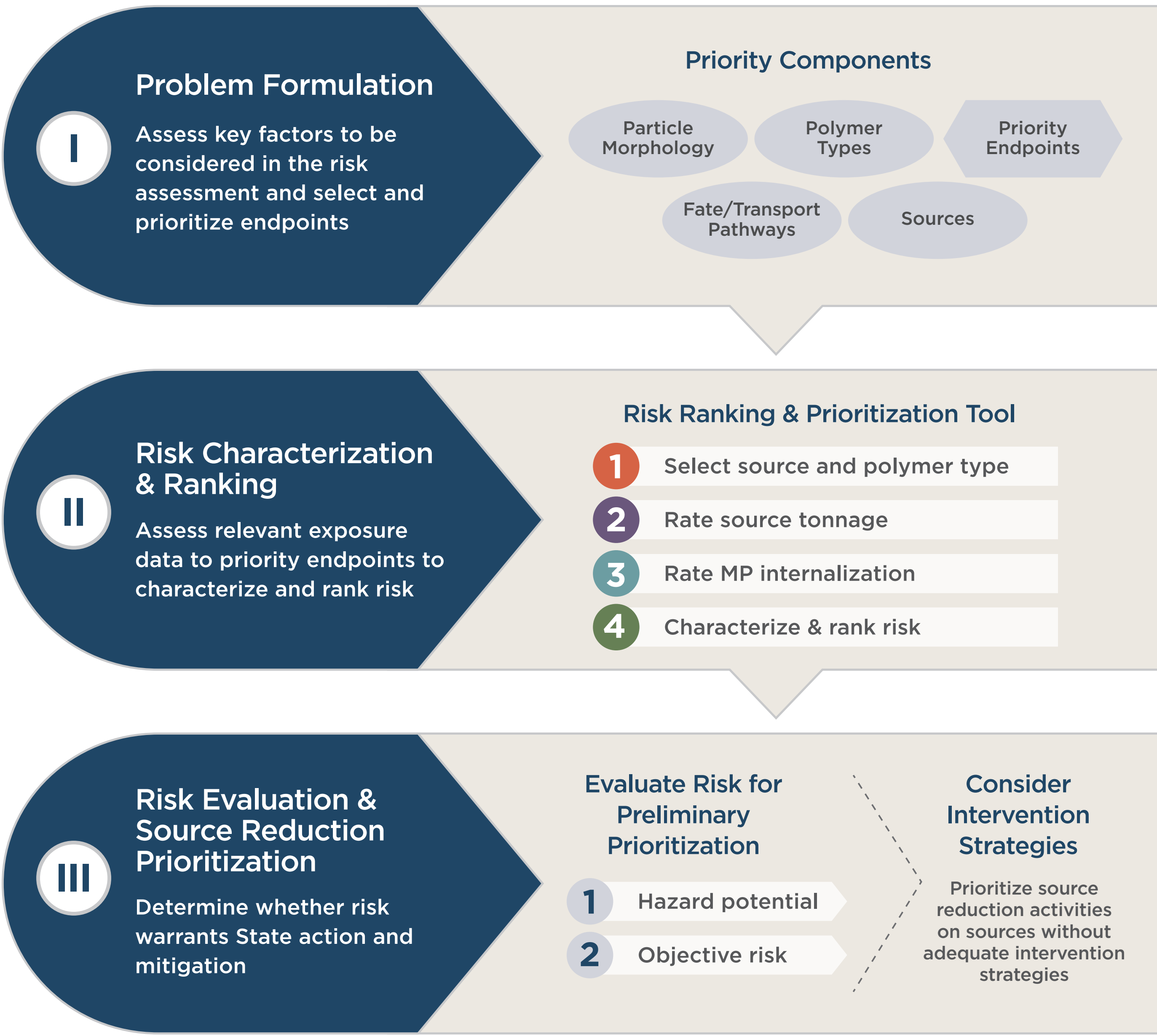


Figure 1. The precautionary risk assessment framework for microplastic pollution, including phases (1–3; left column) and steps and Working Group recommendations (right column) associated with each phase. Steps, key terms, and recommendations will be described in more detail later in the report. See Figure 2 in Phase II: Risk Characterization & Ranking for a more detailed explanation of this phase. MP = microplastic.

Risk assessments are well-established scientific processes that evaluate the likelihood of adverse effects to valued environmental entities (e.g. species, habitats) as a result of exposure to one or more stressors (USEPA 1992 & 1998, NRC 2009). Generally, risk is characterized by combining estimates of duration and magnitude of exposure from a stressor to a receptor (e.g. valued environmental entity) and characterizing resulting effects to the receptor from that exposure. These assessments are a valuable tool to help decision-makers understand and address potential uncertainty for a range of environmental issues (e.g. sustainable fisheries management, hazardous storms and natural disasters, human health impacts, etc.) (Mckenzie et al. 2012, Muralikrishna & Manickam 2017, Armaroli & Duo 2018, Samhouri et al. 2019). Risk assessors aim to clearly distinguish risk assessment, which assesses how "signals of harm" relate to the probability and consequence of an adverse effect, from risk management, which evaluates management options to reduce identified hazards or exposures using the risk assessment to provide insights into the merits of the management options (US EPA 1998, NRC 2009). As there is an increasing need for risk assessments to inform decision-making and to incorporate many different types of expertise (e.g. natural sciences, social sciences), it is necessary to consider more flexible frameworks, such as risk-based decision-making frameworks (NRC 2009). These risk-based decision-making frameworks follow the U.S. EPA risk assessment paradigm, but include additional steps for planning within the appropriate decision-making contexts and assessing options for managing risk (Appendix 2, NRC 2009).

Evaluating existing ecotoxicology approaches

After evaluating the current state of knowledge, existing ecotoxicological approaches, and previous microplastics risk assessment efforts, we recommend the State use a prospective precautionary risk assessment framework to assess microplastic pollution risk in California because of a lack of ecotoxicity threshold data specific to California marine ecosystems (studies and explanation provided below). Sufficient hazard information (e.g. exposure data and limited effect data) was available on primary and secondary microplastics to recommend a precautionary risk assessment framework supporting immediate source reduction and product stewardship activities.

Due to the complex physical and chemical composition of microplastics, some experts have suggested that an ecotoxicological approach to risk characterization, such as a risk quotient (RQ = PEC/PNEC) based on environmental concentrations (PEC = predicted environmental concentration) and effects thresholds (PNEC = predicted no effect concentration), is appropriate (Besseling et al. 2019, Gouin et al. 2019, Everaert et al. 2018). In line with the risk assessment paradigm (NRC 1983, USEPA 1992, USEPA 1998), this method relies on the explicit demonstration and observation of adverse effects to drive policy and management decisions (i.e. burden of proof). To date, efforts have been made to propose and implement methodologies consistent with the risk assessment paradigm for microplastic pollution (Koelmans et al. 2017, Everaert et al. 2018, Besseling et al. 2019, Gouin et al. 2019, Everaert et al. 2020, Koelmans et al. 2020, Adams et al. 2021). These efforts provide a potential quantitative risk characterization approach with preliminary scientific insight into how "signals of harm" relate to the likelihood of consequences (Everaert et al. 2018, Besseling et al. 2019, Everaert et al. 2020, Koelmans et al. 2020). However, the effects threshold data available for these methods remain somewhat limited, and validated or consensus test guidelines are still in the process of being agreed upon. Therefore, in these published examples, globally-sourced data are supplemented by assumptions to correct for the lack of standardization or low availability of information on occurrence or toxicity of particular polymer types and morphologies (e.g. fibers, tire wear particles).

At the California state-level, which is the geographical focus of our efforts, these limitations currently hinder the preparation of regulatorily validated relationships between environmental concentrations of microplastic particles and observed adverse effects (i.e. dose-response relationships). Thus, the currently available threshold

data make it difficult to quantitatively characterize risk to the marine environment in California in accordance with the risk assessment paradigm. We understand that ecotoxicological datasets are rapidly maturing, that efforts to advance test standardization are progressing, and new studies on microplastics are published daily. For example, Koelmans et al. 2020 provided a potential rescaling method to address the misalignment of methods used to assess and report microplastics environmental concentrations and morphologies and effects with a high degree of certainty, which has the potential to solve some of these issues of imprecise effects threshold data (Koelmans et al. 2020). However, the degree to which state and federal regulatory agencies will adopt or accept "rescaling" or "read across" methods in microplastic risk assessments is unknown at the time of the preparation of this framework, particularly due to concerns about specific polymer types (e.g. high prevalence of tire wear particles). Moreover, without effects threshold data assessed for the applicability to environmental conditions associated with microplastic exposures in California specifically, a state-specific quantitative effects risk assessment will continue to be hindered. We instead recommend focused data-collection to address data gaps specific to California, so a statewide risk assessment following the approaches put forth by the publications referred to above (e.g. Koelmans et al. 2020, Everaert et al. 2020, etc.) can be conducted.

Adopting a Particulate Approach

We recommend the State adopt a particulate management (PM) approach to assessing and managing microplastic pollution risk based on the current state of knowledge. Uncertainties in how many of dimensions of effect thresholds (e.g. test-standardization, species, duration, size, shape, polymer and endpoint) will be harmonized in regulatory microplastic risk assessments, as well as future environmental concentrations given the persistence of plastics materials, hinder our ability to immediately characterize State-level risk with quantitative dose-response techniques. Yet, they do not preclude State action and timely decisions to address ecological harm attributable to microplastics and mitigate potentially irreversible losses of biodiversity in State marine resources. We note that the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Global Assessment has identified pollution, "including plastics" as a "direct driver" of "global declines in nature" (IPBES 2019).

A particulate management approach is consistent with established science and risks of small particulates in the environment. This approach is analogous to the particulate matter (PM) risk framework for PM10 and PM2.5, which is used to assess air quality for the protection of human health (Kurt et al. 2016). Parallels with air particulates include: (1) their widespread occurrence in the environment (Law 2017, Rillig & Lehmann 2020, Evangeliou et al. 2020), (2) their tendency to fragment into smaller micro- and nano- particles through continuous degradation (Song et al. 2020, Enfrin et al. 2020), (3) a lack of feasible cleanup strategies (e.g. particularly primary microplastics; Ogunola et al. 2018, Hohn et al. 2020), and (4) the projected increased rates of plastic production and resulting increased entry (release) into the environment (Borrelle et al 2020, Everaert et al. 2020). Our recommendation to currently adopt a particulate management approach is not meant to exclude future considerations of chemical-specific toxicant approaches as sufficient information for California-specific assessments becomes available. Instead, we recommend that this particulate approach be conducted for microplastics first to establish a baseline, similar to approaches for air quality, which can and should be followed up with a toxicant management approach when the toxicity knowledge and data becomes available to reduce these multidimensional uncertainties and complexities.

How to Use the Precautionary Framework

The scope and complexity of risk assessments are constrained and dictated by the nature of the decision, time, available resources to complete the assessment, and decision-makers' need for thoroughness, accuracy, and detail (Suter 2016). Our goal, here, is to provide guidance and direction to the State for addressing emerging concerns about ecological harm associated with microplastics, which are expected to persist and, in the absence of management, increase in environmental concentration in the future. Given our constraints (i.e. lack of high-quality state-specific effects data), we developed a precautionary framework that does not rely on observed adverse effects to drive decision-making, as is required by quantitative effects risk assessments. The precautionary framework allows for preliminary risk prioritization conclusions to be drawn to inform policy and management decisions, using exposure as an indicator of risk. Thus, we are proposing a risk assessment framework that is precautionary in nature and protective of the marine environment, biodiversity, and human health. We relax and deviate from the strict requirements of the risk assessment paradigm to develop a framework that incorporates key risk assessment and risk management components of quantitative effects risk assessment and risk-based decision-making frameworks. We do not prescribe specific management actions, but instead provide guidance for how to interpret characterized risk to inform potential management actions. The precautionary framework will allow decision-makers across sectors to prioritize source reduction solutions and continue to advance pollution mitigation technologies while the knowledge needed to assess risk quantitatively within the state of California becomes available (e.g. SCCWRP effects research).

To use the framework, follow the stepwise instructions and recommendations for each sequential phase. Our instructions and recommendations for the Problem Formulation and Risk Characterization & Ranking phases are further illustrated with case studies. Lasty, we expand upon and discuss key knowledge gaps needed to execute the framework with currently available information and move toward a state-specific quantitative risk assessment framework in the future.

3. Phase I: Problem Formulation

About this Section:

We provide steps that narrow the scope of the microplastic problem and discuss how we applied a traditional risk assessment problem formulation approach to microplastic pollution. We identify priority elements based on available science and discuss the evidence and process leading to these recommendations.

Recommendations:

1. **The following high priority & most prevalent components** of microplastic pollution:
   - **Particle Morphology:** microfibers and fragments
   - **Polymer Types:** microfibers and tire & road wear particles
   - **Fate & Transport Pathways:** stormwater runoff (urban, agricultural), aerial deposition, and wastewater
   - **Sources:** unknown in California, but international literature suggests tire & road wear, laundry & textiles, and plastic litter from aquaculture & fishing
2. **The following priority endpoints** in the California marine environment: microplastic internalization for benthic mollusks, large crustaceans, and lower and upper trophic level fishare available and the chemical effects of microplastics are fully understood.

Problem Formulation is a preliminary assessment of key factors to be considered in the risk assessment, including an examination of scientific evidence, data gaps, policy and regulatory issues, and an assessment of the feasibility, scope, and objectives of the risk assessment (USEPA 1992 & 1998). Given the breadth of the legislative mandate to assess microplastic risk to the entire California marine environment, we relied on our own scientific expertise, advice from the Policy Advisory Committee, and literature reviews to narrow the scope of this framework. Here, we provide stepwise instructions and recommendations (Box 2) to complete this phase of the framework and provide our results.

BOX 2:

Steps to complete the Problem Formulation phase.

(1) Focus the risk assessment on the following highest priority & most prevalent components of microplastic pollution:

- **Particle Morphology:** microfibers and fragments
- **Polymer Types:** microfibers and tire & road wear particles
- **Fate & Transport Pathways:** stormwater runoff (urban, agricultural), aerial deposition, and wastewater
- **Sources:** unknown in California, but international literature suggests tire & road wear, laundry & textiles, and plastic litter from aquaculture & fishing

(2) Use the four priority endpoints

(microplastic internalization for benthic mollusks, large crustaceans, and upper and lower trophic level fish) to further focus the risk assessment

>> STEP 1

Focus the risk assessment on the following highest priority & most prevalent components of microplastic pollution:

- **Particle Morphology:** microfibers and fragments
- **Polymer Types:** microfibers and tire & road wear particles
- **Fate & Transport Pathways:** stormwater runoff (urban, agricultural), aerial deposition, and wastewater
- **Sources:** unknown in California, but international literature suggests tire & road wear, laundry & textiles, and plastic litter from aquaculture & fishing

As part of Step 1, we developed a conceptual model for microplastic pollution. To develop the conceptual model and focus the framework, we began with a broad assessment of the problem and then narrowed the scope on the highest priority and most prevalent components necessary to use the framework to evaluate and prioritize source reduction solutions in a precautionary manner. Similar to previous microplastic risk assessments (Besseling et al. 2019, Gouin et al. 2019, Everaert et al. 2018), we identified six (6) important components of the microplastic problem: particle morphology (i.e. size, shape), polymer type (e.g. microfibers, tire wear, etc.), chemical composition & additives; sources; fate & transport pathways; exposure pathways (e.g. ingestion, inhalation); effects (e.g. lowered fitness); and endpoints (e.g. crustacean fecundity). We identified several elements under each component category and developed the conceptual model based on evidence from the peer-reviewed literature and expert judgement (full conceptual model and definitions for these components in Appendix 3). Acknowledging the uncertainties of the microplastic effects data, we focused on the following components necessary to assess exposure in a precautionary manner: ***particle morphology, polymer type, sources, fate & transport pathways, and endpoints*** **(Box 3).**

BOX 3:

Components and definitions (adapted from USEPA 1992 and WHO 2004) of microplastic pollution.

Particle Morphology & Polymer Types:

unique physical and chemical attributes of microplastic particles to describe polymer types (e.g. microfibers, tire wear)

Sources:

the origin of microplastics for the purposes of an exposure assessment, focusing on where particles originate; including primary microplastics that are intentionally manufactured to be small in size (e.g. nurdles, plastics in personal care products) and secondary plastics from wear and tear or weathering and breakdown of larger plastic products (e.g. tire tread, textiles, litter & food packaging)

Fate & Transport Pathways:

the course (i.e. movement and chemical alteration) microplastics take from a source to an environmental entity (e.g. taxa, species, habitat) in the environment

Endpoints:

an explicit expression of the valued environmental entity that is to be protected; operationally expressed as an entity and relevant attribute (e.g. crustacean survival)

We discuss the first three component categories below and identify the highest priority elements, applying precautionary considerations combined with available science. These high priority elements, in addition to bounding the framework, also provide a starting place for decision-makers to consider microplastic source reduction activities immediately, even before implementing the framework or pursuing high priority research. In recommending the following priorities, we note that consumption of food, including natural prey, has been consistently shown across studies to be adversely affected by the presence of microplastics (Foley et al. 2018). This reduction in consumption can be accompanied by “food dilution” characterized by reduced energy intake and inhibition of growth (Koelmans et al. 2020). Yet, California specific data on the relationship between microplastic exposure and adverse effects on consumption (i.e. cause-effect pathway) are not readily available. As the nutritional value of food is expected to decrease proportionally with increases in environmental volume of ingested microplastics, our priorities below focus on particle morphology, polymer type, pathways, and sources in Step 1 paired with a consideration of microplastic internalization in Step 2.

Particle Morphology & Polymer Types

We initially considered several attributes — including size, shape, polymer type, volume, density, and chemical additives — as unique determinants that help to define the diversity and behavior of plastic particles likely to occur in the environment. **We identified the morphological attributes of size and shape as the determinants of most concern for both potential exposure to and harm from plastic particles** (e.g. Jacob et al. 2020, Gray & Weinstein 2017). We used the size range from 1 nm to 5 mm in diameter, consistent with the microplastic definition in California drinking water (State Water Resources Control Board 2020), and identified several potentially relevant shapes, including fibers, fragments, foams, spheres & pellets, and films (Hartmann et al. 2019, Kooi & Koelmans 2019). While microplastic particles across all size classes pose concerns, smaller particles may be more concerning as they increase exposure potential via ingestion, inhalation, or dermal contact, and have greater potential for systemic exposure (e.g. translocation), thereby increasing the potential for toxicological effects (Jacob et al. 2020, Scott et al. 2019, Jeong et al. 2016). The study of particle size on human health has a long history and the lessons learned from this research can be applied to the smaller sizes of microplastic particles (Costa & Gordon 2013). Additionally, particle morphology provides a potential basis for associating and linking particles back to their sources (Fahrenfeld et al. 2019).

Fibers and fragments are proposed as the highest priority shapes. Fibers are distinguished from other shapes as their long dimensions and high aspect ratio may increase their potential to lodge in organisms’ organs (e.g. gills), which may produce effects that differ from particulate accumulation (Kutralam-Muniasamy et al. 2020, Ribeiro et al. 2019, Watts et al. 2016, 2015). **We identified microfibers and tire & road wear particles as highly prevalent polymer types generated via terrestrial anthropogenic activities in California** (Sutton et al. 2019, Miller et al. 2021). We did not focus on other particle characteristics, such as polymer composition or chemical additives, in the framework as other priorities are more urgent. Moreover, models and empirical data suggest that sorbed chemicals may not be as bioavailable as initially thought (e.g. Koelmans et al. 2016), and that even though data suggest that some additives and sorbed pollutants may be harmful depending on the size and surface area of the microplastic particle (e.g. Ma et al. 2016, Wang et al. 2018). Our decision, here, does not claim that particle composition and chemical additives are unimportant in understanding risk. For example, it has recently been shown that 6-PPD quinone, a potential tire rubber-derived oxidation product, is lethally toxic to salmonids at sufficient dose (Tian et al. 2021). Rather, in line with our particulate management recommendation, we chose to not focus on these characteristics currently as more data are needed to facilitate incorporation into a risk prioritization or assessment strategy. However, additives and other plastic-associated pollutants could be considered in the future.

Fate & Transport Pathways

We determined fate & transport pathways were an important component of evaluating source reduction solutions as they help provide a direct link between particles emitted from sources and exposure and contact to our endpoints. **We identified several fate & transport pathways, but highlight stormwater runoff (i.e. agricultural and urban) as a top priority,** and aerial deposition and wastewater to a lesser extent. Our conclusion is in line with previous work, where investigations in the San Francisco Bay found concentrations of microparticles in urban stormwater runoff (1.3 – 30 microparticles/L, mean 9.2) to be significantly higher than wastewater (0.008-0.2 microparticles/L, mean 0.06). The study went further to extrapolate loadings from these two pathways from simple models and estimated loadings from urban stormwater runoff to be up to two orders of magnitude higher than wastewater to San Francisco Bay (Sutton et al. 2019, Miller et al. 2021). Further, while we lack precise estimates of microplastic loading from agricultural runoff, the size of California's agricultural sector and its potential to emit high amounts of microplastic loading via agricultural runoff cannot be ignored.

The plastic types transported in stormwater runoff are directly associated with site-specific land-use patterns (e.g. urban, rural, agricultural) and, therefore, depending on which sources are of most interest, either urban or agricultural runoff could be selected as a focus for a risk assessment. For example, if one were to assess tire wear or litter, one might consider assessing urban runoff, whereas if fibers were of interest, one might assess both agricultural (via biosolids) and urban runoff (via textiles) (e.g. Gray et al. 2018, Crossman et al. 2020, Grbić et al. 2020). While further research is needed to understand relative contributions, wastewater in the San Francisco Bay area appears to contribute an appreciable but somewhat lower microplastics load than urban stormwater runoff (Sutton et al. 2019).

Most recent studies point to aerial deposition as another substantial pathway to the marine environment (Zhang et al. 2020). Yet, without fully understanding the relative contribution of aerial deposition and having limited intervention potential, we did not focus on this pathway in the framework, but rather raise this concern as a potential focus for greater research and management attention going forward.

Sources

We identified several sources as macroplastic material types (e.g. litter, textiles, personal care products, tire & road wear particles) and, in some cases, the human activities (e.g. transportation, agriculture and industrial activities, leisure activity) associated with those materials. To make the framework more targeted and provide guidance for source reduction, we intended to narrow the scope to the largest emitters (i.e. by tonnage) of plastic material to the marine environment in California. However, knowledge on the largest sources in California and the science to trace sampled particles back to their original sources is currently not adequate for most polymer types.

We can, however, take advantage of plastic loading inventories from the international literature and make informed assumptions on the potential largest sources in California. **Some common large sources**

from European Union microplastics inventories, which we will prioritize and focus our framework, include: tire & road wear, laundry, and plastic litter from fisheries & aquaculture gear (Sundt et al. 2014, Verschoor et al. 2014, Lassen et al. 2015, Magnusson et al. 2016). A recent review found that the U.S. was the largest generator of plastic waste internationally, with a meaningful fraction of this waste illegally discharged domestically or mismanaged in countries that import U.S. waste (Law et al. 2020).

Identifying California-specific large sources for inclusion in a risk assessment would require (1) considering site-specific land-use patterns (e.g. urban, rural, agricultural) and local human population densities, as these factors will likely influence the amount and types of macroplastics potentially reaching the marine environment, and (2) determining whether those sources have adequate and available intervention strategies to assess if reduction would have a meaningful impact. The size and scale of California's agricultural industry and transportation systems (i.e. roads, number of personal vehicles) warrants their consideration and inclusion as potential top sources, and supports the framework's focus on microfibers, from agricultural biosolids, and tire & road wear particles. Any differences between European and Californian wastewater treatment systems should also be considered. In California, there are primary, secondary, and tertiary wastewater treatments prior to discharge of treated wastewater to the ocean. Although primary treatment seems to remove a majority of microplastic via sludge (Sun et al. 2019), studies show further treatment can reduce microplastic content (Sutton et al. 2019). In addition, removal efficacy varies across microplastic sizes and shapes (Sun et al. 2019). We expand upon these considerations and our final selection of California sources to focus the framework later in the Risk Characterization & Ranking phase.

>> STEP 2

Use the four priority endpoints (microplastic internalization for benthic mollusks, large crustaceans, and lower and upper trophic level fish) to further focus the risk assessment.

We recommend further focusing the risk assessment on four priority endpoints: microplastic internalization for benthic mollusks *(mollusks)*, large crustaceans, and lower and upper trophic level fish. We recommend focusing on the following two species (one California native, one data rich) for each prioritized endpoint in the risk assessment: California mussel *(Mytilus californianus)* and Pacific oyster *(Crassostrea gigas)* for benthic mollusks, Dungeness crab *(Metacarcinus magister)* and Grass shrimp *(Palaemonetes pugio)* for large crustaceans, Northern anchovy *(Engraulis mordax)* and Inland silverside *(Menidia beryllina)* for lower trophic level fish, and California halibut *(Paralichthys californicus)* and Chinook salmon *(Oncorhynchus tshawytscha)* for upper trophic level fish. Data from studies on additional species will soon be available through the global toxicity database being assembled by SCCWRP and could be used as needed to obtain sufficient data for use of the prioritization tool.

Endpoints focus risk assessments on environmental entities (e.g. species, taxa, habitat, etc.) and attributes (e.g. survival, fecundity, reproduction, abundance) that may be affected by exposure to a stressor and, therefore, should be selected based on their relevance to decisions on the issue at hand (Suter 1990, USEPA 1992). Three criteria are commonly used to select endpoints (Box 4; USEPA 1992 & 1998)

BOX 4:

Endpoints selection criteria and definitions (adapted from USEPA 1992 & 1998).

Ecological Relevance:

the role of the endpoint (i.e. entity and attribute) in the ecosystem and, therefore, depends on the ecological context

Susceptibility to Stressor:

the sensitivity of the endpoint (i.e. assessment or measurement) to the stressor relative to its potential exposure and, therefore, depends on the identity of the stressor and mode of exposure

Management Relevance:

pertains to the goals set by the decision-makers and, therefore, depends on the societal, legal, and regulatory context of the decision, as well as the preferences of the decision-makers and stakeholders

We applied the U.S. Environmental Protection Agency's (EPA) criteria in a case-study endpoints prioritization process to narrow the scope of the microplastic pollution issue while meeting the legislative mandate (S.B. 1263) to address exposure to marine organisms and humans. This criterion (Box 4) was applied to prioritize endpoints using a combination of professional judgement from both us, the Working Group, and the Policy Advisory Committee, as well as a literature review.

Our case-study management goal was to assess the risk of marine microplastic to ecologically-important taxa and human health (via human consumption of those taxa). By focusing our framework on taxa of economic importance (endpoints) likely to be consumed by people, we indirectly account for potential effects of microplastics to human health due to ingestion of contaminated seafood (Smith et al. 2018). While it is possible to integrate human health and well-being into ecological risk assessments (Harris et al. 2017), we do not explicitly include human health endpoints due to the complexities and lack of feasibility with assessing microplastic exposure and effects to humans. Furthermore, focusing on taxa likely to be consumed by higher trophic levels (e.g. predators) also allows for broader ecosystem and food web effects to be detected, but these broader effects were not explicitly included in this framework.

Microplastic internalization (e.g. particle presence/absence or concentration in organisms) is a precursor to organismal- and population-level effects, such as decreased survival, reproduction, or abundance (Bucci et al. 2019). A focus on microplastic internalization is consistent with the precautionary approach selected in this Problem Formulation, is in alignment with data on "food dilution" being used to parameterize current risk assessment models (e.g. Koelmans et al. 2020), and allows management to move forward despite existing knowledge gaps. Therefore, we argue microplastic internalization may serve as an adequate effect (and endpoint) to be included in any future risk assessment. We recommend future microplastic risk assessments, using this precautionary framework, focus on microplastic internalization instead of other effects due to its measurement feasibility and undesirable occurrence. We provide an examination of the scientific evidence to establish harm from microplastic internalization, furthering our position that microplastic internalization in organisms is undesirable, and justify using the risk prioritization tool in the Appendices (Appendix 6). While we use a concentration-based measure of internalization, volume of internalized particles could be used to address chemical exposure via microplastics, but this is beyond the scope of this effort and our particulate approach.

This endpoints prioritization process may be iterated to select other taxa and species of interest that are most relevant to any management and policy objective at hand, including stakeholders interest. Incorporating and considering stakeholder interests is a key component of any risk assessment (USEPA 1998, NCR 2009), but was beyond the scope of this effort and should be a focus for future risk assessments. Full details of the prioritization process are in Appendix 4 and a full list of identified endpoints is provided in Appendix 5.

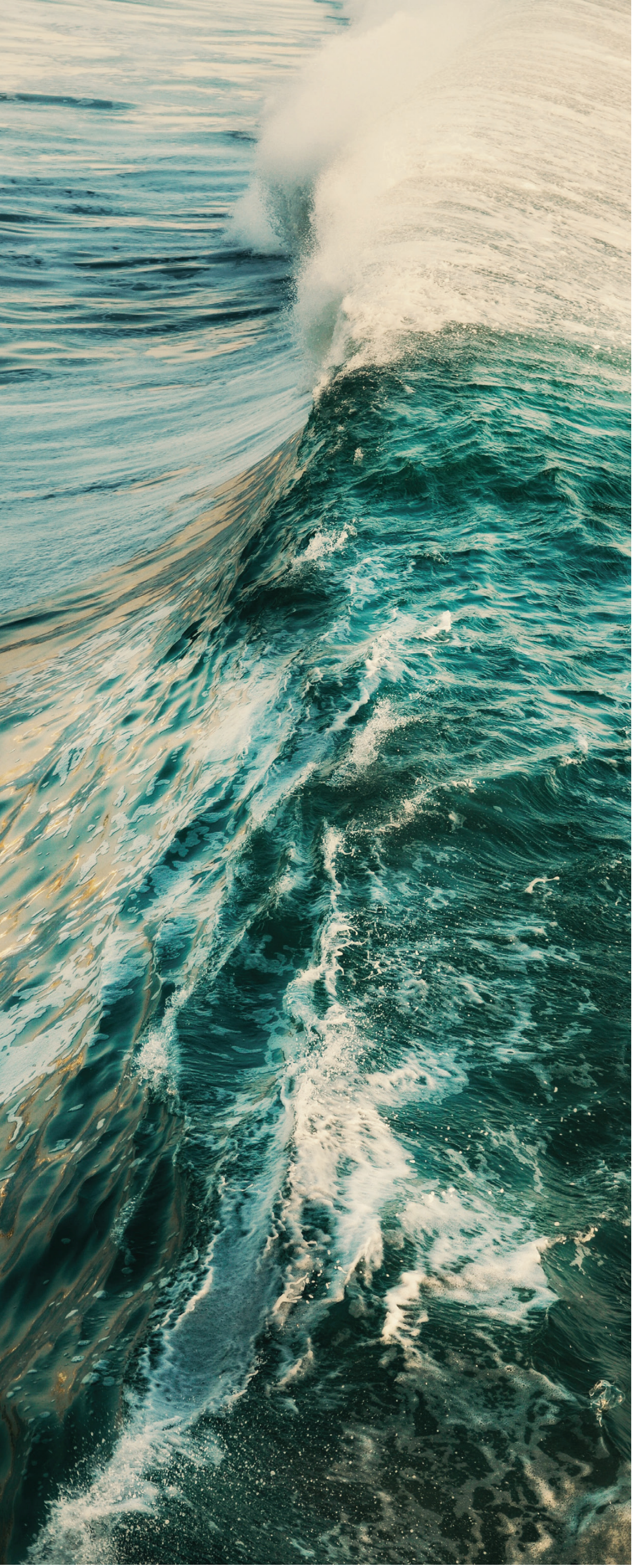
4. Phase II: Risk Characterization & Ranking

About this Section:

We provide stepwise instructions to characterize and rank risk using a risk prioritization tool. Applying the tool involves compiling scientific literature and evaluating study quality for unique combinations of polymer types, sources, and taxa (e.g. microfibers, textiles, and mollusks). Criteria for evaluating study quality and rating source tonnage and microplastic internalization potential are provided.

Recommendations:

1. **Apply the risk prioritization tool,** proposed here, using a weight-of-evidence approach to characterize and rank risk associated with the highest priority and most prevalent components of microplastic pollution (see Phase I: Problem Formulation, including priority endpoints).



Considering the State's objective of evaluating source reduction solutions, we recommend and propose that the most appropriate and feasible risk characterization method, at this point in time, is a risk prioritization tool that relies entirely on exposure data to characterize and rank risk. This approach relies on quantitative data from the peer-reviewed literature, and qualitative rates of both source tonnage and microplastic internalization potential using a weight-of-evidence approach. We recommend that the State focus on the potential largest sources in California to assess source tonnage potential and presence of microplastic particles (e.g. fibers, tire & road wear) in our recommended taxa and representative species of interests (e.g. benthic mollusks, large crustaceans, and lower and upper trophic level fish) for microplastic internalization potential. This prioritization tool is preferable to a quantitative risk assessment as it relies on potential major sources in California to focus source reduction management activities and resources, and overcomes limitations and uncertainties in the effects data.

We recommend this phase, and steps (Fig. 2), be conducted for unique combinations of **polymer types, sources, and taxa** (e.g. microfibers, textiles, and large crustaceans) identified as high priority in the Problem Formulation phase. Therefore, this approach should be primarily focused on polymer types most likely to occur in organisms and large sources most likely to benefit from mitigation. However, this phase can be adapted to other polymer types, sources, and taxa if State priorities change in the future. Lastly, we recognize risk may vary by location, and while this tool is intended to assess risk at the entire state level, we provide short instructions within these steps for assessing risk at finer spatial scales (e.g. regions or sites) if the required data is available.

1 Select appropriate source & polymer type associated with priority endpoints

Use case studies and subject matter expert consultations to make selection

Compile evidence for and rate source tonnage potential

- **2.1** Collect studies on microplastic inventories & loading
- **2.2** Assess data quality (Table 1) to assign overall study quality (Table 2)
- **2.3** Rate source tonnage potential (Table 3)

Compile evidence for and rate organism microplastic internalization potential

- **3.1** Collect studies on particles within taxa
- **3.2** Assess data quality (Table 4) to assign overall study quality (Table 5)
- **3.3** Rate microplastics internalization potential (Table 6)

4 Characterize & rank risk by relating source tonnage & microplastic internalization potential ratings

Characterize and rank risks for potential State action (Table 7)

Figure 2. Steps to complete the Risk Characterization & Ranking phase.

>> STEP 1

Select appropriate polymer types associated with priority endpoints.

Appropriate and reasonable selection of polymer types associated with the priority endpoint of interest can be accomplished by combining two lines of evidence:

1. Identification of polymer types originating from source; and
2. Demonstrating, or establishing the potential for, particle occurrence in taxa.

Deciding which polymer type to focus on may be accomplished through assessing plastic inventories to prioritize top sources and/or case studies of particle occurrence in organisms, or via consultations with local subject matter experts (i.e. scientists, decision-makers, informed stakeholders). For example, recent modeling performed for San Francisco Bay indicated that the fate of microplastics is highly sensitive to buoyancy with even "minimal sinking rates" predicted to result in retention in the Bay (Sutton et al. 2019). Therefore, characterization of tire & road wear particle internalization in benthic organisms in near-shore estuaries represents a high priority combination of polymer type and source, whereas this source and polymer type combination is expected to have low relevance to species found in the open sea due to limited potential for export (Unice et al. 2019). Additionally, fibers and buoyant particles, generally, are more likely to occur and be internalized in pelagic fish (Everaert et al. 2018).

>> STEP 2

Compile evidence for and rate source tonnage potential.

STEP 2.1:
Conduct a thorough review of the peer-reviewed literature to collect studies of microplastic environmental release inventories and/or environmental loading estimates where the source of interest has been identified.

Generally, release inventories describe either the total mass of plastic released to the environment (atmospheric, terrestrial and aquatic compartments) or, specifically, the fraction of the plastic transported to marine or freshwater environments. These inventories rely on several literature sources of information about the tonnage of plastic in use, and derive release factors to prepare estimates of environmental loads (Galafassi et al. 2019). Alternatively, microplastic loading rates can be estimated from environmental studies using measurements and appropriate models of regional watershed characteristics, such as has been recently demonstrated in the San Francisco Bay Microplastics project (Sutton et al. 2019). Collecting studies from other locations outside California is recommended if California-specific data does not exist. However, if the data is available and one would like to assess risk for a region or site within California (e.g. San Francisco Bay), one should only collect studies from that particular region and resume with the following steps using those regional estimates instead of studies from locations outside California.

STEP 2.2:
Assess data quality to assign study quality rating.

For each collected study (or emissions & loading estimates, if studies provide more than one estimate), assess data quality according to inventory-specific and/or environmental loading-specific evaluation metrics and criteria (Table 1), developed based on current sampling and reporting guidelines for microplastic studies (Koelmans et al. 2019, Brander et al. 2020, Cowger et al. 2020) and systematic review of environmental review data under the federal Toxic Substances Control Act (USEPA 2018). Data quality metrics should be assessed for meeting their criteria (i.e., yes or no).

Once each study is assessed by the above data quality metrics and criteria, assign overall study quality ratings according to the following study quality criteria (Table 2), based on the data quality evaluation in Table 1.

Table 1. Data quality evaluation guidelines for source tonnage studies.

METRIC	CRITERIA (YES OR NO)
Criteria Applicable to Inventory and Loading Studies	
Methodology	Inventory or study published in peer-reviewed literature, critically reviewed and accepted in peer-reviewed literature, or reviewed by external reviewers (e.g. scientific advisory panel)
Accessibility and clarity	Methodology for tabulating plastic usage and release factors transparently described
Geographic scope - international	Prepared for OECD* Country
Geographic scope - regional	Prepared for California
Applicability	Inventory or loading estimate reflects a release of identified source (inventory studies) or polymer type (loading studies) to marine environment (as opposed to a non-specific total release or amount used)
Temporality	Inventory estimate or loading measurement prepared within the last 5 years
Variability and uncertainty**	Variability and uncertainty discussed and considered in the inventory (such as seasonal variability or measurement error)
Criteria Applicable only to Loading Studies	
Quality assurance and quality control (i.e. QA/QC)	Study incorporated appropriate QA/QC measures, such as any of the following (Cowger et al. 2020): Error propagation, replicates, limit of detection and polymer identification (considering plastic morphology, size, color, and polymer), blank controls, positive control, and mitigation of contamination
Sample size	Loading estimates based on multiple sampling sites (n ≥ 3 sites)

*OECD = Organisation for Economic Cooperation and Development
**Variability represents true heterogeneity, which may not be reducible by further study; uncertainty represents a lack of knowledge, which can include errors in communication or data description, data gaps, parameter uncertainty, and model uncertainty (Regan et al. 2003, USEPA 1998).

Table 2. Study quality ratings according to combined data quality metrics and criteria.

STUDY QUALITY RATING	CRITERIA *(number of data quality metrics that met their data quality criteria, i.e. yes)*	
	Inventory Studies	**Loading Studies**
High Quality (HQ)	7	9
Medium Quality (MQ)	5 - 6	6 - 8
Low Quality (LQ)	0 - 4	0 - 5

STEP 2.2:
Assign source tonnage potential rating based on quality of studies and number of locations (e.g. countries) with source of interest identified as a major contributor of microplastics to the marine environment in those studies (Table 3).

Only consider and include studies rated as either HQ or MQ when rating source tonnage potential. Only include sources considered to be major contributors where an appreciable tonnage of plastic is estimated to release to the aquatic environment or when sources are ranked highly in source inventories.

Based on currently available information, major contributors on a mass basis are considered to be those that release ≥ 1 g/person/yr of plastic (Galafassi et al. 2019) to the marine environment. Annual mass release estimates (e.g. g/yr) should be converted to per-capita estimates (g/person/yr) using contemporaneous human population estimates to normalize releases between areas of the world. Watershed scale estimates for fibers are limited with varying methods, but a recent study conducted in the Paris Megacity portion of the Seine watershed suggests that sources on the order of 10 million fibers/km^2/yr or 1000 fibers/person/yr should be considered major sources, as well (Dris et al. 2018). The approach described here is intended to operationalize a prioritization scheme based on reasonably available present-day information. As more sophisticated modeling approaches or California-specific data become available, such as additional data on the occurrence of smaller size fractions that may be more likely to translocate (< 10 Qm), it is anticipated that the approach could potentially be refined to relate particle mass and degradation processes to particle size and count in the aquatic environment.

Table 3. Source tonnage potential rating based on number of locations identified as major contributors.

SOURCE TONNAGE POTENTIAL RATING	CRITERIA
High Potential	≥ 3 locations identified as major contributor
Medium Potential	2 locations identified as major contributor
Low Potential	1 location identified as major contributor
Not Considered	No evidence*

* If HQ studies do not identify particle shape or polymer type, consider lowering rating.

>> STEP 3

Compile evidence for and rate organism microplastics internalization potential.

STEP 3.1:
Conduct a thorough review of the peer-reviewed literature to collect studies showing polymers of interest occurring in taxa of interest (e.g. microfibers in mollusks).

To maximize the number of studies, users of the framework may need to collect studies on multiple species within the taxa of interest, in addition to those identified as high priority in the Problem Formulation phase. Studies presenting particle occurrence in organisms are sufficient to demonstrate internalization, and this evidence may be measured as particle presence or absence, prevalence or occurrence (percent of individuals with particles), or concentration (particles per individual, mass, or volume). Similar to our instructions for adapting source tonnage potential to specific regions, if one would like to assess microplastic internalization for specific taxa or species within a California region (e.g. San Francisco Bay) or site, one can simply compile data from studies of microplastic internalization within species and taxa that are similar to those of interest within the California region with regards to taxonomic group, trophic level, and habitat type (e.g. Rainbow Trout is similar to Chinook Salmon). Once these studies are collected, proceed with the following steps in the prioritization tool.

STEP 3.2:
Assess data quality and assign study quality rating.

For each collected study (or microplastic internalization estimates, if studies provide more than 1 estimate), assess data quality according to the following evaluation metrics and criteria (Table 4). Data quality metrics should be assessed for meeting their criteria (i.e. yes or no).

Once each study is assessed by the above data quality metrics and criteria, sum the total number of data quality metrics that met (i.e. yes) their data quality criteria in Table 4. Assign overall study quality ratings according to the following requirements (Table 5).

TABLE 4: Data quality evaluation guidelines for microplastics internalization studies (adapted from Hermsen et al. 2018).

METRIC	CRITERIA (YES OR NO)
Particles observed and measured in organisms	Particle presence measured as: (1) average number of particles per individual or gram (i.e. mass) and (2) percent of individuals with particles present
Quality Assurance vs Quality Control (i.e. QA/QC)	Estimation of particles and laboratory procedures for collection used: blanks used, contamination described, and clean work spaces used (i.e. cotton coats, hoods)
Analytical Identification Method	A representative subsample of of particles identified chemically (e.g., FTIR, Raman, Pyr-GC-MS)

TABLE 5: Study quality ratings according to combined data quality metrics and criteria.

STUDY QUALITY RATING	CRITERIA *(i.e. number of data quality metrics that met their data quality criteria, i.e. yes)***
High Quality (HQ)	3
Medium Quality (MQ)	2
Low Quality (LQ)*	0 - 1

* If neither NR or spectroscopy was used to identify particles (i.e. Analytical Identification Method), study should automatically be rated as LQ.
**We use a simple yes/no (i.e. 0 or 1) scoring scheme, instead of the 0, 1, 2 scheme reported in the literature, for user simplicity and consistency with the scoring scheme in Table 2.

STEP 3.3:

Assign microplastics internalization potential rating based on quality and number of studies (Table 6).

TABLE 6: Microplastics internalization potential rating. Study quality determined by Table 5.

MICROPLASTICS INTERNALIZATION POTENTIAL RATING	CRITERIA
High Potential	> 10 HQ or MQ studies or estimates
Medium Potential	6-10 HQ or MQ studies or estimates
Low Potential	≤ 5 HQ or MQ studies or estimates, or 5 LQ studies or estimates
Not Considered	No evidence*

*If HQ studies do not identify the polymer type of interest in taxa, consider lowering the rating.

>> STEP 4

Characterize and rank risk by relating source tonnage and microplastics internalization potential ratings.

Completion of the previous steps will produce separate ratings (i.e. High, Medium, Low, or Not Considered) for source tonnage and microplastics internalization potential. Relate these two ratings against each other to qualitatively characterize risk according to the endpoints selected in the Problem Formulation and preliminarily prioritize risks for potential State action using a qualitative tiered approach. Any risk with either tonnage or internalization potential rated as High represents risks of highest priority for State action (i.e. Tier 1). Any risk with either metric rated as Medium is of moderate priority (i.e. Tier 2), excluding those with High potential ratings. Lastly, any risk with either metric rated as either Low or Not Considered is of least priority (i.e. Tier 3), excluding those with either High or Medium potential ratings (Table 7). Risk may be elevated between tiers (e.g. Tier 2 to Tier 1) with reliable effects data. We provide details for how to determine whether characterized risks warrant State action and, ultimately, source reduction using these action priority tiers in Phase III: Risk Evaluation & Source Reduction Prioritization.

TABLE 7: Risks, based on source tonnage and microplastics internalization relation, and preliminary prioritization for State action (i.e. Tiers).

RISK *(Tonnage - Internalization, or Internalization - Tonnage)*	ACTION PRIORITY TIERS (1 - 3)
High - High	Tier 1
High - Medium	
High - Low	
High - Not Considered	
Medium - Medium	Tier 2
Medium - Low	
Medium - Not Considered	
Low - Low	Tier 3
Low - Not Considered	
Not Considered - Not Considered	

5. Example: Mollusks, Microfibers, and Textiles

About this Section:

We provide a demonstration of how to apply the risk ranking tool described in the previous Risk Characterization & Ranking phase. As an example to illustrate the method of rating the risk for one combination of polymer type, source, and taxa of interest, we assess the risk that microfibers, from textile sources, pose to mollusks (Fig. 3).

Recommendations:

1. **According to our action priority tiers (Table 7),** the risk of microfibers from textiles to mollusks is ranked as the highest possible action priority tier (i.e. Tier 1). organisms and humans.
2. **To determine whether characterized risk warrants State action,** risk of microfibers from textiles to mollusks should be compared with other combinations (e.g. road & tire wear, tires, crustaceans) to determine which risk is of relative higher priority for State action and, ultimately, source reduction activities.

>> STEP 1

Select appropriate source and polymer type associated with priority endpoints of interest.

Several case studies have documented the occurrence and presence of microfibers within a range of mollusk species (Bendell et al. 2020, Baechler et al. 2020, Li et al. 2015). Importantly, sometimes a large proportion of these microfibers occurring in the marine environment, and internalization by marine organisms, originate from textiles (Rochman et al. 2015). Therefore, the risk of microfibers from textiles to mollusks is a reasonable focus for risk characterization and ranking.

>> STEP 2

Compile evidence for and rate source tonnage potential.

We collected and reviewed 7 emission inventory and environmental loading studies, from which we obtained 11 potential estimates, where microfibers released into the marine environment were quantified. Using our data and study quality criteria metrics (Table 1 & 2), we determined the following number of source estimates aligned with the following study quality ratings (Table 8 & 9):

- 1 estimate was HQ;
- 7 estimates were MQ; and
- 3 estimates were LQ.

Of the 8 estimates that were either HQ or MQ, 4 had textiles specifically quantified as a major contributor of plastics to the marine environment at 3 locations (Table 10 & 11) and, therefore, were eligible to be included in our assessment of tonnage potential for textile sources (Sundt et al. 2014, Lassen et al. 2015, Dris et al. 2016, OSPAR 2017, Dris et al. 2018, Sutton et al. 2019). The remaining 3 MQ or HQ estimates provided supporting information to this conclusion, but did not specifically fingerprint textiles as the source of observed fibers. These studies identified household dust (which includes textile fibers), atmospheric deposition, and stormwater as major indicators or pathways of microfiber transport. Using our source tonnage potential rating criteria (Table 3), we rated textile tonnage potential as High.

>> STEP 3

Compile evidence for and rate organism microplastic internalization potential.

We collected and reviewed 11 studies, from which we obtained 12 estimates of microplastic internalization, that document microfiber occurrence and presence in mollusks. Using our data and study quality criteria metrics (Table 4 & 5), we determined the following number of estimates aligned with the following study quality ratings (Table 12):

- 3 estimates were HQ;
- 7 estimates were MQ; and
- 2 estimates were LQ.

Ten (10) of these estimates were rated either HQ or MQ and, therefore, eligible to be included in our assessment of microplastic internalization potential (Table 12). Using our microplastic internalization potential rating criteria (Table 6), we rated microfibers as having a Medium internalization potential in mollusks.

TABLE 8: Data quality evaluation for inventory studies of fibers. See Table 1 for an explanation of the evaluation categories and Table 2 for an explanation of overall quality.

ESTIMATE IDENTIFIER: STUDY	SOURCE	METHODOLOGY	OECD / CA	APPLICABILITY	TEMPORALITY (≤5 YEARS)	ACCESSIBILITY AND CLARITY	UNCERTAINTY AND VARIABILITY	OVERALL
1: SUNDT ET AL. 2014	Commercial Laundry	Y *(reviewed in Galafassi et al., 2019)*	Y / N	Y (to sea)	N	Y *(complete description of estimation and sources)*	Y *(qualitative discussion)*	**Medium Quality (5)**
2: SUNDT ET AL. 2014	Household Laundry	Y *(reviewed in Galafassi et al., 2019)*	Y / N	Y (to sea)	N	Y *(complete description of estimation and sources)*	Y *(qualitative discussion)*	**Medium Quality (5)**
3: SUNDT ET AL. 2014	Indoor dust	Y *(reviewed in Galafassi et al., 2019)*	Y / N	*N (fraction of dust in fiber fraction not quantified, but expected to be appreciable)*	N	Y *(complete description of estimation and sources)*	Y *(qualitative discussion)*	**Low Quality (4)**
4: OSPAR, 2017	Household Laundry	Y *(reviewed in Galafassi et al., 2019)*	Y / N	Y (to sea)	Y	Y *(complete description of estimation and sources)*	Y *(range presented; some qualitative discussion)*	**Medium Quality (6)**
5: OSPAR, 2017	Artificial Turf	Y *(reviewed in Galafassi et al., 2019)*	Y / N	Y (to sea)	Y	Y *(complete description of estimation and sources)*	Y *(range presented; some qualitative discussion)*	**Medium Quality (6)**
6: LASSEN ET AL., 2015	Textile	Y *(reviewed in Galafassi et al., 2019)*	Y / N	Y (to sea)	Y	Y *(complete description of estimation and sources)*	Y *(range presented; some qualitative discussion)*	**Medium Quality (6)**

TABLE 9: Data evaluation for environmental loading studies for fibers. See Table 1 for an explanation of the evaluation categories and Table 2 for an explanation of overall quality.

ESTIMATE IDENTIFIER: STUDY	PATHWAY	METHODOLOGY	QA/QC	OECD / CA	APPLICABILITY	TEMPORALITY (≤5 YEARS)	ACCESSIBILITY AND CLARITY	SAMPLE SIZE	UNCERTAINTY AND VARIABILITY	OVERALL
7: DRIS ET AL. 2016 & 2018	Atmospheric Deposition	Y (published mass balance approach based on some sampling with assumptions; fraction of fibers analyzed by FTIR)	Y (blank analysis)	Y / N	N (general estimate of aerial deposition of synthetic fibers from all sources)	Y	Y (complete description of estimation and sources)	N (2 sites)	Y (ranges presented with some discussion)	**Medium Quality (6)**
8: DRIS ET AL. 2015 & 2018	Wastewater effluent with assumed removal efficiency	Y (published mass balance approach based on some sampling with assumptions; no protocol for fiber identification)	N (limited)	Y / N	N (general estimate for wastewater treatment plants, but no particle identification)	Y	Y (complete description of estimation and sources)	N (2 WWTP effluents)	Y (ranges presented with some discussion)	**Low Quality (5)**
9: DRIS ET AL. 2015 & 2018	Combined sewer overflow	Y (published mass balance approach based on some sampling with assumptions; no protocol for fiber identification)	N (limited)	Y / N	N (general estimate for CSO, but no particle identification)	Y	Y (complete description of estimation and sources)	N (1 site)	N (limited consideration of variability and uncertainty)	**Low Quality (4)**
10: SUTTON ET AL. 2019	Stormwater from 12 tributaries representing 11% of drainage area and 6% of flow	N (mass balance approach with sample design incorporating knowledge of watershed and calibrated loading model; fraction of fibers identified by FTIR or Raman; study had external advisors, but loading estimate calibration method has not been described in peer-reviewed literature)*	Y (recovery, field and laboratory blanks, field duplicates)	Y / Y	Y (estimates provided for specific portion of watershed, with additional categorization by land use)	Y	Y (complete description of estimation and sources)	Y (12 sites according to a conceptual model)	Y (extensive analytical QA/QC with discussion of results in context of prior studies)	**Medium Quality (8)**
11: SUTTON ET AL. 2019	Wastewater from 8 facilities representing 70% of flow	Y (sample design addressed 24-hour discharge and repeat measurements; fraction of fibers identified by FTIR or Raman; study had external advisors; preceding pilot study peer-reviewed)	Y (recovery, field and laboratory blanks, field duplicates)	Y / Y	Y (based on measurements from identified facilities in summer and fall months)	Y	Y (complete description of sampling plan and methods)	Y (8 facilities representing 70% of treated flow)	Y (extensive analytical QA/QC with discussion of results in context of prior studies)	**High Quality (9)**

*Measurement methodology met data quality evaluation guidelines. However, the loading model calibration had not yet been described in detail in the peer reviewed literature at the time of preparation of this example. Thus, the overall quality for loading was scored as medium.

TABLE 10: Source importance classification for fibers based on emission inventory studies. See Table 3 for an explanation of the final source classification.

ESTIMATE IDENTIFIER: STUDY	ESTIMATE QUALITY (SEE TABLE 8)	LOCATION	GENERAL SOURCE	SPECIFIC SOURCE	DOMINANT POLYMERS NOTED *	AQUATIC OR TOTAL ENVIRONMENTAL LOAD ESTIMATE	TOTAL ESTIMATED RELEASE (TONS/YR)	NORMALIZED ESTIMATED RELEASE (G/ PERSON/ YR)	TYPICAL SIZE	RANKING AMONG SOURCES QUANTIFIED BY AUTHOR	FINAL SOURCE CLASSIFICATION
1: SUNDT ET AL. 2014	Medium Quality	Norway	Textile	Commercial laundry	Synthetic fibers	Aquatic (sea)	50	10	10 to 100 Qm lint (diameter)	(1) tire wear; **(2) paint/textile abrasion**	**Major (>1 g/person/year)**
2: SUNDT ET AL. 2014	Medium Quality	Norway	Textile	Household laundry	PA, PS, A	Aquatic (sea)	60	12	10 to 100 Qm lint (diameter)	(1) tire wear; **(2) paint/textile abrasion**	**Major (>1 g/person/year)**
3: SUNDT ET AL. 2014	Low Quality	Norway	Dust	Household dust including textile fibers	Not specified	Aquatic (sea)	45	9	10 to 100 Qm lint fraction (diameter)	1) tire wear; **(2) paint/textile abrasion**	**Major (>1 g/person/year)**
4: OSPAR 2017	Medium Quality	OPSAR Countries (Europe)	Textile	Household laundry	Synthetic fibers	Aquatic (surface water)	2,900 (Range: 460-5,400)	11 (Range 2 to 20)	12 to 14 Qm (diameter)	(1) tire wear, (2) land-based litter, (3) paints, (4) pellets, (5) cosmetics, **(6) laundry fibers**	**Major (>1 g/person/year)**
5: OSPAR 2017	Medium Quality	OPSAR Countries (Europe)	Artificial turf	Artificial turf synthetic grass fiber	Synthetic fibers	Aquatic (surface water)	Range: 2 to 32	≤0.1	Not specified	1) tire wear, (2) land-based litter, (3) paints, (4) pellets, (5) cosmetics, (6) laundry fibers, **(7) artificial turf and infill**	**Minor (<1 g/person/year)**
6: LASSEN ET AL. 2015	Medium Quality	Denmark	Textile	Household laundry	Synthetic fibers (literature suggested P > PA / PP)	Aquatic (surface water)	Range: 6 to 60	Range: 1 to 11	Not specified	1) tire wear, 2) footwear, 3) ship paint, 4) road markings, 5) paint, **6) textiles**	**Major (>1 g/person/year)**

*PA=polyamide; P = polyester; PP = polypropylene; PS=polystyrene; A=acrylic

TABLE 11: Source importance classification for fibers based on loading studies. See Table 3 for an explanation of the final source classification.

ESTIMATE IDENTIFIER: STUDY	ESTIMATE QUALITY (SEE TABLE 9)	GENERAL LOCATION	WATER-SHED	PATHWAY	POLYMERS*	AQUATIC OR TOTAL ENVIRONMENTAL LOAD ESTIMATE	TYPICAL SIZE	TOTAL ESTIMATED RELEASE (TONS/YR)	NORMALIZED ESTIMATED RELEASE (G/ PERSON/ YR)	FIBERS / KM²/YEAR	FIBERS/ PERSON/ YR	MAJOR OR MINOR SOURCE
7: DRIS ET AL. 2016 & 2018	Medium Quality	France	Seine (Paris Megacity portion)	Atmospheric Deposition	PA, PE, PU by FTIR	Total terrestrial and aquatic	25 Qm (Range: 5 to 100 Qm)	6 to 17	0.6 to 1.7	3×10^7 to 7×10^7	3500 to 7000	**Major (> 1×10^7 fiber/km²; > 1000 fibers/ person/yr)**
8: DRIS ET AL. 2015 & 2018	Low Quality	France	Seine (Paris Megacity portion)	Wastewater effluent with assumed removal efficiency	Assumed 5 to 60% synthetic	Surface water	80 Qm mesh net	0.1 to 45	0.01 to 4.5	8×10^7 to 2×10^{10}	20,000 to 5,000,000	**Major (> 1×10^7 fiber/km²; > 1000 fibers/person/yr)**
9: DRIS ET AL. 2015 & 2018	Low Quality	France	Seine (Paris Megacity portion)	Combined sewer overflow	Not assessed	Surface water	80 Qm mesh net	Not assessed	Not assessed	1.6×10^9 to 2.0×10^9	400,000 to 500,000	**Major (> 1×10^7 fiber/km²; > 1000 fibers/ person/yr)**
10: SUTTON ET AL. 2019	Medium Quality	California	San Francisco Bay	Stormwater from 12 tributaries representing 11% of drainage area and 6% of flow	A, CA, P	Surface water	125 Qm	Not assessed	Not assessed	Microparticles: 1.6×10^9 (if 67% plastic, and 39% of plastic fiber, estimate 4×10^8 fibers)	Microparticles: 2,000,000 (if 67% plastic, and 39% of plastic fiber, estimate 500000 fibers)%	**Major (> 1×10^7 fiber/km²)**
11: SUTTON ET AL. 2019	High Quality	California	San Francisco Bay	Wastewater from 8 facilities representing 70% of flow	A, CA, P, N	Wastewater	125 - 300 Qm	Not assessed	Not assessed	Not assessed	Microparticles: 9000 (if 55% fiber, and 19% to 70% of fiber confirmed plastic, estimate 1000 to 4000 fibers)^	**Major (> 1000 fibers/ person/yr)**

*A = acrylic; CA = cellulose acetate, N = Nylon, P = polyester; PA = polyamide; PE = polyethylene; PU = polyurethane

#Measurement methodology met data quality evaluation guidelines. However, the loading model calibration had not yet been described in detail in the peer reviewed literature at the time of preparation of this example. Thus, the overall quality for loading was scored as medium.

%Not calculated in report. Value shown based on reported microparticle loading of 10.9 x 1012 particles per year and population of 5,000,000 for San Francisco Bay Area counties (http://www.bayareacensus.ca.gov/counties/counties.htm), excluding San Francisco, under the region's municipal stormwater permit.

^Not calculated in report. Value shown based on reported microparticle loading of 47 x 109 particles per year and population of 5,000,000 for San Francisco Bay Area counties (http://www.bayareacensus.ca.gov/counties/counties.htm), excluding San Francisco, under the region's municipal stormwater permit.

TABLE 12: Study quality evaluation for fiber internalization in mollusks. See Table 4 for an explanation of these criteria. Studies were ranked based on 3 criteria: 1) whether fibers were present or absent in mollusks either by count or percentage, 2) whether adequate QA/QC was performed and/or reported (e.g. blanks used, contamination described, clean work space – cotton coats, hoods), and 3) whether spectroscopy was used to identify samples (Table 4).

ESTIMATE IDENTIFIER: STUDY	MOLLUSK SPECIES	SOURCE	LOCATION	AVG MP/ORG^	AVG FIBERS/ORG	QA/QC	ANALYTICAL METHOD, FTIR OR RAMAN	RATING
1: V CAUWENBERGHE & JANSSEN 2014	M. edulis	aquaculture	Europe	0.36 / gram	Not specified	Y	µ-Raman, NR*	Medium Quality
	C. gigas			0.47 / gram				
2: V CAUWENBERGHE ET AL. 2015	M. edulis	wild	Europe	0.2 / gram	Not specified	Y	µ-Raman, NR*	Medium Quality
3: LOURENÇO ET AL. 2017	C. edule	wild	Europe	Not specified	4.3 / indiv	Y	µ-FTIR, (25 fibers)	Medium Quality
	S. plana				3.3 / indiv			
	D. isocardia		Africa		1.5 / indiv	Y		
	S. senilis				1.0 / indv			
4: BAECHLER ET AL. 2019	C. gigas	aquaculture	N. America	10.95 / indiv	Over 99% microfibers	Y	µ-FTIR, (1% fibers)	Medium Quality
	S. patula	wild		8.84 / indiv				
5: MILLER ET AL. 2020	M. edulis	wild / 90d outplant	N. America	1-9 / indiv	98% microfibers	Y	µ-Raman, (16%)	High Quality
	C. fluminea							
6: DE WITTE ET AL. 2014	Mytilus spp.	aquaculture	Europe	Only fibers	2.6-5.1 / 10 per g	Y	hot needle	Low Quality
7: DOWARAH ET AL. 2020	P. viridis	wild	India	3.28/ indiv	Not specified	Y	Raman 12 particles, NR*	Medium Quality
	M. meretrix	wild	India	0.5 / indiv				
8: LI ET AL. 2015	S. subcrenata	market	China	45 / indiv	52%	Y	µm-FTIR (some?)	Medium Quality
	T. granosa			5 / indiv	80%			
	M. galloprovincialis			5 / indiv	67%			
	P. yessoensis			57 / indiv	70%			
	A. plicatula			10 / indiv	26%			
	S. constricta			15/ indiv	82%			
	R. phillippnarum			5 / indiv	64%			
	M. lusoria			9 / indiv	79%			
	C. sinensis			5 / indiv	65%			

*NR = Nile Red. At least 10% of particle spectroscopy identification or a combination of NR and spectroscopy considered sufficient. If neither NR or spectroscopy was used the study is designated LQ.

^ Many of these studies did not provide or report a lower size limit of detection for these estimates, but one can generally assume ≥ 10 microns for Raman and ≥ 50 microns for FTIR

TABLE 12 (Continued):

ESTIMATE IDENTIFIER: STUDY	MOLLUSK SPECIES	SOURCE	LOCATION	AVG MP/ORG^	AVG FIBERS/ORG	QA/QC	ANALYTICAL METHOD, FTIR OR RAMAN	RATING
9: CHO ET AL. 2019	C. gigas	market	South Korea	0.97 / indiv	24%	Y	µm-FTIR (all)	**High Quality**
	M. edulis							
	T. philippinarum							
	P. yessoensis							
10: HERMABESSIERE ET AL. 2019 AL. 2015	M. edulis	wild	France	0.76 / indiv	19%	Y	µ-Raman (no fiber id)	**Medium Quality**
11: HERMABESSIERE ET AL. 2019	C. edule	wild	France	2.46 / indiv	19%	Y	µ-Raman (no fiber id)	**Medium Quality**
12: DAVIDSON & DUDAS 2016	V. philippinarum	wild	Canada	0.9 / g	90%	Y	microscope	**Low Quality**
		aquaculture		1.7 / g				

*NR = Nile Red. At least 10% of particle spectroscopy identification or a combination of NR and spectroscopy considered sufficient. If neither NR or spectroscopy was used the study is designated LQ.

^ Many of these studies did not provide or report a lower size limit of detection for these estimates, but one can generally assume ≥ 10 microns for Raman and ≥ 50 microns for FTIR

>> STEP 4

Characterize and rank risk by relating source tonnage and microplastics internalization potential ratings.

According to our risk ranking tiers (Table 7), we determined microfiber, from textiles, risk to mollusks may be a high priority (i.e. Tier 1) for State action. To determine whether risk of microfibers from textiles to mollusks warrants State action, this risk should be compared with other combinations (e.g. road & tire wear, tires, crustaceans) to determine which risk is of relative higher priority for State action and, ultimately, source reduction activities.

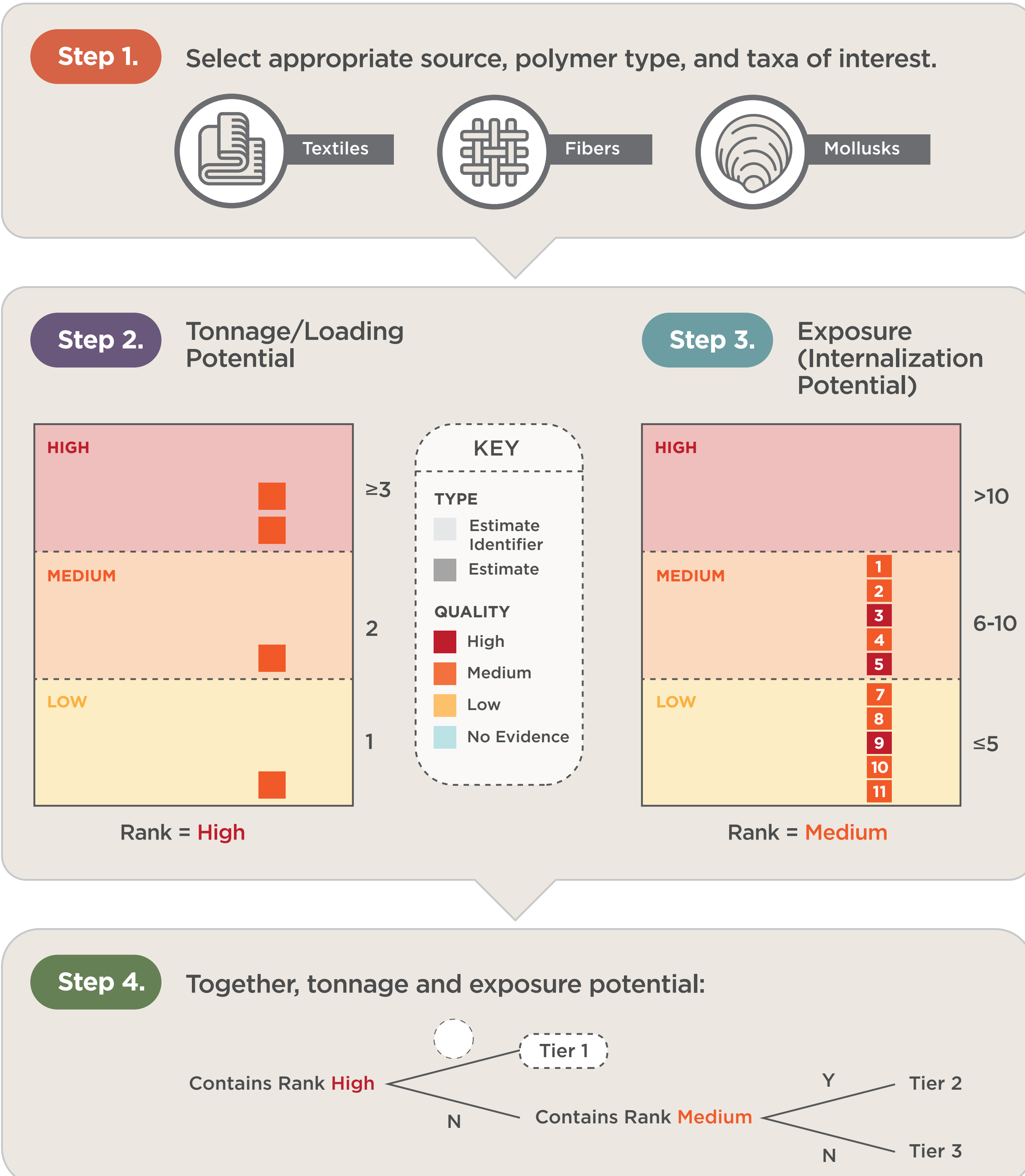


Figure 3. A visual representation of the steps to complete the Risk Characterization & Ranking phase for microfibers, textiles, and mollusks. Estimate Identifier corresponds to estimate identifiers in Tables 8 - 12.

6. Phase III: Risk Evaluation & Source Reduction Prioritization

About this Section:

We describe how to determine if the risk, characterized during the Risk Characterization & Prioritization phase, warrants State action and mitigation. We provide two different approaches based on the availability of exposure data necessary to characterize risk using our prioritization tool.

Recommendations:

1. **True source reduction** of plastic materials may be the most effective precautionary strategy to reduce and prevent microplastic pollution, given lack of feasible microplastic cleanup strategies.

The Risk Evaluation & Source Reduction Prioritization phase determines whether characterized risk warrants State action and mitigation. We recommend two different approaches for decision-makers to consider for evaluating risk, determining when management action might be required, and prioritizing source reduction activities. Here, we provide two approaches to account for potential data gaps, needed to execute the precautionary framework, as well as to account for sources decision-makers may preliminarily determine to not need a risk assessment to make effective management decisions. These approaches should be combined with other key considerations to prioritize source reduction (Box 5).

BOX 5:

Steps to complete the Risk Evaluation & Source Reduction Prioritization phase.

(1) Evaluate preliminary prioritization of source reduction using one or both approaches:

(a) Objective Risk: prioritize source reduction solutions based on a characterized risk's action priority tiers (1 -3) following the Risk Characterization & Ranking phase.

(b) Hazard Potential: prioritize source reduction solutions based on high priority and prevalent sources, fate & transport pathways, and polymer types and morphology following the Problem Formulation phase.

(2) Prioritize source reduction activities for sources, and/or associated fate & transport pathway and polymer types, without effective intervention strategies.

>> STEP 1

Evaluate risk(s) for preliminary prioritization of source reduction solutions using one or both approaches.

Objective Risk

If the required exposure data is available, we recommend completing the Risk Characterization & Ranking phase and prioritizing sources for State action based on their action priority tiers. Risks classified as High in either tonnage or microplastic internalization potential are deemed highest priority (i.e. Tier 1) for the State to address. If neither metric potential is rated High, risk may not be as pressing to mitigate, but could still be considered for reduction. Importantly, the action priority tiers do not exclude or determine when State action is not required, but rather provide a justifiable means to identify risk most in need for mitigation, beginning with Tier 1 (most in need) and ending with Tier 3 (least in need).

Hazard Potential

If the exposure data needed to complete the Risk Characterization & Ranking phase is not available, we recommend prioritizing source reduction activities on the highest priority and prevalent components of microplastics pollution in the Problem Formulation phase (Box 6). While utilizing the precautionary framework is a more objective method, focusing State action on the largest sources, and the top fate & transport pathways, particle morphology, and polymer types, will allow decision-makers to act and address risk before observed harm or adverse effects occur. This approach is more precautionary than the framework itself, and could be useful if the required data (i.e. California source inventories, particle occurrence case studies) to complete the precautionary or a quantitative risk assessment framework is not available.

BOX 6:

High priority and prevalent components of the microplastic pollution issue from the Problem Formulation phase.

Particle Morphology:

microfibers and fragments

Polymer Types:

microfibers and tire & road wear particles

Fate & Transport Pathways:

stormwater runoff (urban, agricultural), aerial deposition, and wastewater

Sources:

unknown for California, but international literature suggests tire & road wear, laundry & textiles, and plastic litter from aquaculture & fishing

>> STEP 2

Prioritize source reduction activities for sources, and/or associated fate & transport pathways and polymer types, without effective intervention strategies.

We recommend prioritizing source reduction activities on sources for which there are currently no adequate intervention strategies to reduce or prevent microplastic release into the environment. Final prioritization and selection of source reduction solutions should consider whether the associated sources, fate & transport pathways, and particles have adequate intervention strategies already in place to address risk and prevent potential harm from exposure. Intervention strategies may vary in their efficacy to mitigate microplastic pollution. For example, while some cleanup strategies (e.g. community-based beach and coastal cleanup events) help to remove macroplastic materials from the environment, they are not designed to remove microplastics, specifically, especially relatively small size ranges that are most hazardous (Ogunola et al. 2018). Other capture and collection strategies, such as those focused on preventing transport (e.g. rain gardens for stormwater, wastewater treatment plants), are relatively effective at capturing and removing microplastics (Gilbreath et al. 2019, Sun et al. 2019), but decision-makers must consider the fate of particles after capture and whether those recycled materials are potentially re-entering the marine environment (or even entering the terrestrial environment) via another source or fate & transport pathway. For example, plastic materials captured in rain gardens are sometimes recycled into agricultural biosolids and, therefore, may re-enter the environment via agricultural runoff.

Other fate & transport pathways, such as aerial deposition, do not currently have any adequate intervention strategies to prevent pollution. Importantly, however, we cannot ignore the potential for aerial deposition to contribute microplastic particles to other sources and fate & transport pathways that may currently have adequate or inadequate intervention strategies. Yet, it is difficult to determine what proportion of microplastic input to these other sources and fate & transport pathways derive from aerial deposition. Due to the complexities of the microplastic stream and uncertainties around intervention strategy efficacy, true source reduction of plastic materials, either through reducing production or curbing societal use, may be the most effective precautionary strategy to reduce and prevent microplastic pollution.

7. Precautionary Framework Knowledge Gaps & Research Recommendations

About this Section:

We identified knowledge gaps that will assist the State in moving forward with a precautionary approach to assess microplastic pollution risk.

Recommendations:

Future research endeavors should focus on the following research needs, in order of highest priority, to assess risk in a precautionary manner:

1. **An inventory of** the top sources of macro- and micro- plastic loading in California that investigates the contribution of agricultural sources relative to urban and industrial runoff, as well as wastewater.
2. **Developing a baseline,** followed by a monitoring program, for trends in environmental microplastic pollution.
3. **Methodology for** "fingerprinting" microplastics.

We recommend three (3) knowledge gaps and associated research questions as the most immediate research needs to address, with the remaining knowledge gaps discussed below.

1. An inventory of the top sources of macro- and micro- plastic loading in California that investigates the contribution of agricultural sources relative to urban and industrial runoff, as well as wastewater

Research Questions:

What are the highest emitting sources of plastic material to the marine environment in California? What is the contribution of agricultural runoff relative to urban and industrial runoff and wastewater effluent pathways?

Potential Research Description:

An inventory of plastic loading in tonnage per capita, including: (1) regional estimates of relative loading; (2) an estimation of release fractions into the marine and terrestrial environment, spatially; and (3) an estimation of the relative contribution of agriculture (including improved estimates of urban runoff and wastewater loading), inland agriculture, and agricultural biosolids relative to other major sources and pathways.

Justification:

As the highest priority knowledge gap, we recommend that the State conduct an inventory of plastic loading to California's marine and aquatic ecosystems. Establishing a baseline for loading can inform source reduction activities by the State in the near term and can be used to measure progress towards exposure reduction goals. Initially, it is envisioned that steps taken to prepare a California-specific inventory will supplement rather than replace the information available from international inventories. As the inventory becomes more refined over time, it is expected that the statewide geospatial extent of each source will be taken into account when differentiating major and minor sources.

This research will better target the precautionary framework for a California assessment by slowly removing dependency on European inventories. Given the significance of agriculture in California (CDFA 2019), understanding the relative loading from this source needs to be investigated.

2. Developing a baseline, followed by a monitoring program, for trends in environmental microplastic pollution

Research Questions:

What does monitoring reveal about trends of microplastic pollution within California's marine environment? What techniques and technologies will improve monitoring feasibility for particles of lower size classes (i.e. down to 1 micron)?

Potential Research Description:

A monitoring program that measures (1) regional and seasonal patterns of environmental concentrations of microplastics down to 1 micron in size within critical marine habitats (i.e. frontal zones, seagrass beds, benthos, etc.), (2) microplastics emitted from sources identified in the report, and (3) microplastics internalized within species representative of the prioritized endpoints. Additionally, clear monitoring goals (e.g. for intervention or risk assessment) will need to be developed, along with methods that improve monitoring feasibility and measurement of particles down to 1 micron in size.

Justification:

We recommend that the State consider developing a microplastic monitoring program to clarify source contributions, measure exposure (critical to a risk assessment), and provide a baseline for tracking future inputs and interventions. Improved understanding of concentrations in different habitats will answer how exposure varies by species and life stages, supporting the development of targeted site-specific risk assessments. While existing monitoring efforts may omit smaller particles (< 20 microns in size; ASTM method), we believe monitoring still has the potential to provide critical information for managers. This knowledge gap is linked to the development of better technologies for measuring ambient concentrations of even smaller particles down to 1 micron in size, which we currently don't have any technologies or instruments available to detect particles below this size threshold. Notably, SCCWRP has been working to standardize Raman spectroscopy sampling and detection methods for particles down to 1 micron in size, which will be a valuable addition to current monitoring efforts.

3. Methodology for "fingerprinting" microplastics

Research Questions:

How (i.e. methods, technologies, tools) do we associate and directly link microplastic particles sampled in the marine environment to sources of concern?

Potential Research Description:

Technologies and methods needed for source identification beyond just polymer types, such as (1) fingerprinting through imaging, AI, or isotopes, (2) non-targeted analysis techniques for source identification, (3) use of chemical signatures to identify if a microplastic is derived from textile or packaging, (4) high throughput ID technology, (4) translation between the units of production (tonnage) to counts in the environment.

Justification:

We recommend developing and/or investigating new methods, technologies, and tools to determine the sources of the highest concentration particles found in the environment. This understanding will be critical to inform State action and source reduction activities and is also an important link for this precautionary framework. Few efforts are attempting to do this.

Other knowledge gaps and research needs to support a precautionary approach include:

Understanding the conditions that create tire & road wear to inform mitigation

Given the large scale of California's transportation system, the number of automobiles, and expected tire & road wear particle loading into the State's marine environment, we suggest investigating the types of roads or conditions (e.g. locations of acceleration & deceleration, turning) that facilitate particle shedding. Data on how tire & road wear particles transport from generation to waterways, including aerial transport, short- and long-range transport, plastic additives to asphalt, and runoff is also lacking, but will help inform source reduction. Additionally, more methods development is needed to strengthen the connection between microparticles and tire & road wear sources.

Improving technology to characterize aerial deposition

The relative contribution of aerial deposition to micro- and nano-plastic and fiber loading into the marine and terrestrial environments is unknown. To understand the magnitude of microplastic pollution, new methods, technology, and techniques will need to be developed to measure plastics at nano scales.

Standardization of methods for detecting microplastics

While in-progress research (SCCWRP) will help standardize methods of measuring microplastics in the lab, we encourage the State to ensure that all labs have access to these new technologies or techniques. Relatedly, labs and research teams should coordinate to follow the same field sampling methods to further improve comparison of results across research efforts and studies.

Agricultural loading & human exposure

Microplastics are sometimes reused in mulch, or retained in sludge that is treated and used in agricultural biosolids, presenting the possibility for microplastics removed from the marine environment to be taken up by crops, or to run off into waterways and transported to marine habitats during storms, as has been suggested by early studies (Wang et al. 2019, Li et al. 2020, Taylor et al. 2020). Yet, more research is needed to investigate whether or to what degree wildlife and humans are exposed to microplastics via this pathway.

8. Effects Knowledge Gaps & Research Recommendations

About this Section:

We identified effects-related knowledge gaps that will assist the State in moving towards quantitative effects risk assessments.

Recommendations:

Future research endeavors should focus on the following research needs, in order of highest priority, to assess risk in a precautionary manner:

1. **Hazard analysis** of microplastics multi-dimensionality and mixtures
2. **Toxicity analysis** of present-day ambient and future concentrations of microplastics mixtures

If the State is interested in advancing the understanding of effects, specifically, we recommend the following top two prioritized knowledge gaps that, if filled, would move the field forward. First, a hazard analysis of microplastic characteristics (e.g. size, shape, density, chemical additives, and polymer type) across concentrations is needed to better understand which features pose the greatest potential hazard to marine organisms and humans. This research will form the basis of toxicant tests that will provide the concentration-response curves needed for risk assessments. Second, concentration-response effects studies of environmentally-relevant concentrations and mixtures of microplastics is a top priority. To date, most studies have focused on laboratory experiments using one type of microplastic, such as plastic spheres of a single size. It is important to understand the effects of microplastics as they are found in nature (i.e. in a mixture of fibers, fragments, tire particles, dyes, etc.), at environmentally relevant concentrations and as a mixture of microplastics with multi-dimensional complexity (Bucci et al. 2019). Addressing this knowledge gap will help us conduct a state-specific quantitative risk assessment.

Focusing limited resources on understanding microplastic exposure and reducing sources is advised from a precautionary standpoint. Yet, more research is needed to understand the full picture of how microplastics in the marine environment affect marine organisms and humans. This knowledge will be critical to advancing the microplastic field toward the development of a robust quantitative risk assessment, using both effects and exposure data (for a brief discussion summarizing microplastics effects, see Phase I, Step 3, pg 18). Additionally, obtaining reliable effects data will encourage future safer-by-design product development initiatives and help support environmental justice objectives.
As the science develops, it will be important to understand how or if organismal effects (including cumulative effects over time) translate to impacts at the ecosystem and population level, such as trophic cascades, food web impacts, biodiversity loss, or decreased ecosystem resilience. The relative vulnerability of different species, life history strategies, or life stages also needs to be better understood. The science of ecosystem-level effects may be several years away, at minimum. Although we do not yet understand how microplastics affect human health, we know humans are exposed via sea salt, seafood, and drinking water (Yang et al. 2015, Smith et al. 2018, Shen et al. 2020). It may be difficult to identify potential human health effects specifically associated with the marine environment because humans are likely exposed to microplastics through many other pathways (e.g., dust). An important knowledge gap is how human exposure to microplastics varies based on socioeconomic factors, and we highlight the likely environmental justice implications for communities disproportionately exposed to microplastic pollution.

An effort is currently underway, led by the Southern California Coastal Water Project, San Francisco Estuary Institute, and University of Toronto, to compile a database of effects within marine organisms. The results of this effort will complement this precautionary framework and support eventual effects-based risk assessments for both marine organisms and humans.

9. Looking Forward

Recommendation:

Given rapidly evolving science, we recommend **revisiting this risk assessment framework in five (5) years** to assess if effects data (e.g. SCCWRP effects research) are sufficient to suggest a state-specific quantitative effects risk assessment.

This precautionary risk assessment framework relies on available exposure data and includes multiple approaches for evaluating risk and prioritizing source reduction solutions based on scientific guidance concerning the highest priority and most prevalent components of microplastics pollution. The framework provides evidence-based guidance that will allow decision-makers to act now under uncertainty.

Knowledge gaps include those revealed by developing the precautionary framework, which should be addressed immediately to use the framework, as well as those (i.e. effects-specific) needed to advance a state-specific quantitative effects risk assessment in the future. Immediate research investments should focus on an inventory of micro- and macro- plastic loading in California, followed by developing monitoring programs and source-identification method development. This work would support the Statewide Microplastics Strategy and assist the State in understanding and addressing this emerging issue, now.

We recommend revisiting this framework in five (5) years to re-evaluate, based on new data and knowledge obtained by addressing these knowledge gaps. We recommend that if the necessary effects (e.g. SCCWRP health effects) and exposure (e.g. California inventory, ambient concentrations across particle size range) data are collected within the next five years, the State can then revisit updating the precautionary framework. Five years should provide sufficient time to implement new policies and evaluate the effectiveness of potential intervention strategies informed by this report. In the interim, there is still a substantial amount of California-specific data that needs to be collected to thoroughly understand and assess risk of microplastic pollution.

Finally, given the state of the science and uncertainties and limitations around intervention strategies (e.g. cleanup) once plastics are already in the environment, focusing future reduction efforts on preventing plastics from entering the environment may be the best solution to address risk and prevent potential harm to the marine environment.

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Appendices

APPENDIX 1:

The process (i.e. phases) for an ecological risk assessment (USEPA 1992 & 1998).

1. **Problem Formulation*:** a preliminary assessment of key factors to be considered in the risk assessment, including an examination of scientific evidence, data gaps, policy and regulatory issues, and an assessment of the feasibility, scope, and objectives of the risk assessment; production of selected endpoints, conceptual model, and analysis plan.
2. **Risk Analysis*:** an assessment of exposure, to estimate the spatial and temporal distribution and potential contact of a stressor relative to the valued environmental entity, and an assessment of effects, to estimate adverse effects elicited by the stressor; production of exposure and stressor-response profiles.
3. **Risk Characterization*:** integration of the exposure and effects assessments to determine the likelihood of adverse effects, including key assumptions, uncertainties, and strengths and weaknesses of the risk analysis.

**Each phase involves acquiring data, iterating the process, and monitoring results, as needed.*

Note: Risk managers and interested parties (e.g. stakeholders) are engaged during initial planning before the commencement of the risk assessment and during communication and management of risk at the end of the risk assessment. Yet, these steps are distinct and separate from the technical assessment of risk outlined in these three phases.

APPENDIX 2:

The process (i.e. phases) for a risk-based decision-making framework (NRC 2009).

1. **Problem Formulation & Scoping^:** problem formulation (similar to USEPA 1992 & 1998) and identification of available risk management options and technical analyses, including risk assessments, to evaluate and discriminate against each management option.
2. **Planning & Conduct of Risk Assessment*^:** determination of risk assessment tools under existing conditions and under potential risk management options, an assessment of risk (including hazard identification, exposure assessment, dose-response assessment, and risk characterization), and an evaluation of the utility of the characterized risk.
3. **Risk Characterization*:** evaluation of the proposed risk management options, including other factors relevant to decisions, and final decision among proposed management options.

**Follows and includes the same core components and phases of the traditional ecological risk paradigm, similar to those identified by USEPA 1992 & 1998.*

^Decision-makers, technical specialists, and other stakeholders are involved and consulted throughout each phase to inform the risk assessment, but not to compromise the technical assessment of the risk.

APPENDIX 3:

Full Conceptual Model.

This example conceptual model table was developed in conjunction with the endpoint prioritization process, using EPA definitions where possible. This model is intended to help visualize a complex pollution issue characterized by significant knowledge gaps across components.

STRESSORS CHARACTERISTICS	SOURCE	FATE & TRANSPORT PATHWAY	EXPOSURE PATHWAY	EFFECTS
Unique physical and chemical attributes of the stressor	*The origin of a microplastic for the purposes of an exposure assessment.**	*The course (i.e. movement and chemical alteration) a stressor takes from the source to the ecological component (i.e. entity) in the environment.*	*Point of contact/ entry of a stressor into an ecological component (i.e. entity). Contact takes place at an exposure surface over an exposure period.*	*Change in the state or dynamics of an organism, system, or (sub) population caused by the exposure to a stressor.*
+ Size (1 nm - 5 mm) + Shape (fibers, fragments, foams, spheres/pellets, films) + Polymer (PE, PET, PA, PP, PS, PVA, and PVC) + Chemical composition/ additives (e.g. plastic additives, flame retardants) + Volume + Density [a]	+ Litter (microplastics and degradation of macroplastics) + Fisheries / aquaculture gear and other maritime activities (e.g. ropes, buoys, boats) + Textiles (e.g. microfibers from clothing) + Ag. and industrial activities + Transportation (road dust/tire wear particles) + Leisure activity (gear from cruise/surfing/ swimwear) + Industrial pellet & scrap, including feedstock + Personal care, domestic products + Atmospheric deposition	+ Atmospheric deposition + Stormwater runoff, including from ag. & industrial activities + Leaching + Vertical movement (floating, sinking) + Currents + Wastewater effluent + Deposition to & resuspension from sea bed + Trophic transfer / food web + Tributary influent + Fragmentation, weathering, chemical transformation	+ Trophic transfer + Leaching (internal & external) + Dermal contact & adhesion + Ingestion (filtration) + Inhalation / respiration + Shading	+ Mortality + Decreased reproduction + Species richness/ evenness + Change in growth/ condition + Change in behavior + Occurrence / exposure time + Reduced feeding/ filtration + Altered digestion + Respiratory stress + Altered metabolism (e.g. reduced glucose uptake) + Altered immune response

*The Source category focuses on where microplastic particles originate and includes "primary microplastics" which are plastics intentionally manufactured to be small in size (e.g. nurdles, plastics in personal care products), "secondary microplastics" which come from wear and tear during the use of larger plastic products (e.g. tires, textiles), and "tertiary microplastics" which come from weathering and breakdown of larger-sized plastic pollution (e.g. litter/food packaging, cigarette butts).

[a] Density Ranges: 0.89-0.98 for PE, 0.96-1.45 for PET, 1.02-1.16 for PA, 0.83-0.92 for PP, 1.04-1.10 for PS, 1.19-1.31 for PVA, and 1.10-1.58 for PVC, <<1 for intact foams

Altogether, these aspects of microplastic pollution help to describe how microplastic exposure may lead to observed adverse effects (i.e. causality pathways). In short, microplastic particles, described by unique stressor characteristics, originate from some source before entering the marine environment. Once in the marine environment, these particles travel through the environment (i.e. fate & transport pathway) until they come into contact with or enter (i.e. exposure pathway) an environmental entity. Once these environmental entities are exposed to these particles, they elicit an observed adverse effect specific to the assessment and/or measurement endpoint being assessed.

APPENDIX 4:

Endpoints Prioritization Process for Microplastics Risk Assessment.

We developed 58 total endpoints across 12 entities, defined as taxa or trophic groups, representing key components of the California marine environment at risk from microplastic pollution. For each taxa, we identified assessment endpoints at both the organismal (n = 5) and population/community level (n = 4) (Appendix 3). We used EPA (USEPA 1992, Suter 1990) definitions with the exception of population assessment endpoints, to which cross-trophic and community-levels were added. We identified measurement endpoints specific to the entity and assessment endpoint.

Using EPA prioritization criteria, we prioritized four endpoints to narrow the scope and focus the precautionary framework for our particular case-study management goal. Per EPA guidance, rankings were applied based on professional expertise and, in some cases, our decisions were justified with evidence from the peer-review literature. Ecological relevance and susceptibility were rated “low”, “medium”, “high”, or “unknown” by us, the Working Group, while management relevance was rated by the Policy Advisory Committee, which included representatives from the California Ocean Protection Council, the Office of Environmental Health Hazard Assessment, the California State Water Resources Control Board, and CalRecycle.

We ranked Ecological Relevance considering the whole ecosystem (e.g. food web, trophic levels, species interactions), but Management Relevance considered state priorities only (i.e. < 3 nautical miles of shore). The final list of priority endpoints were selected based on a rank of “high” in both management relevance and susceptibility, as well as “medium” or “high” in ecological relevance.

APPENDIX 5:

Unique Endpoint Entities & Attributes.

ENTITY (I.E. TAXA GROUPS)	ASSESSMENT ENDPOINT (ORGANISMAL)	ASSESSMENT ENDPOINT (POPULATION, CROSS-TROPHIC, OR COMMUNITY)	MEASUREMENT ENDPOINT	ECOSYSTEM SERVICES
The valued component of the ecosystem	*An explicit expression of the environmental value and/or entity attribute or characteristic that is to be protected. Defined on the organismal level.*	*Assessment endpoint defined on levels above organismal, which may be most relevant to management & policy.*	*Measurable ecological characteristic or response that is related to the valued characteristic chosen as the assessment endpoint.*	*Goods, benefits, and services provided by assessment endpoints to the whole ecosystem, include state & federal waters*
+ macrophytes + phytoplankton + zooplankton + echinoderms + benthic mollusks + crustaceans (large) + cephalopods + finfish (lower trophic level) + finfish (upper trophic level) + marine mammals + marine turtles + seabirds	+ microplastics internalization + reproduction + growth & development + disease susceptibility + survival	+ Biomagnification (animals only) + population size + community diversity	+ Population measures (number, biomass, indices, etc.) + Reproduction measures (spore density, sprout count, egg/larvae/ offspring number/ size, sex ratio, changed behavior, etc. + Growth measures (length/ weight, body size, growth rate, etc.) + Recruitment + Disease outbreak + Mortality levels + Biodiversity (number of species) + Microplastics loading	+ CO_2 sink + Water filtration, detritus processing + Base of food web + Keystone species + Provides habitat + Forage for predators + Human consumption + Top-down control + Promotes climate resilience/ protections + Fisheries/ aquaculture stocks / revenue + Ecotourism revenue

APPENDIX 6:

An examination of the scientific evidence establishes harm from microplastic pollution and justifies our precautionary approach using the risk prioritization tool.

Exposure, ingestion, and particle internalization

Microplastic ingestion has been documented in 800 different species, across varying trophic levels and taxonomic groups (Lusher et al. 2013, Watts et al. 2014, GESAMP 2015, GESAMP 2016, Lusher et al. 2017, Gouin et al. 2019). The prevalence of microplastics is, generally, greater among invertebrate species (e.g. bivalves, shellfish), but these particles can sometimes be quickly egested, as has been observed for copepods, amphipods, bivalves, and planktivorous juvenile fish (Duis & Coors 2016, Batel et al. 2016, Ory et al. 2018). Microplastic ingestion has occurred within species across all four taxa associated with our priority endpoints (i.e. mollusks, large crustaceans, and lower and upper trophic level fish). Ingestion of microplastics has been linked to undesirable effects on other endpoints, such as mortality, reduced growth rates and reproduction, and alterations to food intake (Besseling et al. 2018), supporting prioritization of microplastic internalization in our precautionary approach.

Translocation

Translocation occurs when internalized microplastics move from one part of an organism to another (e.g. from respiratory or digestive system to a secondary tissue). Translocation has most commonly been observed for lower trophic level species (e.g. invertebrates, bivalves, and fish) in the laboratory (Browne et al. 2008, von Moos et al. 2012, Avio et al. 2015, Lu et al. 2016). While there is some evidence in the literature demonstrating translocation across organismal tissue in the environment (Collard et al. 2017, Daniel et al. 2020), more research is needed to assess the true prevalence of microplastic translocation, especially at the nano- to low micrometer size ranges that are currently difficult to measure and detect. If such mechanisms do occur, they raise concerns over potential adverse effects.

Trophic transfer

Microplastics have been observed in organisms across multiple trophic levels, suggesting that trophic transfer of microplastics from lower to upper trophic level species may be occurring. Trophic transfer has been observed in the laboratory for a number of species (Murray & Cowie 2011, Farrell & Nelson, 2013, Setälä et al. 2014, Tosetto et al. 2017). It is unclear whether or to what degree trophic transfer occurs in the environment (Burns & Boxall 2018). While trophic transfer appears to be possible, even in the environment, there is still uncertainty on the prevalence and residence time of microplastics within species given their ability to clear particles from their guts (Güven et al. 2017, Burns & Boxall 2018). Despite these knowledge gaps, observed microplastic occurrence in lower trophic level species, even in the lab, presents the possibility for particles to be transferred to higher trophic level species through the food web (Gouin 2019).

Observed effects

There have been many studies testing the effects of microplastics on organisms. Although the results are variable, there is growing evidence that microplastics negatively impact organisms, including marine organisms (Bucci et al. 2019). In laboratory studies, microplastics have been shown to cause a variety of biological effects, including: changes in gene expression (Frère et al. 2016, Liu et al. 2019), inflammation (von Moos et al. 2012, Qiao et al. 2019), disruption of feeding behaviour (Cole et al. 2015, Wang et al. 2019), decreases in growth (Au et al. 2015, Athey et al. 2020), decreases in reproductive success (Au et al. 2015, Sussarellu et al. 2016), changes in larval development (Nobre et al. 2015, Athey et al. 2020), reduced filtration and respiration rates (Frère et al. 2016, Choi et al. 2020), and decreased survival (Au et al. 2015; Cui et al. 2017, Naidoo & Glassum 2019). A recent meta-analysis demonstrates similarities across these responses in fish species (Jacob et al. 2020).