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Enhancing the science–policy interface: A conceptual framework for marine microplastic pollution

Timothy Grabiel[1], Galen L Miller[2], Amy Youngman[1], Clare Perry[1] and Hannah Hughes[1]

[1]Environmental Investigation Agency, UK and [2]Institut d'études politiques de Paris, France

Overview Review

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Corresponding author:
Timothy Grabiel;
Email: tgrabiel@gmail.com

Abstract

Microplastics have profound and wide-ranging consequences for our oceans, including impacts on marine organisms, the carbon sink function and food webs. The accumulation of marine microplastics threatens to push certain populations and systems past irreversible tipping points with potentially catastrophic effects. Scientists and policymakers must work together to understand these risks and ensure that our production and consumption of plastic, the drivers of increasing concentrations of microplastics in our oceans, stay within a safe operating zone. This article reviews current sources and trends of marine microplastic pollution, outlines the theoretical basis for tipping points, summarises the mechanisms by which potential marine microplastic tipping points are at risk and proposes a conceptual framework to address the issue with a specific emphasis on an effective science–policy interface dedicated to marine microplastic pollution.

Impact statement

This conceptual framework will inform negotiations on an international legally binding instrument on plastic pollution. It is intended to influence the final text, ensuring an effective science–policy interface forms part of the institutional architecture, one specifically designed around understanding and avoiding marine microplastic tipping points. It is also intended to align the actions of relevant actors around building out the conceptual framework, including policymakers, scientists, philanthropy and civil society.

Introduction

Human behaviour has had profound impacts on our oceans, including the mass-scale entry of anthropogenic pollutants. The most notorious class of these is plastics, which make up 80% of all marine pollution (Fava, 2022). Plastic pollution comes in a range of sizes, from very large to extremely small. Microplastics, particles smaller than five millimetres in diameter, are a category of plastic pollutants found in the sediments and waters of aquatic ecosystems across the world, including the most horizontally and vertically remote parts of the ocean.[1] The most common chemical types of these particles are polyethylene (PE) and polypropylene (PP) (Sazlı et al., 2023; Salomone et al., 2023; Kurniawan et al., 2024; Khanjani and Mohammadi, 2026).

The ongoing damage caused by plastic pollution in marine environments is impossible to overlook even under a narrowly defined anthropocentric view. Each year, communities around the world suffer up to an estimated USD $2.5 trillion in damage due to marine plastic pollution (Beaumont et al., 2019). Similarly, research increasingly shows that microplastics may have dire implications for human health (Sharma et al., 2023). The impacts of microplastic pollution also fundamentally change as particles become increasingly small, leading to calls from scientists for the creation of distinct size categories for microplastics and differential consideration in ecological risk assessments (Covernton et al., 2022).

Despite an enormous amount of research on plastic pollution in the ocean, over 4,500 publications as of 2023, understandings of potential impacts are limited and lack cohesion, especially in relation to microplastics (Landrigan et al., 2023). A lack of standardised procedures

[1]The treatment of nanoplastics, those smaller than 1 μm, as a distinct form of plastic pollution rather than a subcategory of microplastics is the subject of ongoing debate. In this article, "microplastics" is used to refer to all plastic particles smaller than 5 mm, including nanoplastics. The various sizes of particles, here treated as a microplastic spectrum instead of bluntly delineated categories, have different impacts and implications for the different systems and tipping points discussed. As such, distinctions are made as to the role of particle size for clarity when needed.

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for sampling and analysis and the intrinsic complexity in accounting such small particles means data related to marine microplastics are only rough estimates (GESAMP, 2016; Fiore et al., 2022). Moreover, microplastics not only enter the oceans in microplastic form but are generated through the degradation or fragmentation of larger plastic products when exposed to oxygen, heat or other forces, adding additional layers of difficulty to research and data collection (Fiore et al., 2022). Nevertheless, a robust understanding of how marine microplastics impact our ocean is needed, one that also serves to inform the articulation, formulation and implementation of policies to reduce marine microplastic pollution and minimise impacts.

To this end, a conceptual framework for marine microplastic pollution is proposed to guide scientists and policymakers alike, premised on avoiding potential marine microplastic tipping points and keeping humanity within a safe operating zone. It is intended to provide the foundation and scaffolding for a future science–policy interface to be built out in the coming years. Following an overview of microplastic pollution, examples of potential marine microplastic tipping points are provided based on recent scientific evidence. The mechanics of an interface for scientists and policymakers is thereafter explored, with a particular focus on its elaboration within the context of an international legally binding instrument on plastic pollution.

Sources and sinks

Two main categories of microplastic sources exist: (i) microplastics that enter into the environment in microplastic form, such as pellets used to produce plastic products or microplastics used in products, including microbeads in personal care products, industrial abrasives and some paint; and (ii) microplastics that result from the degradation of larger plastic products during use and after disposal (Chatterjee and Sharma, 2019). The relative proportions are subject to much uncertainty, but for illustrative purposes, an analysis of global releases of primary microplastics to the world oceans found the following sources and proportions by weight: pellets (0.3%), personal-care products (2%), marine coatings (3.7%), road markings (7%), city dust (24%), tires (28%) and synthetic textile fibres (35%) (Fiore et al., 2022; Nawaz et al., 2025; Pew Charitable Trust and ICF, 2025). But other sources of microplastics also exist, such as plastic-coated fertilisers used on farms and discharges from plastic recycling plants (FAO, 2021; Brown et al., 2023; Dolgormaa, 2026; Tokyo Metropolitan University, 2026). Available evidence also points to the proliferation of secondary microplastics formed from the degradation of macroplastics, although significant uncertainties exist in quantifying relative contributions (UNEP, 2016; Thompson et al., 2024; Pew Charitable Trust and ICF, 2025). Microplastics enter the marine environment in multiple ways, with an estimated 70–80% transported there by rivers (Bowmer and Kershaw, 2010; Horton et al., 2017).

Once in the ocean, microplastics are extremely mobile, moving vertically and horizontally throughout the marine environment and travelling long distances (Zhang, 2017; Cutroneo et al., 2022; Sharma et al., 2023). Due to the different compositions and densities of different fragments, they easily settle at every level of the water column (Sheela et al., 2022). In general, the abundance of smaller microplastic particles decreases with greater depth (Zhao et al., 2025). Yet the distribution of microplastics is not homogenous and tends to become less concentrated as depth increases (Zhang, 2017; Sharma et al., 2024). Microplastic fibres, for example, are more buoyant and less likely to be deposited in deep sediments but may be highly mobile across the surface of the ocean (Cutroneo et al., 2022). The development of microfilms – also called the "plastisphere" – is caused by a process known as biofouling whereby microbial films form on the surface of microplastic particles. This adds an additional layer of uncertainty by changing the buoyancy and physical properties of individual particles. The aggregation of multiple particles together or with other organic or nonorganic matter may have further effects on mobility and buoyancy (Kooi et al., 2017; Zhang, 2017; Sharma et al., 2023). The phenomenon of how and where microplastics move, converge and settle is a critical question with major implications for understanding the impacts and risks particles may pose to different ecosystems and environmental processes (Zhao et al., 2025).

Research over the past decade observed that there appears to be a significant discrepancy between the amount of plastic estimated to be entering the ocean and the actual amount of plastic debris observed floating on the surface (Galgani et al., 2022). Some models predicted an amount of surface plastic 100 times higher than observed quantities (Cózar et al., 2014; Jambeck, 2015; Geyer et al., 2017). This "missing plastics" question suggests that the true amount of plastic debris in the ocean is one to three orders of magnitude greater than the observed mass (Jambeck, 2015). With perhaps only 1% of the total amount of plastic debris believed to have entered the oceans observed floating on the surface, a great many unknowns exist related to the eventual fate and movement of the missing plastic (Oberbeckmann and Labrenz, 2020). Different estimates have been proposed for how much plastic debris ends up deposited in sediments but, in terms of overall plastic debris in the ocean, possibly up to 70% of such debris is microplastic (with the remaining 30% in larger form) (Kim et al., 2023). In this sense, the ocean serves as an important and largely uncharacterized microplastic "sink" (Hale et al., 2020; Zhao et al., 2025). Different estimates exist for how much plastic debris may be deposited in sediments, ranging from 67% of post-1950s plastic pollution stranded or buried along coastlines to 88% accumulated in ocean sediment (Bergmann et al., 2017; Lebreton et al., 2019; Martin et al., 2022). Another potential sink is ocean ice. A significant amount of microplastic particles is trapped in Arctic sediments and ice, and Arctic Sea ice far removed from the edges of ice sheets holds microplastic concentrations multiple times higher than the amounts found in highly contaminated open-water areas, such as the Pacific Gyre (Obbard et al., 2014; Kanhai et al., 2019). Some studies have suggested interactions with marine biota as another potential sink (Oliveira et al., 2012; Clark et al., 2016). In general, the lack of robust monitoring data is a major obstacle in determining the largest marine sinks for plastic debris and microplastics (Landrigan et al., 2023). In addition, the convergence zones of the five major subtropical gyres, including the Pacific Gyre, have been noted as microplastic hotspots (Cózar et al., 2014). Infamously, microplastics have also been discovered in the waters and sediments of the Mariana Trench, the deepest point in the world's oceans (Peng et al., 2018).

Trends

Since the 1950s, plastic production has increased exponentially, doubling from 2000 to 2019 (Chatterjee and Sharma, 2019; OECD, 2024). Somewhere between 8 and 10 million tonnes of plastic pollution enters the ocean each year, with 80% thought to come from land-based sources (Bisht and Negi, 2020; Sheela et al., 2022; Fava, 2022). Plankton, the ocean's most critical and abundant organisms, will soon be exceeded in number by microplastic particles (Khanjani and Mohammadi, 2026). Under current trends,

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annual plastic production will reach 736 million tonnes by 2040, a 70% increase from the 435 million tonnes produced in 2020; by 2050, roughly 12 billion tonnes of plastic waste will have accumulated in landfills or in the natural environment; and, by 2060, the amount of plastic pollution entering the environment each year will triple unless urgent action is taken (Geyer et al., 2017; OECD, 2024; Villarrubia-Gómez et al., 2024).

Few studies explore how much plastic pollution currently exists in the ocean, particularly in their smallest forms that are hardest to detect (Sheela et al., 2022). One study found that the upper North Atlantic alone contains an estimated 27 million tonnes of nanoplastics, suggesting that nanoscale particles may already constitute a significant, if not dominant, fraction of marine plastic pollution (ten Hietbrink et al., 2025). The continual fragmentation of plastic debris in the marine environment is believed to be reducing microplastics down to the smallest size class (Koelmans et al., 2015; Kokilathasan and Dittrich, 2022). These particles are extremely difficult to detect, passing through nets and sieves and evading quantification due to their size and tendency to bind to organic matter (Kokilathasan and Dittrich, 2022). These fragmentation processes may eventually lead to the almost uniform distribution of nanoplastics throughout the water column (Kooi et al., 2017).

The difficulty of correctly estimating microplastic prevalence is equally concerning in regard to the presence of microplastic particles in the organs and tissues of marine organisms. Research on the prevalence of microplastics in aquatic animals has increased substantially between 2013 and 2025 (Khanjani and Mohammadi, 2026). One study detecting microplastics in oyster populations found that extremely small particles, the size most difficult to detect and the easiest to overlook, made up the predominant share of particles inside those organisms (Ribeiro et al., 2021). As a result, the true environmental load and associated risks of micro- and nanoplastics remain critically uncertain, underscoring the need for enhanced detection methods and global monitoring frameworks.

Nevertheless, the trend of increasing concentrations of microplastics in the marine environment is clear. It is estimated that over 170 trillion plastic particles are in the world's oceans, a number that continues to grow (Zhao et al., 2025). The Atlantic Ocean has the highest concentration of microplastics, followed in order by the Arctic, Indian, Pacific and Southern Oceans (Mutuku et al., 2024). In the Eastern Tropical Pacific, for example, the abundance of marine microplastics doubled in between April 2008 and December 2018 with a 10-fold increase projected by 2100 (Bermúdez et al., 2025). Even if the entry of plastic debris into the marine environment was halted today, the abundance of microplastics is expected to increase due to the continuous degradation of plastic debris already present in the world's oceans (Thompson, 2015; Thacharodi et al., 2024).

The proliferation of marine microplastics could have dire implications for global systems, possibly triggering multiple tipping points related to marine microplastic pollution – or "marine microplastic tipping points."

Potential tipping points for marine microplastic pollution

As marine microplastic pollution increases, several potential tipping points of concern appear on the horizon, providing insights into effective policy action (OECD, 2022).

Tipping points are critical thresholds for a disruptive factor in a system that, when exceeded, lead to a significant change in the state of the system – often irreversible (Hoegh-Guldberg et al., 2022). In many contexts, environmental systems have two stable states separated by an equilibrium area that is unstable, with systems experiencing rapid and irreversible changes in response to gradually changing environmental conditions (Scheffer et al., 2001; Dakos et al., 2024). The pace of change between two stable states is often not linear, with systems undergoing catastrophic changes from one state to the other once conditions have sufficiently changed (Scheffer et al., 2001). These systems remain "tipped" even if or when the disruptive factor falls below the critical threshold again.

For example, in the climate system, as average global temperature rises, several tipping points have been identified. These include the thawing of the Boreal permafrost, dieback of the Amazon rainforest, collapse of the Atlantic Meridional Overturning Circulation, die-off of low-latitude coral reefs, loss of the Greenland and Antarctic ice sheets and melting of the Himalayan-Tibetan glaciers, among others (Klose et al., 2020; Armstrong McKay and Loriani, 2023; Milkoreit et al., 2024). These tipping points are often also positive feedback loops, accelerating the very change that caused them as they spiral out of control (as opposed to negative feedback loops that help stabilise the system). For example, permafrost covers around a quarter of the land in the Northern hemisphere, mostly in Canada, Russia and Alaska. When permanently frozen, permafrost serves as a cap – a lid – that sequesters large amounts of methane present in the ground. Methane is a greenhouse gas 86 times more potent than carbon dioxide (CO_2) over a 20-year period, and forms when organic matter decays in the absence of oxygen. When permafrost thaws, it releases methane that further warms the planet, causing more thawing of permafrost, which releases more methane – *ad finem* in a positive feedback loop.

In developing a conceptual framework for marine microplastic pollution, one that incorporates the avoidance of tipping points, several considerations are relevant. As an initial matter, the framework can be divided into three phases: (i) pre-tipping, including prevention, early warning and monitoring, knowledge development, impact anticipation and risk assessment; (ii) reorganisation, including impacts, adaptation, disaster response and impact management; and (iii) stabilisation, including adaptation to a new inhospitable stable state (Milkoreit et al., 2024). The focus on tipping points, rather than broad and highly complicated system dynamics, enables the scientific formulation of policy-relevant and actionable insights (Milkoreit et al., 2024). Moreover, tipping points, by their nature, are irreversible and uncertain. It may only become apparent that a tipping threshold has been crossed years or decades after it has been crossed, requiring policymakers both to work under pessimistic assumptions, including that tipping points will be crossed sooner rather than later, and to take precautionary action (Milkoreit et al., 2024). In other words, it is important to distinguish between the "hazard" (the potential harm caused) and "risk" (the probability of harm occurring). Although the risk or timeline of risk for any given tipping point can be uncertain, tipping points by their nature come with a hazard that should be unacceptable for reasonable policymakers at any level of risk. For these reasons, the concept of hazard is the proverbial North Star of tipping-point governance, especially when considering the profound impacts of microplastics on ocean systems (Persson et al., 2013).

Borrowing the concept of tipping points, and extending it to impacts at the species level, what follows is an illustrative list of potential tipping points that marine microplastics may cause – or contribute to – underscoring the urgency of understanding and acting on ever-increasing microplastic concentrations in our oceans. The intention is not to elaborate a definitive list, nor pre-empt scientific scrutiny into their viability as tipping points. Further scientific research

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will be required to flesh out the extent to which negative impacts and critical thresholds merit specific focus and attention.

Disruption of marine organisms

Although microplastic consumption by marine organisms is difficult to define in terms of the absolute number of individuals and species affected, the exposure of microplastics to marine organisms is evident – literally swimming in a microplastic soup (Kühn and van Franeker, 2020; Amjad et al., 2024). Studies have over decades shown that marine organisms ingest microplastics, a phenomenon occurring at every trophic level (Cole et al., 2011; Chatterjee and Sharma, 2019). The discovery of microplastic particles in the Mariana Trench, the deepest part of the world's ocean, reveals the limitless exposure of microplastic particles to organisms (Peng et al., 2018). Microplastics have been found in deep-sea benthic organisms, and evidence shows that a wide range of marine invertebrates consume microplastics (Wright et al., 2013; Courtene-Jones et al., 2017). Indeed, over 1,565 species have been proven to ingest microplastics, with some scientists estimating that 10% of marine species are directly at risk of extinction due to microplastics (Amjad et al., 2024; Villarrubia-Gómez et al., 2024). Yet there is also significant concern that the smallest microplastic particles could be systemically undercounted in studies. Most of the research on microplastic ingestion by marine organisms focuses on larger microplastics, meaning smaller microplastics, including nanoplastics, may escape detection (Ribeiro et al., 2021; Kokilathasan and Dittrich, 2022; Pitt et al., 2023). In addition, detection of fragments is usually focused on the digestive organs and gastrointestinal tract, meaning concentrations of microplastics in other tissues may be unobserved (Gouin, 2020; Pitt et al., 2023). A similar pattern may occur in samples gathered from the deep ocean with serious underreporting of smaller microplastics in deep sea water, sediments and benthic organisms (Courtene-Jones et al., 2017).

In terms of ingestion rates and impacts once ingested, there appears to be a consensus that the rate of uptake and impacts is highly variable depending on the size of the particles. Ingestion has been shown to increase as particles degrade and become smaller (Wright et al., 2013; Xu et al., 2020). However, uncertainties extend to the movement of different-sized microplastics once inside an organism, with smaller particles likely staying inside organisms for a longer time (Xu et al., 2020). Once inside the digestive track, there is also the threat of translocation, whereby microplastics move from digestive organs into other organs or body tissues (Hale et al., 2020; Covernton et al., 2022). It is not known, however, what sizes of particles are most likely to translocate (Lusher et al., 2017). Research into the bioaccumulation and biomagnification potential of microplastic particles has reached disparate conclusions (Provencher et al., 2019; Walkinshaw et al., 2020; Covernton et al., 2021; McIlwraith et al., 2021; Covernton et al., 2022; Pitt et al., 2023). With respect to nanoplastics, a recent analysis of 100+ studies found evidence of both bioaccumulation and biomagnification (Kokilathasan and Dittrich, 2022). In addition, many hydrophobic chemicals and heavy metals transmitted on the surface of microplastic particles are known to biomagnify (Landrigan et al., 2023). An extensive review further found that exposure to the constituent chemicals of plastic particles can cause severe damage to marine organisms, as can the persistent organic pollutants and heavy metals which adhere to particles (Muniz and Rahman, 2025).

A wide range of consequences exist for different marine organisms. This includes negative impacts on reproduction, growth, energy levels, the ability to feed normally and direct mortality. Impacts also include biochemical and behavioural changes (Sazlı et al., 2023; Khanjani and Mohammadi, 2026). These consequences stem from the direct impact of the microplastics themselves but also include the indirect effects of the multiple chemicals, heavy metals, pathogens and other pollutants which cling to the surface of microplastic particles, serving as a vector for toxic cocktails of organic and inorganic pollutants (Chatterjee and Sharma, 2019; Sharma et al., 2024). Moreover, particles carrying these pollutants, especially pathogens living in the plastisphere, can be picked up in the ocean and transported thousands of kilometres by wind before being deposited in remote areas, resulting in the spread of pathogens and other pollutants throughout the marine environment (Trainic et al., 2020). This can compound the risks posed by marine epidemics, which are already a threat to many species.

Available information on marine microplastic impacts on specific marine organisms is unsettling, with various risks to species and populations with knock-on implications for food webs and ecosystem functions.

- **Phytoplankton and microalgae**. Phytoplankton are single-celled primary producer microorganisms at the base of the ocean's most important systems and the foundation of marine food webs. Phytoplankton can be classified into two primary groups: photosynthetic cyanobacteria and microalgae (Falkowski, 2012). Most of the most serious threats posed by microplastic pollution in the ocean begin with their interactions with and effects on phytoplankton, which can aggregate with plastic particles and impact growth (Lagarde et al., 2016; Long et al., 2017). Although some research suggests that some algae may be able to recover from microplastic exposure in time, others studies suggest a wide range of extremely serious effects, such as toxicity decreasing phytoplankton populations, resulting in a loss of ecosystem productivity and causing a cascade of consequences for biodiversity and ecosystem services (Mao et al., 2018; Muniz and Rahman, 2025). Aggregation can have substantial effects on microalgae growth, a consequence which may become more pronounced as particle size decreases (Sjollema et al., 2016). Aggregation can also alter the buoyancy of microalgae and microplastic fragments (Lagarde et al., 2016). Moreover, nanoplastics can directly penetrate the cell membranes of phytoplankton (Kokilathasan and Dittrich, 2022). When aggregated or penetrated by microplastic particles, the effects on phytoplankton could be incredibly harmful, including reducing photosynthesis, inhibiting growth, inducing oxidative stress and decreasing density (Zhang et al., 2017; Mao et al., 2018; Prata et al., 2018; Chatterjee and Sharma, 2019; Fu et al., 2019; Shen et al., 2020; Sheela et al., 2022; Salomone et al., 2023; Li et al., 2024). Phytoplankton provide nourishment, either directly or through the food web, to practically the entire marine ecosystem (Falkowski, 2012). Indeed, it is highly likely that changes to the global phytoplankton – and by extension zooplankton – populations will have deleterious effects on the ocean carbon sink, while also contributing to other tipping points, discussed below. In addition, marine phytoplankton produces approximately 55–80% of atmospheric oxygen (Richardson, 2008; Boyce et al., 2010; McPherson et al., 2023).
- **Cetaceans**. Marine microplastics pose multifaceted threats to marine megafauna, including cetaceans, threatening long-term survival with broader ecological and conservation implications. In the case of cetaceans, marine microplastics enter their systems through three main pathways, namely direct ingestion

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during feeding, incidental intake while surfacing and trophic transfer from contaminated prey (Hernandez-Gonzalez et al., 2018; Paul et al., 2024). Marine microplastics block filtering apparatuses in baleen whales (*Mysticetes*), which feed at depths of 50–250 m, a stratum which tends to hold the highest level of microplastic concentrations, making these species particularly vulnerable. A study found that a single blue whale (*Balaenoptera musculus*) may ingest up to 10 million microplastic particles per day while filter-feeding, contributing to gastrointestinal blockages, chronic inflammation, internal injuries and reduced feeding efficiency (Kahane-Rapport et al., 2022). Toothed whales (*Odontocetes*), such as dolphins and killer whales (*Orcinus orca*), primarily accumulate microplastics through trophic transfer, reflecting contamination across the food web (Zantis et al., 2021; He and Yin, 2024). Moreover, exposure to marine microplastics and the chemicals therein, such as plasticizers, persistent organic pollutants and heavy metals, can leach into cetacean tissues (Paul et al., 2024). These compounds have been linked to immunotoxicity, endocrine disruption and reproductive impairment, increased susceptibility to disease and reduced fecundity (He and Yin, 2024). Recent studies confirm the presence of microplastics with fibres in the gastrointestinal tracts of multiple species, including franciscana dolphins (*Pontoporia blainvillei*) and Indo-Pacific humpback dolphins (*Sousa chinensis*), predominantly polyester and polypropylene, comprising the majority of detected particles (Zhu et al., 2019; Padula et al., 2025). This evidence of absorption into intestinal wall tissues suggests systemic exposure, raising concerns about long-term physiological impacts. Moreover, climate change is altering cetacean habitats globally and is likely to intensify their risk of microplastic exposure, particularly in polar regions and coastal zones that are hotspots for microplastic pollution from melting sea ice and terrestrial runoff and fishing activities, increasing ingestion (Kelly et al., 2025).

- **Keystone species.** Marine microplastics also pose multifaceted threats to primary producers, bivalves and filter feeders, categories which include many keystone species such as zooplankton, oysters and some crustaceans (Kokilathasan and Dittrich, 2022; Salomone et al., 2023; Khanjani and Mohammadi, 2026). Lower trophic animals, especially zooplankton, are more at-risk from microplastics (Covernton et al., 2022). Planktonic feeders are much more likely than other species to have microplastics in their digestive track with higher quantities relative to body mass (Covernton et al., 2021). When biofilms form around microplastic particles, it increases the likelihood of consumption (Hale et al., 2020). In addition, the pattern of microalgae aggregating with microplastics may turn microplastics into a more attractive "food source" for zooplankton and filter feeders (Lagarde et al., 2016). These patterns may be most pronounced in sea shelf regions, where the high levels of biological productivity overlap most significantly with higher levels of marine microplastic pollution due to proximity to sources of terrestrial pollution. Zooplankton, which are active and abundant in these areas, are especially threatened, making them of particular concern as a keystone species (Clark et al., 2016; Botterell et al., 2019). Zooplankton play a key role in marine ecosystem services, including in maintaining the food web (Lomartire et al., 2021). The ingestion of microplastics by zooplankton is linked with a wide range of detrimental effects, including abnormal feeding behaviour, lack of reproduction and slowed or inhibited growth, development and lifespan (Botterell et al., 2019; Chatterjee and Sharma, 2019; Shen et al., 2020; Kvale et al., 2021; Pan et al., 2022). Moreover, ingestion of marine microplastics by zooplankton reduces their ingestion of phytoplankton, seriously inhibiting the regulation of phytoplankton populations (Kvale et al., 2021). The pivotal role that zooplankton play in the transfer of energy and organic carbon from primary producers to higher order animals is therefore critically threatened (Lomartire et al., 2021). A study of microplastic exposure on copepods, an abundant and globally ubiquitous class of zooplankton, observed detrimental effects including impeded feeding, smaller eggs with reduced hatching success and reduced energy levels, culminating in starvation and death (Cole et al., 2015). The effects on feeding were pronounced even at relatively low microplastic concentrations. Given the impacts on zooplankton combined with their key role in marine ecosystems, the threats to ecological systems posed by microplastic pollution may be more pervasive and serious than previously thought (Pan et al., 2022).
- **Coral reefs.** Microplastics could compound the serious challenges already faced by coral reefs around the world. Reefs have been identified as one of the most at-risk systems to change induced by anthropogenic stressors (IPBES, 2019). Coral reef dieback is already recognised as a serious tipping point, which could have unprecedented consequences for marine food webs and ecosystems (Armstrong McKay and Loriani, 2023). Existing challenges which could be compounded by microplastics include warming-induced bleaching, acidification and deoxygenation (Pearce-Kelly et al., 2025). A microplastic-induced population crash in phytoplankton, a key food source for corals, could lead to mass starvation. Corals may also ingest microplastic particles directly, with potentially unexplored consequences. These particles could serve as a vector to transmit pathogens living in microbial film into corals (Chatterjee and Sharma, 2019). This phenomenon has been demonstrated with *E. coli* bacteria whereby the accumulation of *E. coli* on marine microplastics infected corals which had ingested the particles, leading to rapid death of the corals (Rotjan et al., 2019). Bleaching itself reduces the resilience of corals to disease, potentially allowing microplastic-bound pathogens to wreak greater havoc once introduced (Pearce-Kelly et al., 2025).

Marine organisms living in certain fragile ecosystems are also at increased risk. For example, the waters around the Galapagos Islands, a highly unique and sensitive ecosystem, are already inundated by a concentration of microplastics higher than that accumulated in the Great Pacific Garbage Patch (Lebreton et al., 2019; McMullen et al., 2024), which is the most widely recognised example of plastic accumulation in the ocean.

Loss of ocean carbon sink function

The ocean is the biggest natural sink for CO_2 on the planet, sequestering around 30% of anthropogenic CO_2 emissions (Shen et al., 2020; Croot, 2021). Already, as atmospheric CO_2 increases from human activities, the ocean absorbs less and less carbon, increasing the amounts of CO_2 that remain in the atmosphere (Sabine et al., 2004). Disruptions to the ability of the ocean to sequester CO_2 could fundamentally unsettle the global carbon cycle, triggering apocalyptic consequences for humanity (Shen et al., 2020; Nawab et al., 2026).

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Marine microplastic pollution impacts both major mechanisms of the ocean carbon sink: (i) the biological carbon pump and (ii) the sea-air gas exchange.

- **Biological carbon pump**. The biological carbon pump plays a critical role in moving carbon to deeper levels, where it is stored for long periods of time (Heinze et al., 2015; Vincent et al., 2021). The efficacy and efficiency of the biological carbon pump is the primary determinant of a carbon balance between the ocean and the atmosphere and maintains a vertical equilibrium of carbon in the water column (Sabine et al., 2004; Cavan et al., 2017). Phytoplankton is the core driver of the biological carbon pump, converting CO_2 to oxygen and particulate organic carbon via photosynthesis for the massing of carbon upon which the biological pump relies (Falkowski, 2012). Zooplankton are equally crucial, consuming phytoplankton and the sequestered carbon (Basu and Mackey, 2018). Much of marine snow, the continuous shower of mostly organic detritus falling from the upper layers of the water column, is zooplankton faecal pellets, which carry carbon to the seafloor (Shen et al., 2020). Through these processes, phytoplankton and zooplankton are key regulators of planetary carbon cycling and play a determining role in deep ocean chemistry (Falkowski, 2012). Microplastic pollution threatens the biological carbon pump on multiple fronts. Microplastics can prevent the light penetration necessary for photosynthesis in phytoplankton (Zhao et al., 2019; Shen et al., 2020; Kokilathasan and Dittrich, 2022; Hou et al., 2023; Li et al., 2024). Microplastic exposure can directly induce reductions in chlorophyll and cause cytotoxicity in phytoplankton (Zhao et al., 2019). Zooplankton consumption of microplastic pellets reduces their consumption of phytoplankton, therefore reducing the rates of carbon cycling to the deep ocean (Shen et al., 2020). Microplastic particles aggregate with marine snow and infiltrate zooplankton faecal pellets via consumption, causing them to sink at slower rates and subjecting them to fragmentation, causing less carbon to reach the deep ocean (Cole et al., 2016; Shen et al., 2020; Sheela et al., 2022; Galgani et al., 2022).
- **Sea-air gas exchange**. The sea-air gas exchange is the process by which atmospheric CO_2 dissolves into the ocean. This is facilitated by the sea-surface microlayer, a unique boundary between the atmosphere and the ocean with specific physical, chemical and biological properties, and in which organic compounds accumulate (Wurl et al., 2016; Galgani et al., 2022). Seaslicks, organic formations with biofilm-like properties, are characterised by the presence of active microbial colonies which contribute to slicks of enriched gelatinous and particulate matter (Wurl et al., 2016). Microplastic fragments accumulate at the surface of the ocean and, as particles biofoul and develop a plastisphere, the concentration of organic matter in the microlayer is increased (Garabétian, 1990; Wurl et al., 2016; Wan Mahari et al., 2026). These plastispheres around individual particles have implications for the cycling of CO_2 (and N_2O) in the water column, potentially altering fundamental biogeochemical processes (Cornejo-D'Ottone et al., 2020; Zhang et al., 2020). The plastisphere could seriously damage the sea-air gas exchange, as a result of the presence of microplastics with their corresponding biofilms increasing the production of carbohydrate-like substances and proteinaceous gel compounds on the sea surface (Cornejo-D'Ottone et al., 2020; Galgani et al., 2022). In extreme scenarios, intensified microbial respiration in the sea-air microlayer could make the ocean a net source of CO_2, completely upending the planetary carbon cycle (Garabétian, 1990; Wurl et al., 2016).

In summary, both the biological carbon pump and sea-air exchange, mechanisms that maintain the ocean carbon sink function, are extremely vulnerable to marine microplastic pollution, with potentially catastrophic impacts on atmospheric CO_2 concentrations (Falkowski, 2012; Galgani et al., 2022; Hou et al., 2023).

Ocean deoxygenation

Ocean deoxygenation via harmful algae blooms could be both a cause and effect of food web collapse. Bivalves such as mussels and oysters are a keystone species in the regulation of phytoplankton activity. Damage to bivalve populations can upset the regulatory balance and result in massive harmful algae blooms followed by deoxygenation and mass mortality among other marine species (Huang et al., 2022; Kokilathasan and Dittrich, 2022; Li et al., 2024). Microplastic consumption by zooplankton could trigger similar dynamics (Kvale et al., 2021). When zooplankton ingest microplastic particles, the subsequent decrease in feeding and vulnerability to predators could impact zooplankton populations and result in uncontrolled algae growth (Pan et al., 2022). In addition, the settling and accumulation of microplastic particles on the seafloor can reduce oxygen transfer and trigger hypoxic conditions for aquatic organisms while promoting anaerobic processes (Wang et al., 2018). Taking different mechanisms into account, one study concluded that the physical effects of marine plastic pollution could have an impact on ocean oxygenation equal to 50% of the effect of global climate warming (Kvale et al., 2021).

Food web collapse

The risk of microplastic particles being transported up marine food webs is extremely high (Sazlı et al., 2023). A recent review of over 200 studies published to date concluded that there is "convincing evidence" of trophic transfer of microplastics occurring (McIlwraith et al., 2021). Models identifying thresholds for which microplastics could lead to food web collapse in aquatic environments have already been suggested on at least two occasions (Leoni et al., 2018; Kong and Koelmans, 2019). In addition, in-situ examples of high levels of microplastic pollution threatening food web collapse in freshwater lakes in India also exist (Sruthy and Ramasamy, 2017). Another study suggested a causal link between microplastic pollution and food system tipping points, finding that microplastic consumption at intermediate trophic levels could cause cascading effects on populations both above and below the intermediate level (Qian et al., 2024). These could include abrupt and irreversible declines in marine populations, including a triggering of the "predator loop," a positive feedback mechanism where the biomass of predator species rises uncontrollably in relation to the biomass of consumer species, leading to eventual population collapse. In the ocean, these dynamics could have devastating consequences for the population health of fish species with high degrees of economic importance, such as seabass and mackerel (Khanjani and Mohammadi, 2026). There is compelling evidence to suggest that microplastics do not need to directly affect every marine species to have devastating impacts on an ecosystem (Villarrubia-Gómez et al., 2024). For example, by providing an abundant hard substrate for ocean-dwelling insect species such as *Halobates sericeus* to lay eggs, which had previously been limited in population growth due to

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the natural scarcity of such substrates, microplastics may enable the sudden proliferation of certain species beyond what was previously possible. Sudden changes in the populations of these insects, a predator of plankton, may have dire results for plankton populations (Goldstein et al., 2012). This is just a single example.

Some scientists, however, caution for more research on how microplastics may affect food webs and how impacts on individual organisms may scale up to influence ecosystem tipping points (Kühn and van Franeker, 2020; Qian et al., 2024). Multiple studies have warned against attaching undue credibility to laboratory studies due to the complexities of the natural marine environment being extremely difficult to replicate (Sjollema et al., 2016; Long et al., 2017; Nava and Leoni, 2021).

Sea ice melting

Sea ice melting, most urgently of the Greenland and West Antarctic ice sheets, is considered a highly at-risk climate tipping point (Armstrong McKay and Loriani, 2023). Sea ice is a key regulator of the global climate, with a high albedo that restricts solar radiation absorption by the Earth's surface. This process is known as ice-albedo feedback, where increased warming leads to ice melting, in turn leading to greater solar radiation absorption and more warming, contributing to yet more melting (Comiso et al., 2008). Microplastic pollution could increase this melting, hastening tipping points for sea ice. Microplastics are absorbed into sea ice in significant quantities, concentrating in the first centimetre of ice (Geilfus et al., 2019). Once microplastics are present in ice, they increase light absorption and decrease surface albedo, which makes melting more rapid and releases previously trapped particles (Geilfus et al., 2019; Evangeliou et al., 2020; Chen et al., 2021; Ming and Wang, 2021). These freed particles could be carried into and captured by other ice, causing more melting (Ming and Wang, 2021). As the climate warms, thick and permanent ice may shift to thinner seasonal or annual ice. This change will create a net release of microplastics back into the ocean, flipping the Arctic from being a microplastic sink to a microplastic source (Obbard et al., 2014). In addition to contributing to positive feedback loops in ice melting, microplastics in ice could impact ice algae and other biological processes taking place in ice or settle in Arctic melt pools with unexplored ecological consequences (Geilfus et al., 2019; Evangeliou et al., 2020). Moreover, microplastics contributing to changing albedo in the Greenland Ice Sheet could hasten melting, with increased meltwater entering the North Atlantic Ocean weakening the Atlantic Meridional Overturning Circulation and potentially causing a system collapse (Klose et al., 2020). While climate change is the primary culprit of sea ice melting, the contribution of microplastics as a contributor factor could be prove decisive for a system operating on the margins.

Towards a conceptual framework for marine microplastic pollution

Science and policy must reinforce each other through an interplay that promotes effectiveness, defined here to mean policy that is effective at achieving its objectives and science that effectively supports policymaking.

In theory, science shapes policy in multiple ways, including through research, monitoring, horizon-scanning, early warnings and technological innovation, while policy can strengthen science by defining priorities, allocating resources, facilitating data availability and fostering recognition, among other benefits (Wagner et al., 2023). Yet policymakers often struggle to integrate scientific evidence into policy, hindered by data-quality challenges, poor cross-sectoral collaboration, unavailability of non-technical information and limited capacity to analyse and interpret data (Mastrángelo et al., 2024). A well-designed science–policy interface, however, can help overcome these barriers.

The notion underpinning the conceptual framework for marine plastic pollution outlined here, one specifically designed to identify and monitor marine microplastic concentrations and tipping points, is that without such knowledge the degree of action required by policymakers to stay within – or return to – a safe operating zone will remain undefined and the measures untethered to a clearly defined objective. Therefore, a framework is needed, one built upon an effective science–policy interface to be considered with the other interests, priorities and ambitions that underpin policymaking.

Science–policy interfaces

Science–policy interfaces can take many forms. The overarching objective is to create a framework that enables science to contribute to policy formulation and vice versa (Zhang et al., 2024).

The literature on effective science–policy interfaces identify a range of institutional and operational traits, including multi-level engagement (Wagner et al., 2023), high levels of transparency (Zhang et al., 2024), collaborative structures (Koetz et al., 2012), high levels of relevance for policymakers (Koetz et al., 2012; Zhang et al., 2024), and inclusivity and transdisciplinary work (Wagner et al., 2024; Zhang et al., 2024). Science–policy interfaces also create positive trends in funding availability, open spaces for regional dialogue and grow public awareness and interest in environmental issues. Taken together, these factors have been identified as contributing to the development of "science diplomacy" whereby diplomatic action facilitates international scientific collaboration and vice versa (Mastrángelo et al., 2024).

The most well-known science–policy interfaces are the independent panels dedicated to the planetary crises, namely the: Intergovernmental Panel on Climate Change (IPCC), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Science-Policy Panel on Chemicals, Waste and Pollution (ISP-CWP). The IPCC, IPBES and ISP-CWP co-exist with dedicated scientific bodies established under the treaties on climate change, biodiversity and chemicals. The IPCC, established in 1988 by the United Nations Environmental Programme (UNEP) and the World Meteorological Organisation (WMO), conducts international scientific assessments of climate change and has become the preeminent body understanding the science of global climate change (Wagner and Hornidge, 2025). Its reports, such as the *Special Report on Global Warming of 1.5 Degrees Celsius*, are highly influential (Zhang et al., 2024). Although the IPCC does not necessarily conduct its own research, rather acting as collators and synthesisers of the best existing information, it provides the scientific foundation for climate-related policymaking and international negotiations (Wagner and Hornidge, 2025). Policymakers tend to hold a deep trust in the IPCC to deliver scientifically sound findings (Wagner and Hornidge, 2025). The IPBES, established in 2012, fulfils a similar function for biodiversity. More recently, in 2025, the ISP-CWP was established as an independent panel to strengthen the global science–policy interface on chemicals, waste and pollution and advance scientific understanding – modelled on the IPCC and IPBES (UNEP, 2022). A main advantage of an independent panel is its ability to decide on its own programme of work, producing

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thematic or timely analyses of cross-cutting relevance and addressing issues that fall outside the remit of the subsidiary body or remain overlooked (Busch et al., 2021).

Other science–policy interfaces aim for a closer relationship among scientists and policymakers. Perhaps the most impactful is the Scientific Assessment Panel (SAP) and Environmental Effects Assessment Panel (EEAP) of the Montreal Protocol on Substances That Deplete the Ozone Layer, which bring together top scientists from around the world to assess ozone layer depletion, its effects and related issues (UNEP Ozone Secretariat, n.d.-a). Every 4 years, the Parties to the Montreal Protocol determine the composition and terms of reference of the panels, which produce reports periodically for policymakers, referred to as quadrennial assessments (UNEP Ozone Secretariat, n.d.-b). In support, the Parties also convene a panel of technical and economic experts via the Technical and Economic Assessment Panel (TEAP) to assess technical and economic aspects, such as feasibility of alternatives, mitigation potential and cost implications of proposed measures. In addition, policymakers frequently request *ad hoc* reports on specific topics, in an iterative process that can span several years, to resolve concerns and create a shared understanding of the science and its implications – upon which to then base decisions. In this way, the Montreal Protocol ensures a steady drumbeat of actionable and policy-relevant scientific evidence and technical and economic information, tethered to the priorities of policymakers and decision-making (Mastrángelo et al., 2024).

Designing a science–policy interface

As a starting point, to avoid marine microplastic tipping points, scientists should develop reliable quantitative analyses and models for marine microplastic pollution, identifying scenarios and reductions to stay within a safe operating zone, regularly informed and updated by research.

Three fundamental aspects require particular attention from a scientific and policy perspective.

- **Baselines and trends**. Assessing the spatial presence and temporal trends of microplastics in the marine environment – across the ocean surface, seabed, shoreline, water column and key biota – requires a standardised monitoring framework (Fossi et al., 2018; Sheela et al., 2022). Several aspects have been identified as in need of standardisation, including methodologies for sampling marine microplastics as well as approaches for determining baseline, composition, distribution, retention and transport (GESAMP, 2015; Elawady et al., 2026).
- **Sources and inputs**. Assessing the sources and inputs of marine microplastics into the ocean – from both sea and land – requires a standardised reporting framework. Regular reporting of statistical data on plastic production, use, management and leakage should be required by policymakers, supported by the development of emission factors for different microplastic sources as well as methodologies for calculating degradation of macroplastics through processes like photo-oxidation, fragmentation and mechanical abrasion (GESAMP, 2015). In the absence of robust reporting, only best estimates based on a combination of public and proprietary data are available, providing a less accurate picture of the situation on the ground and the impacts of measures to reduce the sources and inputs.
- **Hazards, risks and thresholds**. Although hazards, risks and thresholds for marine microplastic tipping points remain uncertain, their existence should be undeniable. Scientists should urgently work to identify the hazards, risks and thresholds (concentration levels or ranges) for various marine microplastic tipping points, taking into account regional differences, regularly updating and revising as more scientific evidence becomes available, and outline scenarios for remaining within a safe operating zone.

Taken together, these aspects would enable a science–policy interface on marine microplastic pollution to achieve a clear objective: produce policy-relevant science to facilitate policymaker consideration and adoption of measures to reduce microplastics at the pace and scale required to stay within a safe operating zone, as illustrated in Figure 1:

Once this conceptual framework is mainstreamed across scientists and policymakers, questions will arise on the practical matters related to governance, decisions, responsibilities and outputs of the science–policy interface.

Policymakers and scientists must engage regularly to advance our understanding of the impacts of marine microplastic pollution and how to address it. To this end, the governing body of any new international legally binding instrument, commonly the Conference of the Parties (COP), would benefit from a scientific subsidiary body to conduct periodic assessments and *ad hoc* reports on specific topics related to marine microplastic tipping points, set out in the terms of reference adopted by it. This would enable scientists to shape policy, and for policies to be informed by science, through an iterative process based on the priorities and needs of policymakers to keep humanity within a safe operating zone, as illustrated in Figure 2:

The iterative process above, which is drawn from successful experiences in multilateral spaces, has many benefits. First, it allows policymakers to solicit scientific information needed to inform its decision-making, ensuring high levels of relevance and transparency. Second, it fosters engagement among policymakers and scientists, in open forums, constructing a shared sense of scientific fact and uncertainty upon which to act or explore, particularly important for policymakers from different backgrounds and political persuasions. Third, it provides insights into areas for further research, creating a forum in which to present and enhancing its future impact. In terms of the composition of a scientific subsidiary body, these aspects are addressed upon its establishment and would be regularly reviewed. Similarly, complementary aspects related to baselines, trends, sources, inputs, risks, thresholds, methodologies and approaches for reporting and monitoring form part of the considerations involved.

How policymakers respond to science is the domain of balancing environmental, social and economic interests, priorities and ambitions. But for microplastics overall, and for any given source of microplastics, a series of interventions are available to reduce their contribution to marine microplastic pollution. This includes measures for pellets, personal-care products, marine coatings, cleaning agents, synthetic textile fibres, tires and plastic items that tend to end up in the marine environment where they degrade into microplastics (OECD, 2024; Pew Charitable Trust, 2025). For these reasons, the conceptual framework would further benefit from technical and economic assessment to support policymakers' consideration of potential measures to take in response to the science, similar to the action-oriented model of the Montreal Protocol.

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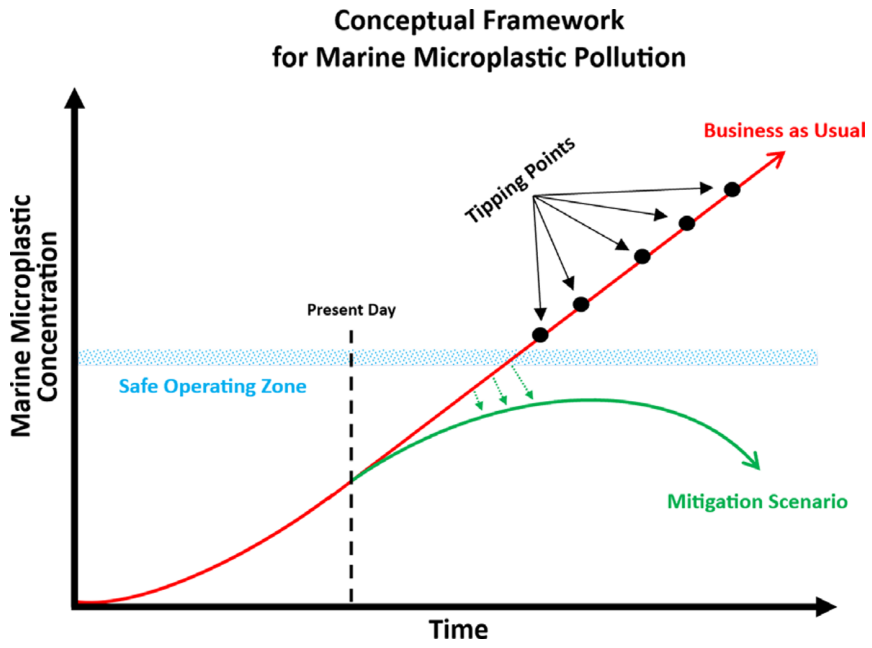


Figure 1. Visualisation of the conceptual framework for marine plastic pollution.

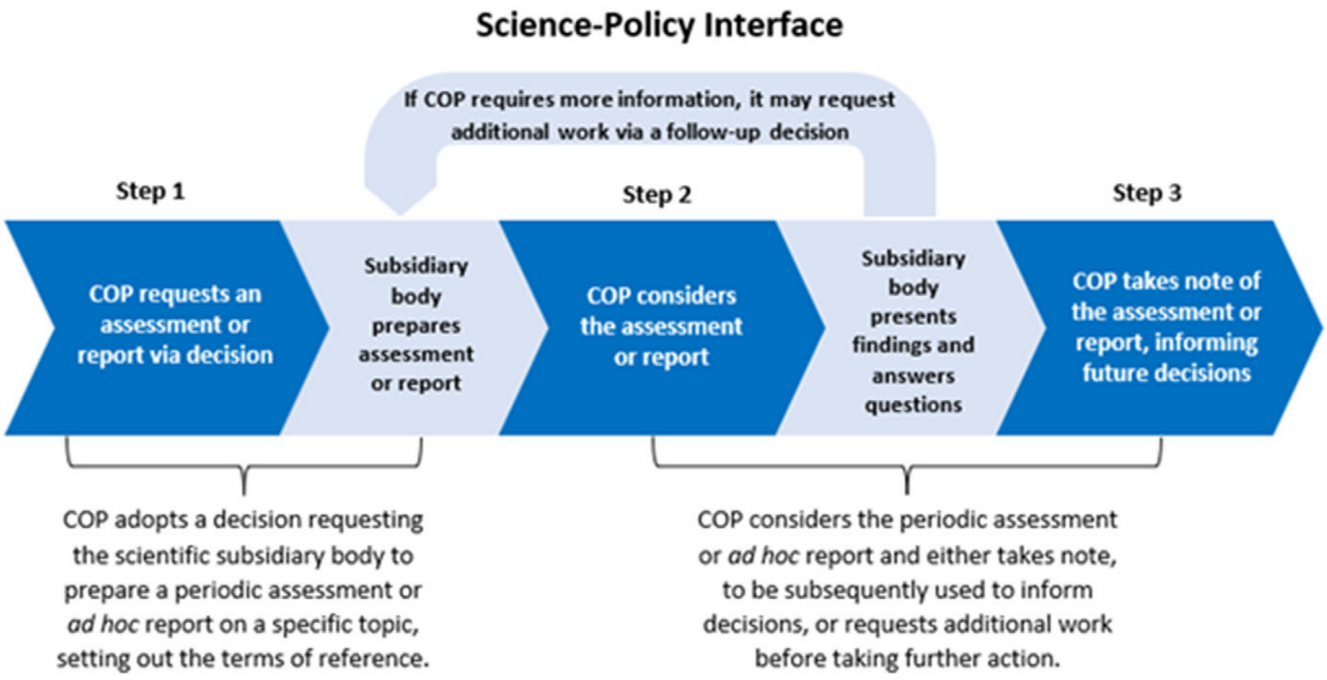


Figure 2. Approach to decision-making under the science–policy Interface.

Finally, the science–policy interface does not operate in a vacuum. It forms a part of the larger fabric of an international legally binding instrument on plastic pollution, and should be coupled with finance, capacity-building and technology transfer to countries in need to promote implementation and scale up solutions, as well as funding for further scientific and technological research and development, as appropriate. All these activities and more would be logical outgrowths of a well-designed science–policy interface for marine microplastic pollution as policymakers seek to keep us within a safe operating zone and avoid marine microplastic tipping points.

Recommendations

Marine microplastic tipping points can only be avoided through international collaboration and coordination.

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In March 2022, the United Nations Environment Assembly (UNEA) adopted resolution 5/14, titled *End Plastic Pollution: Towards an International Legally Binding Instrument*, convening an intergovernmental negotiating committee (INC) to develop the new global agreement on plastic pollution. The INC mandate calls for developing an international legally binding instrument on plastic pollution, including in the marine environment, based on a comprehensive approach that addresses the full lifecycle of plastic, and sets out a series of provisions to be developed. Among them are provisions "[t]o promote national and international cooperative measures to reduce plastic pollution in the marine environment, including existing plastic pollution," and "[t]o provide scientific and socio-economic assessments related to plastic pollution," including "the possibility of a mechanism to provide policy relevant scientific and socio-economic information and assessment related to plastic pollution" (UNEP, 2022). Shortly thereafter, the Scientists' Coalition for an Effective Plastics Treaty was formed, creating a network of independent scientific and technical experts seeking to contribute to the treaty process with summaries and interpretations of scientific knowledge to stakeholders involved in the negotiations (Scientists' Coalition for an Effective Plastics Treaty, n.d.). At the time of publication, negotiations on the international legally binding instrument on plastic pollution are ongoing.

Against this background, the following recommendations are made:

- **Scientists**: Scientists should elaborate upon the conceptual framework for marine microplastic pollution presented herein, fine-tuning and supplementing as needed, setting out an overall vision, its constituent components and an initial programme of work, among other aspects. The immediate aim should be to articulate the substrate of an effective science–policy interface within the new instrument, outlining the key elements for monitoring, reporting, subsidiary bodies, effectiveness evaluations and scientific, technical and economic assessment in order to inform policy over time. Following its entry into force, other opportunities to provide input will arise, for example the terms of reference and mandates of the subsidiary bodies and development of guidelines and methodologies for monitoring and reporting.
- **International legally binding instrument on plastic pollution**: Governments should include provisions in the new instrument that: set out standardised monitoring and reporting frameworks covering marine microplastic pollution; empower the governing body to establish subsidiary bodies to provide periodic and *ad hoc* scientific, technical and economic assessment, designed for relevance and responsiveness to the needs and priorities of policymakers, focused on avoiding marine microplastic tipping points; empower the governing body to adopt policies and measures to address microplastics, taking a comprehensive approach across their lifecycle; and provide financial and technical assistance to countries in need.
- **Intergovernmental science-policy panel on chemicals, waste and pollution**: The ISP-CWP should contribute to horizon-scanning and gap-identification, both of which fall within its mandate, for marine microplastic pollution and chemicals related thereto, playing a complementary and interstitial role (UNEP, 2022).

Although the focus here has been on developing a conceptual framework for marine microplastic pollution, underpinned by avoidance of tipping points, that is but one aspect of overall plastic pollution. Conceptual frameworks for enhancing the science-policy frameworks on other issues of concern will be needed, including chemicals and health as those relate to plastics.

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