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Monitor compartments, mitigate sectors: A framework to deconstruct the complexity of plastic pollution

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ABSTRACT

The rapid growth in science, media, policymaking, and corporate action aimed at "solving" plastic pollution has revealed an overwhelming complexity, which can lead to paralysis, inaction, or a reliance on downstream mitigations. Plastic use is diverse – varied polymers, product and packaging design, pathways to the environment, and impacts – therefore there is no silver bullet solution. Policies addressing plastic pollution as a single phenomenon respond to this complexity with greater reliance on downstream mitigations, like recycling and cleanup. Here, we present a framework of dividing plastic use in society into sectors, which can be used to disentangle the complexity of plastic pollution and direct attention to upstream design for the circular economy. Monitoring plastic pollution in environmental compartments will continue to provide feedback on mitigations, but with a sector framework, scientists, industry, and policymakers can begin to shape actions to curb the harmful impacts of plastic pollution at the source.

1. Intro

The plastic pollution problem is complex. Plastics represent a multitude of polymers, a variety of products and packaging, myriad uses in society, and many pathways to different environmental compartments. Thus, it is unrealistic that the same remediation strategies can be applied to all forms of plastic pollution. To better solve for plastic pollution, we must "divide and conquer;" thereby framing strategies in the context of each specific sector of plastic use in society. Each sector of plastic use in society should apply tailored solutions that mitigate a unique set of polymers, products and packaging, and their potential for leakage.

In this commentary, we describe how solving global contaminants are associated with a clear definition of sources and offer historical precedent. We discuss how an ocean-focused narrative has distracted the global community from a holistic overconsumption problem, and drove excessive attention to downstream mitigations; i.e., recycling and cleanup. We then identify sectors of plastic use in society, ranging from textiles to tires, agriculture to electronics, with each sector requiring research and innovation to design for a circularity and eliminate leakage to the environment and ensuing harm.

2. Historical precedent for solving global contaminants

There are several examples of global scale contaminants that were mitigated through upstream policy mechanisms. In the 1970s and 1980s, efforts to mitigate tar washing ashore on beaches, smog over cities, and the hole in the ozone layer are now seen as major environmental achievements. For each, it was essential to identify the specific industrial sector responsible. In the 1960s, offshore petroleum discharge from oil tankers after unloading cargo was common practice resulting in floating tar balls stranding on shorelines worldwide. MARPOL 73/78 made this discharge activity illegal, and in roughly a decade, beaches were significantly cleaner globally (Butler et al., 1998; Peters and Siuda, 2014; Smith and Knap, 1985). Similarly, in response to impaired human health and acid rain in the 1970s, the Clean Air Act (1963; 1970) in the United States and the International Convention on Long-Range Transboundary Air-Pollution (1979) signed by 32 countries (51 signatories today), regulated vehicle and industrial emissions (Fraenkel, 1989). The result today is a significant reduction in particulate emissions, sulfur, lead, and nitrogen oxide, and an estimated extension of human lifespan by one year (Apte et al., 2018). In the next decade, the hole in the Antarctic ozone layer was discovered in 1985 and was linked to chlorofluorocarbons (CFCs), a common chemical used in refrigerants worldwide. International agreement to sign the Montreal Protocol to

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ban CFCs and other ozone-depleting chemicals went into effect by the late 1980s. With a robust monitoring program in place, the width of the depleted ozone hole has shrunk significantly (Chipperfield et al., 2020). In each case, specificity in the chemistry and the source of the contaminant was key to upstream mitigation success.

A similarity between the actions to remediate these environmental contaminants (i.e., tar, smog, and ozone depletion), is the capacity of advocates to frame the problem as a "hot crisis" with a clear "villain and remedy" (Ungar, 2003). Conversely, climate change has been mired in its complexity and an inability to engage public concern through a lackluster sense of relevance. The subjective cost/benefit analysis of the climate change problem by the public does not demand action for the average global citizen, whereas the case for solving the hole in the ozone layer was framed with a short list of relatable crises (e.g., heat waves, melanoma in kids from UV exposure, and blindness to wildlife from UV light). An understandable and relatable problem was coupled with a zeroing in on a specific industry (refrigerant manufactures) and a specific contaminant (CFCs). Plastic pollution, when described as a single issue becomes more akin to climate change and challenging to solve. Plastic pollution would benefit by reducing its current complexity. A focus on specific sectors and contaminants can frame the problem in more relatable, simple, specific, and actionable terms.

3. Ocean plastic: a limited narrative

The plastic pollution problem has had its roots in the ocean for decades. The earliest reports of plastic pollution first documented impacts on seabirds in 1962 (Rothstein, 1973) and adrift in the oceans by the early 1970s (Carpenter and Smith, 1972). Similarly, policy efforts starting in the 1970s implemented marine approaches; the United Nations Conference on the Human Environment in 1972 stated "the capacity of the sea to assimilate wastes and render them harmless and its ability to regenerate natural resources are not unlimited" (United Nations, 1972). This followed an era of five binding international policies (pre-2000), all of which focused on restricting inputs from maritime sources (Karasik et al., 2020). The International Convention for the Prevention of Pollution from Ships (MARPOL) added Annex V in 1988 established legally binding agreements between 154 countries to end the discharge of plastic from naval, fishing, and shipping fleets (Hagen, 1990). A year later the Basel Convention provided a clear, unified vision for international governance of plastics, stating, "the most effective way of protecting human health and the environment from the dangers posed by [hazardous and other] wastes is the reduction of their generation to a minimum in terms of quantity and/or hazard potential" (UNEP, 1989). In 1991, the Plastic Industry Trade Association launched Operation Clean Sweep, a preventative intervention with a goal of zero loss of plastic pellets, powders, and flake from factories. These interventions were preceded by the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 which stated, "to prevent, reduce and control pollution of the marine environment from any source" (United Nations, 1982), and earlier by the Convention on the Prevention of Marine Plastic by Dumping of Wastes and other Matter (London Convention, 1972). International policy and maritime law interventions that were legally binding and preventative in nature may have slowed the increasing trend of plastic waste in oceans globally (Eriksen et al., 2023).

By the turn of the 21st-century, the mythology of "islands of floating plastic" sealed public interest in the plastic pollution issue. This ocean-focus began with early science reporting and media-sensationalism of garbage patches. Public pressure on policymakers and subjective stakeholder interests furthered an ocean-centric narrative, diverting attention to recovery and recycling rather than prevention. The global ocean became the representative compartment of all types of plastic pollution, which spurred an abundance of innovative technologies, such as giant plastic-catching nets, robots skimming surface water, and plastic-eating bacteria. However, current debate now treats this narrative and many of these downstream proposals as distractions from contemporary upstream strategies. Recovery technologies, such as large oceanic capture devices deployed to the ocean gyres do very little to address single-use plastics, textiles, or tires, and instead mostly recover fishing gear (Lebreton et al., 2022). If solutions remain trapped in the environmental compartments in which the plastic pollution resides, rather than upstream at the industry or activity that is the source of waste, we will continue to neglect mitigations that stop leakage.

Plastic pollution has also grown in complexity. In the last decade, the science has matured; research is asking targeted questions about specific industry emissions, environmental pathways and fate of varied polymer types, and toxicity in specific compartments. Progress moves at different speeds, and typically solutions lag behind scientific research. Nonetheless, this history in the oceans, illustrated by the degree to which research, policy, and technological innovation focused on oceans, is indicative of the reliance today on downstream efforts. This action-reaction, jumping to cleanup, should give scientists and policymakers pause before pursuing future rounds of interventions that focus on downstream rather than upstream solutions. We propose a re-framing around sectors to reduce complexity to facilitate targeted mitigation strategies.

4. Solutions are moving upstream

In recent years, a greater understanding of the sources, pathways, and impacts of plastic in marine and terrestrial environments have prompted calls to reframe the "marine litter" issue as a "plastic pollution" problem, addressing pollution more holistically from source to sink (Carlini and Kleine, 2018; Rochman, 2018). Interventions closer to the source are a way to optimize capture and reduce costs. For instance, the understanding that rivers are a significant transfer route for plastics to the marine environment Lebreton et al. (2017) has prompted organizations such as *The Ocean Cleanup* and *4 Ocean* to expand their focus from collecting plastic in the open ocean and develop technologies to prevent plastics from reaching the ocean using passive river catchment nets (The Ocean Cleanup, 2023) or active aquatic vessels that net debris (4Ocean, 2023), although devices such as these, including river booms, barriers, and nets have been deployed in rivers in many countries since the early 1990s (Schmaltz et al., 2020). A recent study modeling total floating plastic debris in the world's oceans over time estimated that the global implementation of river barrier devices by 2020 (an unrealistic, best-case scenario) would result in a significant reduction (~46 %) of floating plastic in the OSL by the year 2052 (Hohn et al., 2020). Awareness of the importance of waterways (e.g., urban runoff, rivers, stormwater drains) as a significant transport mechanism of plastic into the ocean from land prompted California, USA to adopt a statewide, measured and enforced, TMDL (total maximum daily load) for anthropogenic litter in waterways (Martindale et al., 2020). While an understanding of the true cost of plastic pollution globally are incomplete, best estimates of environmental and social damages are over $US 2.2 trillion per year (Beaumont et al., 2019; Forrest et al., 2019; Ricke et al., 2018; Zheng and Suh, 2019). Capturing plastic from waterways in low-income nations with poor waste management may be relatively more impactful. For example, plastic debris damming waterways along coastlines and estuaries have been linked to destructive flooding in cities like Mumbai and Nairobi (Njeru, 2006; Scheinberg et al., 2010).

The cost/benefit of moving mitigation to the source has economic, social, and environmental benefits. The cost of recovery of plastic pollution, from waste management to cleanup, exceeds the cost of preventative mitigations (Fig. 1). Collecting plastic from the environment undoubtedly provides benefits to society. However, waste management challenges, both practical and economic, remain. Regardless of where plastics are removed in the environment, it is unlikely these items will be recycled due to their high chemical diversity, contamination by persistent organic compounds, and the economic cost of recovery and transportation (Bergmann et al., 2015).

In most cases, the options for collected plastics are incineration or

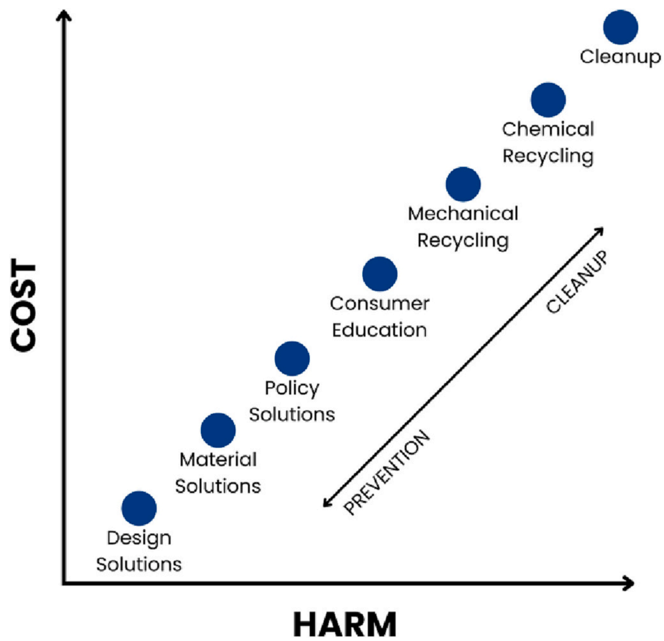

Fig. 1. The range of solutions to plastic pollution each carry different financial costs and impact measured by reduction in demonstrated harm.

permanent burial, both of which have significant economic and environmental impacts and are unsustainable long-term solutions. For instance, improperly buried plastics in older or improperly designed landfills may release toxicants into soil and groundwater (Hahladakis et al., 2018; Knight, 1983), and incineration of plastic collected from all the world's rivers would result in approximately 1.3 gigatons of cumulative CO_2 emissions by 2050 (Hohn et al., 2020). Incineration can also release toxicants such as dioxins and small hazardous particles into the air (Verma et al., 2016). Human health and environmental externalities associated with collecting plastic from the environment demonstrate the need for a more comprehensive strategy to address plastic pollution. Furthermore, capturing plastic in waterways using nets and other barriers (capable of capturing ~97 % or more of plastic >5 mm) may be a highly effective strategy for reducing inputs to marine environments in high-income nations with sophisticated waste management infrastructure, and can also inform sources of debris across different environmental compartments (Schmaltz et al., 2020). However, global implementation of such technologies will face significant financial barriers, as low and low-middle income countries are often burdened with the greatest amounts of mismanaged waste. Environmental compartments may continue to receive cleanup efforts, but this will likely remain a minor contribution to a more comprehensive mitigation strategy focused on cost-effective preventative solutions.

5. Monitor compartments, mitigate sectors

5.1. Monitor compartments

The abundance of plastic pollution in varied environmental compartments often represents inputs from one or more sectors. The ocean compartment is dominated by fishing gear and single-use plastics (Lebreton et al., 2022), whereas terrestrial compartments often reveal abundant smoking materials, single-use plastics, and illegal dumping. Each compartment offers a different opportunity to link the plastic pollution, including its type, abundance, and distribution, to a specific sector and mitigation strategy, with continued monitoring to measure effectiveness. For example, a study of microplastics in surface waters of the Laurentian Great Lakes revealed abundant plastic microbeads from cosmetics (Eriksen et al., 2013). This downstream monitoring effort elicited an upstream mitigation strategy, resulting in a U.S. federal bill, the 2015 Microbead-Free Waters Act. The policy solution elicited design and material innovation in the hygiene and cosmetics industries, prompting stakeholders to remove microplastics from products and find benign alternatives. In this case, the cost/benefit of a preventative strategy in a specific sector far outweighed the costs and practicality of cleanup or recycling.

For other types of plastic pollution, the environmental compartment to monitor emissions may differ. Single-use plastics from food ware and packaging may have inputs from maritime activities, but typically enter from riverine or coastline compartments and are transported via rivers. Due to the likelihood of these items to settle into sediment or wash ashore on coastlines, sediment and coastlines are likely better candidates for monitoring single-use plastics compared to the open ocean. Stormwater in cities often reveal high abundances of tire-wear particles (Cho et al., 2023; Zhu et al., 2021), which likely sink in aquatic environments near their inputs because of their density. Microfibers have been recorded in diverse environments around the world (Athey and Erdle, 2021), but monitoring environmental compartments such as air (e.g., indoor air, outdoor air) and water (e.g., wastewater) would resolve the relative contributions of different sources. Due to the varied polymers with different physical characteristics, inputs, and transport mechanisms, it is paramount to understand which environmental compartment is most suitable for different plastics with various uses in society to understand environmental leakage, and suitable interventions to limit their release.

5.2. Mitigate sectors

A shift from where the plastic pollution resides (i.e., environmental compartment) to the activities that generate it (i.e., sector) could help construct a framework for the adoption of sector-specific preventative solutions. This will also avoid bias favoring downstream mitigations when attempting to solve the problem at the level of the compartment, whereby a mixture of products, packaging, polymers and chemical additives make upstream mitigations seem too complex to unravel. Several researchers have argued that the plastic pollution issue is complex (Courtene-Jones et al., 2022; Wagner, 2022), however policymakers and innovators require tools to help disentangle this complexity and find appropriate interventions. Researchers have recently proposed emissions inventories of plastic pollution to identify relative amounts of plastic from a diverse set of sources (Zhu and Rochman, 2022). With these inventories, specific sectors can be identified and support a comprehensive and cost effective mitigation strategy.

Consider that plastics are a "diverse contaminant suite" (Rochman et al., 2019), representing many polymers used in diverse sectors of society. Sectors of plastic use in society have different polymers, chemical additives, inputs to the environment, pathways within and between environmental compartments, and effects (e.g., ecological, social, and economic). There are many diverse sectors of plastic use in society, which can be used to determine leakage to the environment, but are also important when analyzing overall production, use, and end-of-life scenarios. These sectors of plastic use in society could contain unique sectors such as 1) textiles, 2) tires, 3) hospital and medical, 4) fishing gear, 5) home décor and furnishings, 6) shipping and transportation, 7) hygiene and cosmetics, 8) toys, sports, and recreation, 9) construction, 10) smoking materials, 11) events, travel, and hospitality, 12) agriculture, 13) food service and packaging, 14) electronics, 15) primary microplastics, 16) durable goods, and 17) appliances and machinery (Fig. 2). With a sector-based approach, intervention points can be identified across the plastic lifecycle. Solutions to capture emissions can be more cost effective (e.g., washing machine filters, rain gardens), but these should be paired with other interventions across a the lifecycle of items within each sector to evaluate patterns of consumption, such as overall plastic production within that sector, the amount of plastic in use, the average lifespan of those products, and end-of-life (e.g., rates of

Fig. 2. Plastic use in society is diverse. Here, we show 17 proposed sectors of plastic use in society. Each sector will have tailored solutions.

recycling, landfill, incineration, composting, environmental leakage).

Some sectors have received considerable focus already – food service and packaging have coalitions around the world devoted to bans, material redesign, and improved waste management within that sector. However, solutions for single-use plastics will be very different from approaches to solve for emissions in textiles, electronics, or durable goods. Further, the discussions and the experts involved will vary. For example, experts on microfibers may be ill-equipped to advocate for solutions on tire wear particles. Although both microfibers and tire wear particles may be found together in certain environmental compartments (e.g., stormwater) (Zhu et al., 2021), there are vast differences in use (textile vs. car tire), polymer, particle shape and size, additive mixture, pathways in the environment, and effects to biota. Thus, how society addresses tire crumb and rubber recycling, is a very different conversation than mitigating microfibers and waste from textiles.

The volume of research – either directly or indirectly involved in each sector – is rapidly expanding, and the need to create sub-disciplines is growing. New journals have already emerged to handle the exponential growth in research on plastic pollution (e.g., Microplastics and Nanoplastics), but there may be a need for additional journals, targeted conferences, and working groups on specific sectors. Like other evolving disciplines, increased study results (in bifurcating research paths), and the development of sub-disciplines come with emerging specialists. Even though some specialization has occurred naturally, the plastic pollution movement could help facilitate targeted discussions among scientists, industry, and policymakers to provide reinforcement to find interventions within each sector. The number of sectors may differ depending on how policymakers, innovators, and researchers see fit. There may be a need to further lump or split our proposed sectors, but sectors need to be well defined enough to draw in various experts and have solutions unique to the other sectors.

Promoting strategies that overemphasize downstream measures to solving the plastic pollution issue consequentially divert resources away from more upstream-focused preventative strategies of reduction and reuse in each sector. Global implementation of downstream intervention techniques, including increasing collection capacity, reducing post-collection leakage, increasing landfill capacity and incineration, and reducing exports of plastic from low-leakage to high-leakage countries, are estimated to only reduce terrestrial and aquatic plastic pollution input rates by 57 % (Lau et al., 2020). Instead, a comprehensive, system change approach implementing all interventions – changing consumption patterns, reduction and substitution at the source, reuse, recycling, and waste management – could drop plastic pollution inputs into the environment down to pre-2016 levels by 2040 (Lau et al., 2020). Borrelle et al. (2020) identified the need for an ambitious strategy focused on key policies that eliminate the use of unnecessary plastics; setting global limits for virgin plastic production; create globally aligned standards of design for recovery and recycling; and developing and scaling waste management and recycling. Furthermore, a comprehensive system change approach would incur less costs than any other strategy, including taking no interventions (18 % lower) (Lau et al., 2020). The conversation about solutions has moved upstream in favor of more target mitigations to stop emissions in specific sectors.

6. Conclusion

For several decades, plastic pollution research, policy, and technologies have remained trapped in the oceans. With this emphasis on the ocean compartment, the narrative about solutions has attempted to apply broad solutions to a complex mixture of pollutants from multiple sectors, which creates bias in favor of downstream mitigations. Our concern is not only that innovative recovery technologies exaggerate the promises of their proposed solutions, but also with the ways in which years on focusing research on environmental compartments may have distracted policymakers from advancing upstream interventions. Calls for international dialogue, including the Global UN Treaty, largely include preventative strategies addressing product and packaging design, material innovations, producer responsibility, reuse business models, and improve waste management systems. We suggest continuing to monitor environmental compartments, but mitigate by sector of plastic use in society.

CRediT authorship contribution statement

Lisa M. Erdle: Conceptualization, Writing- Original draft preparation, Writing - Review & Editing, Visualization.

Marcus Eriksen: Conceptualization, Writing- Original draft preparation, Writing - Review & Editing, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marcus Eriksen reports financial support was provided by The 5 Gyres Institute. Lisa Erdle reports financial support was provided by The 5 Gyres Institute. Marcus Eriksen, Lisa Erdle reports a relationship with The 5 Gyres Institute that includes: employment and travel reimbursement.

Data availability

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