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Oceans of plastic: A research agenda to propel policy development

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ABSTRACT

Although the phenomenon of marine plastic debris is now widely recognized as a problem for the international community, significant gaps in understanding still inhibit the creation and implementation of effective policy responses. This paper reviews the state of scientific knowledge about the causes and consequences of marine plastic debris, including its sources, pathways, composition, location, and impacts on ecosystems and human activities. Much remains unknown about the large scale impacts of plastic debris on ecosystem functions and human health, among other information gaps. Additional scientific research about the nature, extent, and harms of marine plastic debris could increase the political salience of the problem, and produce urgent and focused attention on the formulation of solutions. Although many policy responses have been proposed, and even pursued, additional research could assist in the prioritization of the most cost-effective strategies. The research agenda outlined would support a more detailed and comprehensive assessment of the nature of the problem of marine plastic debris, and inform the creation and implementation of effective solutions.

1. Introduction

Large amounts of plastic debris have been entering the ocean for many decades, yet only recently has this phenomenon been recognized as a major problem by the international community. Part of the explanation for this delayed realization relates to the distance, and relative invisibility, of marine plastic sinks in the center of ocean basins or on the sea floor. In the 1970s and 1980s, it was assumed that any land-based pollution would be obvious to the coastal state, which would bear the brunt of negative impacts and therefore have a strong incentive to mitigate pollution inputs, without need for international coordination [1]. The discovery of large concentrations of plastic in the North Pacific in the late 1990s was therefore a jarring experience. Through the efforts of individual advocates, the activities of non-governmental organizations, and increased media attention, a much larger audience now harbors concerns about the amount of plastic in the ocean [2].

Despite a significant increase in scientific research on marine plastic debris since the turn of the century, we still lack important information about the sources, pathways, composition, and impacts of marine plastic debris [3]. Uncertainty about causes and consequences decreases the likelihood that effective solutions will be formulated and implemented. More research can clarify the impacts of marine plastic debris, which ensures that the issue remains politically salient [4]. Consolidation of evidence about harms also supports the strengthening and diffusion of environmental norms against plastic litter [5]. Scientific evidence makes possible a full cost-benefit assessment that compares inaction to various regulatory options, which is critical to justify the sacrifices necessary to solve the problem [6]. And knowledge about the precise causes of harm, including the sources and pathways of plastics in the marine environment, informs the creation of targeted and maximally effective interventions.

This article surveys what is known about marine plastic debris, in order to identify areas of uncertainty that inhibit the formation of a clear, coherent, and consensus-based understanding of the problem. The first section considers the sources, pathways, locations, and composition of plastic debris sinks in the ocean. The second section addresses the reasons marine plastic debris is understood to be a pollution problem, and identifies the research still needed to establish the full scope of negative consequences for marine ecosystems and human uses of the ocean. The third section focuses on research which would be useful in the creation and implementation of particular solution sets. The overall goal is to outline an agenda for future research on marine plastic debris.

2. Marine plastic sinks

Marine plastic debris is a quintessential externality in that it is largely hidden from sight, harmful in a diffuse and difficult-to-quantify way, and exists primarily beyond the jurisdiction of any single nation-state. Understanding the problem requires information about where plastic debris comes from, where it ends up, and how it gets there. This section summarizes what is known about the sources, movements,

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locations, quantities, and composition of marine plastic debris in aggregate terms, and identifies areas of uncertainty that require additional research.

2.1. Sources and pathways

Marine plastic debris is an externality of the on-going "plastic binge" that has become a pervasive feature of modern industrial civilization. Plastic is widely used in a variety of products, and at least half of all plastics are disposed after single use [7,8]. An inherent characteristic of plastic – its durability – explains both its appeal as a product and the challenge it presents for waste management. Because plastics take a very long time to naturally degrade, almost all the plastic ever created still exists. Of the plastic produced over the last century, only 9% has been recycled, with 12% incinerated and 79% deposited in landfills or the natural environment [9]. There are no rigorous estimates of the origins and totals for marine plastic debris as a proportion of all plastic waste [3]. But it is estimated that 10% of the plastic produced every year ends up in the oceans [10].

Researchers initially assumed that the majority of plastic waste found in the open ocean, and on the beaches of remote and uninhabited islands, came from ship dumping on the high seas [11]. By the late 1990s it became clear that poor management of waste on land was a significant source of marine plastic debris, which was dispersed across extremely long distances by winds and ocean currents [11].

Plastic debris enters the ocean through a variety of pathways, including coastal recreation, wastewater outflows, wind and rivers, accidental spills, leaching from landfills, discarded or lost fishing gear, and storm surges during extreme weather events. Pathways vary depending on an item's size and composition. The smallest pieces – nano and micro plastics – often come from cosmetics, cleaning, medicine, and personal hygiene products, and enter the marine environment through waste water outflows [7]. The water used to launder clothing made from synthetic fabrics is a significant source of microplastic fibers; a single garment may lose around 2000 plastic fibers per wash [12]. Nano-plastics used for agricultural or industrial uses, such as small-scale manufacturing using 3D printers, are often windblown into the marine environment [13]. Although land-based outflows contribute the majority of marine plastic debris, ocean-based sources are still significant. It is estimated that half of ocean-based plastic debris comes from commercial fishing boats, although the primary source of data on discarded or lost fishing gear comes from the fishers themselves [7,14].

It is widely cited that eighty percent of marine plastic debris comes from land, and twenty percent from ships. This estimate is not supported by robust data, however. There are "no direct estimates of plastic input to the ocean," and no reliable global estimates of ship based pollution, discarded fishing gear, or the debris that enters the marine environment as a result of natural disasters [14]. Rivers are likely a large source of land-based plastic pollution, but there is no data to support estimates of how much debris becomes immobilized in the sediment or on the banks of rivers, and how much gets carried out to sea [15].

In terms of land-based sources of debris, policymakers are often interested in how much comes from which countries. The quantity of plastic debris that enters the ocean depends largely on population size and the quality of waste management [3]. Although many countries contribute to marine plastic debris, many of the worst offenders are Asian coastal developing states [7,16]. Several African states are also top contributors. The United States is responsible for a significant proportion of marine plastic debris, largely because of high per capita consumption and disposal of plastic products [17]. The most commonly cited list of top contributor states comes from a single study, which combines available data on total waste with a model that predicts waste mismanagement. The study focuses on waste from within 50 km of the coast, and may therefore underestimate the load carried by rivers from inland sources. The authors acknowledge that the estimates suffer from uncertainty related to limited data on waste generation, composition, collection, and disposal outside urban areas, and do not account for illegal dumping or the import and export of waste internationally [3]. Lack of data, and variation in methodologies for sampling, makes it very difficult to produce an accurate estimate of total quantities, and top contributors, of marine plastic debris [18].

Plastic debris has been found in every major ocean, but how plastic arrives at various ocean sites remains unclear; there is "deep ignorance and high uncertainty" about the exact pathways for plastic in the marine environment [19]. There is limited knowledge of how floating debris moves, and at what speeds, as a result of wind and currents. Experimental studies are needed to determine the precise trajectories and routes of marine debris [20].

2.2. Composition and distribution

Plastic fragments are generally identified by size – macro-plastics, micro-plastics, and nano-plastics – but authors disagree about the distinctions between these categories. Microplastics are alternatively described as less than 5 mm or less than 1 mm, and nanoplastics as less than 200 nm or less than 100 nm. Some researchers use additional categories such as 'mesoplastics' and 'megaplastics,' which creates inconsistency in the use of the term 'macroplastics' (usually greater than 5 mm or greater than 25 mm). Some items enter the ocean very small, such as plastic microbeads or synthetic fibers. But larger plastics also degrade into micro- and nano-sized pieces, as a result of UV radiation, mechanical abrasion, 'biofouling' such as microbial colonization, and other processes [21]. Little is known about how quickly different types of plastics break down in different marine settings [14]. It is unclear whether primary or secondary microplastics predominate, although limited samples suggest that most marine microplastics are the result of degradation in the marine setting [22].

Scientific research about micro and nanoplastics is "still in its infancy" [2]. Because of the challenges of sampling, scientists do not have a clear idea of the amount, density, or distribution of microplastics in the ocean environment [23,24]. It is very difficult to reliably separate microplastics from organic debris in field settings. Nanoplastics are the "least known area of marine litter," in terms of sources, prevalence, and effects [25]. There are no estimates of the amount of nanoplastics in the ocean because "no methods exist for the reliable detection of nanoplastics in samples" [26]. But it is clear than micro and nanoplastics exist throughout the ocean.

Plastic debris is distributed across every major ocean, and throughout the water column [7]. One study found that, despite there being more sources of plastic in the northern hemisphere, plastic debris seems to exist in comparable amounts in both northern and southern parts of the ocean. This may be because of overlooked pathways, or because of differential rates of breakdown and sinking (where there is more plastic in the northern hemisphere, but more of it sinks and is therefore unaccounted for) [22]. In general, plastic debris does not diffuse evenly across the ocean [27]. Churning water facilitates vertical mixing, and the buoyancy of plastic can change as it degrades and attracts communities of microorganisms [23]. The density of debris in any given location depends on the nature of the plastic items, their initial entry point into the ocean, air and water currents, and other natural and anthropogenic factors [27]. For these reasons, the type and density of debris can differ between areas of accumulation.

It is widely understood that marine plastic debris accumulates in sub-tropical 'convergence zones' or gyres. These gyres exist in near the centers of ocean basins because of 'Ekman transport', a current effect created by the complex interaction of the Earth's rotation and wind patterns. Five such accumulation zones have been identified: two in the Atlantic, two in the Pacific, and one in the Indian Ocean. Models also predict the existence of plastic accumulation areas in semi-enclosed seas such as the Mediterranean, and high concentrations of debris have been found in the Bay of Bengal, South China Sea, and Gulf of Mexico