In This Issue:

ET&C Perspectives

THE PERSPECTIVES COLUMN IS A REGULAR SERIES DESIGNED TO DISCUSS AND EVALUATE POTENTIALLY COMPETING VIEWPOINTS AND RESEARCH FINDINGS ON CURRENT ENVIRONMENTAL ISSUES.

The Challenge: Plastics in the marine environment

The widespread occurrence of plastics in the marine environment has resulted in a range of concerns about potential negative effects, and many suggestions have been made about how best to tackle these problems. Science on the issue is developing rapidly, which prompts us to examine the current state of knowledge from 3 perspectives. Here we consider the extent to which we are able to bridge the gap between the sometimes controversial views on the problem of plastic debris in our environment.

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In Response: An industry perspective on the key challenges and guidance

Annual global plastic production is estimated to be on the order of 280 million tons per year, with further estimates that as much as 10% of all plastic will become debris in the global marine environment [1]. The presence of plastic in the world's seas and oceans can result in a myriad of physical hazards, such as entanglements, which can lead to suffocation or drowning, and physical obstructions in throats or digestive tracts. Plastic also can act as a vector of transport for both invasive species and—given its high capacity to sorb hydrophobic chemicals—organic chemicals, particularly those that are persistent, bioaccumulative, and toxic (PBT) [2]. Assessing the risks associated with the presence of plastic in the marine environment thus represents a challenge, because the difficulties in prioritizing the various hazards with respect to their relative potential to affect populations and ecosystems are considerable.

In an economic environment in which financial resources are limited, it is of critical importance to affected industries to identify efforts aimed at prioritizing and assessing the risks associated with hazards that have the potential to significantly impact marine populations and ecosystems. Unfortunately, there currently exists a general lack of standardization associated with the quantification of plastics in the environment, which makes it difficult to adequately assess the extent of the problem. As noted by van Cauwenberghe et al. [3], there is a lack of standard methods and units used to quantify the debris; studies almost always focus on litter in 1 marine compartment only (a multimedia approach is needed); and to date, only a few studies have examined concurrently the occurrence of both macro- and microplastics in various compartments.

The challenges associated with a lack of standardization are echoed by Hidalgo-Ruz et al. [4] and Ryan et al. [5]. It is suggested that these shortcomings must be addressed, supported by robust quantification of sources and sinks of plastic debris. The nature of this activity is not likely to be a trivial exercise; however, the adoption of standard sampling methods combined with improved understanding of sources and sinks of plastic debris would greatly help to provide perspective regarding the relative importance of information generated by laboratory studies, which have focused on assessing various hazards associated with exposure to plastics of varying sizes. In many instances, the laboratory studies are able to demonstrate an effect; but unfortunately, it is currently not possible to confidently relate the exposure effect concentrations observed in the laboratory to environmentally relevant exposure concentrations.

Another key challenge is a need to differentiate between the impacts that plastic debris has on individuals and the impacts on populations. Images of marine organisms entangled in plastic debris or of those that have succumbed to starvation as a consequence of ingesting large quantities of plastic are extremely powerful and invoke an appropriate emotional response. However, it is not entirely clear how plastic fate and effects, at the individual level, impact the population as a whole and how this then impacts on ecosystems. There thus appears to be a need to provide greater clarity regarding the protection goals that we are working toward. Classical risk assessment of chemicals emitted to the environment, for example, generally works toward assessing the concentration at which 50% of the population is effected (EC50). Knowledge based on the EC50, combined with the number of species tested and the ecotoxicological nature of the test, is then used to quantify the relative extent of the hazard. Assessment factors are then adopted in an effort to protect communities. This information, combined with the actual exposure concentration, is then used to assess the associated risk. In the case of plastic debris, should we adopt an analogous approach?

In the absence of well-defined protection goals and standard methods for quantifying the sources, sinks, and relative levels of exposure, it is likely that it will remain difficult to robustly assess the risks associated with marine plastic debris. Nevertheless,

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based on information presented in a number of recent studies, some of the issues that have been linked to plastic debris warrant lower priority. For example, Teuten et al. [2] suggested that plastics can act as a vector of transport for PBT chemicals. The observation that plastics contaminated with PBT chemicals could increase exposure for both benthic and pelagic organisms that might consume the contaminated material led to additional research aimed at assessing the relative potential of plastic to act as a vector of transport for PBT chemicals. Empirical studies aimed at addressing this question, however, are unfortunately difficult to control, as the variability in observations may not be significantly greater than what would be expected from analytical variability. Therefore insights obtained from modeling the potential issue can prove beneficial in assessing the relative scale of the problem. Modeling studies conducted by Zarfl and Matthies [6], Gouin et al. [7], and most recently Koelmans et al. [8] all demonstrate that although plastic has an inherently high sorption capacity for hydrophobic chemicals, the release of the accumulated chemical is not necessarily a favorable process, and therefore it may be that other physical hazards associated with exposure to plastic debris may prove to be a cause of greater concern.

In summary, the presence of plastic debris in the marine environment continues to be of great concern, and it is important that limited resources be directed toward assessing the issues that are likely to represent the greatest risk. A key concern for affected industries is that prioritization be directed toward improving our definition of the protection goals we are working toward, as well as developing robust standard methods that can be used to assess the sources, sinks, and relative levels of plastic in the marine environment. This information is critical to ensure that risks are appropriately identified and that risk management strategies aimed at reducing concerns pertaining to the issues associated with the greatest risk(s) can be effectively and efficiently implemented. Where appropriate, models can prove to be a beneficial tool in directing prioritization exercises by helping to provide perspective on an important and challenging issue, such as the environmental risks associated with marine plastic debris.

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In Response: The evidence—What actions are needed, and who should take responsibility? An academic perspective

Plastics have enormous potential to reduce the human footprint on our planet. Yet some of the most widely publicized issues are the negative effects of end-of-life plastics that are accumulating in the environment. To maximize the benefits plastics can bring, it is essential that we address environmental issues associated with their production, consumption, and disposal [1]. What, then, is the current state of knowledge about the problems and the potential solutions?

Each year, more than 280 million tons of plastic are produced globally. A key benefit of plastics is their durability; yet approximately one-third of production consists of disposable packaging that is discarded within a year or so. These items are accumulating in the environment as debris, as well as in regulated landfills [2].

Seventy-five percent of all marine debris is plastic, which contaminates habitats from the poles to the equator and from shorelines to the deep sea [3]. Methods of counting debris vary between researchers and habitats, and there are few comparable estimates of abundance [4]. However, it is apparent that the distribution of debris is not uniform, that debris can be transported considerable distances to hot spots far from population centers [5], and that it can persist for decades. Patterns of abundance over time are less clear; some studies show an increase while others show considerable variability with no clear trends. Some have suggested there may be as yet unrecognized sinks where considerable quantities of plastic are accumulating [3].

Plastic debris is unsightly, has negative economic effects on tourism, and can present a hazard to mariners [1]. As a consequence, nations worldwide invest considerable sums in removing debris from ports and shorelines [6]. There are reports of encounters with marine debris for over 660 species, and 80% of these encounters are with plastic debris. There is evidence of physical harm to individuals, with entanglement leading to lacerations and mortality. Considerable numbers of species are known to ingest plastic debris, and studies have shown that microplastic fragments can transfer from the gut into organs and be retained; however, the consequences of ingestion are less apparent than those of entanglement [7]. For species like the northern fulmar, the majority of some populations (>95% of individuals examined) have plastic in the digestive tract [8]. There is no evidence of population-level consequences of encounters between plastic and marine life; however, it should be noted that there are only a few clear examples of population-level effects from any form of man-made contamination. This is because it is very difficult to link population-level changes to single causative agents, and so a lack of evidence does not necessarily imply a lack of effect.

In addition to physical effects, there are concerns that ingestion of plastic debris could lead to toxicological harm as a consequence of either the accumulation of persistent contaminants from seawater, or the release of chemicals that were incorporated during manufacture (e.g., plasticizers, flame retardants, and antimicrobials). Polyethylene and other plastics are known to sorb persistent organic pollutants from seawater, and these can become orders of magnitude more concentrated than in the surrounding water [9]. These chemicals can then be released in the gut, where desorption is facilitated by surfactants

[10]. Recent mathematical modeling indicates that the role of plastics in the transport of contaminates to organisms may be relatively small compared with other pathways [11,12]; however, more work is needed to understand the relative importance of plastics as a vector under differing environmental and physiological conditions (temperature, pH, salinity) and in relation to the potential for uptake via other pathways including feeding and respiration. In contrast to the role of plastics in the transport of contaminants from seawater, the release of additive chemicals from plastics represents a direct addition to the environment or organisms. There are concerns about the release of additives such as bisphenol A from products used by the human population [13], and there is evidence of high concentrations of additive chemicals used in plastics leaching into aquatic habitats from landfill sites [14]. However, the potential for additives released from debris to harm wildlife is not clear.

Before closing my assessment of impacts, there are 3 important additional issues to consider. First, from the perspective of sustainable use of resources, we use approximately 8% of world oil production to make plastic items, and approximately one-third of the items we produce are then discarded within a short time frame. Plastics are inherently recyclable, so by recycling end-of-life plastic it is possible to reduce the accumulation of debris while at the same time reducing our demand for fossil carbon [1]. Second, plastic items are important to society; however, there is something fundamentally different between the problem of marine debris and other current societal dilemmas. Unlike turning on an electric light or taking an airplane journey, the emission (in this case of debris to the oceans) is not directly linked to the benefit. Putting it another way, we can obtain the benefits from plastic items without end-of-life plastics accumulating in the oceans. Third, together with other scientists, policy makers, and representatives from industry and nongovernmental organizations, I regularly attend international meetings focused on marine debris problems and solutions. While there may be discussion and sometimes disagreement about the relative importance of the various impacts, there is typically universal consensus to reduce inputs of debris to the ocean. Hence, in summary, marine debris is damaging to the economy, to wildlife, and to the environment; it is wasteful and unnecessary; and we all agree it needs to stop. That being the case, then, what are the problems that impede progress?

The problems that relate to prioritizing solutions are: Who should take the action; and if there are costs, who should pay? The solutions are well known [1,2] (Figure 1); they principally are to be found on land rather than at sea and, in decreasing order of merit (for 1–5), are as follows: 1) reduce material usage—any reduction in the amount of new plastic produced will directly reduce the quantity of end-of life material that results; 2) reuse items—this will directly reduce the need for new plastic items and so directly reduce the quantity of end-of life material; 3) dispose of end-of-life items properly—ideally, recycle them; 4) recycle—turning end-of life material back into new items in a closed loop reduces accumulation of waste and simultaneously reduces demand for fossil carbon; 5) recovery—when items cannot easily be reused or recycled, and as a poor alternative to solutions 1 to 4, consider energy recovery via incineration. Lastly, and potentially most important because it is overarching, 6) redesign—for every plastic product, consider at the design stage the hierarchy of options given above to maximize the overall environmental footprint (i.e., reduce use of fossil carbon and reduce the accumulation of waste by designing end-of life products as raw material for new production). Such principles are gaining momentum, for example, as seen in the recent European Union recommendations for resource efficiency in Europe [15]. There is public interest and response from industry; for example, some supermarkets in the United Kingdom have voluntarily opted to reduce use of single-use bags, and some manufacturers have decided to phase out the plastic microbeads used in their cosmetics. Other actions could work against these goals unless they are used appropriately; for example, use of biobased carbon from agriculture is seen as

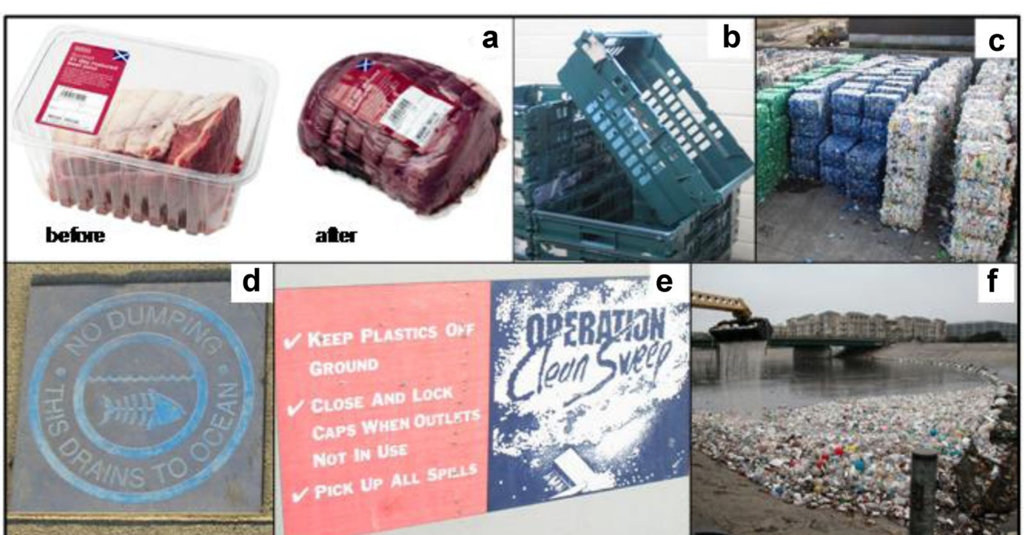

Figure 1. Solutions to marine debris include (**a**) measures to reduce the production of new plastics from oil, as in the example showing how small changes in product packing reduced the weight of packaging required by 70% while (**b**) reuseable plastic packing crates have reduced the packaging consumption of the same retailer by an estimated 30 000 tons per annum. Recycling (**c**) is another solution for reducing marine debris. Bales of used plastic bottles have been sorted prior to recycling into new items, such as plastic packaging or textiles. Measures to reduce the quantity of plastic debris in the natural environment include: (**d**) educational signage to reduce contamination (**d**) via storm drains and (**e**) via industrial spillage, together with (**f**) booms to intercept and facilitate the removal of riverine debris Photographs (**a**) and (**b**), and associated usage statistics, courtesy of Marks and Spencer; photograph (**c**) courtesy of P. Davidson WRAP; photographs (**d–f**) courtesy of C. Moore, Algalita Marine Research Foundation [1].

a sustainable alternative to fossil carbon. However, altering the carbon source does nothing to reduce marine debris; and where arable land is at a premium, a more efficient solution is probably to recycle our waste rather than developing a grow-to-throw culture. Similarly, designing plastic products so that they degrade or disintegrate more rapidly can compromise the potential for product reuse, contaminate recycling streams, and lead to more rapid accumulation of fragments in the environment [1]. What is needed is policy-led coordination, supported by sound science, to utilize the measures suggested above to achieve change as efficiently and rapidly as possible. This will involve voluntary actions, incentives, taxes, and education [2]. In particular, there is a need to re-educate. My lifetime has been spent in a world with rapidly increasing production of disposable short-term products and packaging, and of durable goods that cannot be repaired or renewed. In short, we are in a growing culture of throw-away living; there is an urgent need to recognize that there is no such place as "away."

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In Response: Science for solutions to marine plastics: A governmental perspective

Environmental contamination with plastic particles has been documented by scientific literature since the 1970s [1]. Four decades later, the scientific community is still grappling with the issue of plastics in the environment. Current interest has focused on coastal and marine waters as the eventual receiving environment for plastic and microplastic particles.

Plastic material does not belong in the marine environment. This concept resonates with everyone—industry, academics, nongovernmental organizations, governments, and the public. Floating plastic is a reminder of human-caused environmental pollution. It threatens marine habitats and organisms and can be an eyesore. While most people agree that plastic should not be in the water, the solution for how to prevent its presence is not straightforward.

For the past several years, research on marine plastics has focused on the microsized fraction, given concern about the hazards to marine organisms from ingested microplastic. Microplastic particles are defined in various ways. The US National Oceanic and Atmospheric Administration (NOAA) recognizes a definition born from a 2008 microplastics workshop, where a number of experts in the field convening for the first time on this issue determined that the term "microplastic" includes particles $\leq$5 mm through the microspectrum [2]. Primary microplastics are manufactured within that size range (e.g., preproduction resin pellets), while secondary microplastics are formed via the degradation of larger materials. Since the 2008 workshop, the published literature has greatly expanded (Figure 2). There are now a significant number of reports of macro- and microplastic

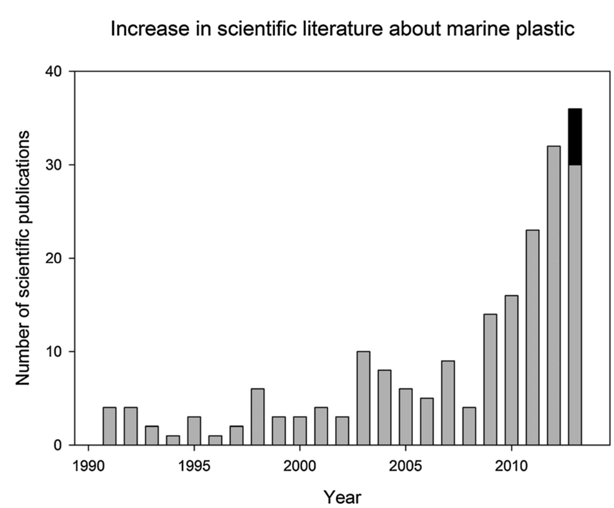

Figure 2. The number of original research and review articles on the topic of plastic debris is plotted over time. Note the increasing trend to present (01 November 2013). The black bar estimates publications in November and December 2013 (based on extrapolation given an equivalent rate of publication as January-October 2013). Data originate from a Web of Science cited reference search for "marine debris" and "plastic."

concentrations, mainly on beaches and in coastal environments. Scientific inquiry is at a stage at which some answers are becoming clearer. Marine plastics have been found in remote locations, an indication of persistence and long-range transport [3,4]. Preliminary results from recent surface water monitoring conducted by NOAA in the Chesapeake Bay (VA, USA) indicate that microplastic fragments are fairly ubiquitous. However, there is poor understanding of the particle life cycle. Little information is available about the relative contribution of primary versus secondary particles. Rates of input and export are unknown. Questions about the factors that govern particle fragmentation are still unanswered [3]. The scientific community has not yet developed a steady-state model that accounts for observed particle concentrations [5]. These are important considerations for understanding the risk posed by microplastic particles. Available data on the concentration of particles in relevant environmental matrices, coupled with knowledge about particle behavior (e.g., settling, fouling, and fragmentation rates) will assist scientists in estimating likely encounter rates with key marine species.

Recent studies have shed light on the toxicological implications of microplastic particle ingestion [6]. Effects caused by chemical leaching from the polymer matrix to the organism have been cited often in the literature. However, few studies support the conclusion that ingestion of microplastic particles leads to negative effects because of uptake of sorbed contaminants and additive chemicals. Recent studies suggest that, in some instances, microplastic particles may not significantly alter contaminant accumulation in marine organisms [7]; however, complementary laboratory and field experiments are needed to expand this field of study. Research is just beginning to investigate the influence of plastics on marine microbial communities, which highlights the lack of available information on the physical effects of marine plastics [8]. Effects as a result of entanglement and ingestion are known anecdotally, but the state of the science is not fully formed for either species or community impacts resulting from physical interaction with plastic debris. In addition, research has not focused on defining the relative contribution of additive chemicals (e.g., brominated flame retardants and phthalates) to the environment from items that end their life as marine debris. These are key topics to be addressed and are echoed in our colleagues' perspectives.

With the increase in scientific research, the scope of the issue and the need for a better understanding of plastic are becoming better defined. From a scientific perspective, an important need is the development of a mass balance model that quantifies the inputs and exports of plastics from a system; incorporates sinking, fouling, and fragmentation rates and transport mechanisms; and estimates encounter rates with marine organisms and rates of consumption by commercially important marine species. This should be integrated with the continuing research on ingestion effects, with particular attention paid to relevant equilibrium concentrations, which vary by polymer type and condition [9]. In localized areas, plastic materials may be a source of additive chemicals; and as the scientific community obtains better estimates of the inputs of plastics to the marine environment, it will be possible to estimate the introduction of additive chemicals sourced from plastic debris.

Understanding debris source is a key variable needed for additional research as well as for development and enhancement of preventative solutions. Some institutions are focusing on the issue of monitoring to understand debris quantity and composition and to determine spatial and temporal trends. For instance, developing monitoring and data standards is of utmost importance for programs or governments charged with measuring a reduction in microplastic fragments [10]. Under its Marine Strategy Framework Directive, the European Commission has pushed for quality controls, standardization of field and analytical techniques, and even harmonization of the many metrics used to quantify plastic materials in the environment [10]. Other institutions may focus on researching impacts and mitigation in order to make policy changes.

Marine plastics research will likely continue to address the many questions and important gaps in our understanding. Government agencies have a responsibility to provide credible science to develop sound management practices. In some cases, mandates drive agency action, but it is important to note that all agencies do not have the capability to address marine plastics within a regulatory framework. The complex matrix of stakeholders with varied tools at their disposal has led to discussions about the scope of this issue and the need for science to guide management options to mitigate and prevent marine plastics, but water quality standards for marine plastics are largely absent. From an agency perspective, NOAA has focused on a state-of-the-science approach and is most interested in understanding the risk of plastic materials and preventing their entrance into the marine environment. The NOAA Marine Debris Program is committed to furthering the research that will help answer these questions and communicating the results of studies to all stakeholders. In the future, we will use the knowledge gained from a comprehensive approach to develop solutions that fit the magnitude of the problem.

It is critical that statements made about the effects of plastics be based on sound science. As the science evolves and demonstrates the presence and effects of plastic debris, it seems that the most important next step is to identify the inputs and sources of plastics to the marine environment. Successful solutions will use information about inputs and sources to focus scarce resources on the best targets for reduction. Solutions will likely focus on measures to understand and curb the entrance of primary micro- and macroplastics, as well as measures to create better waste management infrastructure and behavior change to prevent the entrance of larger plastic materials to the marine environment. Solutions should involve cross-sector partnerships to increase buy-in from all stakeholders, to achieve long-term success in the prevention of plastic debris.

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