Almost all of standard economic theory is in reality concerned with services. Material objects are merely the vehicles which carry some of these services, and they are exchanged because of consumer preferences for the services associated with their use or manufacturing process. Yet we persist in referring to the “final consumption” of goods as though material objects such as fuels, materials, and finished goods somehow disappeared into the void.

Robert U. Ayres and Allen V. Kneese (1969, p. 284)

Plastics are essential and ubiquitous materials in our daily lives and address numerous societal challenges. They save fuel and reduce carbon dioxide emissions by providing light materials for cars and airplanes. Plastics contribute to high-performance insulation materials that reduce energy consumption, and plastic packaging enhances food safety. Emerging three-dimensional printing technology that uses plastic materials may save human lives by enabling medical innovation.

Plastic waste is a relatively new problem. However, cumulative production of plastic now exceeds 8,000 million metric tons, of which approximately 9 percent has been recycled, 12 percent incinerated, and 79 percent accumulated in landfills or the natural environment. With the exception of concrete and steel, plastics are now the most common manmade material. In 2015, plastic production was 380 million tons, and if unchecked, production rates are expected to double during the coming decades (Maphoto/Pravettoni 2018).

More than 10 million tons of plastic enter the oceans annually (Jambeck et al. 2015) and more than 80 percent of marine litter is plastics (European Parliament 2019). Environmental
economics studies of marine plastic pollution (MPP) have been scarce thus far and often focus on a single issue, such as lost nonmarket values from plastic debris on beaches (e.g., Leggett et al. 2018). However, the sheer scale of MPP, coupled with the emerging toxicological science (GESAMP 2015), suggests the potential for significant additional harm to human health. This article, which is part of a minisymposium on MPP, provides an introduction to plastics and MPP and its potential effects on marine ecosystems and human health, discusses some of the policy and technical issues, and suggests priorities for further research.

**Introduction to Plastics and MPP**

There are thousands of different types of plastic polymers, but the market, and the litter found in the marine environment, is dominated by six substances: polypropylene (PP), polyethylene (PE), polyvinylchloride (PVC), polyurethane (PUR), polyterephthalate (PET), and polystyrene (PS), which together comprise approximately 80 percent of total plastics production (PlasticsEurope 2017). Not all plastics are equally problematic. Beach, ocean, and river litter surveys show that certain plastic products and materials are more likely to enter the environment than others, with about 50 percent of items found in beach surveys being single-use plastic items (Addamo, Laroche, and Hanke 2017). These are commonly used products that are difficult to recycle, easily littered, and often made of low-density plastic polymers, which means they float.

Land-based coastal pollution (within 50 km of coastlines) is the major source of MPP, contributing about 9 million tons per year (Jambeck et al. 2015). Land-based inland pollution contributes 0.5 million tons, at-sea sources contribute 1.75 million tons, and microplastics (<5 mm) contribute 0.95 million tons (Eunomia 2016). It is estimated that 94 percent of these plastics accumulate on the sea floor (Eunomia 2016), 5 percent ends up on beaches, and 1 percent remains on the ocean surface (Eunomia 2016). More than 80% of MPP is land based, thus any effective policy to reduce MPP must target land-based plastic pollution. The Great Pacific Garbage Patch (GPGP), located between California and Hawaii, is the largest aggregation of floating plastics, with fishing gear accounting for almost half of the mass. Microplastics account for 8 percent of the total mass of the GPGP but 94 percent of the total 1.8 trillion pieces of plastic floating in the GPGP (Lebreton et al. 2018).

There are large uncertainties about the major sources of marine plastics. Schmidt, Krauth, and Wagner (2017) use two models to estimate how much plastic is exported by rivers globally. One suggests that a substantial share of land-based marine plastic debris enters through pathways such as storm water runoff, wind dispersal, and littering, rather than through rivers. The other suggests that rivers are the major source of land-based plastics entering the sea, with eight large rivers in Asia and two in Africa accounting about 90 percent of the total riverine input. Jambeck et al. (2015) provide support for the argument that rivers are the major source and estimate that more than 50 percent of marine plastic waste emanates

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1. Abbott and Sumaila (2019) focus on how economics can be used to inform effective policies for addressing MPP.
2. The average concentration of plastics on the ocean surface is 0.7 kg/km², but it is 80 kg/km² in the GPGP. The average concentration of plastics on the sea floor is 70 kg/km², while on beaches it is 2,000 kg/km² (Lebreton et al. 2018).
from mismanaged plastic waste in five East Asian countries. However, there are insufficient data to estimate the portion of marine plastic debris that results from manufacturing and preconsumer stages versus postconsumer stages.

Plastics are long lasting and typically undergo limited degradation; instead they undergo secondary breakdown from weathering and fragmentation (Andrady 2011), which is how microplastics are formed. The distribution of microplastics found in marine samples is consistent with the overall distribution of plastic types and their uses (Hidalgo-Ruz et al. 2012). However, it is generally not possible to identify where these microplastics originate.

Potential Effects on Marine Ecosystems and Human Health

With this background on MPP, we next discuss the potential effects of MPP on marine ecosystems and human health. We briefly address macroplastic debris effects, which are well established (Gregory 2009), but focus on microplastics and their associated chemicals. We also consider the human health effects of exposure to the chemicals in plastic products.

Potential Effects of (Micro)plastics on Marine Ecosystems

The impacts of plastics on marine ecosystems range from direct health effects in marine organisms, due to ingestion or entanglement in litter and fishing gear, to hitchhiking (i.e., attaching to and floating with plastics) of organisms, including invasive species and pathogens, to impacts on fisheries (including damaged gear, decreased catches), to loss of ecosystem services (GESAMP 2015).

Research on microplastics indicates that ingestion of microplastics by marine organisms can cause a range of effects, including blockage of intestinal tracts, inflammation, oxidative stress, hormone disruption, reproductive impact, and metabolic and behavioral changes (Wright, Thompson, and Galloway 2013). However, recent research finds that exposure to smaller, nanoplastic particles is more likely to cause adverse outcomes (Rochman et al. 2016). The impacts of micro- and nanoplastics on marine environments at the ecosystem level are largely unexplored, but may include changes in nutrient cycles and food chains as well as changes in microbial communities growing on plastics (Zettler, Mincer, and Amaral-Zettler 2013). Although some research has indicated that microplastics may cause severe effects, current research is dominated by two opposing views: microplastics have clear impacts on marine ecosystems (Rochman et al. 2016), and the current risks associated with microplastics have thus far not been proven to exist (Burns and Boxall 2018).

However, many frequently used chemical additives in plastic products have been found in marine ecosystems (Hermabessiere et al. 2017), and these chemicals cause endocrine disruption, developmental disorders, and reproductive abnormalities in a wide range of vertebrate species (including fish and marine mammals) (Frye et al. 2012). The sources of these chemicals in marine environments may be linked to leachates from plastic debris (i.e., chemicals such as flame retardants, phthalates, and phenols may leak out of plastic objects into marine

Nanoplastics are particles that range in size from 1 to 1000 nm, or $10^{-9}$ to $10^{-6}$ m. For comparison, a strand of human DNA is 2.5 nm in diameter and a human hair is approximately 80,000–100,000 nm wide.
waters) or diffuse sources (e.g., wastewater, sewage, atmospheric deposition), which result from the pervasive use of both plastics and chemicals worldwide.

Potential Effects of Plastics on Human Health

The direct impacts of marine plastics on human health have not been well established, and no studies explicitly examine this issue, although plastic debris has been identified as a potential human health issue (Vethaak and Leslie 2016). For example, plastic products may cause direct harm when plastic bags block drainage pathways and lead to rising floodwaters or when plastic debris provides breeding grounds for mosquitoes (Gubler and Clark 1996). In addition, it has been shown that microplastics are colonized by microbes (Zettler, Mincer, and Amaral-Zettler 2013), including potential pathogens (Kirstein et al. 2016). Microplastics may also affect human health due to particle toxicity (Rist et al. 2018), and microplastics are increasingly being found in water sources and human food, including seafood (Rochman et al. 2015).

Exposure to the chemicals in plastic products does have human health effects (Thompson et al. 2009). Chemicals in plastics have been associated with disease and pathologies, including endocrine disruption, cancers, developmental disorders, and reproductive abnormalities (Trasande et al. 2015). In fact, chemical exposure is the most rigorously studied human health impact of plastics. For example, humans are exposed through the additives and contaminants in plastic materials that come in contact with food (e.g., packaging, storage containers, utensils) (Groh et al. 2018), children’s toys (Guney and Zagury 2014), and electronics (Zeng et al. 2016). There is some evidence that microplastics may act as vectors, transferring chemicals from the marine environment into organisms that are normally consumed by humans (Rochman et al. 2014). However, microplastics likely play a minor role in the accumulation of chemicals in the food chain (Hartmann et al. 2017); the greatest source of exposure for humans is via chemicals in food contact materials (European Food Safety Authority Panel on Contaminants in the Food Chain 2016). There is also a concern that human exposure to mixtures of these chemicals may cause nonlinear effects, and that long-term, low-level exposures may result in a range of pandemic diseases that are not easily detected or attributed to any one cause (Grandjean and Landrigan 2006).

Policy Issues

How should the problem of MPP be addressed? Many policies have implications for plastics recycling, which is often proposed as a solution to MPP and as part of a future circular economy4 (e.g., ten Brink et al. 2018). Thus we will first discuss some of the technical challenges of plastic recycling in general as well as the specific challenges plastic recycling poses for addressing MPP. Then we will focus more closely on another policy—extended producer responsibility (EPR)—and its potential to contribute to the management of plastic pollution.

4 A circular economy refers to the idea that the value of products, materials, and resources is maintained in the economy for as long as possible, thus minimizing the extraction of virgin material and the generation of waste (Boulding 1966).
Challenges of Plastics Recycling

The complexity of plastic materials makes recycling difficult. More specifically, a plastic product consists not only of the polymer itself, but also potentially thousands of chemical compounds, of which hundreds are known to be toxic (Groh et al. 2018). These chemical additives can be problematic in recycling programs because they reduce the quality and safety of materials.

The challenge of maintaining material quality

To maintain material quality, recycling efforts need to be specific for each type of plastic, including chemical additives (e.g., phthalates, flame retardants). This is a challenge, given the many types of plastics and the lack of transparency concerning the chemical composition of materials. For example, Leslie et al. (2016) found that a number of banned toxic substances found in older products are actually recirculated into the consumer market. Marine plastics that are collected for recycling will contain unknown chemical mixtures; products may have leached additives into the surrounding oceans, but also will have absorbed environmental toxicants (man-made toxic compounds) (Hirai et al. 2011).

Recycling is particularly problematic when applied to mixed plastics (i.e., consisting of several different polymers), as this leads to unpredictable material qualities. Thus the market for recycled mixed plastics is small. Because of these challenges, beach cleanup recycling programs should focus on a limited number of polymers (e.g., PP, PE) (Pietrelli et al. 2017).

“Biodegradable” plastics

To address the problems and challenges caused by marine plastics, there have been some efforts to promote the use of “biodegradable” plastics (although the term itself lacks a clear definition; see Haider et al. 2019). However, these materials will generally not degrade in marine environments (Napper and Thompson 2019). Moreover, it is unclear whether these materials are “safer” from an ecotoxicological perspective, which can be misleading for consumers and may actually have negative environmental impacts (Haider et al. 2019). Biodegradable plastics are also a problem for recycling systems, because including more than 5 percent biodegradable plastics can lead to decreased material integrity and performance (Samper et al. 2018). Thus it is unlikely that these materials will be able to provide a long-term solution to the plastic pollution problem.

EPR

EPR is an environmental policy that extends a producer’s responsibility for a product to the product’s postconsumer stage. In this way, EPR shifts the responsibility upstream, from municipalities (and taxpayers) to the producers, and it provides incentives for producers to consider the environmental impacts of the design of their products (Organisation for Economic Co-operation and Development 2001). More specifically, EPR requires producers to finance the collection, recycling, and/or the safe disposal of products.

Walls (2006) lists several environmental objectives for EPR: reduction in the use of virgin material, provision of increased incentives for ecodesign, reduced pollution at the production
stage, reduction of hazardous components, reduction in waste volumes, and reduction in waste disposed. Historically, product flows have been linear, from extraction of virgin material to generation of waste, as illustrated in the upper part of figure 1 (which shows a linear economy, from left to right). In theory, EPR changes this linear flow, stimulating a clockwise circular flow (see figure 1). By shifting the responsibility and the costs of managing the postconsumer stage of a product from the municipality to producers (who pass as much as possible of the handling costs to consumers), EPR motivates producers to reduce the costs for handling the waste. Ideally this can achieve all six EPR objectives.

However, to reduce their costs, firms in an industry often share the costs of EPR requirements by forming producer responsibility organizations. Such cooperation may result in welfare losses if firms also cooperate (i.e., collude) on other issues, such as consumer prices (Walls 2006). Sharing costs among firms also reduces the incentives for ecodesign, which suggests a need for more individual producer responsibility (Lifset, Atasu, and Tojo 2013).

EPR is used extensively in the European Union (EU) and is applied to various products, including electrical and electronic equipment, batteries, accumulators and vehicles, packaging waste, tires, waste oil, paper and card, and construction and demolition waste. In fact, EPR is now an essential element of the EU’s objective of creating a circular economy. EU regulations now include mandatory EPR schemes for all packaging and explicit targets for recycling rates for various types of waste. The general recycling target for all packaging is 65 percent by 2025, and for plastics the target is 50 percent by 2025. Single-use plastic cutlery, plates, straws, cotton bud sticks made of plastic, and expanded polystyrene cups are banned beginning in 2021 (European Parliament 2019). If these targets are achieved, they will hopefully encourage the rest of the world to undertake similar efforts so that MPP becomes a more manageable problem.

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5Several EU countries also have voluntary producer responsibility systems for farm plastics, medicines and medical waste, plastic bags, photochemicals and chemicals, newspapers, refrigerants, pesticides and herbicides, lamps and lightbulbs and fittings.
Research Priorities

As with so many environmental issues, addressing the problem of MPP will require multidisciplinary research and cross-boundary cooperation. Our review of the current state of knowledge concerning the environmental and economic aspects of MPP has helped us identify several priorities for research on plastics pollution in general and MPP in particular, including

- **Development of polymers that are safer and more easily disposed of or recycled.** This concerns both polymers and chemical additives. Research should focus on polymer chemistry and recycling techniques, as well as policies that restrict the use of compounds known to be toxic (i.e., which cause negative effects on marine ecosystems or human health). Policy should also focus on increasing transparency concerning the use of polymers and chemical additives to ensure safety. This information will facilitate the use of recycled plastics in additional products.

- **Further evaluation of environmental and health impacts of marine plastics, microplastics, and nanoplastics.** This includes the potential implications of new materials and new applications (because new uses introduce new risks). Further research is also needed on the impact of plastics (including microplastics) and associated chemicals on food production, aquaculture, agriculture, and food safety.

- **Examination of nudges, norms, and longevity of behavioral changes.** Behavioral economics has identified several important ways to influence behavior (Sunstein and Thaler 2009). Thus an important task for multidisciplinary research is to examine how to apply these findings to the issue of plastic pollution (Alpizar et al. n.d.), including the technical challenges of plastics recycling and the design of specific policies to reduce MPP.

- **Further analysis of EPR.** Legal change combined with mandatory EPR for various plastics has been a successful strategy for the EU, but much more can be done to improve the results from using EPR. In particular, the analysis of various economic approaches to improve incentives for ecodesign, to stimulate both recycling and reuse, and to ensure that EPR targets are met at the lowest possible cost are all important areas for future research.

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