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The Plastic Economy

A review of the positive and negative impacts of plastic and its alternatives

Lihini De Silva, Jacqueline Doremus and Rebecca L. C. Taylor

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The Plastic Economy

A review of the positive and negative impacts of plastic and its alternatives

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Abstract

The proliferation of plastic has generated wide-ranging consequences in terms of waste management, pollution, human and animal health, the economy and the environment. This report reviews the literature on the impacts of plastic, both positive and negative. We begin with a brief explanation of the processes by which plastic is produced and an overview of the structure of the plastic economy. We then discuss the impacts of plastic, organized by whether they occur upstream, midstream or downstream. Next, we compare virgin plastic production against a range of alternative materials and processes that have been developed with the aim of matching the physical characteristics of plastics while contributing less to the problem of waste generation. Lastly, acknowledging the transboundary challenge of plastic pollution, we examine plastic regulations and discuss evidence of their efficacy at reducing plastic use and pollution.

Keywords

Plastic production, microplastics, macroplastics, plastic pollution, plastic alternatives, plastic policy.

JEL Classification Numbers

Q52, Q53, Q54, Q55, Q58

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Contents

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1. Introduction

"Plastic is one of the most ubiquitous materials in the economy and among the most pervasive and persistent pollutants on Earth. It has become an inescapable part of the material world, flowing constantly through the human experience in everything from plastic bottles, bags, food packaging, and clothing to prosthetics, car parts, and construction materials."

— Center for International Environmental Law (2019)

The term plastic is used to describe a family of materials that are extremely common and versatile in modern society. Among other things, plastic is in the clothes we wear, the transportation we use to move around and the packaging of products we consume. While plastics come in numerous forms, each varying in their chemical and physical properties, all plastics are organic compounds made from natural resources such as coal, crude oil or cellulose. Plastic as a family has a broad set of useful attributes, including low cost, durability, lightness, strength, good thermal insulation and corrosion resistance. With these attractive attributes, global plastic production has increased from 0.5 million tonnes in 1950 to more than 300 million tonnes in 2014, as seen in Figure 1 (World Economic Forum, 2016). Growth has been particularly rapid this century, with half of all plastics ever made manufactured in the last 13 years (Balton et al., 2020). Looking forward, plastic production is expected to reach four times the current levels by 2050 (Geyer et al., 2017). This ramping up of production is underpinned by the recent announcement from the American Chemistry Council that the industry is expecting to invest $47 billion in plastic production over the next 10 years (Joyce, 2019).

The proliferation of plastic has generated wide-ranging consequences in terms of waste management, pollution, human and animal health, the economy and the environment. The goal of this report is to review the literature on the impacts of plastic, both positive and negative. Why do we use plastics? What harm do they cause? What are the alternatives to plastic and how do they compare?

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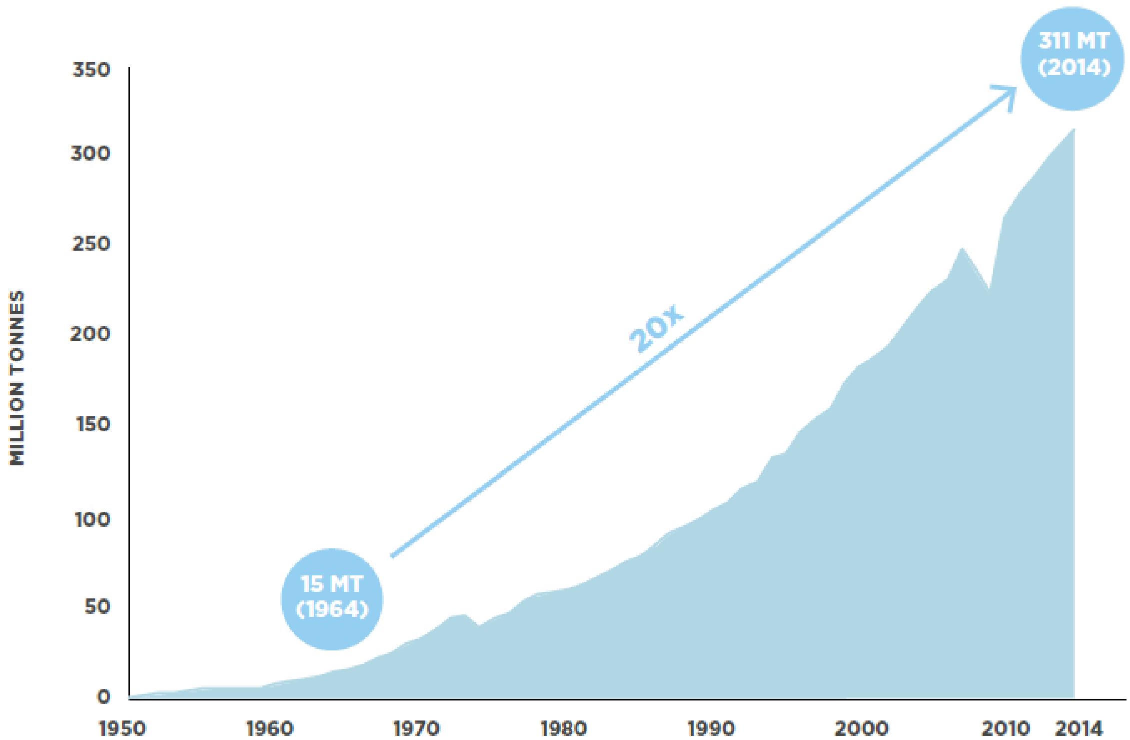
FIGURE 1

Growth in plastic produced from virgin feedstock (1950–2014)



Source: World Economic Forum (2016). Note: This includes plastics produced from virgin petroleum-based feedstock only. It does not include bio-based, greenhouse-gas-based or recycled feedstock plastic prooduction.

Before discussing the positive and negative impacts of plastic, this report will begin with a brief explanation of the processes by which plastic is produced and an overview of the structure of the plastic economy. We give particular attention to the petrochemical industry, the starting point for the vast majority of plastic production. The processes for creating plastic differ by feedstock (e.g., crude oil versus natural gas), the prevalence of which varies by country. For instance, while the majority of plastic comes from natural gas in the U.S., plastics produced in China, Japan and Europe are more likely to stem from crude oil (CIEL, 2017). There is also a large degree of vertical integration between petrochemical and plastic producers, with petrochemical companies involved in plastic production and plastic companies involved in producing petrochemicals.

Second, this report will consider how the positive and negative impacts of plastic vary across its different applications. The impacts of plastic can be divided into three categories — those that occur upstream, midstream and downstream. Upstream impacts occur at the production stage. Midstream impacts

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materialize at the postproduction stage, during which the plastic is used by the consumer. Downstream impacts occur after product consumption and vary by the method and location of disposal. While the majority of the negative impacts of plastic discussed in this report occur downstream, once the plastic item has been used and discarded, the positive impacts discussed occur upstream and midstream, during its production and use. Furthermore, this section reveals that plastic is a double-edged sword — often the characteristics that make plastic beneficial during its use are the same characteristics that make it harmful during its end of life. For instance, plastic's light weight reduces transportation costs and carbon emissions, yet makes it easy for plastic to blow into the environment, where it can harm wildlife, fishing and tourism. Plastic's impermeability and durability protect food and medicine from contamination, yet also cause the material to persist as waste once it is discarded, which is especially problematic when waste enters oceans and waterways.

Third, this report compares plastic against a range of alternatives that have been developed with the aim of matching the physical characteristics of plastics while contributing less to the problem of waste generation. Given the versatility and range of applications for plastics, there is no single suitable alternative material to compare it against, making neat comparisons challenging. Alternative materials include biodegradable plastics and non-plastic materials such as paper, glass and metal. In addition, we consider alternative disposal methods besides landfill, such as incineration and recycling.

Finally, this report examines the regulation of plastics. There is broad agreement among policy makers worldwide that current plastic consumption and management are suboptimal for economic and environmental wellbeing (UNEP, 2020). We identify three key market failures in plastic markets that lead to this suboptimality. We then characterize the consequences of these market failures over the plastic life cycle and across stakeholders. Lastly, we link specific examples of plastic regulations to these market failures and discuss evidence on their efficacy at reducing plastic use and pollution. Although individual governments have enacted some successful plastic regulations within their borders, the transboundary nature of plastic pollution necessitates coordinated policies at the international level.

While this report summarizes the literature concerning the many costs and benefits of plastic, it is important to note that we do not perform a cost–benefit analysis. This is due to (1) the need for more data and scientific research on the downstream impacts of plastic, such as around the impact of microplastics; and (2) the subjective and complex nature of valuing nonmarket goods, such as consumer convenience and marine ecosystems, on a global scale. In order to perform cost–benefit analyses, future research needs to focus on quantifying the monetary value of the various impacts discussed in this paper.

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2. How is plastic produced?

More than 99% of all plastics are formed from petrochemicals (CIEL, 2019). This process involves linking single monomer units (smaller molecules) to form a longer polymer chain. These monomers are by-products of the petrochemical industry. Two of the most common monomers are ethylene and propylene, which are used to make a variety of polymers that vary in terms of their chemical and physical properties. The distinct properties of the resulting molecule are what determine the suitability of specific plastics for various applications. Table 1 describes the most common polymers, including their respective characteristics, uses and quantities produced globally, and their share of global plastics demand.

TABLE 1

Common polymer types: characteristics, uses, amount produced globally and share of total global demand

Polymer	Characteristics	Uses	Amount produced globally (kt)	Share of total global demand
Polypropylene (PP)	✓ Abundant ✓ Cheap ✓ High melting point ✓ Flexible, but hard ✓ Fatigue-resistant ✓ Good chemical resistance ✓ Good electrical insulator ✓ Waxy surface	✓ Medical equipment ✓ Car bumpers ✓ Bottle tops ✓ Ketchup bottles ✓ Yogurt containers ✓ Potato chip bags ✓ Plant pots ✓ Drinking straws ✓ Lunch boxes ✓ Heavy-duty bags	61,870	16%
Low-density polyethylene (LDPE)	✓ Tough but flexible ✓ Good transparency ✓ Low melting point ✓ Resistant to moisture	✓ Refuse sacks ✓ Packaging films ✓ Bubble wrap ✓ Bottles ✓ Shopping bags	45,730	12%

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	✓ Stable electrical properties ✓ Waxy surface	✓ Wire sheathing		
Polyvinylchloride (PVC)	✓ Good transparency ✓ Rigid ✓ Hard ✓ Good chemical resistance ✓ Resistant to weathering ✓ Stable electrical properties	✓ Door frames ✓ Credit cards ✓ Carpet backing ✓ Synthetic leather ✓ Pipes ✓ Wire sheathing	43,040	11%
High-density polyethylene (HDPE)	✓ Good moisture resistance ✓ Good chemical resistance ✓ Somewhat flexible ✓ Soft waxy surface	✓ Detergent and bleach bottles ✓ Snack food boxes ✓ Milk bottles ✓ Garden furniture ✓ Plant pots ✓ Pipes ✓ Buckets ✓ Toys ✓ Wheeled garbage bins ✓ Compost bins	40,350	10%
Polyethylene terephthalate (PET)	✓ Good gas and moisture resistance ✓ Good heat resistance ✓ Clear ✓ Hard ✓ Strong ✓ Good solvent resistance	✓ Soft drink bottles ✓ Food trays ✓ Roasting bags ✓ Fiber in clothing and carpets ✓ Shampoo and mouthwash bottles	18,830	5%
Polystyrene (PS)	✓ Clear or opaque ✓ Brittle ✓ Affected by fats and solvents ✓ Rigid or foamed ✓ Glassy	✓ Yogurt tubs ✓ Video cases ✓ Coat hangers ✓ Toys ✓ Disposable cups ✓ Disposable cutlery ✓ Fast-food trays	18,830	5%

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Acrylonitrile butadiene styrene, acrylonitrile styrene acrylate and styrene-acrylonitrile resin (ABS, ASA, SAN)	✓ High rigidity ✓ Good impact resistance ✓ Good insulation and stability properties ✓ Abrasion and stain resistance	✓ Electronic housings ✓ Auto parts ✓ Consumer products ✓ Pipe fittings ✓ Lego toys	8,070	2%
Elastomers (mainly styrene-butadiene rubber)	✓ Abrasion resistance ✓ Crack endurance ✓ Compression and water resistance ✓ Good aging characteristics	✓ Tires ✓ Shoe soles ✓ Auto parts	7,069	2%
Polycarbonate (PC)	✓ Impact resistance ✓ Transparency ✓ Heat resistance	✓ Bulletproof glass ✓ Eyewear ✓ Clear tubes ✓ Diffusers and light pipes for LEDs	2,690	1%

Source: UNEP (2018).

2.1 Sources of ethylene and propylene

The way ethylene is produced by the petrochemical industry varies by location. The U.S., for example, is a large producer of natural gas and hence this is the source for almost 90% of ethylene produced there. Natural gas liquid is hard to transport across borders, and thus in other parts of the world such as China, Japan, and Europe naphtha is a more common feedstock for plastics. Naphtha is a by-product of crude oil, formed at the refining stage. It is easier to transport than natural gas and has a more concentrated market of producers, including the five large petrochemical producers — BP, ExxonMobil, Shell, Chevron and the China National Petroleum Corporation.

Propylene is produced in the process of transforming ethane monomers into ethylene. Thus, the two processes are inherently tied together. However, different processes vary in terms of the amount of propylene produced. For example, the cracking of natural gas liquid produces less propylene than the cracking of naphtha. This means that the rise in U.S. natural gas liquid production is slowing down the

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rate of propylene production. In contrast, China is ramping up propylene production and investing heavily in new facilities (CIEL, 2017).[1]

Once the plastic material is manufactured by polymer producers, it is distributed for use in a number of downstream industries, such as packaging, transportation, construction, industrial machinery, coatings, personal care products and textiles.

2.2 Petrochemical and fossil fuel linkages

The producers and consumers of plastic feedstock are not entirely distinct, with several large fossil fuel companies also having subsidiaries involved in plastic production (CIEL, 2017). For example, Shell, Chevron, BP, Sinopec and ExxonMobil are all involved in plastics at the production level to some extent. The integration between petrochemical and plastic producers goes the other way as well. For example, a major plastic producer, Dow Chemical Company, is also involved in producing petrochemicals. Thus, there are strong linkages at the production stage of the plastic economy, affecting the manufacturing of both ethylene and propylene.

These linkages have become more apparent in recent years as the fossil fuel industry experiences declining demand from other sectors, such as electricity and vehicles with internal combustion engines. Even prior to the Covid-19 pandemic, demand for fossil fuel was slow, at below 1% per annum (Roberts, 2020). As the world shifts to alternative energy sources, the fossil fuel industry seems to be hedging against future losses and pinning its long-term viability on the continued success of the plastic industry.[2] Currently, the petrochemical industry makes up only 14% of total global oil demand (Gardiner, 2019). However, it is expected to be the single biggest source of growth in demand going forward. To be specific, the International Energy Agency predicts that petrochemicals will account for nearly half of the growth in global oil demand between now and 2050 (IEA, 2018).[3]

It is these projections that are driving large investments in new plastic production facilities. For example, Shell has invested $6 billion in an ethane cracking facility in Pennsylvania. This is one of many recent investments by the industry to build a petrochemical corridor in Pennsylvania, Ohio and West Virginia

[1] China is currently the world's largest producer of plastic, making up roughly a quarter of total global output (UNEP, 2014).
[2] This is evident given the current fracking boom in the U.S. and the consequent fall in natural gas prices. Since fracking releases not only natural gas but also the feedstock for plastic (i.e., ethane), producers are seeking to cut losses experienced from fracking via this by-product (Gardiner, 2019).
[3] If current trends in global plastic production and consumption continue, it is anticipated that plastics will be responsible for 20% of total global oil consumption by 2050, up from 6% in 2016 (World Economic Forum, 2016).

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(Cunningham, 2019; Schneider, 2019). The fossil fuel industry's reliance on the future of plastic is also revealed by its lobbying efforts. The American Chemistry Council, on behalf of the fossil fuel industry, is lobbying the U.S. government to have Kenya remove its strict restrictions on plastic imports as negotiations continue regarding the U.S.–Kenya trade agreement. This is part of a broader effort by the industry to secure markets in Africa for plastic goods, as well as a destination for plastic waste (Tabuchi et al., 2020). These recent shifts within the fossil fuel industry toward plastics highlight the extent to which the futures of the fossil fuel and plastic industries are interdependent.

3. Why do we use plastic?

The versatility and attractive characteristics of different plastics — such as low cost, durability, lightness, strength, good thermal insulation and corrosion resistance — have made them beneficial across several industries and functions. This section reviews the positive impacts of plastics, as exemplified in three industries: food, medicine and transportation.

3.1 Food

One of the key benefits of plastic is visible in its use as packaging in the food industry. Plastic packaging keeps food safe from contamination and allows it to stay fresher for longer. This leads to positive public health implications and also helps to reduce food waste. For example, plastic is used in modified-atmosphere packaging that helps extend the shelf life of meat and vegetables. It is also used in systems designed to provide communities with supplies of clean drinking water (Andrady and Neal, 2009).

The role of plastic packaging in the context of food can be broken down into primary and secondary functions (Allen et al., 2019). The primary function is to protect the food from external sources of damage (chemical, biological and physical) and to keep it in a state fit for consumption for longer. This function largely depends on whether the food has its own natural protective layers. Hence, overpackaging is certainly a possibility.[4] The secondary function of the packaging is to relay information to the consumer about the product, such as information about food safety and nutritional value.

[4] Recent research also indicates there is room for improvement in packaging sustainability, particularly among small and medium-sized companies. Technological developments in packaging materials enable companies to reduce packaging while not reducing their shelf life. For example, a recent study found that there is potential to reduce the packaging weight of sliced bread by approximately 20% without affecting its shelf life (Licciardello et al., 2017).

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Plastic packaging has also increased consumer convenience with features that allow the product to be visible through the packaging, resealable and microwavable. These advances save both time and effort required in food preparation. Examples of products that have utilized plastic for added convenience include boil-in bags and packets of precut fruit and vegetables.

Despite the growing outcry over the need for less plastic packaging at the point of sale, it is likely that plastic has played a large role in the preservation of food at all stages of production. As food is transported from farms to factories to supermarkets, plastic is commonly used to protect against pests and diseases and increase shelf life. In fact, according to the United Nations Food and Agriculture Organization (FAO), insufficient plastic packaging and refrigeration generate significant food losses in developing countries. The FAO (2014) states that "huge resources that could otherwise be spent on more productive activities go into producing and transporting goods that only go to waste. Losses at almost every stage of the food chain may be reduced by using appropriate packaging." Thus, while there may be an argument for limiting excess plastic packaging, the material has been crucial in maintaining food security.

Finally, plastic has an advantage over alternative food packaging materials with respect to carbon footprint, including glass, canvas and paper. Because of plastic's light weight and high strength-to-weight ratio, less material is required (in terms of weight) to make the same product, and consequently, less has to be transported and disposed of at the end-of-life stage. Thus, plastic's lightness not only makes it a more economically efficient option for packaging, but it also reduces its impact on carbon emissions relative to alternatives. For example, lifecycle assessments have found plastic packaging to have lower global warming potential in food jars (Humbert et al., 2009), supermarket carryout bags (Edwards and Fry, 2011), and fruit shipment crates (Albrecht et al., 2013). Similarly, the plastic industry argues that the use of plastic in packaging, as opposed to other materials, reduces the weight of packaging by a factor of 3.6 and emissions by a factor of 2.7 (or 61 million tonnes of carbon dioxide equivalent, or CO_2e, per year[5]) (Brandt and Pilz, 2011). While there remains some debate between experts in the field regarding the assumptions underpinning these studies, the overall consensus in the literature is that, in many cases, plastic food packaging contributes less to carbon emissions than viable alternatives.

[5] "Carbon dioxide equivalent" is used to describe different greenhouse gases in a common unit. The CO_2e of a quantity of greenhouse gas is the amount of carbon dioxide that would have an equivalent global warming impact.

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3.2 Medicine

Plastic has been similarly helpful in pharmaceuticals and medical equipment thanks to its protectiveness. This includes blister-packed disposables, caps, bottles, bags and wraps, which keep substances free from contamination. Freinkel (2011) explains how plastic has been particularly useful in the case of storing donor blood. The first blood-collection bag was designed by American surgeon Carl Walter in 1949 using plasticized polyvinylchloride (PVC). This material was sturdy, did not contaminate the blood and allowed the necessary oxygen to disperse within the bag. Also, the flexibility of the bag meant it could be squeezed to release the blood faster and easily connected to other bags to separate the components of the blood in a sterile manner if necessary.

Plastic packaging also eliminates the need to put equipment through a long sterilization process before use, thereby reducing water usage, which is particularly advantageous for drought-stricken regions. Once packaged, this equipment can be easily transported and used for in-home care. In addition, the medical industry uses plastic widely for its equipment, due its lightness and adaptability. Thus, different polymers are used to make various medical items, including bedpans, gloves, syringes and bandages. The material is also frequently used in surgery in the form of plastic pacemakers, scaffolding and implants (Freinkel, 2011).

3.3 Transportation

Plastic's light weight has also led to its wide use in transportation. For example, it is used commonly for certain components in vehicles, with the aim of reducing weight and thereby atmospheric carbon dioxide emissions. Plastic now makes up approximately 20% of both public and private vehicles in the form of door liners, steering wheels and parcel shelves. One example of this is the Boeing 787 Dreamliner (rolled out in 2011), which has a 50% plastic interior, contributing to savings of approximately 20% in fuel costs (Andrady and Neal, 2009).

Plastics are also contributing to significant fuel efficiency with respect to automotive vehicles. In this sector, manufacturers have used plastics to replace several metal components that in some cases were more than double the weight of the plastic (Andrady and Neal, 2009).

Shredded plastic is also proving useful as a suitable material for roads. One notable example of this is a busy major road in Chennai, India, made of shredded waste plastic, which has maintained its durability over time — weathering monsoons, floods and heat waves. Since Jambulingam Street was developed 15

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years ago, the concept of roads made of plastic litter has become increasingly popular, and there are now more than 33,000 km of plastic road in India alone. A caveat, however, is that, as the road ages, it is more likely that plastic fragments will enter the surrounding soil and waterways as a result of weathering. Thus, strong oversight is needed to ensure that the quality of the roads is maintained (Subramanian, 2016).

3.4 Future benefits

With technological change taking place at an unprecedented rate, it is likely that plastic will play a crucial role in the creation of new applications going forward in both science and medicine. For example, there is much scope for plastic in new medical functions, such as in tissue and organ transplants. There will also be a role for plastic, as a lightweight material, in building more energy-efficient modes of transport (Thompson et al., 2009).

In addition, greater use of plastic is anticipated in construction for renewable energy systems designed to reduce carbon emissions. An example of this is modern solar water heaters that are made of plastics such as polyethylene (PE) and PVC. These provide households with up to 65% of their hot water usage. Plastics have been vital in driving these innovations given they are adaptable, have good heat insulation and are resistant to ultraviolet (UV) light (Andrady and Neal, 2009).

It is also expected that eventually smart plastic packaging will be created that will be able to monitor the quality of food, limiting food waste (Halonen et al., 2020).

4. What harm does plastic cause?

In this section, we discuss the negative impacts of plastic production and consumption, which can be divided into three categories: upstream, midstream and downstream.

4.1 Upstream impacts

Upstream impacts are impacts that occur at the production stage of plastic.

4.1.1 Virgin plastic pellets

Plastics that escape into and pollute the environment can generally be divided into two categories: macroplastics and microplastics. The National Oceanic and Atmospheric Administration (NOAA) (2020)

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defines microplastics as those less than 5 mm in length, while macroplastics are any plastics greater than 5 mm in length.

Common pollutants at the production stage are virgin plastic pellets, the starting point for most thermoplastics.[6] These pellets are formed in polymer production facilities and have a cylindrical shape with a diameter of around 2–5 mm. Hence, they are considered a microplastic. Once produced, the pellets are transported so that they can be made into the final item. Unfortunately, they are frequently lost due to mishandling at different stages of the process, deposited into rivers, estuaries or drains, before waves or wind eventually carry them into the open ocean and onto beaches (Karlsson et al., 2018).

Plastic pellets pose a threat to bird and marine species as they can damage reproductive behaviour and metabolism (Karlsson et al., 2018). Not only are the pellets themselves dangerous, but they also act as carriers of toxins (either in the form of chemicals in seawater absorbed by the pellets or the additives originally placed in the pellets). One study found that the levels of persistent organic pollutants (POPs) in plastic pellets were 107 times that found in seawater (Koelmans et al., 2016). However, the authors add that it is still unclear how the toxicity of these particles compares with other contamination to which bird and marine species are exposed in the environment.

Despite a growing public outcry for greater regulation and the development of international, regional and national regulatory frameworks, plastic pellet pollution remains a global issue. For example, it is estimated that between 5 billion and 53 billion pellets are emitted into the environment each year in the U.K. (Cole and Sherrington, 2016); 60% of the microplastic pollution sampled from the Rhine River in Europe comprised spherical pellets, most likely from plastic manufacturers located along the river (Mani et al., 2015); and plastic pellets were found on 92% of sandy beaches sampled in Brazil (Moreira, 2016). Karlsson et al. (2018) model the potential spread of pellets from an ethylene production facility in Stenungsund, Sweden. They estimate this single facility loses between 3 million and 36 million pellets annually. They also find evidence of spills around areas used by subcontractors of the plant, including transportation, storage and cleaning firms. They argue that these results are likely representative of those that occur in most other production facilities and predict that greater enforcement of the existing regulatory frameworks could substantially reduce the concentration of pellets in the environment.

4.1.2 Carbon dioxide emissions

Given the primary source of plastic is fossil fuels, considerable energy inputs are needed for plastic production, emitting carbon dioxide in the process. In 2015, the production of conventional fossil-fuel-

[6] A thermoplastic is a plastic that becomes pliable above a specific temperature and solidifies again upon cooling.

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based plastics emitted almost 1.8 billion tonnes of CO_2e, or 3.8% of total global greenhouse gas emissions (Zheng and Suh, 2019). If demand continues to grow at the current pace of 4% a year, emissions from the plastic industry will account for 10–13% of total global greenhouse gas emissions by 2050 (CIEL, 2019).[7]

It is also worth noting that the production and transportation phase of plastic tends to be the most emission-intensive, compared to other phases over the life cycle. In fact, out of the total greenhouse gas emissions from plastics, 60% is emitted during resin production or transport and 30% during manufacturing of the final product (Zheng and Suh, 2019). At the refining and manufacturing stages, the main energy- and emission-intensive processes are the chemical reactions, such as polymer cracking. Estimates suggest that the emissions from cracking will rise rapidly, as more than 300 petrochemical plants are set to be built in the U.S. alone over the medium term (CIEL, 2019).

However, while the size of carbon dioxide emissions from plastic production is substantial, this not only reflects the carbon-intensive nature of the production process, but also the fact that plastic represents a large portion of the global economy. Thus, it is important to consider the carbon footprint of the plastic industry against its alternatives, such as glass, paper and canvas. As discussed in more detail in Section 5 below, in most cases plastic fares better than viable alternative materials with respect to carbon intensity.

4.2 Midstream impacts

Midstream impacts are impacts that materialzie at the postproduction stage of plastic, where the plastic is being used by the consumer.

4.2.1 Chemical additives

One potential negative impact of the use of plastic comes from their chemical additives. Plastic products are rarely 100% plastic. Instead, manufacturers combine the basic polymer with certain additives to give the final product its desired qualities. For example, UV stabilisers may be added to prevent the plastic from breaking down in sunlight.

There has been an ongoing debate regarding the potential health consequences of additives, as some can seep out of the plastic.[8] Some researchers argue that there is limited evidence against additives (Andrary

[7] This estimate is contingent on the assumption that the increase in global temperature does not exceed 1.5°C (the maximum increase allowed under the goals of the Paris Agreement) or, in other words, that total global greenhouse emissions remain at 420–570 gigatons of carbon.

[8] Chemical additives also impact the upstream and downstream stages of the plastic life cycle. However, we choose to discuss them in the midstream stage, since much of the concern surrounding chemical additives is on human health impacts during the use of plastics.

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and Neal, 2009). For example, bisphenol A (BPA) is an additive used in polycarbonate plastics (often used for storing food). The use of BPA is controversial given it can harm hormones that are necessary for growth and development (Bauer, 2019). Nevertheless, several scientific studies show that the current amount to which humans are exposed daily is not problematic (Health Canada, 2012; FDA, 2014; EFSA, 2015). This includes an in-depth analysis by the U.S. National Toxicology Program in 2018 over two years. This study involved testing the effects of BPA exposure on rodents, and found that the average level of human exposure was not a public health concern (NTP, 2018).

Another potentially concerning group of additives are plasticizers. These are added to increase flexibility and durability in the final product, with the majority used in products made of PVC. The two most common plasticizers are phthalate and adipate. Several studies test the potential for chemical migration of these substances under different conditions. While some phthalates such as diisononyl phthalate (DINP) and diisodecyl phthalate (DIDP) are considered safe, others such as dibutyl phthalate (DBP) and diethylhexyl phthalate (DEHP) require risk-reduction measures, such as limiting the concentration by weight of the substance in plasticized material (Andrady and Neal, 2009). Li et al. (2016) test chemical migration in five phthalates used in disposable crockery. They find that the concentration of DBP and DEHP exceeded the limits established by some governments. DEHP is known to interfere with the production of masculinizing hormones, and even small quantities can reduce sperm production. Around 80% of Americans have measurable traces of DEHP and many are ingesting more than the Environmental Protection Agency (EPA) daily recommended amount (Freinkel, 2011).

There is also a lack of regulation around the use of chemical plastics additives, particularly in the U.S. Under the previous Toxic Substances Control Act of 1976, regulatory bodies had to prove whether a certain substance carried an “unreasonable risk” before they could request more information from the manufacturer about the specific chemical. This difficult standard of proof meant that more than 60,000 chemicals that had not undergone testing were allowed in commercial products (Scialla, 2016).

A new version of the bill, the Frank R. Lautenberg Chemical Safety for the 21st Century Act, came into effect in 2016 and demonstrates a push toward greater regulation. Under this bill, the EPA will be testing tens of thousands of chemicals, with a minimum of 20 at a time. However, according to Scialla (2016), the time given for testing and compliance with new rules means the process may take decades. Nevertheless, the bill makes it harder for manufacturers to keep ingredients confidential and requires states to uphold the EPA’s final ruling.

In addition, some manufactures have taken on a greater role in addressing the problems posed by chemical additives. For example, the Food and Drug Administration does not require that manufacturers

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label products containing DEHP, but some are doing so nevertheless. There has been significant pressure in this area in the medical equipment sector in particular. Initiatives such as Health Care Without Harm have been instrumental in influencing several bulk medical equipment manufacturers to produce goods that are DEHP-free (Freinkel, 2011).

4.3 Downstream impacts

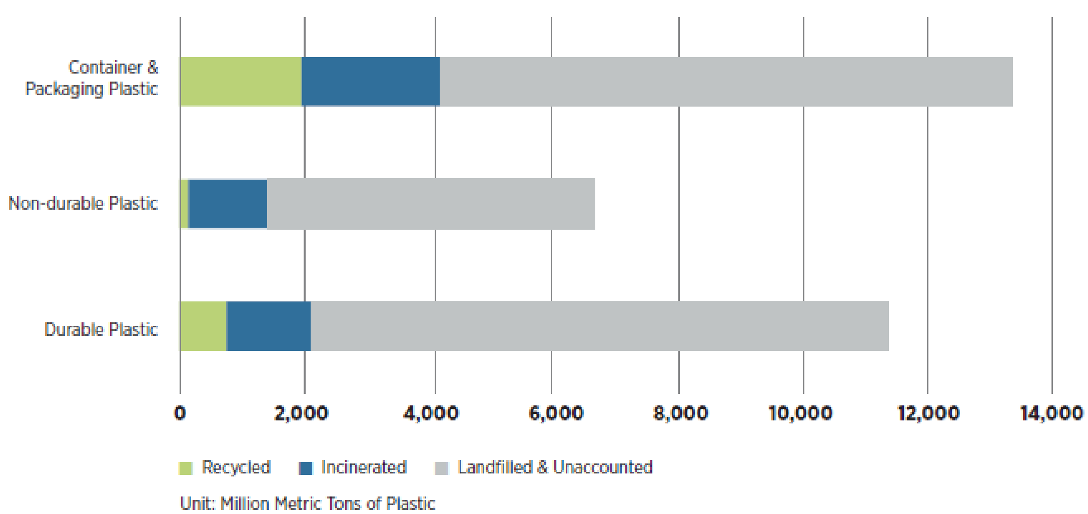
Downstream impacts occur after product consumption and vary by the method and location of disposal.

4.3.1 Waste management

One of the advantages of plastic is its longevity. However, this also means that plastic waste can take centuries to break down. Plastic makes up around 10% of the mass of the municipal waste stream. While it is a relatively small percentage by weight, it is a more considerable amount by volume (Thompson et al., 2009). Despite there being vast improvements globally in waste management, treatment and recycling over the last 30 years, most plastic waste is sent to landfills or incinerated. Europe, which is both a technologically advanced and relatively environmentally conscious region, sends about 50% of plastic to landfills (Hahladakis et al., 2018). Geyer et al. (2017) estimate that, as of 2015, approximately 6,300 million tonnes of plastic waste had been generated globally, of which 79% was sent to landfill, 12% was incinerated, and 9% was recycled. Figure 2 shows the disposal methods by type of plastic used in the U.S.

FIGURE 2

Method of disposal for different types of plastic in the United States (2015)



Source: CIEL (2019).

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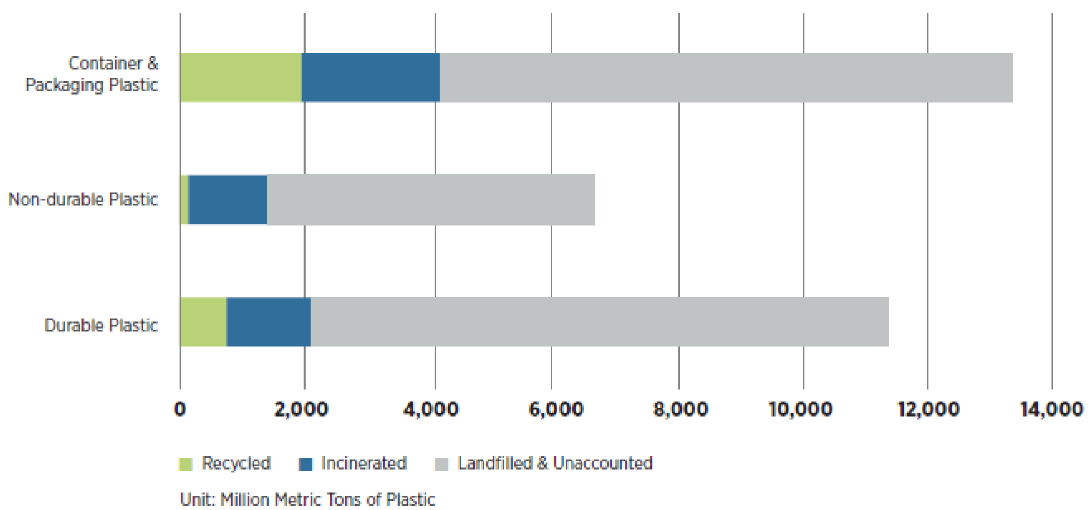
With respect to plastic packaging, a recent report by the World Economic Forum (2016) detailed that 95% of the material value of plastic packaging (approximately $80–120 billion) is lost annually. This is because, over time, it has become increasingly designed for single use, with added flexibility and multilayered materials, making collection, separation and recycling more complicated. As seen in Figure 3, 40% of plastic packaging went to landfill in the U.S. 2013, 14% was incinerated and 14% was recycled. The remaining 32% was unaccounted for.

FIGURE 3

Life cycle of global plastic packaging material (2013)



Source: World Economic Forum (2016).

The use of landfills is contentious, as some view it as a waste of resources or simply leaving the problem for later. Also, some countries are running out of landfill space (Robson, 2017; Paulo, 2020). An added issue is that of chemical additives such as plasticizers potentially leaching from landfills and contaminating soil and waterways (Teuten et al., 2009). Alternatives to landfill include recycling and energy recovery, which are discussed in greater detail in Section 5.

The cost of waste management itself is also considerable. Collecting waste can cost $20–250 per tonne, use of landfills can cost $10–100 per tonne and incineration with energy recovery can cost $40–200 per tonne (Hoornweg and Bhada-Tata, 2012). Governments may also need to reconsider waste management costs in light of China's Operation National Sword, which banned imports of low-grade plastic waste in January 2018. The policy bans 24 types of solid waste, including post-consumer plastics. Surrounding

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countries in the Asia-Pacific region, such as Vietnam and Thailand, subsequently announced their own restrictions on plastic imports (Staub, 2018). This particularly affects countries like the U.S. that have largely relied on exporting their low-grade plastic waste instead of using local waste management facilities (Lee, 2018). As a result, in some parts of the U.S. recycling programs have been halted altogether as local governments face higher costs from recycling companies seeking to minimize losses (Corkery, 2019; Rosengren et al., 2019). Thus, nations that previously exported their plastic waste may have to reconsider the cost of different domestic waste management methods, including landfill, incineration and recycling.

4.3.2 Management of plastic waste

The longevity of plastic has also intensified the issue of mismanaged waste, especially in developing countries where waste mismanagement has been an ongoing issue for decades. The poor handling of waste in these countries is often due to a combination of factors, including substandard waste management infrastructure, a lack of awareness about the public health implications of plastic, weak environmental regulations and poor living conditions (Adane and Muleta, 2011). Estimates by the United Nations Environment Programme find that 57%, 40% and 32% of all plastic is not collected in Africa, Asia and Latin America, respectively (UNEP, 2018). Consequently, in these regions plastic waste is gradually accumulating on shorelines and roads. Poor waste management systems have also meant that developing countries have become the largest source of land-based plastic entering the ocean (Jambeck et al., 2015).

The buildup of plastic waste in developing countries poses multiple public health concerns (Harvey, 2019). For one, the accumulation of plastic can block waterways, causing flooding. Furthermore, individuals also resort to burning plastic, as a cheaper alternative to kerosene, which can release harmful toxins. With the proliferation of mismanaged waste in many developing countries, local people have resorted to making a living as “waste pickers” by scavenging rubbish dumps. This exposes these individuals to possible health risks, such as injury from the landslides, fires and explosions that often occur at rubbish dumps due to the presence of gases. In addition, workers at these dumpsites are frequently exposed to harmful toxins.

While developing countries do tend to suffer from poorer waste collection infrastructure, developed countries and multinational corporations also share the blame for the rapid buildup of plastic waste in developing countries as they export large quantities of their plastic waste to these countries. The flow of plastic from developed to developing countries has only worsened since China’s Operation National Sword. Following this ban in 2018 on the vast majority of plastic being sent to China, countries such as

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the U.S. have begun redirecting a greater proportion of plastic waste to poorer countries such as Thailand, India, Indonesia and Senegal, which have less established waste management services (McCormick et al., 2019).

Nevertheless, there are signs of progress. In 2019, for example, the United Nations signed a landmark agreement under which 187 countries will be required to track plastic waste outside their own borders (UNEP, 2020). The deal further stipulates that exporting nations will have to obtain the recipient country's permission before sending contaminated plastic waste. Thus, the agreement seeks to make the global plastic trade more transparent, and improve health standards and environmental quality in developing nations (Holden, 2019).

4.3.3 Losses to the environment

Plastic waste that is not properly landfilled, incinerated or recycled escapes into the natural environment. Plastic contamination of the natural environment is a global issue, with 8 million tonnes of plastic entering the ocean every year (Balton et al., 2020) — 64% from macroplastics and 36% from microplastics. Table 2 displays the extent to which macro- and microplastic losses to the environment vary by source, as well as the type of polymers most commonly lost. The largest source of macroplastic loss is mismanaged waste (i.e., open dumping and inadequate landfilling), while the largest source of microplastic loss is car tire and brake abrasion (UNEP, 2018).

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TABLE 2

Microplastic and macroplastic losses to the environment

Loss source	Amount (million tonnes)	Share (%)	Polymer type
Total microplastic loss	5.27	63.6%	
Mismanaged waste treatment	3.87	46.7%	PP, LDPE and LLDPE, HDPE, PET, PP fibers
Littering	0.80	9.7%	PP, LDPE and LLDPE, HDPE, PET, PP fibers
Fishing nets	0.60	7.2%	Can quantify only polyamide (PA) fiber losses
Total microplastic loss	3.01	36.4%	
Microbeads	0.01	0.2%	PP, PE, HDPE, PA
Rubber from tire abrasion	1.41	17.1%	Elastomers
Weathering from marine coatings	0.05	0.5%	Unknown
Washing of textiles	0.26	3.2%	PP, PET, PA fibers
Road markings	0.59	7.1%	All types
City dust	0.65	7.9%	All types
Plastic production (pellets)	0.03	0.4%	All types
Total plastic loss	8.28	100.0%	

Source: UNEP (2018).

Marine plastic pollution, in particular, has become a global concern since the very first accounts were released of marine plastic debris in the stomachs of dead seabirds found on shorelines in the early 1960s (Harper and Fowler, 1987). Marine plastic debris can be generated at all stages of a product's life. It is the result of a number of factors, such as population density, tourism, port activities, solid waste management, management of dumpsites near coastal areas, management of plastic packaging waste, management of commercial and industrial waste, and management of agricultural waste (Mehlhart and Blepp, 2012). Although plastic pollution is an issue for many parts of the world, it is worth noting that more than 50% of marine plastic debris originates from just five developing countries — China, Indonesia, the Philippines, Vietnam and Sri Lanka (Abbott and Sumaila, 2019).

One study by UNEP (2014) estimated the natural capital cost of plastic use and the environmental damage it can cause.[9] It finds that the largest downstream cost associated with plastic is marine pollution, which

[9] Natural capital valuation is a means of expressing the financial cost businesses would incur were they to internalize the indirect impacts of their current plastic use. These impacts include those that occur upstream and downstream and are assessed by

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has a natural capital cost of $13 billion. This accounts for, on average, 17% of the total lifecycle impact of plastic. However, this is likely a severe underestimation, since the study focuses on direct plastic use and does not include certain impacts, including those caused by microplastics.

Marine litter has two main sources: land-based releases (land littering, leached sewage, or waste from open dumpsites carried over by wind or rainfall) and sea-based releases (spillages or dumping at sea by commercial fisheries and petroleum producers) (Hahladakis et al., 2018). Sea-based releases arise from the fact that the majority of fishing equipment (e.g., nets and ropes) are made from plastics such as PE and polypropylene (PP). Floats (an essential piece of equipment in fishing and aquaculture) are also made from plastic, specifically expanded polystyrene. It is estimated that 0.6 million tonnes of plastic nets and 303 tonnes of dolly rope are lost directly into the ocean per year (UNEP, 2018). The amount of marine plastic that is attributable to the fishing sector varies by location — in South Korea, for example, three-quarters of annual marine debris is made up of lost fishing equipment (UNEP and GRID-Arendal, 2016). While it is thought that weather and poor management of fishing gear are largely to blame, the causes of lost fishing gear are not well understood (Macfadyen et al., 2009).

Recreational fishing can also significantly contribute to marine debris, especially in areas in which it is popular. One such example is southern Norway, where recreational fishing leads to the loss of more than 2,000 lobster traps every season (recreational fishers represent around 80% of the Norwegian fishery) (UNEP and GRID-Arendal, 2016).

Since plastics are buoyant, ocean currents can then carry them several thousand kilometers. In fact, plastic accounts for 50–80% of shoreline debris, with some shorelines having more than 100,000 items per square meter. Under certain circumstances, plastics can also sink below the surface. In Brazil, for example, seabeds in shallow areas were even more contaminated than the shorelines nearby (Thompson et al., 2009).

Data collected from beach litter cleanups over the past 25 years show that the majority of marine macroplastic debris comes from short-lived consumer goods or fishing/marine activities (Ocean Conservancy, 2011). These products include plastics such as PP, low-density polyethylene (LDPE), high-density polyethylene (HDPE) and polyethylene terephthalate (PET). Table 3 shows the distribution of macroplastics by type among beach litter in 2011.

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employing lifecycle analysis techniques. However, UNEP (2014) note that the upstream costs are documented more consistently, whereas there is an absence of robust data and scientific research with respect to downstream and midstream costs.

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TABLE 3

Most commonly observed macroplastics found in beach litter samples by Ocean Conservancy (2011)

Macroplastic type	Number of items found
Food wrappers/containers	14,766,533
Caps and lids	13,585,425
Beverage bottles	9,549,156
Plastic bags	7,825,319
Straws and stirrers	6,263,453
Rope	3,251,948
Clothing and shoes	2,715,113
Toys	1,459,601
Fishing line	1,340,114
Plastic sheeting/tarp	1,298,171
Balloons	1,248,892
Fishing nets	1,050,825
Bleach/cleaner bottles	967,491
Six-pack holders	957,975
Oil/tube bottles	912,419
Buoys/floats	823,522
Strapping bands	801,886
Condoms	623,522
Bait containers	382,811
Crab/lobster/fish traps	314,322
Crates	313,997

Source: Ocean Conservancy (2011).

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Beach litter cleanups themselves also represent a cost in terms of the time spent by volunteers. The Alliance for the Great Lakes reported that, in 2012, the value of time spent by volunteers cleaning up beaches around the Great Lakes was more than $250,000 (Driedger et al., 2015). Another study conducted for the EPA found that communitieson the west coat of the U.S. spend roughly $13 per inhabitant annually on beach (and other waterway) cleanups, storm-drain cleaning, picking up litter and anti-litter campaigns (Stickel et al., 2012).

In terms of microplastics, the largest sources are abrasion of tires and city dust. Microplastics are also found in cosmetic and personal care goods, in the form of microbeads and microfibers. Given their size, microplastics can easily disperse and travel far, carried by the wind and ocean currents. Brahney et al. (2020) found microplastics in 98% of samples taken from remote and protected conservation areas in the U.S., and they have even been found in Antarctic waters (Hahladakis et al., 2018). Data collected from shorelines, oceans and deceased marine life show that microplastic levels are gradually rising. Microplastics commonly form as a result of mechanical and chemical deterioration over time due to exposure to sunlight, wind and water. They can also be directly released from domestic and industrial cleaning products and spillages of plastic pellets and powders, as discussed above.

Another source by which microplastics enter the environment is through the washing of cosmetics, personal care products and textiles (UNEP, 2018). For instance, microfibers made up the majority of synthetic materials found by Brahney et al. (2020) in protected conservation areas, with fiber composition consistent with those of textiles used for clothing. An efficient method to limit the amount of microfibers in wastewater is via wastewater treatment plants, which remove 65% and 92% at the primary and secondary treatment stages, respectively (UNEP, 2018). Unfortunately, the extent to which people are connected to such treatment plants varies from 3% in Africa to 92% in western Europe. Once microplastics are removed from wastewater, the wastewater sludge is either deposited in landfill, used as fertilizer, incinerated or used for composting. These processes may result in a small quantity of microplastics entering the environment, particularly through sludge when it is used as fertilizer (UNEP, 2018).

4.3.4 Wildlife

Perhaps the most widely publicized impact of plastic litter is that on wildlife, either through ingesting plastics or getting entangled in them. This can impair movement, inhibit reproductive systems and cause cuts, ulcers and death. The Ocean Conservancy reported that, in 25 years of international coastal cleanups, the majority of the 4,073 identified cases of animals injured by marine debris were from fishing lines (1,636 cases), fishing nets (672 cases), ropes (426 cases) and plastic bags (404 cases). Thus,

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discarded fishing equipment (which is designed to kill marine animals) and plastic packaging seem to be the most problematic for wildlife (Ocean Conservancy, 2011).

Marine animals affected by plastic often go unnoticed, as they either sink to the ocean floor or are eaten by other animals. In addition to the lack of adequate data collection, it is hard to identify clear historical trends in the rates of ingestion and entanglement due to population changes and varying impacts between species (Ryan et al., 2009). Many species of marine life are victims of plastic debris, with seabirds that feed at the ocean surface being particularly susceptible. For instance, a study found that all of the northern fulmar (*Fulmarus glacialis*) carcasses that were tested had accumulated some quantity of plastic in their stomachs (Balton et al., 2020). To date, there are records of more than 260 species that have been impacted by plastic debris, including turtles, fish, seabirds and mammals. It is worth noting that different plastic goods are problematic for different species, given that they resemble the specific food the animals eat. For example, clear plastic bags are a particular issue for sea turtles, which normally feed on the jellyfish they resemble (Gregory, 2009).

Heavier plastic marine debris is also damaging, given that more than two-thirds of plastic ends up on the ocean floor (UNEP, 2005). For example, most modern fishing nets are made of plastic nylon, which has a greater density than water. Thus, when nets are lost, discarded or abandoned, they often sink, damaging fragile reefs and marine life that exist deeper in the water (UNEP, 2014).

Plastic marine litter can also be a vehicle for carrying toxic substances into the food chain (Mato et al. 2001; Teuten et al. 2009). For one, it can act as a vessel to transport non-native species, where the longevity of plastic provides time for the organisms to mature during transport. Second, plastic may carry toxic chemicals that can penetrate cells and damage endocrine systems in animals. These chemicals can either be a part of the plastic itself or absorbed into the plastic.

In addition to oceans, plastic also contaminates natural terrestrial and freshwater habitats. For example, sewage sludge has the potential to contaminate soil, and plastic fragments are often carried into freshwater sources by rainwater. More research is needed to better understand the impact of plastic contamination on these two habitats (Thompson et al., 2009).

4.3.5 Carbon absorption and sequestering

Microplastics may have the capacity to diminish the ocean’s ability to absorb and sequester carbon dioxide (CIEL, 2019). Since the advent of industrialization, oceans have absorbed 20–40% of anthropogenic carbon emissions. This is largely thanks to phytoplankton and zooplankton, which capture carbon and prevent it from returning to the atmosphere. However, laboratory experiments suggest that

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microplastics may interact with phytoplankton and zooplankton in such a way that inhibits the organisms' carbon-sequestering abilities. It is worth noting that research in this field is still ongoing (Cole et al., 2016).

4.3.6 Fishing, tourism and recreation

In addition to its impact on wildlife, litter can damage fishing, tourism and recreation industries, especially in coastal regions. Beaumont et al. (2019) estimate the economic cost of marine plastic in terms of marine natural capital. They postulate that the fall in annual marine ecosystem service delivery as a result of plastic is between 1% and 5%, using 2011 estimates of the existing stock of plastic in the oceans. This equates to an annual economic loss of between $500 billion and $2,500 billion.

In terms of tourism specifically, a recent study funded by the NOAA's Debris Division examined the effect of increasing marine debris waste on the recreation gained by beachgoers and the economic consequences of reduced tourism (NOAA, 2019). They focused specifically on four coastal regions within the U.S., and found that doubling the quantity of marine debris on beaches reduces the number of days tourists are willing to spend at the beach. For example, on Lake Erie beaches in Ohio, they anticipate that doubling marine debris will lead to 2.8 million fewer visitor days per year and an associated fall in recreational value of $84 million. They found a similar relationship between marine debris and beachgoers at the other sites, with a doubling of debris reducing annual recreational value by $32.3 million in Alabama, $140.9 million in Delaware and Maryland, and $275.1 million in Orange County, California. This study also estimated the impact that changes in marine debris levels would have on regional economies. It found that reducing marine debris to almost zero would increase economic activity (measured as the valued added) by $29 million in Alabama, $27.8 million in Delaware and Maryland, $206 million in Ohio, and $137.8 million in Orange County, California. Thus, this study provides evidence of a strong relationship between the amount of marine debris on beaches and the recreational value of beachgoers, as well as on regional economies.

Other studies have found that ocean debris in general has a direct negative economic impact on fishing, tourism and recreation. For example, the Asia-Pacific Economic Cooperation believes that the cost of ocean debris to fishing, shipping and tourism industries in this region is $1.3 billion per year (McIlgorm et al., 2008). In Scotland, the estimated cost of marine litter is $26.9 million per year (Potts and Hastings, 2011). In response, regions that are particularly reliant on fishing, tourism and recreation may have to incur higher costs to remove marine debris. For instance, municipalities in Spain, Portugal and the Netherlands spend $43,000–77,000 per kilometer per year to clean up marine debris from recreational beaches (Werner et al., 2016). Similar expenses are seen in other coastal regions, such as the archipelago

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of Svalbard, which increased funding directed toward debris cleanups from $2.15 million to $30.1 million between 2016 and 2018 (Abate et al., 2020). In the U.S., communities along the west coast spend more than $520 million per year in efforts to reduce marine debris (Stickel et al., 2012).

When it comes to the fishing industry, a common cost caused by plastic debris is damage to vessels. For example, plastic debris can get caught in ship propellers, damage driveshafts, foul anchors and clog intake pipes (McIlgorm et al. 2008, Arabi and Nahman, 2020). This imposes a financial burden on the shipping and fishing industries, particularly through replacing damaged or lost gear and the potential of reduced fishing time and catch. Such losses can be substantial. For instance, a study into the impact on Shetland fishing boats in Scotland found that marine debris can cause damage of up to $45,000 a year per vessel. Similarly, a 2002 U.K study found that the fishing industry incurs losses of more than $31 million per year due to marine debris (UNEP and NOAA, 2011). A study conducted on Hong Kong's high-speed ferry network estimated that marine debris leads to losses of approximately $19,000 (McIlgorm et al., 2008). These cleanup operations can also be costly for harbors — for example, harbors in the U.K spend approximately $2.6 million annually in marine waste removal efforts. Likewise, the Port of Barcelona in Spain spent roughly $330,000 in 2012 alone carrying out daily debris removal (Werner et al., 2016).

The fishing industry is further impacted when plastic waste restricts the size of the catch due to litter accumulating in nets. A study on Scottish fishing boats found that litter was ending up in the nets of 86% of vessels, at a cost of between $12.8 million and $14.2 million per year (approximately 5% of total annual revenue for affected fisheries) (Oosterhuis et al., 2014).

5. What are the alternatives to plastic?

As discussed above, the use of petrochemical-based plastics has a number of associated costs and benefits, which vary depending on the physical and chemical properties of the plastics themselves. Recently, a number of potential plastic alternatives have been developed, with the aim of matching the physical characteristics of plastics while contributing less to the problem of waste generation. It is important, however, to compare these materials alongside plastics on a range of factors. In addition, this section will consider alternative disposal methods for plastic besides landfill.

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5.1 Biodegradable plastics

A key negative impact of conventional petrochemical-based plastics is their long lifespan and subsequent accumulation in either landfills or the natural environment. One alternative is biodegradable plastics (BDPs). BDPs are plastics that can decompose through the actions of microorganisms. They can be either bio-based or petrochemical-based, with the former being made from natural raw materials (such as starch and cellulose) and the latter deriving from petrochemicals. Hence, bio-based BDPs are renewable, while petrochemical-based BDPs are not. Many BDPs commonly used today contain both the bio-based and petrochemical-based versions for the purposes of cost reduction and performance enhancement (Song et al., 2009).

Manufacturers have designed a range of different BDPs to match the functionality of different conventional plastics based on their various applications. Thanks to technological advancements, many of these polymers can now be produced on an industrial scale. Nevertheless, BDPs are still costly to produce and make up less than 1% of all plastics (Thompson et al., 2009). For example, burger boxes that are made from sugarcane cost twice as much as those made out of polystyrene. Similarly, forks made out of starch cost 3.5 times as much as a basic PP fork (Gray, 2018). Most BDPs are more expensive partly because they have a higher density than conventional plastics.

BDPs enable composting as a potential option for end-of-life waste treatment. Composting is a way to recover waste material, to produce a useful product as compost and to reduce the concentration of plastics in landfills. This is amid some countries running out of space in landfills and growing public concern about toxic materials leaching out of landfills (Thompson et al., 2009). Consequently, BDPs are most commonly found as replacements for conventional plastics in disposable and single-use goods. These include items such as trays, bottles, pots, cutlery, bags, agriculture mulch films and diapers. Not only does composting plastics have the potential to reduce space in landfills, but it also allows waste to be transformed into a useful product for agriculture. Furthermore, it can encourage increased composting of other bio-based waste generated, such as food scraps. This is useful given that more than half of municipal solid waste is organic (either food waste or garden waste) and can be composted (Song et al. 2009; Thompson et al. 2009).

However, not all BDPs can be composted in the same manner. Some biodegradable polymers can be broken down only in an industrial composter, whereas others can also be broken down in a home composter. Therefore, the waste of BDPs must be managed appropriately in ways that use their respective features. Song et al. (2009) provide the example of highly perishable goods wrapped in biodegradable

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plastic, for which it may be necessary to dispose of the good with its unopened packaging. They show that home composting of such a polymer would be extremely slow. Instead, industrial composting at 50°C for about 12 weeks proved ideal for generating compost.

One drawback of BDPs is that appropriate management of the waste material must be ensured in order for the benefit of biodegradability to become manifest. Song et al. (2009) state that managing BDP waste using recycling is not viable because, even though it is possible to recycle it without compromising its chemical and physical properties, the lack of supply makes the process cost-inefficient for most existing recycling plants. Sending BDPs to landfill is also unsuitable because, as they undergo anerobic decomposition, they release methane (a greenhouse gas 25 times more potent than carbon dioxide) into the environment. Incineration with energy recovery at the end-of-life stage could be a viable option, but there is still need for research into the value of energy recovery from BDPs.

Song et al. (2009) stress that the transition to increased BDPs requires that governments put in place robust information campaigns to ensure that the public is sufficiently aware about labeling systems, separation procedures and collection of these materials. There is also a need for public awareness around the difference between home composting and industrial composting, since some BDPs meet only the standards necessary for the latter.

Additionally, BDPs are not a viable solution to the problem of plastic marine debris. A common myth is that, given their ability to break down, BDPs represent a solution to the plastic that accumulates in marine environments. Unfortunately, however, these materials degrade only under specific conditions and are not necessarily more likely to degrade in marine environments than traditional plastics (Thompson et al., 2009).

Thus, given the costs of, and need for, technological and public information investments, the benefits of BDPs (i.e., decreased space in landfills and generation of compost) are not widely realized.

5.2 Recycled plastic

As discussed earlier, another alternative to using conventional plastics and sending them to landfill is to recycle them instead. Recycling can be broken down into four categories, all of which are used around the world to some extent (Hopewell et al., 2009):

1. Primary — recycling into a product that has the same properties (i.e., closed loop)
2. Secondary — recycling into a product that requires lower properties (i.e., downgrading)

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3. Tertiary — recovering the chemical constituents of the material (i.e., chemical or feedstock recycling)
4. Quaternary — recovering energy.

At its core, the recycling of plastics is about changing the perception of discarded plastics from waste materials to raw materials. As described by Thompson et al. (2009), most plastic production is linear — petrochemicals are eventually transformed into plastic waste. Recycling, on the other hand, adopts a circular usage. Not only does recycling reduce the need for nonrenewable resources, but lifecycle analyses have shown that 100% recycled PET bottles can reduce carbon dioxide emissions by 27% over virgin PET bottles (Thompson et al., 2009). However, even though PET is recycled more than any other type of plastic, almost half of all PET is not recycled and only 7% is recycled bottle to bottle (World Economic Forum, 2016).

When it comes to recycling plastics, one issue is the presence of additives. Thus, while closed-loop recycling is theoretically possible for many thermoplastics, the widespread use of chemical additives, especially in plastic packaging, makes this process complicated (Hopewell et al., 2009). As a result, products such as PET bottles are more suited for primary recycling, as all PET bottles require a similar grade of plastic. Similarly, pre-consumer packaging tends to be recycled more than post-consumer packaging, as it contains fewer impurities. Also, the volume of post-consumer packaging is five times that of pre-consumer packaging, so large volumes would need to be collected to achieve high recovery rates.

Another challenge for recycling is that, due to their unique molecular structure, most plastics are miscible only with themselves. For example, even a small quantity of PVC will contaminate a PET-recycling stream, as the presence of PVC will generate hydrochloric acid gas, degrading the PET. On the other hand, if a small amount of PET contaminates a PVC-recycling stream, lumps of solid, crystallized PET will form in the recycled PVC. This not only compromises the quality of the recycled product, but also its market value (Hopewell et al., 2009).

Since some recycled plastics cannot be used for their original applications, an alternative is to downgrade them to make goods that require fewer properties (Hopewell et al., 2009). For example, the HDPE in bottles can be recycled to make plastic crates. This is secondary recycling.

Alternatively, tertiary recycling involves obtaining the chemical components of the plastic to make a feedstock, from which “new” plastics can then be manufactured. Essentially, the material is depolymerized and then repolymerized. However, this process is not currently economically viable given that it must compete with the extremely affordable virgin plastic resin (Hopewell et al., 2009).

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One drawback of plastic recycling is that several potentially toxic substances (PoTSs), such as toxic metals, brominated flame retardants and POPs, may be released during the process. This is more of a concern in developing countries where waste collection and sorting are less stringently managed. The presence of these substances can also degrade the quality of the final recycled product. This may be a further concern if imported products potentially containing PoTSs end up in the recycling stream (Hahladakis et al., 2018). Thus, if plastic recycling is not overseen via an appropriate regulatory framework, the risk of harmful substances contaminating even more sensitive goods, such as food containers, is higher.

Hence, the use of recycling largely depends on how uncontaminated the feedstock is, the quality of recycling infrastructure in the country and the properties required in the intended good. For example, goods that can be easily sorted out of comingled waste, such as PET bottles and HDPE milk bottles, are more easily recycled. Thus, care must be taken at the post-consumer stage to ensure proper collection, separation and cleaning (Hopewell et al., 2009).

Balton et al. (2020) provide an example of a successful recycling system, the Icelandic Recycling Fund (IRF), which uses financial incentives to increase recycling rates. Under the system, fisherman can return equipment such as nets and ropes to specific collection points without having to pay a fee. This gear is then recycled. The IRF has also taken steps to increase awareness among fisherman about the risks of marine plastic pollution.

5.3 Energy recovery by incineration

Another alternative to landfill is to recover energy via incineration (quaternary recycling). In many developed nations, using energy recovery for plastic waste is more common than other forms of recycling. For example, in Europe 39.5% of plastic waste is sent for energy recovery, compared to 29.7% for recycling (Hahladakis et al., 2018). This process, however, does not alter the need for raw materials at the input stage and is thus considered less energy efficient than recycling (Thompson et al., 2009). There is also the added concern of carbon emissions from the incineration process, as well as the risk of hazardous substances such as POPs and acid gases being released during uncontrolled combustion (Hahladakis et al., 2018). For example, in 2015 incineration of plastic packaging alone generated 16 million tonnes of CO_2e (CIEL, 2019).

5.4 Non-plastic materials

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When seeking alternatives to virgin plastic, it is important to consider non-plastic materials, such as canvas, paper and glass. Studies have compared the carbon footprint of plastic against these alternatives across a range of products, many of which find that plastics fare better than viable alternatives (Humbert et al., 2009; Brandt and Pilz, 2011; Albrecht et al., 2013). One such study by the U.K. Environment Agency conducted lifecycle analyses of supermarket carryout bags, comparing a conventional lightweight plastic bag, a lightweight plastic bag with an additive that breaks the plastic down into smaller components, a biodegradable bag made from starch, a paper bag, a thicker plastic bag, a heavier non-woven plastic reusable bag and a cotton bag (Edwards and Fry, 2011). The main aim of the study was to estimate the number of times each bag would have to be used in order to have a lower carbon footprint than that of the conventional lightweight plastic bag. For each bag, the authors considered the following stages of the life cycle:

1. Extraction of resources and production of the raw material, accounting for material use, energy use, emissions and waste generated
2. Packaging
3. Conversion of raw material into carrier bags
4. Transportation of raw materials to the bag manufacturer
5. Distribution of finished bags
6. Transportation by municipal waste collection vehicles to waste management facilities
7. End-of-life process.

The authors found that the paper, heavier plastic and cotton bags would have to be reused 3, 11, and 131 times, respectively, to have a lesser impact on global warming in comparison with a conventional lightweight plastic bag used one time.

The benefits of plastic relative to alternatives are also visible in terms of transportation infrastructure, mainly due to the material's light weight. For example, the aircraft and motor vehicle industries have embraced replacing metal parts with plastic parts — where replacing aluminum with plastic generates fuel cost savings of approximately 20–30%. The exterior of the Boeing 787 Dreamliner, rolled out in 2011, is 100% plastic composite and the interior is 50% plastic composite. Similarly, the average amount of plastic in a light vehicle has increased to approximately 12% of its total weight (Andrady and Neal, 2009).

Energy savings have also been found for plastics compared to other materials. For example, one study compared energy use when manufacturing disposable polystyrene cups against reusable ceramic cups.

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After including energy expended in cleaning, the authors found that a ceramic cup would have to be reused 500 times to match the energy use associated with a polystyrene cup (Hocking, 2006).

Compared to other materials, plastics also benefit from their high strength-to-weight ratio, which minimizes the quantity required to achieve a desired strength (Andrady and Neal, 2009). Plastic packaging, for example, makes up around only 1–3% of the final product's weight. Table 4 displays the amount of plastic required to package various quantities of common items:

TABLE 4

Amount of plastic required to package items of different sizes/volumes

Item	Amount of plastic packaging required	Plastic packaging share of total weight
200g of cheese	2g of plastic film	1.0%
1.5L of liquid	38g plastic bottle	2.5%
125g of yogurt	4.5g plastic tub	3.5%

Source: Andrady and Neal (2009).

However, it is important to note that lifecycle assessments do not take into account the fact that, if the plastic is replaced by alternatives, there may be changes to the design, function and service of the product that can impact energy use and emissions. Moreover, studies also often fail to consider the costs associated with plastic waste in the natural environment, such as losses to tourism, impacts on marine life and cleanup efforts. Thus, when considering the environmental impact of plastic against its alternatives, the benefits of reducing plastic waste and litter must be weighed against the costs of increased carbon emissions from heavier alternatives.

6. What policies work for reducing plastic use and pollution?

The adoption by 187 nations of the United Nation's 2019 Basel Convention amendments,[10] aimed at enhancing control of the transboundary movements of plastic waste (UNEP, 2020), shows that there is broad international agreement that current plastic consumption and management are suboptimal for

[10] The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal is the only global, legally binding instrument to specifically address plastic waste (UNEP, 2020).

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economic and environmental wellbeing (Borrelle et al., 2017). Policies designed to address failures in plastic markets may help. In this section, we first identify three key market failures in plastic markets. We then characterize the consequences of these market failures over the short run and long run. Next, we group potential stakeholders in plastic policy. Finally, we link plastic policies to these market failures and the plastic life cycle.

Plastic policy can target three main types of market failures. First, there is an incomplete information failure. This report has highlighted a need for more data and scientific research on the impacts of plastic, especially its downstream impacts as waste and pollution. Incomplete information makes policy targeting and cost–benefit analyses highly imprecise. Second, as documented in this report, there are costs from plastic consumption to humans, organisms and ecosystems that do not produce or consume plastic. These external costs are not reflected in market prices and create a second market failure, a negative externality. Finally, as with carbon emissions, plastic pollution crosses jurisdictional boundaries. In the few cases where the right to a maximum level of plastic in water, food and air has been established and producers and retailers are liable for exceeding these levels, they lack global property rights. Together, these three market failures create a public goods problem that cannot be solved without coordination, as with global climate change resulting from carbon dioxide emissions. Public goods problems occur when production or use is unregulated and property rights to regulate use do not exist.

In the short run, the consequences of these three market failures are excess plastic pollution and policy holdup from uncertainty surrounding the plastic life cycle and its costs. Over the long run, without policy intervention there are more consequences: producers fail to invest in research and develop few alternatives (Jaffe et al., 2005), and they lock in their production processes to low-cost plastic, making plastic pollution abatement more costly in the future.

As discussed throughout this report, there is a wide, diverse chain of actors affecting upstream, midstream and downstream plastic. A greater number of actors makes it more difficult to coordinate policy (Coase, 1960). When considering how to coordinate action and reduce plastic at each stage, a useful typology is to consider public and private actors. Public actors are those imbued with some kind of sovereign authority. They occur at different governance scales, e.g., local, state, national and international. Private actors span many groups, e.g., firms, communities, consumers, NGOs and researchers. Table 5 provides examples of policy alternatives by type of actor. The top panel describes public policies and the bottom panel private actors' policies.

Public policies mostly address market failures directly. They can create property rights, and thus legal standing for producer or state liability, as in the case of the UN Basel Convention (UNEP, 2020).

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Reclassification of plastic as a pollutant, as seen in California's "Trash Amendments," has a similar effect by establishing the public right to a maximum level of plastic pollution in water (California EPA, 2020a). While these policies directly address property rights, they indirectly affect external costs and information failures. They create incentives for better monitoring and reduction of plastic waste through liability. Take-back mandates, such as the European Union's extended producer responsibility (Walls, 2006), make firms responsible for their waste. This shifts the costs of pollution management from states and municipalities to firms. In response, firms may change the design of their product to reduce and recycle plastic, as well as change plastic management midstream, during consumer use.

In contrast to policies that target property rights, classic environmental policy tools used to regulate water and air pollution can also be applied to plastic markets: minimum quality standards, bans, taxes and subsidies. In the context of plastics, minimum quality standards for yarn and fiber to reduce fraying would reduce external costs from microfibers. They would also indirectly create a consumer right to fabric that meets these minimum standards. Bans lower external costs by reducing the quantity of plastic consumed and redistribute rights in a similar way, shifting them from producers to consumers. Examples of these types of bans include the U.S. federal microbeads ban (2015), the California pellet waste ban (California EPA, 2020b), bans on smoking cigarettes on beaches (California Senate, 2019), polystyrene bans (Wagner, 2020) and bans on disposable plastic bags (Homonoff et al., forthcoming). Import bans, such as China's Operation National Sword, work differently. In this case, regulation is incomplete, meaning plastic exporters can shift their exports to other countries, which they are expected to do (Brooks et al., 2018).

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TABLE 5

Policies to address plastic waste, by sector

Policy type	Example
Public: multilateral, national, state, and local	
Property rights and liability	2019 UN Basel Convention
Reclassification as pollutant	California drinking water standard
Extended producer responsibility	Take-back mandates
Minimum quality standard	Yarn and fiber
Ban	Microbeads, pellet waste, bags
Subsidy	Avoid plastic films in agriculture
Tax	Tax on plastic bags
Information campaign	Littering notices, ag extension
Investment — research	Public grants
Investment — management	Korea trash boom
Pollution monitoring	California drinking water
Information sharing	Intergovernmental, public–private
Private: firms, communities, NGOs, consumers, and researchers	
Voluntary pledge by firm	Pledge to phase out microbeads
Voluntary use of alternative input	Diageo cardboard packaging
Behavioral nudge	Consumers must request a plastic straw
Industry initiative	Operation Clean Sweep
Investment	Tetra Pak closed loop
Eco-label	DIN-Geprüft Biobased certification
Private good	Filter for washing machine
Firm marketing and branding	Refill Shoppe
Coordinated public action	Beach cleanup
Media campaign/education	Garbage patch on social media
Boycott	Beat the Microbead campaign

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Price instruments like taxes and subsidies indirectly change the quantity of plastic waste. In agricultural contexts, subsidies might be more effective in reducing the use of plastic packaging and films, whereas taxes might be better suited to addressing waste from bags and bottles in cereal crop production (De Lucia and Pazienza, 2019). In the case of disposable plastic carryout bags, it has been shown that taxes and bans reduce their use (Taylor and Villas-Boas, 2016; Homonoff, 2018). However, bans can also have unintended consequences, some of which reduce their effectiveness at reducing plastic waste (Taylor, 2019; Homonoff et al., 2021). Governments can combine taxes and subsidies in order to encourage consumers to recycle plastic items, such as deposit-refund programs for plastic beverage containers (i.e., bottle bills). These programs charge consumers a deposit (i.e., a tax) for each plastic beverage container they purchase and then refund these deposits (i.e., a subsidy) if consumers return the containers to a certified redemption center (Berck et al., 2020).

In addition to changing prices and reducing plastic consumption, taxes may also serve as an information tool, changing attitudes toward plastic pollution and increasing support for other policies (Thomas et al., 2019). They complement more formal information tools, such as agricultural extension to increase awareness of plastic pollution or a proposed New York Assembly bill (2017), which would require a label that a garment contributes to microplastic pollution if it is made with more than 50% synthetic material.

Some policies target incomplete information failures. For example, through its State Science Information Needs Program grants, California incentivized university research on microplastic pollution within the California State University system to address incomplete information (CSU COAST, 2020). California also mandated monitoring of microplastic pollution in drinking water in Senate Bill 1422, which included the development of both a protocol for testing water and standard measures of microplastic pollution (California Senate, 2018). Information sharing among public actors, coordinated in policies such as the Regional Seas Conventions, can also address information failures (da Costa et al., 2020).

Private policies are those policies initiated and implemented by actors outside the public sector, mainly communities, NGOs and firms. They work through three main channels: transforming demand, changing consumption costs, and strategic firm initiatives that in some cases may anticipate and weaken future public policy.

Among the policies listed in the bottom panel of Table 5, several may reshape the way consumers value plastic products. There are two main channels, which may interact: correcting asymmetric information between consumers and firms, and changing consumer preferences. Correcting asymmetric information can be done through a firm's marketing, or even form a cornerstone of the firm's brand, as in the case of

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the Certified B Corporation the Refill Shoppe, a store specializing in bulk refill of existing containers for cleaning and beauty products (Ballestreros-Sola et al., 2020). Another credible way to inform consumers about plastic content is by satisfying the requirements of an eco-label. For example, DIN CERTCO's DIN-Geprüft Biobased certification (2020) independently verifies the share of a product that is bio-based.

Alternatively, a firm, NGO or community may transform demand by changing consumers' willingness to pay for a product. This can be done by educating consumers on plastic content and risks from plastic pollution, as was the case in the Beat the Microbead campaign in response to plastic microbead pollution (Dauvergne, 2018). To reduce plastic pollution, this policy tactic should decrease demand for products containing plastic and increase demand for products without plastic. However, campaigns do not reach all consumers, and thus they risk making plastic demand more elastic. This can have the unexpected effect of increasing plastic pollution, as in the case of the immediate response to the microbeads boycott (Doremus et al., 2019). Beach cleanups, organized by NGOs, may both reduce plastic pollution and educate consumers, potentially changing their preferences for plastic goods.

Other policies available to private actors include those that change consumers' cost to consume plastic. This could be a firm implementing a charge on disposable plastic bags or a subsidy on reusable bags, independent of regulation (Penn et al., forthcoming). However, it has been shown that subsidies are ineffective at encouraging consumers to forego disposable plastic bags (Homonoff, 2018), resulting in many retailers rolling back these incentives. Thus, in the instance of disposable plastic bags, sticks (charges) are more effective than carrots (bonuses). Similarly, firms might change consumers' default choice, as in the case of a restaurant that makes plastic straws available on request, instead of de facto (Wagner and Toews, 2018). Behavioral "nudges" might work similarly, by thoughtfully presenting the choices people make, taking into consideration fast decision-making (Thaler and Sunstein, 2009). For plastic, an example of a policy nudge includes presenting nature-based photos and reflection questions when consumers are making a decision (Wensing et al., 2020).

Firms may choose to voluntarily self-regulate in different ways. For example, firms may pledge to stop the use of plastic in their products, as they did for U.S. production of goods containing plastic microbeads (Dauvergne, 2018). The industry initiative Operation Clean Sweep, from the early 1990s, encouraged firms to reduce plastic pellet loss and may have been successful in this (Ryan, 2008). In other environmental policy contexts where we have more data, the motivations for firm and industry initiatives are complex. For example, while some firms are motivated by the environmental ethos of their leadership (Nakamura et al., 2001; Galati et al., 2017), others are motivated by benefits to their public image (Mikulková et al., 2015). Less optimistically, firms may introduce initiatives to sow confusion among

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consumers (Harbaugh et al., 2011) and doubt among policy makers (Chiroleu-Assouline and Lyon, 2020), and make misleading claims about the environmental quality of their practices to “greenwash” their image (Lyon and Montgomery, 2015). These practices make it less likely that meaningful plastic policy will originate from firms.

7. Conclusions

Global plastic production, particularly of single-use throwaway products, has increased dramatically since the 1950s. Plastic combines a set of favorable characteristics, including low cost, light weight and durability, which has led to a number of applications that benefit society, especially with respect to food security, medicine and transportation. Ironically, it is these same characteristics, in combination with inadequate regulation and waste management, that have brought about several costs to society, such as widespread plastic debris in the natural environment. By considering how the positive and negative implications vary according to the specific use of plastics, it is clear that single-use plastic packaging and discarded fishing equipment are significant sources of the problems identified above — more so than other applications of plastic. While individual governments have enacted successful regulations of plastics within their borders, the transboundary nature of plastic pollution necessitates coordinated policies at the international level.

Comparing the alternatives to plastic sheds light on the advantages of the material, particularly at the production level, where its light weight leads to lower carbon emissions. To date, however, the upstream relationship between plastic production and carbon footprint has been better quantified than many of the negative downstream impacts of plastic, such as the relationship between microplastics and the health of the natural environment. More data collection and research are needed on these downstream impacts in order to conduct full cost–benefit analyses.

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References

Abate, T. G., Borger, T., Aanesen, M., Falk-Anderson, J., Wyles, K. J. and Beaumont, N. (2020). Valuation of marine plastic pollution in the European Arctic: Applying an integrated choice and latent variable model to contingent valuation. *Ecological Economics*, *169*, 106521.

Abbott, J. J. and Sumaila, U. R. (2019). Reducing marine plastic pollution: Policy insights from economics. Review of *Environmental Economics and Policy*, *13*(2), 327–36.

Adane, L. and Muleta, D. (2011). Survey on the usage of plastic bags, their disposal and adverse impacts on environment: A case study in Jimma City, southwestern Ethiopia. *Journal of Toxicology and Environmental Health Sciences*, *3*(8), 234–48.

Albrecht, S., Brandstetter, P., Beck, T., Fullana-i-Palmer, P., Grönman, K., Baitz, M., Deimling, S., Sandilands, J. and Fischer, M. (2013). An extended life cycle analysis of packaging systems for fruit and vegetable transport in Europe. *International Journal of Life Cycle Assessment*, *18*(8), 1549–67.

Allen, M., Clifford, J. and Atkinson, D. (2019, April). *Exploring consumers' reliance on plastic in fresh food packaging: Adding to the waste?* [Paper presentation]. 39th International Scientific Conference on Economic and Social Development — "Sustainability from an Economic and Social Perspective," Lisbon, Portugal.

Andrady, A. L. and Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B*, *364*(1526), 1977–84.

Arabi, S. and Nahman, A. (2020). Impacts of marine plastic on ecosystem services and economy: State of South African research. *South African Journal of Science*, *116*(5–6), 1–7.

Ballesteros-Sola, M., Davidson, L., Farrell, E. and Hermida, C. (2020). The Refill Shoppe: A Certified B Corp on the quest for growth to end plastic pollution. *Entrepreneurship Education and Pedagogy*. https://doi.org/10.1177/2515127420979197

Balton, D., Janis, B., Logaddottir, H. H., Maddox, M. and Ulmer, F. (2020). *Policy and action on plastic in the Arctic Ocean: October 2019 workshop summary and recommendations*. Cambridge, MA and Washington, DC: The Arctic Initiative, Harvard Kennedy School and the Polar Institute, Woodrow Wilson International Center for Scholars. https://www.wilsoncenter.org/publication/policy-and-action-plastic-arctic-ocean

Bauer, B. A. (2019, December 18). *What is BPA and what are the concerns about BPA?* Mayo Clinic. https://www.mayoclinic.org/healthy-lifestyle/nutrition-and-healthy-eating/expert-answers/bpa/faq-20058331

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., Hooper, T., Lindeque, P. K., Pascoe, C. and Wyles, K. J. (2019). Global ecological, social and economic impacts of marine plastic. *Marine Pollution Bulletin*, *142*, 189–95.

Berck, P., Blundell, M., Englander, G., Gold, S., He, S., Horsager, J., Kaplan, S., Sears, M., Stevens, A., Trachtman, C., Taylor, R. and Villas-Boas, S. B. (2020). Recycling policies, behavior and convenience: Survey evidence from the CalRecycle Program. *Applied Economic Perspectives and Policy*. https://doi.org/10.1002/aepp.13117

Borrelle, S. B., Rochman, C. M., Liboiron, M., Bond, A. L., Lusher, A., Bradshaw, H. and Provencher, J. F. (2017). Opinion: Why we need an international agreement on marine plastic pollution. *Proceedings of the National Academy of Sciences*, *114*(38), 9994–97.

Electronic copy available at: https://ssrn.com/abstract=3859528

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M. and Sukumaran, S. (2020). Plastic rain in protected areas of the United States. *Science*, *368*(6496), 1257–60.

Brandt, B. and Pilz, H. (2011). *The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe*. PlasticsEurope. https://www.plasticseurope.org/en/resources/publications/167-impact-plastic-packaging-energy-consumption-and-ghg-emissions

Brooks, A. L., Wang, S. and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Science Advances*, *4*(6), eaat0131.

California Environmental Protection Agency [California EPA]. (2020a). *Statewide water quality control plans for trash*. State Water Resources Control Board, Sacramento, CA, USA. https://www.waterboards.ca.gov/water_issues/programs/trash_control/documentation.html

California Environmental Protection Agency [California EPA]. (2020b). *Preproduction plastic debris program*. State Water Resources Control Board, Sacramento, CA, USA. https://www.waterboards.ca.gov/water_issues/programs/stormwater/plasticdebris.shtml

California Senate. (2018). *SB-1422 California Safe Drinking Water Act: Microplastics*. California Legislative Information. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1422

California Senate. (2019). *SB-8 State parks: State beaches: Smoking ban*. California Legislative Information. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201920200SB8

California State University Council on Ocean Affairs, Science, and Technology [CSU COAST]. (2020). *CSU researchers awarded microplastic research funding to assist State of California* [Press release]. https://www2.calstate.edu/impact-of-the-csu/research/coast/funding/Documents/MPMF_SSINP_Press_Release.pdf

Center for International Environmental Law (CIEL). (2017). *Fueling plastics: Fossils, plastics and petrochemical feedstocks*. https://www.ciel.org/wp-content/uploads/2017/09/Fueling-Plastics-Fossils-Plastics-Petrochemical-Feedstocks.pdf

Center for International Environmental Law (CIEL). (2019). *Plastic and climate: The hidden costs of a plastic planet*. https://www.ciel.org/plasticandclimate

Chiroleu-Assouline, M. and Lyon, T. P. (2020). Merchants of doubt: Corporate political action when NGO credibility is uncertain. *Journal of Economics & Management Strategy*, *29*(2), 439–61.

Coase, R. H. (1960). The problem of social cost. In C. Gopalakrishnan (ed.), *Classic papers in natural resource economics* (pp. 87–137). London: Palgrave Macmillan.

Cole, G. and Sherrington, C. (2016). *Study to quantify pellet emission in the UK*. Eunomia. https://www.eunomia.co.uk/reports-tools/study-to-quantify-pellet-emissions-in-the-uk.

Cole, M., Lindeque, P. K., Fileman, E., Clark, J., Lewis, C., Halsband, C. and Galloway, T. S. (2016). Microplastics alter the properties and sinking rates of zooplankton faecal pellets. *Environmental Science & Technology*, *50*(6), 3239–46.

Corkery, M. (2019, March 16). As costs skyrocket, more U.S. cities stop recycling. *The New York Times*. https://www.nytimes.com/2019/03/16/business/local-recycling-costs.html

Cunningham, N. (2019). *A fracking-driven industrial boom renews pollution concerns in Pittsburgh*. Yale Environment 360. https://e360.yale.edu/features/a-fracking-driven-industrial-boom-renews-pollution-concerns-in-pittsburgh

Electronic copy available at: https://ssrn.com/abstract=3859528

da Costa, J. P., Mouneyrac, C., Costa, M., Duarte, A. C. and Rocha-Santos, T. (2020). The role of legislation, regulatory initiatives and guidelines on the control of plastic pollution. *Frontiers in Environmental Science*. https://doi.org/10.3389/fenvs.2020.00104

Dauvergne, P. (2018). The power of environmental norms: Marine plastic pollution and the politics of microbeads. *Environmental Politics*, *27*(4), 579–97.

De Lucia, C. and Pazienza, P. (2019). Market-based tools for a plastic waste reduction policy in agriculture: A case study in the south of Italy. *Journal of Environmental Management*, *250*, 109468, https://doi.org/10.1016/j.jenvman.2019.109468.

DIN CERTCO. (2020). *Biobased products*. DIN CERTCO. https://www.dincertco.de/din-certco/en/main-navigation/products-and-services/certification-of-products/environmental-field/biobased-products

Doremus, J., Hamilton, S. and Richards, T. (2019). *Can consumer boycotts backfire when retailers mediate sales? The case of microbeaded toothpaste.* [Working paper].

Driedger, A. G., Dürr, H. H., Mitchell, K. and Van Cappellen, P. (2015). Plastic debris in the Laurentian Great Lakes: A review. *Journal of Great Lakes Research*, *41*(1), 9–19.

Edwards, C. and Fry, J. M. (2011). *Life cycle assessment of supermarket carrier bags: A review of the bags available in 2006*. Environment Agency. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291023/scho0711buan-e-e.pdf

European Food Safety Authority [EFSA]. (2015, January 21). *No consumer health risk from bisphenol A exposure*. European Food Safety Authority. http://www.efsa.europa.eu/en/press/news/150121?wtrl=01

Food and Agriculture Organization (FAO). (2014). *Appropriate food packaging solutions for developing countries*. Rome: FAO. http://www.fao.org/3/a-mb061e.pdf

Food and Drug Administration [FDA]. (2014). *Bisphenol A (BPA): Use in food contact application*. U.S. Food & Drug Administration. https://www.fda.gov/food/food-additives-petitions/bisphenol-bpa-use-food-contact-application#summary

Freinkel, S. (2011). *Plastic: A toxic love story*. New York, NY: Houghton Mifflin Harcourt.

Galati, A., Gianguzzi, G., Tinervia, S., Crescimanno, M. and Veca, D. S. L. M. (2017). Motivations, adoption and impact of voluntary environmental certification in the Italian forest based industry: The case of the FSC standard. *Forest Policy and Economics*, *83*, 169–76.

Gardiner, B. (2019). *The plastics pipeline: A surge of new production is on the way*. Yale Environment 360. https://e360.yale.edu/features/the-plastics-pipeline-a-surge-of-new-production-is-on-the-way#:~:text=A%20world%20awash%20in%20plastic,the%20fracking%20boom%20%E2%80%94%20come%20online.

Geyer, R., Jambeck, J. R. and Law, K. L. (2017). Production, use and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782.

Gray, R. (2018, July 6). *What's the real price of getting rid of plastic packaging?* BBC. https://www.bbc.com/worklife/article/20180705-whats-the-real-price-of-getting-rid-of-plastic-packaging

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings — entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2013–25.

Electronic copy available at: https://ssrn.com/abstract=3859528

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E. and Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of Hazardous Materials*, *344*, 179–99.

Halonen, N. J., Palvölgyi, P. S., Bassani, A., Fiorentini, C., Nair, R., Spigno, G. and Kordas, K. (2020). Bio-based smart materials for food packaging and sensors — a review. *Frontiers in Materials*, *7*, 82.

Harbaugh, R., Maxwell, J. W. and Roussillon, B. (2011). Label confusion: The Groucho effect of uncertain standards. *Management Science*, *57*(9), 1512–27.

Harper, P. C. and Fowler, J. A. (1987). Plastic pellets in New Zealand storm-killed prions (*Pachyptila* spp.), 1958–1998. *Notornis*, *34*, 65–70.

Harvey, F. (2019, May 14). Mismanaged waste "kills up to a million people per year globally." *The Guardian*. https://www.theguardian.com/environment/2019/may/14/mismanaged-waste-kills-up-to-a-million-people-a-year-globally

Health Canada. (2012). *Health Canada's updated assessment of bisphenol A (BPA) exposure from food sources*. Government of Canada. https://www.canada.ca/en/health-canada/services/food-nutrition/food-safety/packaging-materials/bisphenol/updated-assessment-bisphenol-exposure-food-sources.html.

Hocking, M. B. (2006). Reusable and disposable cups: An energy-based evaluation. *Journal of Environmental Management*, *18*(6), 889–99.

Holden, E. (2019, May 11). Nearly all countries agree to stem flow of plastic waste into poor nations. *The Guardian*. https://www.theguardian.com/environment/2019/may/10/nearly-all-the-worlds-countries-sign-plastic-waste-deal-except-us

Homonoff, T. (2018). Can small incentives have large effects? The impact of taxes versus bonuses on disposable bag use. *American Economic Journal: Economic Policy*, *10*(4): 177–210.

Homonoff, T., Kao, L.-S., Selman, J. and Seybolt, C. (2021). *Skipping the bag: The relative effectiveness of taxes versus bans* , (NBER Working Paper No. 28499). Cambridge, MA: National Bureau of Economic Research. http://dx.doi.org/10.3386/w28499

Homonoff, T., Taylor, R. L. C., Kao, L.-S. and Palmer, D. (Forthcoming). Harnessing behavioral science to design disposable bag regulations. *Behavioral Science and Policy*.

Hoornweg, D. and Bhada-Tata, P. (2012). *What a waste: A global review of solid waste management* (Urban Development Series, Knowledge Papers No. 15). Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/17388

Hopewell, J., Dvorak, R. and Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B*, *364*(1526), 2115–26.

Humbert, S., Rossi, V., Margni, M., Jolliet, O. and Loerincik, Y. (2009). Life cycle assessment of two baby food packaging alternatives: Glass jars vs. plastic pots. *International Journal of Life Cycle Assessment*, *14*(2), 95–106.

International Energy Agency [IEA]. (2018). *The future of petrochemicals: Towards more sustainable plastics and fertilisers*. International Energy Agency. https://webstore.iea.org/download/summary/2310?fileName=English-Future-Petrochemicals-ES.pdf

Electronic copy available at: https://ssrn.com/abstract=3859528

Jaffe, A. B., Newell, R. G. and Stavins, R. N. (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics*, *54*(2–3), 164–74.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R. and Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, *347*(6223), 768–71.

Joyce, C. (2019, July 9). *Plastic has a big carbon footprint — but that isn't the whole story*. National Public Radio. https://www.npr.org/2019/07/09/735848489/plastic-has-a-big-carbon-footprint-but-that-isnt-the-whole-story

Karlsson, T. M., Arneborg, L., Broström, G., Almroth, B. C., Gipperth, L. and Hassellöv, M. (2018). The unaccountability case of plastic pellet pollution. *Marine Pollution Bulletin*, *129*(1), 52–60.

Koelmans, A. A., Bakir, A., Burton, G. A. and Janssen, C. R. (2016). Microplastic as a vector for chemicals in the aquatic environment: Critical review and model-supported reinterpretation of empirical studies. *Environmental Science & Technology*, *50*(7), 3315–26.

Lee, Y. N. (2018, April 16). *The world is scrambling now that China is refusing to be a trash dumping ground*. CNBC. https://www.cnbc.com/2018/04/16/climate-change-china-bans-import-of-foreign-waste-to-stop-pollution.html

Li, C., Xu, J., Chen, D. and Xiao, Y. (2016). Detection of phthalates migration from disposable tablewares to drinking water using hexafluoroisopropanol-induced catanionic surfactant coacervate extraction. *Journal of Pharmaceutical Analysis*, *6*(5), 292–99.

Licciardello, F., Giannone, V., Del Nobile, M. A., Muratore, G., Summo, C., Giarnetti, M., Caponio, F., Paradiso, V. M. and Pasqualone, A. (2017). Shelf life assessment of industrial durum wheat bread as a function of packaging system. *Food Chemistry*, *224*, 181–90.

Lyon, T. P. and Montgomery, A. W. (2015). The means and end of greenwash. *Organization & Environment*, *28*(2), 223–49.

Macfadyen, G., Huntington, T. and Cappell, R. (2009). *Abandoned, lost or otherwise discarded fishing gear* (UNEP Regional Seas Reports and Studies No. 185; FAO Fisheries and Aquaculture Technical Paper, No. 523). Rome: UNEP/FAO. http://www.fao.org/3/i0620e/i0620e00.htm

Mani, T., Hauk, A., Walter, U. and Burkhardt-Holm, P. (2015). Microplastics profile along the Rhine River. *Scientific Reports*, *5*(17988), 1–7.

Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C. and Kaminuma, T. (2001). Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science and Technology*, *35*(2), 318–24.

McCormick, E., Murray, B., Fonbuena, C., Kijewski, L., Saraçoğlu, G., Fullerton, J., Gee, A. and Simmonds, C. (2019, June 17). Where does your plastic go? Global investigation reveals America's dirty secret. *The Guardian*. https://www.theguardian.com/us-news/2019/jun/17/recycled-plastic-america-global-crisis.

McIlgorm, A., Campbell, H. & Rule, M. (2008). *Understanding the economic benefits and costs of controlling marine debris in the APEC region*. Coffs Harbour: APEC Marine Resources Conservation Working Group. https://www.apec.org/Publications/2009/04/Understanding-the-Economic-Benefits-and-Costs-of-Controlling-Marine-Debris-In-the-APEC-Region

Mehlhart, G. and Blepp, M. (2012). *Study on land-sourced litter (LSL) in the marine environment: Review of sources and literature in the context of the initiative for the Declaration of the Global Plastics Associations for Solutions on Marine Litter*. Darmstadt/Freiburg: Öko Institut eV.

Electronic copy available at: https://ssrn.com/abstract=3859528

Mikulková, A., Hájek, M., Štěpánková, M. and Ševčík, M. (2015). Forest certification as a tool to support sustainable development in forest management. *Journal of Forest Science, 61*(8), 359–68.

Moreira, F. T., Balthazar-Silva, D. and Barbosa, L. (2016). Revealing accumulation zones of plastic pellets in sandy beaches. *Environmental Pollution, 218*, 313–21.

Nakamura, M., Takahashi, T. and Vertinsky, I. (2001). Why Japanese firms choose to certify: A study of managerial responses to environmental issues. *Journal of Environmental Economics and Management*, *42*(1), 23–52.

National Oceanic and Atmospheric Administration [NOAA]. (2019). *The effects of marine debris on beach recreation and regional economies in four coastal communities: A regional pilot*. Silver Spring, MD: NOAA. https://marinedebris.noaa.gov/sites/default/files/2019.07.Econ_.Impacts.Marine.Debris.complete.wFN_30Aug2019_508.pdf

National Oceanic and Atmospheric Administration [NOAA]. (2020). *Microplastic marine debris: Fact sheet*. NOAA. https://marinedebris.noaa.gov/sites/default/files/Microplastic%20Marine%20Debris%20Fact%20Sheet.pdf

National Toxicology Program [NTP]. (2018). *Clarity-BPA Program*. National Toxicology Program. https://ntp.niehs.nih.gov/whatwestudy/topics/bpa/index.html

New York Assembly. (2017). *Assembly Bill A10599*. The New York State Senate. https://www.nysenate.gov/legislation/bills/2017/a10599

Ocean Conservancy. (2011). *International coastal cleanup report. Tracking trash: 25 years of action for the ocean*. Washington, DC: Ocean Conservancy. https://oceanconservancy.org/wp-content/uploads/2017/04/2011-Ocean-Conservancy-ICC-Report.pdf

Oosterhuis, F., Papyrakis, E. and Boteler, B. (2014). Economic instruments and marine litter control. *Ocean Coast Management*, *102*, 47–54.

Paulo, D. A. (2020, March 22). *Indonesia stands at the crossroads of a waste crisis and plastics problem*. Channel News Asia. https://www.channelnewsasia.com/news/cnainsider/indonesia-stands-crossroads-waste-crisis-plastics-problem-12564234

Penn, J., Bastola, S. and Hu, W. (Forthcoming). Nudging away from plastic bags with charitable donations. *Land Economics*.

Potts, T. and Hastings, E. (2011). *Marine litter issues, impacts and actions*. Scottish Government. https://www.gov.scot/publications/marine-litter-issues-impacts-actions/pages/1

Roberts, D. (2020, October 28). *Big Oil's hopes are pinned on plastics. It won't end well*. Vox. https://www.vox.com/energy-and-environment/21419505/oil-gas-price-plastics-peak-climate-change

Robson, D. (2017, April 28). *Hong Kong has a monumental waste problem*. BBC. https://www.bbc.com/future/article/20170427-hong-kong-has-a-monumental-waste-problem

Rosengren, C., Witynski, M., Li, R. Crunden, E. A., Boteler, C. and Pyzyk, K. (2019, November 15). *How recycling has changed in all 50 states*. Waste Dive. https://www.wastedive.com/news/what-chinese-import-policies-mean-for-all-50-states/510751

Ryan, P. G., Moore, C. J., van Franeker, J. A. and Moloney, C. L. (2009). Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society of London B, 364*(1526), 1999–2012.

Schneider, K. (2019, March 26). Shell sees new role for former steel region: Plastics. *The New York Times*. https://www.nytimes.com/2019/03/26/business/shell-polyethylene-factory-pennsylvania.html

Electronic copy available at: https://ssrn.com/abstract=3859528

Scialla, M. (2016, June 22). *It could take centuries for EPA to test all the unregulated chemicals under a new landmark bill*. PBS. https://www.pbs.org/newshour/science/it-could-take-centuries-for-epa-to-test-all-the-unregulated-chemicals-under-a-new-landmark-bill

Song, J. H., Murphy, R. J., Narayan, R. and Davies, G. B. H. (2009). Biodegradable and compostable alternatives to conventional plastics. *Philosophical Transactions of the Royal Society B*, *364*(1526), 2127–39.

Staub, C. (2018, June 27). Thailand bans scrap plastic imports. *Plastics Recycling Update*. https://resource-recycling.com/plastics/2018/06/27/thailand-bans-scrap-plastic-imports

Stickel, B. H., Jahn, A. and Kier, B. (2012). *The cost to west coast communities of dealing with trash recycling marine debris*. Blue Lake, CA: Kier Associates. https://kierassociates.net/Cost_of_Dealing_With_Marine_Debris_Kier%20Associates.pdf

Subramanian, S. (2016, June 30). Plastic roads: India's radical plan to bury its garbage beneath the streets. *The Guardian*. https://www.theguardian.com/sustainable-business/2016/jun/30/plastic-road-india-tar-plastic-transport-environment-pollution-waste

Tabuchi, H., Corkery, M. and Mureithi, C. (2020). Big Oil is in trouble. It's plan: Flood Africa with plastic. *The New York Times*. https://www.nytimes.com/2020/08/30/climate/oil-kenya-africa-plastics-trade.html

Taylor, R. L. and Villas-Boas, S. B. (2016). Bans vs. fees: Disposable carryout bag policies and bag usage. *Applied Economic Perspectives and Policy*, *38*(2), 351–72.

Taylor, R. L. C. (2019). Bag leakage: The effect of disposable carryout bag regulations on unregulated bags. *Journal of Environmental Economics and Management*, *93*(1), 254–71.

Teuten, E. L., Saquing, J. M., Knappe, D. R., Barlaz, M. A., Jonsson, S., Björn, A., Rowland, S. J., Thompson, R. C., Galloway, T. S., Yamashita, R. and Ochi, D. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2027–45.

Thaler, R. H. and Sunstein, C. R. (2009). *Nudge: Improving decisions about health, wealth, and happiness*. London: Penguin.

Thomas, G. O., Sautkina, E., Poortinga, W., Wolstenholme, E. and Whitmarsh, L. (2019). The English plastic bag charge changed behavior and increased support for other charges to reduce plastic waste. *Frontiers in Psychology*, *10*, 266.

Thompson, R. C., Moore, C. J., vom Saal, F. S. and Swan, S. H. (2009). Plastics, the environment and human health: Current consensus and future trends. *Philosophical Transactions of the Royal Society B*, *364*(1526), 2153–66.

United Nations Environment Programme [UNEP]. (2005). *Marine litter, an analytical overview*. Nairobi: UNEP. http://wedocs.unep.org/handle/20.500.11822/8348

United Nations Environment Programme [UNEP]. (2014). *Valuing plastics: The business case for measuring, managing and disclosing plastic use in the consumer goods industry*. Nairobi: UNEP. http://wedocs.unep.org/handle/20.500.11822/9238.

United Nations Environment Programme [UNEP]. (2018). *Mapping of global plastics value chain and plastics losses to the environment (with a particular focus on marine environment)*. Nairobi: United Nations Environment Programme. http://wedocs.unep.org/handle/20.500.11822/26745.

United Nations Environment Program [UNEP]. (2020). *Basel Convention Plastic Waste Amendments*. Basel Convention. http://www.basel.int/Implementation/Plasticwaste/PlasticWasteAmendments/Overview/tabid/8426/Default.aspx

Electronic copy available at: https://ssrn.com/abstract=3859528

United Nations Environmental Programme [UNEP] and GRID-Arendal. (2016). Marine litter vital graphics. Nairobi and Arendal: United Nations Environment Programme and GRID-Arendal. https://www.grida.no/publications/60

United Nations Environment Programme [UNEP] and National Oceanic and Atmospheric Administration [NOAA]. (2011). *The Honolulu strategy: A global framework for prevention and management of marine debris*. Nairobi and Washington, DC: UNEP and NOAA. https://marinedebris.noaa.gov/sites/default/files/publications-files/Honolulu_Strategy.pdf

Wagner, T. P. (2020). Policy instruments to reduce consumption of expanded polystyrene food service ware in the USA. *Detritus*, *9*, 11.

Wagner, T. P. and Toews, P. (2018). Assessing the use of default choice modification to reduce consumption of plastic straws. *Detritus*, *4*, 113.

Walls, M. (2006). *Extended producer responsibility and product design: Economic theory and selected case studies* (RFF Discussion Paper No. 06-08). Washington, DC: Resources for the Future. http://dx.doi.org/10.2139/ssrn.901661

Wensing, J., Caputo, V., Carraresi, L. and Bröring, S. (2020). The effects of green nudges on consumer valuation of bio-based plastic packaging. *Ecological Economics*, *178*, 106783. https:// doi.org/10.1016/j.ecolecon.2020.106783

Werner, S., Budziak, A., Van, J., Galgani, F., Hanke, G., Maes, T., Matiddi, M., Nilsson, P., Oosterbaan, L., Priestland, E. and Thompson, R. (2016). *Harm caused by marine litter* (JRC Technical Report). Luxembourg: European Union. http://dx.doi.org/10.2788/690366.

World Economic Forum. (2016). *The new plastics economy: Rethinking the future of plastics*. Geneva: World Economic Forum. http://www3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf

Zheng, J. and Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change*, *9*(5), 374–78.

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