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HIGH LEVEL PANEL *for*
A SUSTAINABLE
OCEAN ECONOMY

BLUE PAPER

Leveraging Multi-Target Strategies to Address Plastic Pollution in the Context of an Already Stressed Ocean

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About this Paper

Established in September 2018, the High Level Panel for a Sustainable Ocean Economy (HLP) is a unique initiative of 14 serving heads of government committed to catalysing bold, pragmatic solutions for ocean health and wealth that support the UN Sustainable Development Goals and build a better future for people and the planet. By working with governments, experts and stakeholders from around the world, the High Level Panel aims to develop a roadmap for rapidly transitioning to a sustainable ocean economy and to trigger, amplify and accelerate responsive action worldwide.

The HLP consists of the presidents or prime ministers of Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau and Portugal, and is supported by an Expert Group, Advisory Network and Secretariat that assist with analytical work, communications and stakeholder engagement. The Secretariat is based at World Resources Institute.

The HLP has commissioned a series of 'Blue Papers' to explore pressing challenges at the nexus of the ocean and the economy. These papers summarise the latest science and state-of-the-art thinking about innovative ocean solutions in the technology, policy, governance and finance realms that can help accelerate a move into a more sustainable and prosperous relationship with the ocean. This paper is part of a series of 16 papers to be published between November 2019 and October 2020. This paper examines the leakage of plastics and other pollutants into the ocean and the resulting impacts on marine ecosystems, human health and the economy. The paper comments on the kind of regenerative global industry that needs to be built, as well as integrated solutions to reduce all pollutants to the ocean.

This Blue Paper is an independent input to the HLP process and does not represent the thinking of the HLP, Sherpas or Secretariat.

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Foreword

The High Level Panel for a Sustainable Ocean Economy (HLP) commissioned us, the co-chairs of the HLP Expert Group (a global group of over 70 content experts), to organise and edit a series of ‘Blue Papers’ to explore pressing challenges at the nexus of the ocean and the economy. The HLP identified 16 specific topics for which it sought a synthesis of knowledge and opportunities for action. In response, we convened 16 teams of global content experts. Each resulting Blue Paper was independently peer-reviewed and revised accordingly. The final Blue Papers summarise the latest science and state-of-the-art thinking on how technology, policy, governance and finance can be applied to help accelerate a more sustainable and prosperous relationship with the ocean, one that balances production with protection to achieve prosperity for all, while mitigating climate change.

Each Blue Paper offers a robust scientific basis for the work of the HLP. Together, they provide the foundation for an integrated report to be delivered to the HLP. In turn, the HLP plans to produce by the end of 2020 its own set of politically endorsed statements and pledges or recommendations for action.

Historically, the ocean has been viewed as so vast and untouchable as to be capable of absorbing everything that we discharge into it. It has become the ultimate sink for land-based pollution—the most recent and most visible being solid plastic waste. Thankfully, we have seen a wave of action targeting plastic waste—with individuals shifting their own behaviours and governments stepping up to put in place a variety of policy measures. This paper aims to complete the picture on pollution in our ocean—by looking across four main sectors at the full extent of waste that is currently being discharged into our ocean—and identifying a pathway to change the way we see our ocean and what we put into it.

As co-chairs of the HLP Expert Group, we wish to warmly thank the authors, the reviewers and the Secretariat at World Resources Institute for supporting this analysis. We thank the members of the HLP for their vision in commissioning this analysis. We hope they and other parties act on the opportunities identified in this paper.

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Key Messages

- Plastic is the newest pollutant to be entering the ocean in significant quantities. It joins nonplastic solid waste; nutrients; antibiotics, parasiticides and other pharmaceuticals; heavy metals; industrial chemicals including persistent organic pollutants; pesticides; and oil and gas, each of which has a longer history of scholarship and greater body of existing research as an ocean pollutant than does plastic.

- There are four major sources that discharge pollutants into the ocean: municipal, agricultural (including aquaculture), industrial and maritime. These pollutants have damaging impacts on ecosystems and marine life, human health and the economy.

- The presence of plastic in the ocean in growing quantities is symptomatic of many societal challenges that are relevant to the other pollutants and pollution pathways: the lack of access to sanitation and wastewater and stormwater processing for millions of people around the world, the need for safe use and disposal of chemicals, the development and degradation of coastal zones, the need for an efficient use of natural resources, and the need for improved access to safe food and water.

- This paper proposes seven holistic approaches for the reduction of pollutants in the ocean: improve wastewater management; improve stormwater management; adopt green chemistry practices and new materials; implement coastal zone improvements; practice radical resource efficiency; recover and recycle the materials we use; and build local systems for safe food and water.

- These seven approaches address the major sources of pollution entering the ocean and contribute to multiple United Nations Sustainable Development Goals.

- Each of the approaches identified are cross-sectoral and system-level in nature, making them perfect candidates for delivery through public-private partnerships, innovative financing arrangements and leveraging capital from a range of sources.

- To solve the pollution challenge we need to start with the premise that there is no such thing as waste. The Earth is a closed system and there is nowhere for damaging pollution to go that won’t harm ecosystems, plant and animal life and, ultimately, human life.

- Once we adopt a no-waste approach, our economy will be very effective at finding the most efficient ways to stop the problem of pollution

1. Introduction

Overview

The ocean is the ultimate sink for anthropogenic pollution. According to the HydroSHED model, over 80 percent of the land mass on Earth is in a watershed that drains directly to the ocean (Lehner and Grill 2013). Until recently, the ocean seemed to be endlessly able to absorb all the waste that human activity has discharged into it. The Ocean Health Index (OHI) scores the health of the ocean on a range of criteria, from how clean the water is to the ability of the ocean to continue providing services such as food provision, carbon storage, tourism and recreation, and biodiversity (Halpern et al. 2012). The 2019 combined global ocean score was 71 out of 100 (as it has been for the last five years), showing that significant impairment has occurred, but that many of the functions and services of the ocean remain and must be better managed (OHI 2019). The Clean Water section of the OHI includes details on the statuses and pressures of chemical, nutrient, pathogen and trash pollution. It also includes social pressure as a further pressure. Indicators of resilience were based upon the Convention on Biological Diversity (in particular for marine ecosystems) and quality of governance (using Worldwide Governance Indicators). The score for Clean Water has tracked closely to the overall score, remaining at 70 for the past five years (OHI 2019). With an estimated 91 percent of all temperate and tropical coasts predicted to be heavily developed by 2050 (Nellemann et al. 2008), this is a critical time to significantly reduce and prevent anthropogenic pollution to the ocean.

Pollutants enter the ocean in four ways: They may be discharged directly into the ocean, discharged into rivers which flow to the ocean, washed from land by stormwater into rivers or directly into the ocean or deposited from the air onto land to be washed into waterways or directly into the ocean.

There are many anthropogenic sources of pollution, and this paper focuses on pollution inputs to the ocean from four sectors: municipal, agricultural, industrial and maritime. This paper focuses first on plastic, as the newest and least well understood pollutant, and puts plastic pollution in the context of an ocean already receiving significant pollution from nutrients, heavy metals, persistent organic pollutants (POPs), pesticides and oil.

While successful implementation of all the United Nations (UN) Sustainable Development Goals (SDGs) would help protect the ocean, SDG 14: Life Below Water is the primary SDG directly related to the ocean. But there are several other SDGs that are very relevant to pollution reaching the ocean: SDG 2: Zero Hunger, SDG 3: Good Health and Well-Being, SDG 6: Clean Water and Sanitation, SDG 8: Decent Work and Economic Growth, SDG 9: Industrial Innovation and Infrastructure, SDG 11: Sustainable Cities and Communities and SDG 12: Responsible Consumption and Production.

Context

Plastic is the newest pollutant to be entering the ocean in significant quantities. It joins nonplastic solid waste; nutrients (nitrogen, phosphorous); antibiotics, parasiticides and other pharmaceuticals; heavy metals; industrial chemicals including persistent organic pollutants; pesticides; and oil and gas, each of which has a longer history of scholarship and greater body of existing research as an ocean pollutant than does plastic. This paper seeks to put ocean pollution from plastic into the context of total pollutant inputs to the ocean and identify the interventions that can have the greatest total impact on all pollution to the ocean, capitalising on the current global attention on plastic pollution.

In this Blue Paper, four major sectors that create pollutants are explored—municipal, agricultural (including aquaculture), industrial and maritime—and three types of impacts are characterised—ecosystems and marine life, human health and economic. The impacts on ecosystems include harm to marine life from ingestion of and entanglement from plastic, eutrophication and hypoxia, and biomagnification of chemicals. The human health impacts from direct or indirect exposure to these pollutants include reproductive, developmental, behavioural, neurologic, endocrine and immunologic adverse health effects; acute or chronic toxicity; cancer; increased exposure to pathogens and mosquito-borne diseases; and risk of entanglement or entrapment. The economic impacts come from impaired productivity of fisheries, loss of seafood supply resulting from toxicity and reduced tourism and recreation in coastal areas.

The presence of plastic in the ocean in growing quantities is one symptom of a set of societal challenges that are also relevant to the other pollutants and pollution pathways: the lack of access to sanitation and wastewater and stormwater processing for millions of people around the world; the need for safe use and disposal of chemicals; the development and degradation of coastal zones; the need for an efficient use of natural resources; and the need for improved access to safe food and water.

At the heart of these challenges is recognising that the notion that things can be thrown away is a myth—there is no 'away' where pollutants can safely go.

This paper proposes seven intervention approaches that lead with reducing plastic inputs to the ocean but also seek to maximise the reduction of other pollutants as co-benefits. Four types of actions were considered: innovation, infrastructure, policy and mindset. Specific actions of each type were identified across the sectors and pollutants described in the report. These actions were then bundled into the following seven holistic opportunities for action (not in ranked order):

1. Improve wastewater management
2. Improve stormwater management
3. Adopt green chemistry practices and new materials
4. Implement coastal zone improvements
5. Practice radical resource efficiency
6. Recover and recycle the materials we use
7. Build local systems for safe food and water

These seven opportunities for action address the major sources of pollution entering the ocean, and contribute to achieving the United Nations Sustainable Development Goals (SDGs). They would directly influence SDG targets 2.1, 2.3, 3.9, 6.1, 6.2, 6.3, 6.B, 8.3, 11.6, 12.2, 12.4, 12.5 and 14.1 and indirectly influence a number of others, such as through expanded economic opportunities, benefits to people's livelihoods and increased well-being. The cross-sector, system-level nature of these challenges makes them perfect candidates for public-private partnerships, innovative financing arrangements and leveraging capital from a range of sources.

Finally, while the body of research on plastic is growing rapidly, there remain significant data gaps both on inputs and impacts. More research is needed to better understand and document the scope and scale of plastic pollution, as well as its impacts on ecosystem and human health. Given the global nature of the problem, open data protocols that can facilitate the aggregation and sharing of compatible data are critical.

2. Sources of Ocean Pollution

This paper includes pollution inputs from land and sea, grouped into four sectors: municipal, agricultural, industrial and maritime.

Municipal sources are residential and commercial solid waste and wastewater as well as runoff from roads and landscaping activities. Additionally, debris entering the ocean as a result of natural disasters is included here.

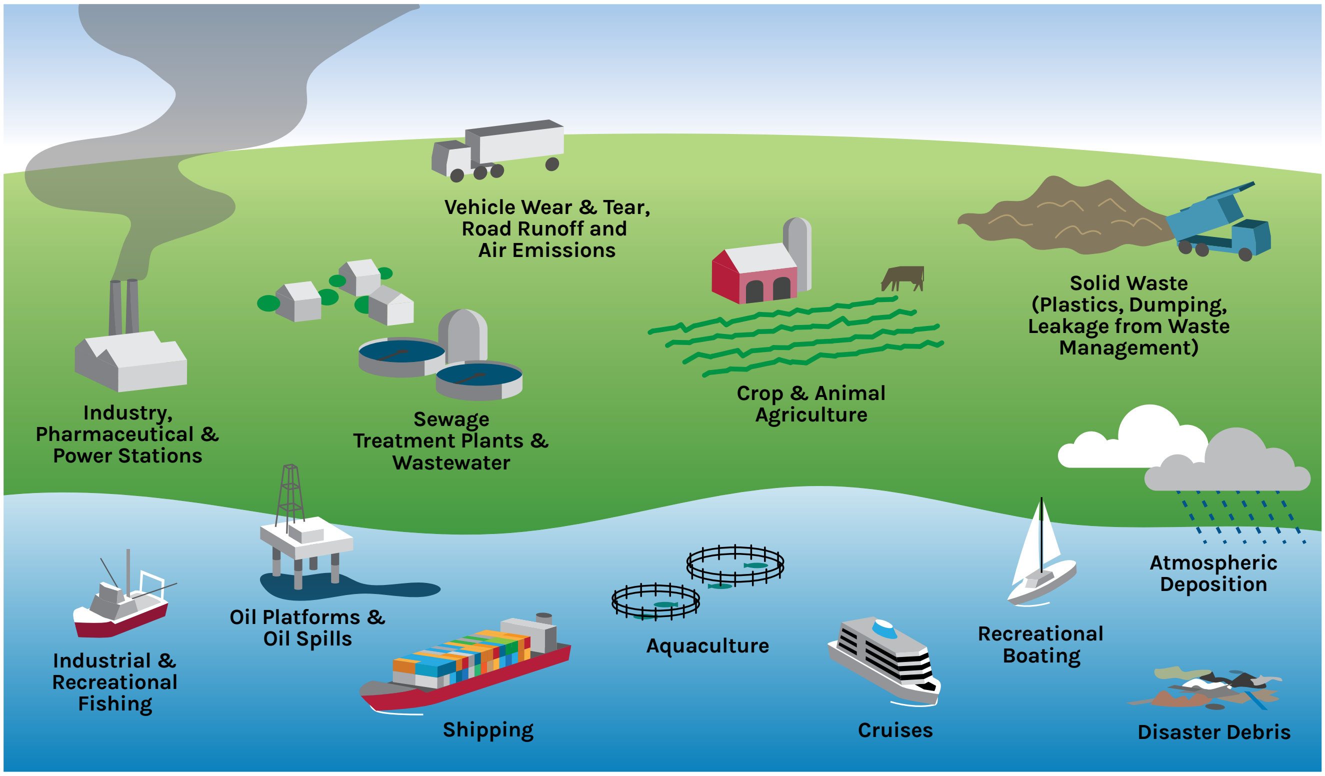
Land-based agricultural activities impacting the ocean include plastic, pesticide and nutrient use as well as waste management for animal agriculture. **Ocean-based aquaculture**'s pollution impacts include the use of antibiotics and parasiticides, antifoulants containing heavy metals, loss of equipment and management of fish waste.

The **industrial** sector includes manufacturing, mining and energy production. Pollutants coming from this sector include plastic pellets and waste, other solid waste, dredge spoils, industrial chemicals including POPs, heavy metals, pharmaceuticals and pharmaceutical waste products, and oil and gas.

Maritime pollution comes from the shipping, cruise and fishing industries and from recreational boating. Pollution from these sources includes litter, food waste, sewage and accident debris.

Figure 1 shows the primary sources of pollution in the marine environment from these sectors. Table 1 summarises the types of pollution entering the ocean and the ways that each sector contributes to ocean pollution.

Figure 1. Sources of Ocean Pollution



Source: Graphic developed by K. Youngblood

Table 1. Sources of Pollutant Discharges into the Ocean

	MUNICIPAL (COASTAL OR NEAR RIVERS)	AGRICULTURAL AND AQUACULTURAL	INDUSTRIAL	MARITIME
SUBCATEGORIES	RESIDENTIAL, COMMERCIAL	CROPS, ANIMAL LAND, AQUACULTURE	MANUFACTURING, ENERGY	FISHING, CRUISE, SHIPPING, RECREATION
Microplastics (<5 millimetres [mm])[a]	Microbeads, microfibres, tire dust, fragments in runoff from land	Slow release fertiliser pellets, plastic mulch fragments	Industrial pellets	Pellets lost at sea in shipping accidents, dredged materials and breakdown of other wastes dumped at sea[b]
Macroplastics (>5 mm)[a]	Unmanaged plastic waste within 50 kilometres (km) of river or ocean[1]	Aquaculture infrastructure and equipment, greenhouses, plastic sheeting and associated equipment	Unknown	Fishing gear, lines and lures; litter from ships and boats; debris from shipping accidents
Other solid waste	Unmanaged solid waste within 50 km of river or ocean, disaster debris, wood, food waste dumping[c]	Lost/unmanaged aquaculture infrastructure and equipment, manure and biosolids land application	Dredge spoils	Fishing gear, litter from ships and boats, debris from shipping accidents, food waste discharge from ships
Pesticides[2]	Residential and commercial landscaping and gardening	Crop-based agriculture	Minimal	Minimal
Nutrients (N, P)	Untreated municipal wastewater, residential and commercial landscaping and gardening, airborne nitrogen from vehicle exhaust deposition into ocean	Crop-based agriculture, lagoon leakage, aquaculture fish waste	Airborne nitrogen from energy production deposition into ocean	Sewage discharges into ocean
Antibiotics, parasiticides, other pharmaceuticals	Treated and untreated wastewater	Aquaculture/mariculture, land-based animal agricultural runoff	Pharmaceutical production wastewater	Treated and untreated wastewater from ships
Heavy metals	Urban runoff: copper, chromium, nickel; mismanaged electronic waste	Aquaculture/mariculture: arsenic, mercury, cadmium, lead	Mining manufacturing: copper, zinc, lead, cadmium, chromium, nickel, arsenic, mercury	Paints and pigments: zinc, tributyltin, lead, cadmium
Industrial chemicals and persistent organic pollutants[c]	Treated and untreated wastewater, urban runoff	Use of organochlorine pesticides	Regulated and unregulated discharge from manufacturing	Treated and untreated wastewater from ships
Oil and gas	Urban runoff	Accidental discharge from agricultural equipment use and maintenance	Spills, water contamination, and improper disposal from oil refineries and logistics (pipelines, rail, trucks)	Drilling rigs, bilge water and fuel release, tanker spills, shipping

Notes: Table 1 notes shown on page 7.

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Other than specific pollutants regulated by international treaties in certain situations—e.g. International Convention for the Prevention of Pollution from Ships (MARPOL) for plastic discharges; Stockholm Convention for specific chemicals; Basel Convention for waste exportation; London Convention and Protocol for ocean dumping—and acts that have regulated discharge nationally and locally—e.g. total maximum daily loads under the Clean Water Act in the United States—pollutants continue to enter the ocean without consistent and global limits or regulation.

Past emissions of ocean pollution remain relevant today, especially in the case of persistent pollutants such as plastics, heavy metals and POPs, as they remain in the ocean interacting with each other and the marine environment. For example, while 28 POPs are banned or restricted and have been for a number of years (12 since 2004, 16 since 2010), they are readily absorbed by plastic in the ocean, which creates a new mechanism for them to interact with the marine ecosystem (Rochman et al. 2013; Rochman et al. 2014b; Rochman 2015). Heavy metals have also been found to adhere to plastic in the ocean as biofilms accumulate on its surface (Rochman et al. 2014a; Richard et al. 2019).

It should be noted that the ocean is also subject to other forms of pollution, including acidification (see Blue Paper 2, Gaines et al. 2019) and other nonphysical forms like thermal, noise and biological pollution. Thermal pollution is a change in temperature in the ocean water from discharges, often warmer water from powerplant cooling, that can change both physical and chemical properties of the ocean, impacting, for example, bivalves since they are stationary (Dong et al. 2018). Noise pollution in the ocean from shipping, oil and gas exploration and military activities can also impact marine life (Francis and Barber 2013). The International Whaling Commission and Convention on Biological Diversity have groups working on noise pollution. Biological pollution is the transfer of, for example, invasive species, which has been exacerbated by evolving habitats due to climate change and ocean acidification (Miranda et al. 2019), topics covered in Blue Paper 2 (Gaines et al. 2019). The transport of invasive species by plastic is covered in this paper. While these other pollution sources are out of scope for this paper, it is worth noting them here as they underscore the high number of stressors that ocean ecosystems are facing.

2.1 Plastic Pollution

Plastic is a material that has permanently changed our world since its introduction into mainstream society (in some countries) after World War II; global annual plastic production has increased from 1.7 million metric tons per year (MMT/yr) in 1950 to 422 MMT/yr in 2018 (Geyer et al. 2017; PlasticsEurope 2019). Along with a steep increase in production, we have seen a resulting increase in plastic in the waste stream from 0.4 percent in 1960 to 13.2 percent in 2017 (by mass) in the United States (EPA 2014; EPA 2019). In 1966, two U.S. Fish and Wildlife Service employees, Karl W. Kenyon and Eugene Kridler, were among the first scientists to document plastic and wildlife interactions when they discovered plastic had been consumed by seabird (albatross) chicks that died in the Hawaiian Islands National Wildlife Refuge (Kenyon and Kridler 1969). Since then, analysing plastic material

Table includes both point source (e.g. specific discharge points) and nonpoint source (e.g. stormwater runoff) forms of pollution.

a. Macroplastics are any plastics larger than 5 mm. Microplastics are small pieces or fragments of plastic smaller than 5 mm (Galgani et al. 2010; SAPEA 2019).

b. Wastes allowed to be dumped at sea according to the London Convention and Protocol include dredged materials; sewage sludge; fish waste, or material resulting from industrial fish processing operations; vessels and platforms or other man-made structures at sea; inert or inorganic geological material; organic matter of natural origin; bulky items comprising primarily iron, steel, concrete or non-harmful materials; and carbon dioxide streams from carbon dioxide capture processes for sequestration.

c. Jambeck et al. 2015.

d. Persistent organic pollutants are organic compounds that are resistant to environmental degradation through chemical, biological and photolytic processes. They include polybrominated diphenyl ethers (PBDEs), per- and polyfluoroalkyl substances (PFASs), polychlorinated biphenyls (PCBs) and organochlorine (OC) pesticides.

Sources:
1. Jambeck et al. 2015.
2. Weibel et al. 1966.

flows (especially the waste streams), contamination in our environment and the economics of the material has become a recognised scientific discipline, with rapid increases in the science, especially in the last five years (Beaumont et al. 2019). But as a relevantly young scientific discipline, there are still many gaps in knowledge and a lack of information for solutions to plastic pollution (Bucci et al. 2019; Forrest et al. 2019). Even with knowledge gaps, plastic pollution has quickly become one of the most salient topics of late—people around the world passionately care about and want to address this issue.

> As of 2017, 8 billion metric tons of plastic had been produced for human use. Because a large quantity was used for packaging (about 40 percent) and single-use items, 6.4 billion metric tons had already become waste by 2015.

2.1.1 Municipal plastic pollution

Plastic pollution is often subdivided into macroplastics and microplastics (e.g. the U.S. National Oceanic and Atmospheric Administration uses this division), and although there is much discussion internationally about terminology (GESAMP 2015), these size categories are currently used extensively around the world. Macroplastics are any plastics larger than 5 millimetres (mm) and can include both short-use items (e.g. food packaging and foodservice disposables) and longer-use items (e.g. flip flops, printer cartridges, synthetic textiles). Microplastics are small pieces or fragments of plastic less than 5 mm (Galgani et al. 2010; SAPEA and Academies 2019) that enter the environment as a consequence of either the direct release of small particles such as microbeads from cosmetic products; the fragmentation of larger items of litter in the environment; or the wear or abrasion of products during use, such as the release of fibres from textiles or particles from car tires (Law and Thompson 2014). The term microplastic was first used in this context in 2004 (Thompson et al. 2004) and the identification of microplastics is a relatively new field (Shim et al. 2017), with nanoscale plastics (not even yet formally defined) especially challenging to identify because of limits to the capabilities of the current instrumentation used for environmental samples. As a consequence, quantifying inputs has been challenging (Koelmans et al. 2015; Rist and Hartmann 2017; SAPEA and Academies 2019).

As of 2017, 8 billion metric tons of plastic had been produced for human use. Because a large quantity was used for packaging (about 40 percent) and single-use items, 6.4 billion metric tons had already become waste by 2015 (Geyer et al. 2017). Many packaging and single-use materials are composed of polyethylene (high and low density, HDPE and LDPE), polypropylene and polyethylene terephthalate (PET). These polymers are often the materials used in the most common items found littering the environment, especially on coastlines: cigarette butts, plastic bottles, plastic food wrappers, straws, plastic bags and bottle caps (Ocean Conservancy 2018).

The total quantity of plastic entering the ocean every year is still unknown. While there have been estimates of some sources (e.g. municipal waste), there are more sources that do not have current estimates. While many scientists would agree that a large portion of mismanaged plastic comes from land, even the 80 percent from land is a questionable statistic since the true total from all sources remains unknown. Some of the sources have been quantified. Jambeck et al. (2015) found that the annual input from mismanaged solid waste on land (one of the major sources) in 2010 was between 4.8 and 12.7 MMT/yr. Other estimates have come from riverine input and other geographic information system (GIS) analyses, which have found that from 0.41 to 4 MMT of plastic is entering the ocean every year from rivers (a subset of the total quantity entering the ocean) (Lebreton et al. 2017; Schmidt et al. 2017). Up to 99 MMT of mismanaged plastic waste has been estimated to be available to enter waterways around the world (Lebreton and Andrady 2019). The estimate of 8 MMT as a middle estimate for input to the ocean (Jambeck et al. 2015) remains the most widely used value for land-based input of plastic waste into the ocean, although this is likely conservative. Forrest et al. (2019) built on the existing research by incorporating additional estimates of plastic waste flows to the ocean arising from imported waste by developing countries from wealthier consumer economies. This export/import imbalance was initially outlined in (Brooks et al. 2018), which describes the plastic import ban, more commonly known as the National Sword policy, imposed by China and its impacts on global plastic scrap trade. Forrest et al. (2019) estimated current plastic flows to the ocean from all sources to be at least 15 MMT/yr.

There are at least two more global baseline estimates in the process of being calculated for plastic, one by a working group through the National Socio-Environmental Synthesis Center funded by the U.S. National Science Foundation and one through The Pew Charitable Trusts and SYSTEMIQ, which, while not available before publishing this document, will make it possible to measure the impacts of interventions at the global and country levels, similar to the wedges approach developed for climate change (Pacala and Socolow 2004). Clearly topography and proximity to the ocean are relevant for land-based or riverine plastic, but some of the biggest data gaps in modelling and measuring quantities entering the ocean exist for these pathways. The most credible current estimates nonetheless indicate that the quantities of plastic entering the ocean are significant. The only regulatory limits on plastic concentrations in the ocean are the total maximum daily load limits in aquatic systems in the United States (Smith 2000; DoE 2010), the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (the ‘London Convention’ for short, and then later the ‘London Protocol’ upon its revision in 1996) (International Maritime Organization 2019), and MARPOL Annex V, all of which have zero tolerance for plastic pollution.

2.1.2 Agricultural plastic pollution

Land-based agricultural plastic use typically includes greenhouse or hoop house sheeting, netting, plastic mulch (film), irrigation tape and piping, agrochemical containers, silage, fertiliser bags and slow release fertiliser pellets. The best current estimate of agricultural plastic usage extrapolates from the European Union’s (EU’s) demand for agricultural plastics of 1.6 million tons annually to place world demand at approximately 8–10 million tons in 2015 (Cassou et al. 2018). A separate calculation projected that the global agricultural film market would reach 7.4 million tons in 2019 (Sintim and Flury 2017). At the end of the growing season, plastic mulch should be recovered from fields but this is difficult because it shreds easily, so it is common practice to till plastic mulch into the soil (Steinmetz et al. 2016). Depending on the proximity to the ocean or ocean-bound waterways, this improper end-of-life management of the mulch could contribute to inputs of plastic, especially microplastic, into the ocean.

Aquaculture also contributes significantly to marine plastic pollution. Several studies have reported abandoned, lost and discarded aquaculture gear in coastal waters or on shores (Heo et al. 2013; Liu et al. 2013; Hong et al. 2014). Near aquaculture centres, beaches often contain large amounts of lost or discarded plastic materials (Fujieda and Sasaki 2005; Hinojosa and Thiel 2009; Andréfouët et al. 2014; Jang et al. 2014b; Bendell 2015). Lost aquaculture gear that is floating at the sea surface can also be transported over long distances, potentially bringing non-native species to other ecoregions (Astudillo et al. 2009). One of the few studies that has estimated the losses from aquaculture activities and their contribution to marine plastic debris has been conducted in South Korea (Jang et al. 2014b). The authors showed that lost aquaculture gear contributes a significant amount of plastic litter (mostly expanded polystyrene, or EPS) in the coastal waters of South Korea.

2.1.3 Industrial plastic pollution

Plastic resin pellets, the raw material from which plastic items are made, continue to leak into the ocean despite voluntary industry campaigns like Operation Clean Sweep that encourage secure handling of the pellets. Pellet pollution in the ocean has been further documented because they are used to study POPs and bacteria as well (Heskett et al. 2012; Rodrigues et al. 2019). While quantities of inputs have not been published on a global scale, one case study quantified inputs from a facility along the west coast of Sweden (Karlsson et al. 2018). While most of the pellet pollution was reported to be localised, 3 to 36 million pellets (above 300 micrometres) were estimated to enter the waterways surrounding the production facility annually. Karlsson et al. (2018) also stated that while there are regulatory frameworks that can be applied to reduce this pollution, they are not being effectively applied or enforced. Lechner and Ramler (2015) found that the regulations in Austria still allowed a production facility to legally discharge 200 grams of pellets per day and up to 200 kilograms (kg) during a high rainfall event. An important legal precedent was just set in the United States with Formosa Plastics agreeing to pay a US$50 million settlement for a lawsuit against them for discharging resin pellets into Lavaca Bay and other nearby waterways (Collier 2019). Besides paying the settlement, it has to adhere to a 'zero discharge' policy moving forward with fines that increase over time for any future discharges (Collier 2019).

2.1.4 Maritime plastic pollution

Fisheries activities contribute to pollution through the accidental or intentional discarding of nets, ropes, buoys, lines and other equipment, also known as 'abandoned, lost or otherwise discarded fishing gear' (ALDFG) (see Box 3 for a discussion of aquaculture). Historic fishing nets were made from biodegradable, locally sourced natural materials like cotton, flax or hemp, but as materials like nylon and other polymers were introduced, fishing practices (and efficiencies) were increased, as early as 1951 in the United States and Canada (Pycha 1962). United Nations General Assembly and United Nations Environment Assembly resolutions (2014, 2016, 2017) have addressed ALDFG, encouraging the reduction of impacts from this marine debris that is designed to capture and kill marine animals (Gilman 2015; Gilman et al. 2016). The Food and Agriculture Organization of the United Nations' (FAO's) Committee on Fisheries, the FAO Code of Conduct for Responsible Fisheries and the FAO's Voluntary Guidelines for the Marking of Fishing Gear have also presented on marking fishing gear and ALDFG reporting and recovery (Gilman et al. 2016). Richardson et al. (2019) reviewed 68 publications from 1975 to 2017 that contain quantitative information about fishing gear losses and found that at an annual rate, all net studies reported gear loss rates from 0 percent to 79.8 percent, all trap studies reported loss rates from 0 percent to 88 percent, and all line studies reported loss rates from 0.1 percent to 79.2 percent. Based upon this review, Richardson et al. (2019) performed a meta-analysis estimating global fishing gear losses for major gear types, finding that 5.7 percent of all fishing nets, 8.6 percent of all traps, and 29 percent of all lines are lost around the world each year. Abandoned, lost or discarded fishing gear can ensnare or entangle marine wildlife, have economic consequences due to losses of commercially important food fish and can smother sensitive coral reef ecosystems (Macfadyen et al. 2009; Gunn et al. 2010; Wilcox et al. 2013; Richardson et al. 2018). Commercial shipping and discharge from ocean-going vessels result in plastic inputs through accidental releases of cargo during ocean transit, which may occur during rough weather or when containers are insufficiently secured during transport (World Shipping Council 2017).

Box 1. Spotlight on Africa's Current and Future Rapid Growth

Africa's contribution to waste generation is currently low by global standards.[a] However, the continent is set to undergo a major social and economic transformation over the coming century as its population explodes, cities urbanise and consumer purchasing habits change.[b] These changes will lead to significant growth in waste and wastewater generation, including nutrient exports to coastal waters,[c] with sub-Saharan Africa forecast to become the dominant region globally in terms of municipal solid waste generation.[d] This will put significant strain on already constrained public and private sector services and infrastructure.[e]

As noted by Yasin et al. (2010) and UNEP (2018a), there are limited reliable, geographically comprehensive waste and water quality data for Africa. This makes it extremely difficult to assess the potential impacts of waste and wastewater systems locally and regionally. However, anthropogenic sources of nutrients in rivers, including agricultural sources and human sewage (often untreated) from urban centres, will become more important than natural sources in large parts of Africa.[f] Furthermore, with growing population comes increased waste generation and changing waste types.[g] As such, in the absence of reliable waste and water quality data, population growth and economic development can provide signals of potential 'geographic areas of concern' with regard to plastic, industrial, agricultural and municipal wastes. According to the United Nations' Department of Economic and Social Affairs, more than half of the world's projected population growth between 2017 and 2050 is expected to come from only 10 countries, with 6 of these in Africa—Nigeria, the Democratic Republic of the Congo, Ethiopia, Tanzania, Uganda and Egypt (ordered by their expected contribution to global growth).[h]

Where the impacts of plastic and nutrients on coastal systems in Africa have been modelled, the models have forecasted significant growth in waste generation and potential impact.[i] Tonnages of mismanaged plastic waste is expected to increase significantly between 2010 and 2025, particularly in coastal countries such as Nigeria, Egypt, Algeria, South Africa, Morocco and Senegal (ordered by their forecasted 2025 mismanaged plastic).[j] The nutrient risk for large marine ecosystems forecast for 2050 shows very high coastal eutrophication risk off the coast of West Africa around the Gulf of Guinea.[k]

While waste volumes produced in Africa are currently low, waste is impacting the environment due to a number of factors, including limited environmental regulation and often weak enforcement, inadequate waste and wastewater systems and the transport of waste into Africa, often from developed countries.[l] With an average municipal solid waste collection rate of only 55 percent for Africa,[m] the potential for plastic to leak into the environment is high. There is growing citizen and government concern around the leakage of plastic waste into the environment, resulting in many African countries moving to ban single-use plastics as a way of limiting their negative impacts. According to UNEP (2018b), 29 countries in Africa, predominantly coastal countries, have already implemented some sort of regulation against plastics. Currently, these regulations vary from a ban on single-use (thin) plastic bags, with associated requirements for bag thickness, to a complete ban on all plastic carrier bags. However, the growing concern around plastic waste is sparking discussions in many African countries on possible further bans on other single-use plastic products, such as PET beverage bottles and food service industry products such as straws, cups, containers and utensils.

There is, however, a growing response from a number of brand owners, retailers and convertors to address the current waste problems in Africa. South Africa, for example, has had voluntary industry initiatives in place for over a decade aimed at growing the local plastic recycling industry. Initiatives such as the South African PET Recycling Company, which has achieved a 65 percent post-consumer PET bottle recycling rate in South Africa,[n] are now being rolled out in Kenya, with plans to launch in Ethiopia and Uganda.[o] There are also a number of social innovations emerging in Africa to deal with the plastic waste problem. These often focus on innovative community-driven collection systems and associated financial rewards for recyclables, such as Wecyclers in Nigeria and Packa-ching in South Africa.

Notes:
a. Kaza et al. 2018.
b. African Development Bank 2012; UNDESA 2015a; UNDESA2015b.
c. Yasin et al. 2010; UNEP 2015.
d. Hoornweg et al. 2015.
e. UNEP 2015.
f. Yasmin et al. 2010.
g. UNEP 2015.
h. UN 2017.
i. Jambeck et al. 2017; UNEP 2018a.
j. Jambeck et al. 2015.
k. Seitzinger and Mayorga 2016.
l. Brooks et al. 2018; UNEP 2018a.
m. UNEP 2018a.
n. PETCO 2018.
o. Coca Cola 2019.

2.2 Other Pollutants Compounding Ocean Stress

Pollution in this category stems from anthropogenic development (including in rural and urban areas). Municipal sources of pollution can be especially high where population densities are high. Lack of infrastructure that can handle sanitation and waste management in rapidly growing cities, especially near the coasts, is a large source of ocean pollution. Sources in this sector include residential and commercial solid waste and wastewater as well as runoff from roads and landscaping activities. Additionally, debris entering the ocean as a result of natural disasters is included here.

2.2.1 Other municipal solid waste pollution

The World Bank estimates that 2 billion metric tons of municipal waste are generated globally with 33 percent (663.3 MMT) being managed by 'open dumping' (Kaza et al. 2018). Approximately 50 percent or more of this waste is organic waste (e.g. food waste) in many places except for Europe and North America, which generate around 30 percent organic waste. In high-income countries (as ranked by the World Bank), 51 percent of the waste stream is plastic, paper, cardboard, metal and glass, while in low-income countries, only 16 percent of the waste stream is estimated to be dry waste and able to be recycled (Kaza et al. 2018). These statistics do not even include special waste materials like medical and electronic waste (e-waste), which pose even further management challenges beyond municipal waste. While regulated by the Basel Convention in international trade, e-waste continues to be processed in areas without adequate infrastructure or protection for workers; to access the metal, the plastic housing and coatings on wires are often burned, releasing toxic emissions impacting ecosystems and human health (Asante et al. 2019).

Box 2. Waste Management in Indonesia

The Indonesian government, through President Act No. 83 in 2018 regarding marine debris management, has committed to reducing plastic waste up to 70 percent by 2025.[a] To support this effort, the Coordinating Ministry of Maritime and Investment Affairs plans to build a protocol to collect marine debris data from several big cities in Indonesia, including Banjarmasin, Balikpapan, Bogor and Denpasar, and has taken action through the Mayor Act (Peraturan Wali Kota) and Governor Act (Peraturan Gubernur) to regulate the reduction of single-use plastic. While some regulations regarding waste reduction, segregation, collection and transport already existed, the lack of enforcement has caused them to be poorly implemented. To amplify efforts to reduce plastic waste, the national government has also constructed a cross-government collaboration approach through a National Plan of Action (Rencana Aksi Nasional) on marine plastic debris for 2018–2025, which includes five main actions: change behaviour, reduce land-based leakage, reduce sea-based leakage, enhance law enforcement and financial support, and increase research and development.[b]

In addition to regulatory solutions, some villages are setting up their own waste management facilities. In 2018, Muncar, a small village in East Java, worked with a private organisation named SYSTEMIQ on a pilot project called Project STOP, which, if successful, can be implemented in other villages throughout Indonesia. For this project, they built a waste management system in the area that focuses on waste segregation in households and capacity building through a sorting centre. The plan has five strategies, including optimised waste collection, behaviour change, regulation setting, village waste management, institutional capacity building and optimised waste processing for both inorganic and organic waste. In December 2019, 47,500 people received waste collection, mostly for the first time, from two facilities established by the project. These facilities have collected 3,000 tons of waste so far and employ 80 local people.[c]

Indonesia is also looking for alternatives to landfills for plastic waste that cannot be recycled. One option being investigated is a plastic road tar that uses plastic waste, mainly LDPE and HDPE. The plastics are shredded, melted and added into road-tar mix. In 2017, this method was piloted at Udayana University, Bali, where they laid a 700-metre-long plastic road. However, an evaluation hasn't yet been done assessing the potential for contamination into the environment.

Notes:
a. Purba et al. 2019.
b. Coordinating Ministry for Maritime Affairs 2018.
c. National Geographic 2020.

Another contribution beyond municipal waste is disaster debris. With climate change increasing both the intensity and frequency of storms around the globe, this pollution input may increase in the future. One quantified example of disaster debris originated from the 2011 Japanese tsunami that washed out 3.6 MMT of debris, with 0.91 MMT floating across the Pacific Ocean and portions of it reaching the western shores of North America (NOAA 2013).

2.2.2 Pesticide pollution

Municipal pesticide pollution has been recognised in nonpoint source stormwater runoff since the 1960s (Weibel et al. 1966). It is sourced from use in commercial and residential landscaping and wastewater (Sutton et al. 2019). Pesticide use and pollution can be significant in densely populated areas where use is common, but it is often on a smaller scale compared with agriculture use. One study of the Marne River in France determined that urban uses of pesticides were considerably lower (47 tons/yr) than agricultural ones (4,300 tons/yr) (Blanchoud et al. 2007), with similar trends observed in eight urban streams in the United States (Hoffman et al. 2000).

Agricultural pesticides represent a category of human-made or human-appropriated chemicals that are used to prevent, destroy, repel or mitigate any pest, or as a plant regulator, defoliant or desiccant (U.S. Code 1947). Pesticides are categorised based on the target class of organisms they are designed to impact. The most common categories include herbicides, insecticides, fungicides, rodenticides, algaecides and antimicrobials.

The ocean is exposed to pesticides through air, water, soil and biota. The air transports pesticides globally, documented as early as 1968 (Risebrough et al. 1968; Seba and Prospero 1971), and has resulted in detectable levels of pesticides in every part of the biosphere, including in arctic ice (Pućko et al. 2017; Rimondino et al. 2018). Pesticide transport through surface runoff occurs in both the liquid phase, where the pesticide is solubilised in the runoff water, and the solid phase, where the pesticide is bound with soil particles that erode with surface runoff. Both mechanisms transport pesticides from their application sites to the ocean. More areas are likely to face high pesticide pollution risk as global population grows and the climate warms, likely requiring even higher rates of pesticide use for increased agricultural activity and crop pests (Ippolito et al. 2015).

2.2.3 Nutrient pollution

Untreated sewage carries a large volume of pollutants to the ocean (Islam and Tanaka 2004) and wastewater itself contains a number of pollutants: nutrients, pathogens, plastics, chemicals, pharmaceuticals and other suspended solids. On a volume basis, raw sewage discharge is of most concern where sanitation infrastructure is still developing. For example, in Southeast Asia, more than 600,000 tons of nitrogen are discharged annually from the major rivers. These numbers may become further exacerbated as coastal population densities are projected to increase from 77 people per square kilometre (people/km2) to 115 people/km2 in 2025 (Nellemann et al. 2008). The global anthropogenic nitrogen (N) load to fresh water systems from both diffuse and point sources in the period 2002–2010 was 32.6 MMT/yr (Mekonnen and Hoekstra 2015), though only a portion of this might reach the ocean.

The accumulated anthropogenic N loads related to gray water footprints in the period 2002–2010 was 13×10^{12} cubic metres per year, with China contributing about 45 percent to the global total. Twenty-three percent came from domestic point sources and 2 percent from industrial point sources (Nellemann et al. 2008). From 2002 to 2010, the global total phosphorous (P) load to freshwater systems from the sum of anthropogenic diffuse and point sources was estimated to be 1.47 MMT/yr, though only a portion of this might reach the ocean. About 62 percent of this total load was from point sources (domestic, industrial) while diffuse sources (agriculture) contributed the remainder. China contributed most to the total global anthropogenic P load, about 30 percent, followed by India (8 percent), the United States (7 percent), and Spain and Brazil (6 percent each) (Bouwman et al. 2011).

A global indicator of wastewater treatment to inform the SDGs has been recently created: Wastewater treatment was normalised by connections to wastewater systems around the world. The regions with the greatest average scores (i.e. the most comprehensive wastewater treatment) are Europe (66.14 ± 4.97) and North America (50.32 ± 17.42). The Middle East and North Africa (36.45 ± 6.33), East Asia and the Pacific (27.06 ± 6.91), Eastern Europe and Central Asia (18.34 ± 5.40), and Latin America and the Caribbean (11.37 ± 2.51) had scores falling in the middle, with some infrastructure lacking. Sub-Saharan Africa (3.96 ± 1.50) and South Asia (2.33 ± 1.34) have the lowest scores with extensive needs for wastewater treatment improvements (Malik et al. 2015). Even where treatment facilities exist, they may sometimes discharge untreated sewage into waterways and the ocean due to decayed infrastructure, facility malfunctions or heavy rainfall events that overwhelm systems using combined sewers and stormwater drains (known as combined sewer overflows).

Nutrient pollution from agricultural sources comes from using synthetic nitrogen and phosphorus fertilisers and from discharging animal waste into the ocean, either via direct runoff, rivers or disaster events (e.g. hurricanes). Globally, humans increased the application of synthetic nitrogen fertilisers by nine-fold and phosphorous fertilisers by three-fold between the 1960s and the 2000s (Sutton et al. 2013). The global agricultural system fixed 50–70 Teragrams (Tg) of N biologically, while nearly double that, 120 Tg per year of N, was added as synthetic fertilisers to support the production of crops and grasses as well as feedstock for industrial animal agriculture (Galloway et al. 2008; Herridge et al. 2008). A large share of the human-applied N is lost, including some 40–66 Tg N/yr exported from rivers to the ocean from 2000 to 2010 (Seitzinger et al. 2005; Seitzinger et al. 2010; Voss et al. 2011; Voss et al. 2013). Estimates show an increase in the total N and P exports to coastal waters by almost 20 percent and over 10 percent, respectively, from 1970 to 2000 (Seitzinger et al. 2010). Diffuse sources, including agriculture, contributed about 28 percent of the global total P load to freshwater systems, which eventually lead to the ocean.

Global crop production is often seen as the primary accelerator of N and P cycles. However, the demand for animal feed produced from different crops and by-products of the food industry has rapidly increased in the past century. At present, about 30 percent of global arable land is used for producing animal feed, probably also involving a similar fraction of fertiliser use to produce crops for human consumption (Steinfeld et al. 2006). In addition, total N and P in animal manure generated by livestock production exceed the global N and P fertiliser use (Mekonnen and Hoekstra 2018). Livestock production has increased rapidly in the past century, with a gradual intensification that has influenced the composition of livestock diets. In general, intensification is accompanied by decreasing dependence on open range feeding in ruminant systems and increasing use of concentrate feeds, mainly feed grains grown with fertiliser and fed to animals at feedlots with concentrated manure to manage.

2.2.4 Antibiotics and other pharmaceuticals

Antibiotics and other pharmaceuticals are present in most wastewater both from improper disposal (flushing down sinks or toilets) and from human waste. Where wastewater treatment facilities exist, treatment primarily removes solids and pathogens, but is not typically able to remove pharmaceuticals without advanced treatment (Keen et al. 2014). A rapid increase (up 65 percent in defined daily doses) of antibiotic use between 2000 and 2015 was seen globally, with the largest increases in lower-middle-income countries where wastewater treatment may be less available (Klein et al. 2018).

Box 3. The Impacts of Aquaculture

The four primary discharges to the ocean from ocean-based aquaculture, as identified and quantified by the Global Aquaculture Performance Index, are antibiotics, antifoulants (primarily copper), parasiticides and uneaten feed and faeces, the last of which impacts the biochemical oxygen demand of the water.[a] There are two additional biological impacts—escaped fish and pathogens—that are considered out of scope for this paper. Plastics discharged by aquaculture are presented at the beginning of this section. The relative volume and impacts of these four discharges vary by species, geography and type of aquaculture, with impacts ranging from relatively benign to quite damaging for the marine environment and marine life. The index identified the worst-performing sector as marine finfish in tropical and subtropical water, such as groupers, red drum and cobia, and the worst geography as Asia, with Asian countries holding the lowest 15 spots in the species-country ranking. These countries tended to score particularly poorly on biochemical oxygen demand and use of antibiotics and parasiticides.[b]

Notes:
a. Volpe et al. 2013.
b. Volpe et al. 2013

2.2.5 Heavy metals, persistent organic pollutants and oil and gas

Urban runoff, especially roadway runoff, is the primary source of heavy metals, POPs and oil and other chemicals from municipal sources, although some of these can also be contained in wastewater. One recent example from China shows road runoff contains significant cadmium, chromium, copper, manganese, nickel, lead and zinc when classifying with a pollution load index, and that roadways have two to six times greater metal concentrations than rooftop runoff (Shajib et al. 2019).

Pollution from industry refers to any discharges of hazardous substances, which may be a result of effluent discharges from manufacturing operations and cleaning equipment and any accidental spills. Industrial activities may generate waste that contains heavy metals, carcinogenic hydrocarbons, dioxins, pesticides, and noxious organic and inorganic substances. Hazardous substances are used to produce electrical equipment, oil and petrochemicals, organic and inorganic chemicals, pesticides and heavy metals (mercury, arsenic, lead, cadmium), and are used by the wood/pulp processing and electroplating industries. Additionally, by-products of industrial processes include toxic dioxins (e.g. $C_4H_4O_2$) produced in the manufacture of certain herbicides and chlorine from paper pulp bleaching. Hazardous materials can be explosive, toxic or carcinogenic, and must be treated and managed appropriately. Like other pollutant pathways already discussed, industrial pollutants can enter the ocean directly through point discharges or by flowing in rivers (water or sediment transport) to the ocean, but may also come from atmospheric deposition as illustrated in a river and estuary source and transport case study of organochlorine compounds by Wu et al. (2016).

Industrial water consumption comprises 22 percent of global water use (UN Water 2018). In 2009, industrial water use in Europe and North America was 50 percent of total water use compared with 4–12 percent in developing countries, but it is expected to increase by a factor of five in the next 10–20 years in rapidly industrialising countries (UN Water 2018). As far back as 2002, 160,000 factories were estimated to discharge between 41,000 and 57,000 tons of toxic organic chemicals and 68,000 tons of toxic metals into coastal waters (UNDP 2002). Globally, 80 percent of wastewater, including some industrial wastewater, is discharged into the environment without treatment (UN Water 2018). In the United States, around 60 percent of coastal rivers and bays had already been degraded by 2006 (UNEP/GPA 2006). The Mediterranean coastline has faced major environmental pressures from industrial development, with wastewater flows from the mineral, chemical and energy sectors (GRID-Arendal 2013). Meanwhile, China has discharged approximately 20–25 billion tons per year of industrial wastewater since 2000 (Jiang et al. 2014). The real number may be even higher, due to underreporting and a mismatch in both water quality standards and wastewater standards. In 2018, only about 71 percent of the industrial wastewater was treated in Vietnam—craft villages near Hanoi, for example, were discharging 156,000 cubic metres of water a day into the Red River Delta near the coast (World Bank 2019). The World Bank (2019) also states that treating 22 million cubic metres of wastewater from industrial clusters along the Nhue-Day River could considerably improve coastal water quality. The Ganga River, despite being a sacred river, is heavily polluted by untreated industrial activities. Seven hundred sixty-four units of industry generate 501 million litres of wastewater from tanneries, textile mills, paper, pulp and other sources (India Ministry of Water Resources 2017). The Tiram River in Malaysia had high levels of toxics due to the improper treatment of industrial effluent in 2015 (Asri 2015). Only one-third of Philippine river systems are considered suitable for public water supply due to untreated domestic and industrial wastewater (Asian Development Bank 2009). These polluted rivers stream to the ocean and threaten the coastal resources in the Philippines. Monitoring of fish and macroinvertebrates in Manila Bay, Philippines, showed the content of cadmium, lead and chromium were considerable (Sia Su et al. 2009). Heavy metal pollution for lead and hexavalent chromium had accounted for 99.2 percent of disease burden from toxic exposure among those in India, Indonesia and the Philippines (Chatham-Stephens et al. 2013). Seawater along the coast of the Korean Peninsula was analysed for heavy metal concentrations three times from 2009 to 2013 and copper and zinc concentrations were found to exceed acceptable standards all three times (Lee et al. 2017). Untreated industrial discharges threaten not only ecosystem services, but potentially billions of people.

Box 4. Jakarta Bay Struggles with Industrial Pollution

Jakarta Bay is on the northern coast of Jakarta Metropolitan City, Indonesia. Three large rivers, the Citarum, Ciliwung and Cisadane, flow into Jakarta Bay. These rivers are used by inhabitants as well as industry in the Jakarta, West Java and Banten Provinces. There has been significant anthropogenic impact on the Citarum River dating back to the increase in use of the area for industrial activities in the early 1980s.[a] Septiono et al. (2016) discovered heavy metals—namely cadmium, chromium hexavalent, zinc, mercury, lead and copper—exceeding the national concentration standards in the river. The concentrations of lead and copper in the sediment of Jakarta Bay increased five and nine times, respectively, between 1982 and 2002 (Arifin 2004). In 2006–07, sampling found that sediment distribution in the estuary of Jakarta Bay consisted mostly of black clay, which is indicative of anthropogenic influences from the Jakarta River Basin.[b] Sampling done from June 2015 to June 2016 showed that around 97,000 debris items entered the bay daily through nine rivers, and about 59 percent of it was macroplastic,[c] a further stressor on Jakarta Bay.

Thousands of people, such as fishers in North Jakarta and those along the Thousand Islands, depend on the ecosystem goods and services provided by the river. However, the extreme pollution of toxic chemicals, eutrophication and sediment load in the area, as well as overexploitation of marine resources, are threatening coastal communities. Production of the capture fishery sector decreased in the last five years. Fish production continuously declined from about 35,000 tons in 1999 to almost 18,000 tons in 2002.[d] Jakarta Bay is under stress from both intensive fishing and degraded water quality due to pollution from both land and marine sources. Mercury content in green mussels and arsenic concentrations in green mussels and tuna samples in Jakarta Bay are above the national standard concentrations (1.0 milligram per kilogram),[e] yet the polluted green mussels can be found in local markets. Despite being highly used for food and to support livelihoods, Jakarta Bay is a sea of wastewater and solid waste.

Notes:
a. Bukit 1995; Parikesit et al. 2005; Dsikowitzky et al. 2017.
b. Tejakusuma et al. 2009.
c. Cordova and Nurhati 2019.
d. Arifin 2004.
e. Koesmawati and Arifin 2015.

2.2.6 Maritime pollution

Pollution into the ocean does not arise only from land; the ocean is also impacted by ocean-sourced pollution. Pollution other than plastic (see section 2.1.4 for a discussion of plastic pollution), results from fishing, shipping and transportation, cruises, recreational boating, ocean exploration and other maritime activities. Similar to land-based sources, wastewater and grey water contribute to nutrient and chemical loading in the ocean, and unique to ocean-going vessels, improper management of bilge water can also cause pollution. Sewage and grey water are regulated under MARPOL Annex IV and bilge water under Annex I. Beyond that, oil spills are one of the most evident forms of ocean pollution due to large areas that may be impacted and the visible consequences for seabirds and other marine wildlife (Palinkas et al. 1993). Most maritime oil spills occur due to transportation mishaps or accidents on oil rigs. Less frequently, a sunken vessel or discharge of oil-containing bilge or ballast water may be released.

Because of policies by the International Maritime Organization (IMO) and goals to improve safety and reduce environmental risk, the overall trend of oil spills from tankers (not including rigs and platforms) has decreased over time (Kontovas et al. 2010). However, in 2010 BP's Deepwater Horizon oil spill resulted in 4.9 million barrels of oil entering the ocean, the largest oil spill in the history of the petroleum industry; thousands of scientific papers have assessed the impacts of this oil spill since it occurred.

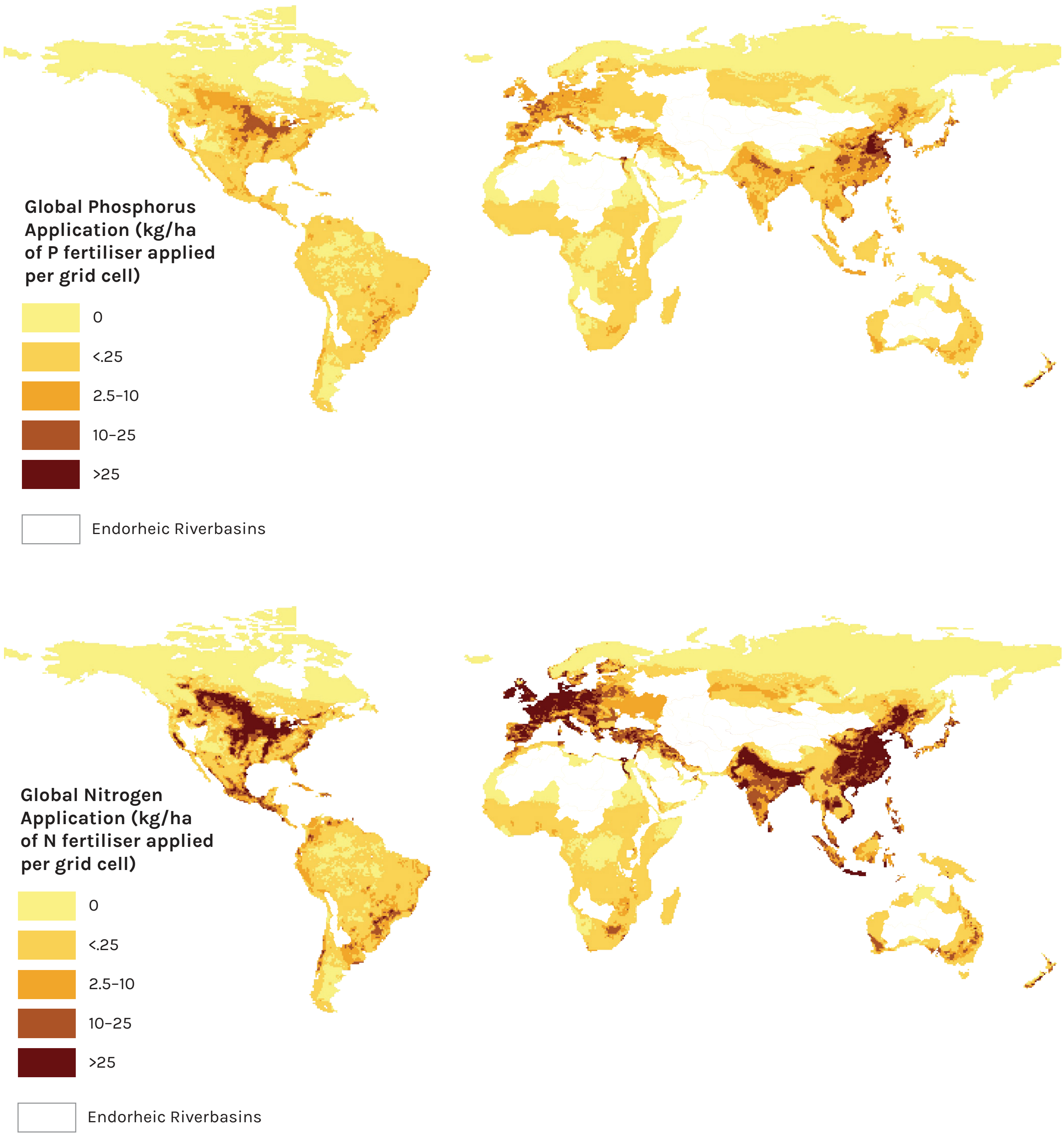
2.3 Compounding Effects of Multiple Pollutants

More than one source and pollutant can cause a complex mix of stressors on the ecosystem and marine life, with sometimes synergistic effects (the impact of the two together is greater than the sum of their individual impacts).

Distinct pollutants may also enter the ocean through similar pathways. The municipal sector, for example, is a source of both plastic waste and wastewater. In general, wastewater also carries all the contaminants of urban stormwater runoff in addition to pollutants in sewage. When municipal infrastructure for handling solid and liquid wastes is lacking, rapid economic development exacerbates pollution. In some cases, open sewage canals are sometimes used to 'manage' wastewater in urban systems, yet solid waste on land washes into these canals and drains into waterways that can lead to the ocean. In other cases, aging infrastructure incapable of handling stormwater leaks both sewage and plastic into waterways from combined sewer overflow events. Just as negative synergies exist, so do positive ones: Waste management of the residual solids from wastewater treatment are often managed within the solid waste management sector, and development of infrastructure to manage biosolids can help properly manage other solid waste, including plastic waste.

The agriculture sector has the highest input of nutrients to the ocean. In one of the largest river basins, the Mississippi River, fertiliser use delivered 64 percent and 41 percent of the N and P, respectively, to the Gulf of Mexico. Pasture use delivered another 5 percent and 38 percent of the contribution, for a total N and P from agriculture of 70 to 80 percent of the total (by comparison, urban use is 9 to 11 percent) (Alexander et al. 2008). The research also found that source reductions on land near large rivers (nearly 1:1) or quickly flowing streams (2:1) had the greatest reduction of overall nutrient loading to the Gulf (Alexander et al. 2008). This means that in large river basins, it is possible to get a nearly kg per kg reduction to the ocean by decreasing fertiliser use and adjusting management of grazelands. Figure 2 shows use of N and P on land, as well as all the major watersheds that drain to the ocean.

Figure 2. Global Nitrogen and Phosphorous Applications (minus endorheic basins)



Notes: These applications could impact the ocean based upon runoff and drainage. Kg/ha stands for kilogram per hectare. N stands for nitrogen, and P for phosphorous. As used here, an endorheic basin is a body of water that has no outflow to other bodies of water, such as rivers or the ocean.

Sources: Potter et al. 2010; Potter et al. 2011a; Potter et al. 2011b. Map created by A. Brooks.

Box 5. Spotlight on Vietnam

Vietnam has a coastline of 3,260 kilometres with over 3,000 islands and 114 river mouths and estuaries. Due to the rapid rate of population increase, urbanisation and industrialisation, a large amount of pollution has been introduced into the coastal zone in recent decades. The major sources of pollution discharges into the ocean include untreated or incompletely treated effluents from the municipal and industrial sectors, as well as waste from agriculture activities and seaport and tourism activities.

The total amount of domestic wastewater in both urban and rural areas in Vietnam is estimated to be 8.7 million cubic metres per day (million m^3/day).[a] Major pollutants are nutrients, organic matter, suspended solids and nitrogen-containing organic substances. According to the Vietnam Ministry of Construction, the total designed capacity of 39 domestic wastewater treatment plants over the country is approximately 907,950 m^3/day, which covers only 11 percent of domestic wastewater.[b] In Ha Noi capital and Ho Chi Minh City, the two largest cities in the country, the percentage of all domestic wastewater processed by centralised wastewater treatment plants is 20.6 percent and 13 percent of the total wastewater, respectively.[c] By the end of 2016, 344 industrial zones had been established with the amount of industrial wastewater varying in the regions, and 220 industrial zones were in operation of which 86 percent had a centralised wastewater treatment plant. Only 98 of 620 industrial clusters, or 16 percent, were designed with a wastewater treatment system—and those treatment systems have been shown to have a number of limitations. In addition, wastewater from handicraft villages also contributes to marine pollution.[d]

Waste from agricultural activities also contributes to marine pollution, especially from the livestock, aquaculture and crop sectors. The estimated livestock solid waste—including nutrients, suspended solids, organic matter, pathogens and pharmaceuticals—was reported to be 47 million tons in 2016, of which 40–70 percent was treated and the rest discharged into lakes, streams and rivers.[e] For instance, 70–90 percent of the wastewater from one pig farm, comprised of nutrients (nitrogen), minerals, heavy metals and pharmaceuticals, was reported to be excreted into the environment. Aquaculture activities also release a large amount of untreated waste directly into the ocean with high levels of nitrogen and phosphorus. In 2014, more than 10 billion cubic metres of wastewater containing 51,336 metric tons of nitrogen and 16,070 metric tons of phosphorus in a pangasius fish farm were estimated to be discharged to local canals to eventually end up in the Mekong Delta River.[f]

The use of pesticides and chemical fertilisers in agricultural production is another major source of surface water pollution. Fertilizer use is increasing in Vietnam. From 1983 to 2013, fertiliser consumption increased nearly seven-fold to 26 MMT in 2013, and about 80,000–100,000 tons of pesticides, herbicides and fungicides were used from 2012 to 2014.[g] On average, 20–30 percent of pesticides and chemical fertilisers applied will not be retained by plants and will be washed by rainwater and irrigation water into surface water resources as well as accumulate in the soil and groundwater in the form of residues. In summary, the pollutants released by these activities include, among others, nutrients, organic chemicals, sediments and pesticides, which ultimately end up in the sea of Vietnam. In addition, wastewater is also discharged from ocean-going ships, other maritime facilities, ship building and repair plants, seaports and freight yards and stores.

The two major river basins in Vietnam, the Mekong and the Red River, annually discharge approximately 500 million and 137 billion cubic metres of water into the ocean, respectively.[h] Sediment is discharged from the Mekong alone at a rate of 36 MMT/yr, although this is a decrease from previous estimates since dams are now reducing that transport.[i] However, both of these water and sediment flows can transport pollutants from the anthropogenic activities in the river catchment and coastal areas to the ocean.[j] About 13 MMT of solid waste is mismanaged in Vietnam each year, with 1.8 MMT of that plastic, and an estimated 0.28–0.73 MMT entering the ocean from Vietnam each year.[k]

In Vietnam, not many studies on plastics, including microplastics, have been conducted, although Vietnam is one of the top countries in the world in terms of plastic waste.[k] The plastic industry during 2010–2015 was the third-largest industry in terms of

continued on page 20

Box 5. Spotlight on Vietnam, continued

growth, with an annual increase of 16–18 percent (following the telecommunications and textile industries). The amount of plastic used per capita increased from 3.8 kg/year in 1990 to over 41 kg/year in 2015.[l] Although there are no official statistics on the amount and varieties of plastic in the Vietnamese sea, plastic waste, originating from wastewater and solid waste from the mainland, can enter the ocean through 114 river mouths and estuaries.

Fishing, aquaculture and on-sea activities are also major sources of plastic in the Vietnamese sea. Every day, about 80 tons of plastic waste and bags are thrown away in Ho Chi Minh and Ha Noi combined.[m] In Ho Chi Minh, microplastics were found in urban canals with 172,000 to 519,000 items/m^3,[n] and in the surface water in Can Gio Sea at a rate of 0.176 ± 0.0 items/m^3.[o]

Vietnam is addressing the plastic issue on both the national and regional scales. The government has released a national action plan for marine litter (Government of Vietnam 2020). Regionally, the Lower Mekong Initiative, a multinational partnership among Cambodia, Laos, Myanmar, Thailand, Vietnam and the United States to create integrated subregional cooperation among the five Lower Mekong countries, launched in 2009, is now also working to address plastic contamination upstream before it gets to the ocean.

To more effectively address plastic waste, more research is needed. In particular, research that provides a more complete characterisation of macro and microplastics at sea is needed, as well as further study on effective strategies for managing plastic waste—particularly microplastics (including microbeads).

Notes:
a. MONRE 2016.
b. Nam 2016.
c. MONRE 2017.
d. MONRE 2017.
e. MONRE 2016; World Bank Group 2017.
f. World Bank Group 2017.
g. MONRE 2014; World Bank Group 2017.
h. World Bank 2019.
i. Thi Ha et al. 2018.
j. World Bank 2019.
k. Jambeck et al. 2015.
l. VPAS 2019.
m. Vietnam News 2019.
n. Lahens et al. 2018.
o. Hien et al. 2019.

3. Impacts of Ocean Pollution on Ecosystems, Marine Life, Human Health and Economies

There are a multitude of potential impacts pollutants can have on the ocean, which we have categorised into four types: ecosystem, marine life, human health and economic. See Table 2 for a brief outline of these impacts.

Table 2. Potential Ecosystem, Marine Life, Human Health and Economic Impacts from Ocean Pollution

POLLUTANT	ECOSYSTEM IMPACTS	MARINE LIFE IMPACTS	HUMAN HEALTH IMPACTS	ECONOMIC IMPACTS
Microplastics	▪ Potential to alter the distribution of sediment dwelling organisms in assemblages ▪ Can provide surface vectors that facilitate the transport of potentially harmful microorganisms	▪ Negative effects on food consumption, growth, reproduction and survival across a wide range of organisms at the individual level ▪ Starvation (due to ingestion) ▪ Potential of exposure to toxic substances (in or absorbed by plastics) ▪ Trophic transfer	▪ Unknown impact of ingestion through consumption of marine animals with microplastics in their tissues ▪ Unknown exposure to toxic chemicals due to ingestion ▪ Unknown exposure to pathogens	▪ Reduction in global marine ecosystem services has been estimated at US$0.5–2.5 trillion[1]

Table 2. Potential Ecosystem, Marine Life, Human Health and Economic Impacts from Ocean Pollution

POLLUTANT	ECOSYSTEM IMPACTS	MARINE LIFE IMPACTS	HUMAN HEALTH IMPACTS	ECONOMIC IMPACTS
Macroplastics	▪ Smothering and impact on coral reefs ▪ Transport of invasive species	At the individual level: ▪ Starvation (due to ingestion) ▪ Entanglement ▪ Chemical exposure	▪ Increase in mosquito-borne diseases ▪ Potential for exposure to pathogens	▪ Estimated $40 billion in negative externalities annually[2] ▪ Global damage to marine environments from plastic pollution estimated at a minimum $13 billion per year[3] ▪ Aggregated estimates across the plastics life cycle concluded that annual damages from plastic production and the current stock of plastic waste in the ocean amount to $2.2 trillion[4] ▪ Fishermen lose time and efficiency from catching trash in nets ▪ Damage to maritime industries in the APEC[a] region was estimated at $1.26 billion per year[5] ▪ Loss of revenue from tourism, e.g. reducing marine debris by 100 percent was estimated to improve the savings and welfare of local residents by $148 million over the three-month summer period[6]
Other solid waste	▪ Additive nutrients to the ocean as source of hypoxia (from organic waste) ▪ Source of heavy metals (e-waste)	▪ Ingestion, entrapment or entanglement causing impairment or death ▪ Transport of invasive species	▪ 15 million people worldwide work informally in waste management in poor, unhealthy conditions[7] ▪ Risk of entrapment/ bodily injury ▪ Heavy metal contamination and exposure (e-waste) ▪ Pathogen exposure (medical waste)	▪ Fishermen lose time and efficiency from catching trash in nets ▪ Debris in water can damage fishing gear and nets ▪ Loss of revenue from tourism

Table 2. Potential Ecosystem, Marine Life, Human Health and Economic Impacts from Ocean Pollution

POLLUTANT	ECOSYSTEM IMPACTS	MARINE LIFE IMPACTS	HUMAN HEALTH IMPACTS	ECONOMIC IMPACTS
Pesticides	▪ Reduced photosynthetic efficiency of sea grass, corals and algae (herbicides), resulting in chronic stress ▪ Measurable impacts on seagrass productivity, especially when combined with light attenuation from high sediment loads from agricultural runoff ▪ Can restrict or fully inhibit coral settlement and metamorphosis at concentrations as low as one part per billion, and at higher concentrations can cause coral branch death	▪ Death, cancers, tumours and lesions on fish and animals, reproductive inhibition or failure, suppression of immune system, disruption of endocrine system, cellular and molecular damage, teratogenic effects, poor fish health marked by low red to white blood cell ratio, excessive slime on fish scales and gills, intergenerational effects, and other physiological effects such as egg shell thinning[b]	▪ Toxicity via consumption of marine species who have bioaccumulated or biomagnified pesticides in their tissue. Most at risk are vulnerable populations (children, elderly) in communities with high levels of seafood consumption	▪ Loss of productivity and resiliency of seagrass beds and coral reefs due to pesticide pollution impacts global economic security by reducing provision of ecosystem services that are essential for human society. While exact level of damage is not known, if we assume a reduction in productivity of these ecosystems by 25%, the annual economic impact of those pesticides in the ocean would be $200 billion per year[8]
Nutrients (N, P)	▪ Eutrophication and hypoxia ▪ Biodiversity losses ▪ Ecosystem losses	▪ Fish kills, red tides ▪ Decreases in population and species diversity with benthic and fish communities ▪ Release of ammonia and hydrogen sulfide, which can be toxic to marine life	▪ Respiratory irritation from harmful algal blooms (HABs), e.g red tides ▪ Illness from consuming seafood exposed to HABs	▪ Black Sea fishery value was reduced by 90% (from roughly $2 billion). Other economic impacts included an estimated loss of $500 million in tourism revenue[9] ▪ A major and extensive red tide outbreak occurred along the coast of Hong Kong and south China, covering an area of more than 100 km^2. Over 80% (3,400 tons) of mariculture fish were killed, and the total loss was over $40 million[10] ▪ Major economic impacts on fisheries, aquaculture and tourism

Table 2. Potential Ecosystem, Marine Life, Human Health and Economic Impacts from Ocean Pollution

POLLUTANT	ECOSYSTEM IMPACTS	MARINE LIFE IMPACTS	HUMAN HEALTH IMPACTS	ECONOMIC IMPACTS
Antibiotics, parasiticides, other pharmaceuticals	▪ The occurrence of subtherapeutic doses of antibiotics on bacteria over a prolonged period leads to resistance, which is a threat to the environment	▪ The occurrence of subtherapeutic doses of antibiotics on bacteria over a prolonged period leads to resistance, which is a threat to the environment	▪ Carcinogenic, mutagenic and reproductive toxicity potential ▪ Endocrine system impacts	▪ Unknown
Heavy metals	▪ Toxicity to some microorganisms and animals, cancer in animals, uptake by plants	▪ Increase in the permeability of the cell membrane in phytoplankton and other marine algae, leading to the loss of intracellular constituents and, therefore, cellular integrity ▪ These include lymphocytic infiltration, lesions and fatty degeneration ▪ In addition, cadmium, lead and mercury are potential immunosuppressants; of concern is the buildup of mercury, which marine mammals tend to accumulate in the liver	▪ Acute toxicity at high doses, chronic toxicity, cancer, impacts to the nervous system and behaviour (especially lead)	▪ Unknown
Industrial chemicals and persistent organic pollutants[c]	▪ Food chain interactions, birth defects, cancer, accumulation and transformations in the environment	▪ Abnormal behaviour, birth defects in fish, birds, mammals ▪ Biomagnification in the food chain	▪ Reproductive, developmental, behavioural, neurologic, endocrine, and immunologic adverse health effects	▪ Unknown

Table 2. Potential Ecosystem, Marine Life, Human Health and Economic Impacts from Ocean Pollution

POLLUTANT	ECOSYSTEM IMPACTS	MARINE LIFE IMPACTS	HUMAN HEALTH IMPACTS	ECONOMIC IMPACTS
Oil and gas	▪ Coat and smother benthic areas	▪ Death ▪ Negative impacts on reproductive health ▪ Carcinomas and papillomas on the lips of bottom-feeding fish, as well as changes in the cell membrane ▪ Severe eye irritation with subsequent blindness in seals ▪ Individual birds become unable to swim or fly and nervous system abnormalities can occur ▪ Population-level effects of oil toxicity on aquatic birds occur through the loss of egg viability	▪ Localised health impacts from immediate exposure, potential for longer-term impacts from exposure, e.g. cancer, mental health issues if fisheries and livelihoods are impacted	▪ BP's Deepwater Horizon spill in the Gulf of Mexico is estimated to have cost the company $61.6 billion in penalties and fines; cleanup and remediation; and payments to affected companies, communities and individuals[11] ▪ The 'true' cost of the 2010 Deepwater Horizon oil spill including loss of tourism, cost of cleanup, and loss of fisheries is estimated to be $144.89 billion[12]

Notes: Pathogens present in human and animal waste discharged to the ocean can infect marine animals, but this is considered out of scope for this analysis.
a. APEC stands for Asia-Pacific Economic Cooperation.
b. These effects are not necessarily caused solely by exposure to pesticides or other organic contaminants, but may be associated with a combination of environmental stresses such as eutrophication and pathogens.

Sources:
1. Beaumont et al. 2019.
2. World Economic Forum et al. 2016.
3. UNEP 2014.
4. Forrest et al. 2019.
5. McIlgorm et al. 2008.
6. Leggett et al. 2014.
7. Medina 2008.
8. Cesar et al. 2003.
9. World Bank 2009.
10. Yang and Hodgkiss 2004.
11. Mufson 2016.
12 Islam and Tanaka 2004.

3.1 Impacts of Plastic

3.1.1 Impacts on ecosystems and marine life

MICROPLASTICS

Microplastics have accumulated across a wide range of environmental compartments including marine, terrestrial and freshwater habitats as well as in the air (SAPEA and Academies 2019; Eerkes-Medrano et al. 2015). These areas also include remote locations far from population centres such as in the deep sea (Woodall et al. 2015) and the Arctic (Obbard et al. 2014). There is clear evidence that microplastics are ingested by a wide range of species including marine mammals, birds, fish and small invertebrates at the base of the food chain (Law and Thompson 2014; Lusher 2015). While it has been shown that particles can pass through the digestive system and be excreted, it has also been established that some particles can be retained in the body for several weeks (Browne et al. 2008; Ory et al. 2018). Microplastics can also transfer between prey and predator species within food webs (Watts et al. 2015; Chagnon et al. 2018). Many of the species that have been shown to be contaminated with microplastics are commercially important for human consumption (Lusher et al. 2013).

Laboratory experiments indicate that at high doses ingesting microplastics can induce physical and chemical toxicity (SAPEA and Academies 2019). The physical presence of microplastic particles has been shown to have negative effects on food consumption, growth, reproduction and survival across a wide range of organisms, and there is evidence that zooplankton, non-mollusc invertebrates and juvenile fish are particularly sensitive (Cole et al. 2015). For example, a reduction in feeding efficiency has been demonstrated for zooplankton, lugworms and fish. In addition, when ingested, microplastics can transfer potentially harmful chemicals to biota; this can occur as a consequence of the transfer of hydrophobic chemicals from the surrounding water or the release of additive chemicals incorporated at the time of manufacture (Teuten et al. 2007; Tanaka et al. 2013). While the transfer of chemicals by plastics to biota has been demonstrated, it is the dose that determines the poison. In a recent bird feeding experiment, Roman et al. (2019) found that plastic ingestion caused higher frequencies of male reproductive cysts and minor delays in chick growth and sexual maturity, but did not affect ultimate survival or reproductive output. With regard to the transfer of chemicals by plastics from seawater, recent work has shown that other pathways including direct uptake from water and natural foods are likely to be more important pathways than microplastics (Bakir et al. 2016; Koelmans et al. 2016). Less is known about the risks associated with the release of additive chemicals from plastic. Determining the release of additives is particularly challenging since chemical formulations are not typically in the public domain (SAPEA and Academies 2019).

Most experimental work on effects has focused on those on individuals, but there is some evidence of wider ecological effects including the potential to alter the distribution of sediment-dwelling organisms in assemblages (Green 2016) and to influence the sinking rates of faecal material to the seabed (Cole et al. 2013). Microplastics also provide a surface that can readily become colonised by microorganisms including pathogens and there are concerns that microplastic particles may therefore provide vectors facilitating the transport of potentially harmful microorganisms (Zettler et al. 2013; Kirstein et al. 2016).

Plastic is rapidly colonised by microorganisms in a marine environment (Harrison et al. 2014). Plastic surface habitat has even been defined as the 'plastisphere' in recognition of the unique communities it harbours (Zettler et al. 2013). In fact, litter items made with many materials appear to have unique biofilm communities (Woodall et al. 2018). These communities include potentially harmful pathogens such as *Vibrio* spp. (Kirstein et al. 2016) and *E. coli* (Rodrigues et al. 2019) and are known to colonise the surfaces of submerged plastic surfaces, similar to how they colonise other hard submerged surfaces (Shikuma and Hadfield 2010). A submerged plastic cup laid on a seagrass meadow can serve as a home for more than 500 individual meiofauna, which potentially affects meiofauna community structure (Susetiono 2019). These communities might also impact biogeochemical cycles (Cornejo-D'Ottone et al. 2020).

It is important to recognise that most studies of physical and particle toxicity have been conducted using concentrations and/or particle sizes that are not typical of those currently recorded in the environment (Lenz et al. 2016). There are challenges since environmental concentrations are not known with confidence, especially for particles smaller than 300 micrometres, which are less likely to be collected from water using conventional net sampling. Plastics can fragment because of environmental exposure and so the abundance of very small particles in the nano-size range could be considerable. These particles are currently too small to detect in environmental samples, but laboratory studies show the potential for these particles to transfer from the gut to the circulatory system with the potential to rapidly become widely distributed in organisms (Brandelli 2020). More work is needed to understand the potential toxicological impacts of this. Despite the uncertainties about environmental concentrations in relation to evidence of harm, there is some consensus based on risk assessment approaches that if microplastic emissions to the environment remain the same or increase the ecological risk may become widespread within a century (SAPEA and Academies 2019).

MACROPLASTICS

To date, around 700 species of marine life have been demonstrated to interact with plastic (Gall and Thompson 2015), with the main impacts occurring through entanglement, ingestion and chemical contamination (Wilcox et al. 2015). Far more is known about harm to individuals through interaction with plastic than is known about harm to populations, species and ecosystems within the marine environment (Rochman 2015).

Entanglement in plastic debris

Impacts on marine systems from entanglement are most commonly associated with abandoned, lost, or derelict fishing gear. Called 'ghost fishing', derelict fishing nets can continue to indiscriminately catch fish (and other marine organisms) for weeks, months or decades, which, in addition to impacting ecosystems and marine life, results in food security issues through lost resources to feed the world's population (and the associated economic consequences of lost revenue). With an estimated 640,000 tons of gear lost to the ocean each year per a census taken a decade ago (Macfadyen et al. 2009), some areas have reported up to three tons of derelict nets per kilometre of coastline in a given year (Wilcox et al. 2013). Derelict nets have been reported to ensnare or entangle invertebrates, crabs, fish, sharks, rays, sawfish, turtles, seabirds, crocodiles, dugongs, whales, dolphins and numerous other marine taxa. Ghost nets can also damage fragile habitats (such as by smothering or breaking coral reefs (Sheavly and Register 2007), entangle propellers, cause navigation hazards to other vessels (Gunn et al. 2010; Hong et al. 2017) and transport invasive species (Macfadyen et al. 2009). Impacts can be substantial—it has been estimated that in the Gulf of Carpentaria in northern Australia alone, derelict nets have likely entangled more than 10,000 sea turtles (Wilcox et al. 2013).

Ingestion of plastic debris

There are numerous demonstrated effects of plastic ingestion by marine fauna. These may include not only death (van Franeker 1985; Schuyler et al. 2012; Wilcox et al. 2015) but also reduction in body mass (Schuyler et al. 2012), starvation that may result from the physical blockage of the gut (van Franeker 1985; Laist 1987; Acampora et al. 2014; Hardesty et al. 2015), ulceration or perforation of the digestive tract (van Franeker 1985; Laist 1987; Schuyler et al. 2012) and potential toxicity due to sorption of chemicals contained within and sorbed to the plastic (Teuten et al. 2009). In some studies, incidence of plastic ingestion was as high as 60–80 percent or more of individuals sampled (crustaceans as reported by (Murray and Cowie 2011); green turtles in Brazil as reported by (Bugoni et al. 2001) and deep sea species as reported by (Jamieson et al. 2019).

> Plastics can fragment because of environmental exposure and so the abundance of very small paticles in the nano-size range could be considerable. More work is needed to understand the potential toxicological impacts of this.

Chemical contamination from plastic debris

At present, far less is known and understood about the effects of chemical contamination (which takes place through ingesting plastic) than impacts from entanglement. In laboratory experiments, it has been demonstrated that ingested plastic can induce hepatic stress in fish (Rochman et al. 2013). Plasticisers (softening and other chemical agents such as dibutyl phthalate and diethylhexyl phthalate that are often added to plastics) have been detected in the preen gland oil of wild-caught seabirds, with higher levels of plasticisers found in birds that had eaten more plastic pieces (Hardesty et al. 2015). Polystyrene, heavily used in fisheries and aquaculture, is also of particular concern, as styrenes have been shown to leach into marine systems (Kwon et al. 2015). Jamieson et al. (2019) found plastics in animals in some of the deepest parts of the ocean. Endocrine-disrupting compounds leaching into tissues from plastics are of increasing concern, not only for wildlife (Olivares-Rubio et al. 2015), but also for humans (Meeker et al. 2009; Halden 2010).

3.1.2 Human health impacts

The risk of marine plastic debris to human health can be measured by the likely exposure of humans to marine plastic multiplied by the potential for harm by the plastic. This is not a simple equation, as plastics comprise many and diverse chemical additives in addition to their primary polymer component. The limitless combinations of polymers and additives mean that each plastic product has a different combination of chemicals, uses and disposal pathways with varying levels of risk to humans. As a result, plastics should not be treated as a single product, and need to be addressed separately (Lithner et al. 2011). To understand the risk, potential exposure should be identified and quantified, and the potential for harm, including from factors such as the concentration of chemical additives, size fraction (Smith et al. 2018) and ageing (Kedzierski et al. 2018), should also be determined. Because there are so many confounding variables and ethical issues, and a lack of a control group, studying human exposure to various plastic materials and forms is challenging. This section outlines exposure pathways, but without reliable measures for all exposure pathways (pre and post waste) it is not possible to calculate the relative risk of plastic waste on human health.

Humans have been exposed to plastics and their constituent components since they were first mass produced in the 1940s and 1950s. The growing use of plastics in primary food packaging has resulted in increased exposure to them over recent years, and the increased waste has resulted in more plastic entering the environment (Jambeck et al. 2015). Consequently, a host of recent studies have reported microplastics found in nonmarine foodstuffs—e.g. honey (Liebezeit and Liebezeit 2013), beer (Liebezeit and Liebezeit 2014) and seafood (Rochman et al. 2015)—and the air (Dris et al. 2016). However, realistic measures of humans' exposure to plastics have neither been taken nor modelled (Koelmans et al. 2017).

POTENTIAL PATHWAYS OF HARM

Ingestion

A recent review (Wright and Kelly 2017) concluded that toxicity from chemical constituents could occur via leaching from plastics ingested by eating seafood, and this also could result in the chronic exposure of some chemicals due to the bioaccumulation of toxins in tissues. It is known that additives such as plasticisers (e.g. phthalates) and bisphenol (BPA) can cause harm directly or from their breakdown products. For example, BPA, which has received the most interest to date, can migrate out of polycarbonate to contaminate food and drink products (Guart et al. 2013). Once internalised, this chemical interacts with hormone receptors, resulting in a complex bodily response (Koch and Calafat 2009). Plastics are also known to adsorb persistent organic pollutants and heavy metals once they have become waste in the natural environment. With a larger surface area–to–volume ratio, microplastics can act as a conduit and/or sink for these chemicals, and hence can transport them into humans through ingestion. Physical interactions between internal tissues and microplastics may also be problematic. Smaller particles have been flagged as the most concerning (reviewed in Galloway 2015), but, again, knowledge gaps mean the potential for harm is unknown.

Inhalation

Inhaling fibrous material is known to be hazardous to human health at high concentrations; consequently, this type of exposure has been monitored by industry for many years. These studies have shown that fibres (natural and synthetic), once inhaled, can cause chronic irritation and inflammation (reviewed by Prata 2018).

The harm caused at the exposure level generally found in the environment is unknown.

Littering and human health

The connection between human well-being and ocean proximity has only recently been investigated, and studies have revealed that coastal proximity and blue spaces positively affect well-being (Wheeler et al. 2012; White et al. 2010). However, beach litter and microplastics are considered a risk to well-being (Gollan et al. 2019), and are one of the biggest threats to the benefits local communities receive from the marine estate. Litter can undermine the positive effects of a coastal estate and inhibit beach use (Wyles et al. 2016; Rangel-Buitrago et al. 2018), potentially reducing enjoyment outdoors and exercise, both of which are known to positively affect mental and physical health (Gladwell et al. 2013). As society begins to better recognise mental health challenges, this is an area that requires more research as it could be the most important influence marine plastic has on human health.

3.1.3 Economic impacts

Plastic pollution in the ocean also has broad economic consequences. All sectors of the economy use plastic, and, across sectors, plastic waste is generated in near proportion to the level of use (Lin and Nakamura 2019). The full life cycle cost of plastics is not reflected in the pricing of plastic products (Oosterhuis et al. 2014). Plastic production is therefore not a fully costed system. Instead, the economic costs of plastic pollution are predominantly borne by the environment and by society (United Nations Environment Assembly of the United Nations Environment Programme 2017; Forrest et al. 2019).

The costs of plastic pollution can be broadly divided into two categories: direct and indirect. The direct costs of plastic pollution include prevention (e.g. environmentally sound waste management, awareness-raising, behaviour change campaigns), remediation (e.g. beach grading, fishing-for-litter programmes) and direct damage (e.g. lost productivity from fish mortality or reduced ecosystem services, repairs to equipment). The indirect costs of plastic pollution have proven difficult to quantify, partly due to differences in the values held by individuals (such as the importance of a clean beach), but also due to the challenges in placing an economic value on a healthy environment. Irrespective of the categorisation and estimation methodologies, the above direct and indirect costs are 'avoidable costs' (McIlgorm et al. 2008).

Direct and indirect costs of plastic pollution

The impact of plastic not being a fully costed system is highlighted by the particularly problematic plastic packaging sector. It produces a conservatively estimated $40 billion annually in negative externalities, such as degradation of natural systems and greenhouse gas emissions, outstripping the profits of the sector (World Economic Forum et al. 2016). Including plastic products, the total environmental cost in 2015 to society from plastics was estimated to be over $139 billion, which equated to nearly 20 percent of revenues in the plastic manufacturing sector (TruCost 2016).

The UN Environment Programme has estimated the global damage to marine environments from plastic pollution to be a minimum of $13 billion per year (UNEP 2014). Moving beyond damage costs to the environment, the reduction in global marine ecosystem services has been estimated at $0.5–2.5 trillion, based on 2011 stocks of marine plastic pollution (Beaumont et al. 2019). Forrest et al. (2019) aggregated estimates across the plastics life cycle to conclude that annual damages from plastic production and the current stock of plastic waste in the ocean amount to $2.2 trillion. The European Parliament's new measures to regulate single-use plastics cite benefits including avoiding the emission of 3.4 million tons of carbon dioxide equivalent and environmental damages equivalent to €22 billion by 2030, as well as an estimated savings to consumers of €6.5 billion (EU Comission 2019).

Marine litter and plastics in particular both originate mainly from sea-based and coastal activities (fishing, aquaculture, tourism, shipping) and can, in turn, significantly impact these economic sectors (Newman et al. 2015; Krelling et al. 2017). For example, fishermen report nets fouled with plastic litter (Wiber et al. 2012; Brennan and Portman 2017) sometimes even reaching levels that cause them to move to areas less polluted with plastic litter (Nash 1992). Litter accumulating in the net may also affect the efficiency of the nets

(Eryaşar et al. 2014). Fishermen lose time cleaning litter out of nets but surprisingly then dump the same litter overboard (Neves et al. 2015). Similar to cultured species, commercially caught fish may have ingested microplastics (see, for example, Rochman et al. 2015), which could affect the health of the fisheries and, eventually, the economic value of the catches.

> Fishermen lose time cleaning litter out of nets but surprisingly then dump the same litter overboard. Similar to cultured species, commercially caught fish may have ingested microplastics, which could affect the health of the fisheries and, eventually, the economic value of the catches.

Aquaculture may suffer from marine litter through fouled holding cages and health risks to the cultured species, which may ingest small microplastics. There is special concern regarding cultured bivalves, which have been shown to contain microplastics in their tissues in several independent studies (De Witte et al. 2014; Van Cauwenberghe and Janssen 2014; Davidson and Dudas 2016; Li et al. 2016; Li et al. 2018; Li et al. 2018; Naji et al. 2018; Phuong et al. 2018; Cho et al. 2019; Teng et al. 2019). While this is of concern for consumers, there are other sources of microplastic ingestion (e.g. from air on food) that might far exceed those taken up by bivalves (Catarino et al. 2018). Interestingly, ingesting small microplastics (between 1 and 10 micrometres) by oyster larvae had no effect on the survival or growth of those larvae (Cole et al. 2015), but a similar study on mussel larvae showed detrimental effects of microplastic ingestion (Rist et al. 2018).

There is also concern of trophic transfer of microplastics (Nelms et al. 2018), but a recent study suggested that large predators rapidly egest microplastics taken up with their small prey organisms (Chagnon et al. 2018). Commercially important crustaceans can contain large numbers of microplastics, but it is suggested that they significantly reduce their accumulated microplastic load during moulting (Welden and Cowie 2016). In addition, the risk of ingesting microplastics is reduced when the gut is removed (such as those of fish, crustaceans and most other species) prior to consumption by humans (Lusher et al. 2017).

Shipping can be severely impacted as vessels can get entangled with marine litter, causing high risk of damage to the ships and injury to mariners and travellers (Newman et al. 2015; Hong et al. 2017). These risks might be exacerbated in harbour waters where the same structures that protect the harbour from wave exposure accumulate large quantities of marine litter (Aguilera et al. 2016), including fishing lines (Farias et al. 2018), which ships can become entangled in.

McIlgorm et al. (2008) estimated damage to maritime industries in the Asia-Pacific Economic Cooperation (APEC) region to be $1.26 billion per year in 2008 terms. For comparison, the gross domestic product for this same region of 21 member countries was $29 billion in 2008 (McIlgorm et al. 2008). McIlgorm et al. (2020) have updated these numbers, now estimating $10.8 billion in damage per year to industries in the marine economy attributable to marine debris. This is eight times greater than the previous estimate due to improved data, growth in the marine economy and an increase in the amount of plastic in the ocean over that time. By 2050, this damage is projected to be $216 billion (McIlgorm et al. 2020).

Beach litter may cause annoyance among beach visitors (Schuhmann et al. 2016; Brouwer et al. 2017; Shen et al. 2019) or even induce people to abandon a heavily littered beach (Krelling et al. 2017) and travel to more distant, cleaner beaches (Leggett et al. 2014). A study in South Korea showed that following a litter event (rains flushing inland litter onto coastal beaches) visitor numbers decreased dramatically; the authors estimated income losses of millions of dollars (Jang et al. 2014a). On tourist beaches, large amounts of litter are removed daily (Williams et al. 2016), incurring substantial costs for local municipalities (de Araújo and Costa 2006). Interestingly, several studies show that people would be willing to pay to visit beaches if they were cleaned (Brouwer et al. 2017; Shen et al. 2019). Besides the impact on the aesthetic value of beaches (Rangel-Buitrago et al. 2018), litter can also pose a health risk to visitors (Campbell et al. 2016), especially to young children (Campbell et al. 2019).

In California, modelling indicated that a 25 percent reduction in marine debris on all 31 of its beaches would improve the welfare of local residents by $32 million over three summer months by improving the welfare value of beach visits by residents and increasing the number of visits made. Improving marine debris reduction to 100 percent raised the savings to $148 million for the same period (Leggett et al. 2014). The chemical burden and disease cost of endocrine-disrupting chemicals within the European Union has been estimated at €119 billion (Trasande et al. 2015), of which some daily contact is likely via plastics (Feldman 1997; Magliano and Lyons 2013). The environmental costs of marine plastic pollution are not fully understood. The concern, however, is of such gravity that the issue is now being considered within the realm of a planetary boundary threat (Villarrubia-Gómez et al. 2018).

3.2 Impacts of Other Solid Waste

Inadequate waste collection and uncontrolled dumping or burning of solid waste still occurs around the world, but primarily where waste infrastructure is lacking, often in low- and middle-income countries (Kaza et al. 2018). This other waste includes all other municipal waste, medical waste, e-waste and disaster debris, and mismanagement of it has a range of impacts. Inadequate sanitation and mismanagement of organic waste and medical waste can cause exposure to pathogens and disease, and e-waste mismanagement results in the release of heavy metals into the environment. For example, the plastic used to house wires and cases is often open burned where informal processing takes place, releasing dioxin, particulate matter and heavy metals into the air (Asante et al. 2019).

3.2.1 Impacts on ecosystems and marine life

Leachate (liquid that accumulates from waste containing organic compounds as well as heavy metals and POPs) can drain directly into the ocean (depending on the proximity of the waste) or into rivers, groundwater and the soil (Yadav et al. 2019), further contributing to ocean pollution. Organic waste from garbage can also contribute to nutrient loading in waterways and the ocean, and the open burning of solid waste gives off particulate matter and emissions (Wiedinmyer et al. 2014) that can contribute to atmospheric deposition into the marine ecosystem. According to the International Solid Waste Association, greenhouse gas emissions across the economy—which indirectly impact the ocean through climate change effects—can be reduced by 15–20 percent with improved global waste management (UNEP 2015).

3.2.2 Human health impacts

Inadequate waste management, especially open burning and dumping, around the world produces pollution (Vasanthi et al. 2008; Wiedinmyer et al. 2014) that can impact people living near management facilities and those working directly with solid waste. About 15 million people globally, often called waste pickers (who include men, women, children, migrants and the underemployed), work informally in the waste sector (Medina 2008). In China alone, it is estimated that 3.3 to 5.6 million people work informally in the recycling of solid waste (Linzner and Salhofer 2014), and Forrest et al. (2019) acknowledge the millions of people working in poor conditions for little money in jobs that would not qualify as decent work by the International Labour Organization. While these issues must be addressed, it is also important to recognise that waste and plastic management constitute the livelihoods of millions of people. Any interventions used to address plastic and other waste must incorporate the views and participation of informal workers, and especially waste pickers, so that millions of people aren't negatively impacted through the unintended consequences of 'traditional' infrastructure, such as eliminating a crucial source of income (Dias 2016). Women can be disproportionately harmed by the formalisation of waste management, as they are typically excluded from formal employment in the formalized sector. But they can be helped through inclusive improved recycling operations, capacity building, provision of equipment, formal training and awareness building, financial assistance and health insurance since they have high levels of participation in the informal sector but often have less access to these kinds of benefits (Krishnan and Backer 2019).

3.2.3 Economic impacts

While there are global data on the cost of plastic pollution (see section 3.1, Impacts of Plastic), there is not a global number for the cost of mismanaged waste. The World Bank estimates that proper waste management infrastructure would cost $50–100 per metric ton (Kaza et al. 2018), which is in the same range as tipping fees charged for municipal solid waste disposal in the United States. In Palau, where the ocean is extremely important to the economy, the cost of waste-related pollution, or mismanaged waste (not the cost of waste management which is estimated at $87 per ton), was estimated at be $1.9 million per year, which is 1.6 percent of the country's gross domestic product and equates to an annual cost of $510 per household (Hajkowicz SA et al. 2005).

3.3 Impacts of Pesticides

Pesticide mixtures include active and inert ingredients; both are important, as the active ingredient is the toxicant for the target organism, and the inert ingredient often amplifies the exposure mechanism. For example, an herbicide with an active ingredient might be mixed with an inert ingredient that is water soluble to more effectively penetrate soil, while the same active ingredient can be mixed with a non-water-soluble oil to more effectively penetrate the leaf. The same active ingredient can have different toxic effects on the target organisms, and potential environmental effects, based on the carrier or inert ingredient. In the United States, only the active ingredients must be disclosed in pesticide labelling, making impact assessments very difficult to conduct.

Pesticides are very effective at improving the efficiency of agricultural production by reducing crop and animal losses. However, there are risks associated with pesticide applications to nontarget organisms. Nontarget organisms include the people who apply the pesticides, process the products and consume the products. There are also risks to nontarget organisms in the fields and paddocks where these pesticides are applied. Broad spectrum insecticides kill desirable insects such as pollinators and the biological predators of undesirable insects. Some pesticides persist in the environment and move through the food chain, resulting in toxic impacts on nontarget organisms including song birds, raptors, rodents, reptiles and fish (UNEP 2019).

3.3.1 Impacts on ecosystems and marine life

Pesticides that reach the ocean can impact nontarget organisms in several ways, depending on the active ingredient pesticide category, inert ingredient mediator, transport mechanism and depositional environment. The toxic impact of pesticides is generally proportional to the concentration, so very low concentrations often have very low impacts. However, pesticides can be bioconcentrated and biomagnified through the food chain to result in cumulatively higher impacts on predators and scavengers (including humans). Bioconcentration is the process of uptake of a chemical by an organism from the abiotic environment, resulting in higher concentrations in that organism than in the environment (LeBlanc 1995). Bioconcentration of pesticides occurs when the active ingredient persists in the environment long enough to be ingested by an organism such as krill, where it is either metabolised, excreted or stored in fatty tissues (Cincinelli et al. 2009). The pesticides that are stored in fatty tissues can persist through many cycles of ingestion, and thus accumulate in the organism. Biomagnification is the process whereby the amount of the pesticide is amplified up the food chain, and the active ingredient can be concentrated in the fatty tissues of top predators such as swordfish, sharks and tuna. These concentrations can be amplified over 1,000-fold through this process. Most modern pesticides have been designed to not persist in the environment, and thus are less prone to bioconcentration. However, early 20th-century pesticides, which are banned in Europe and the United States but are still manufactured and used in many countries, can last over 100 years in the environment and are very prone to bioconcentration and biomagnification (Dromard et al. 2018). In general, organochlorine pesticides (OCPs), which were developed in the early-to-mid 20th century, are the world's most persistent legacy pollutants in the ocean. These include dichlorodiphenyltrichloroethanes (DDTs), hexachlorocyclohexanes, heptachlor, aldrin, alpha and beta-endosulfans, dieldrin, endrin, endrin aldehyde, endrin ketone, methoxychlor, endosulfan sulfate and heptachlor epoxide (Guo et al. 2007).

Pesticides have been documented to reduce the photosynthetic efficiency of sea grass, corals and algae (herbicides), resulting in chronic stress (Brodie et al. 2017). Certain herbicides in common use, including Diuron, Atrazine, Hexazinone and Tebuthiuron, have been shown to have measurable impacts on seagrass productivity, especially when combined with light attenuation from high sediment loads from agricultural runoff (Flores et al. 2013). Seagrass beds are critical habitats for many marine species and support global fisheries. Insecticides, including organophosphates, organochlorines, carbamates and pyrethroids, as well as fungicides, have been shown to restrict to fully inhibit coral settlement and metamorphosis at concentrations as low as one part per billion (Markey et al. 2007). Concentrations just 10 times that amount have caused coral branch death. These concentrations are at or below detection levels for conventional laboratory analyses, rendering these pesticides virtually invisible to investigators.

3.3.2 Human health impacts

The primary exposure mechanism to humans from ocean-borne pesticides is through ingestion of species that biomagnify those pollutants. The most common pesticides found in seafood at concentrations above background levels are OCPs. Communities whose diets are seafood-based are most at risk given their higher rates of fish consumption. Consuming fatty piscivores such as hairtail, mackerel and tuna in South Korea was shown to increase exposure of vulnerable populations (children and elderly) to increased OCPs (Moon et al. 2009). In general, these pesticide concentrations are below chronic toxicity levels for most people (Smith and Gangolli 2002). Toxicants of concern in fish from biomagnification include heavy metals (mercury, cadmium and lead—see section 3.7 on heavy metals), and legacy organochlorines from industry such as polychlorinated biphenyls (PCBs) (Storelli 2008).

3.3.3 Economic impacts

The economic impacts of pesticides in the ocean are largely through decreased productivity rather than human toxicity. The loss of productivity and resiliency of seagrass beds and coral reefs is having a significant impact on global economic security. These critical ecosystems provide a portfolio of ecosystem services that are essential for human society, including the provision of food, water, energy and other resources, and tourism. The estimated net present value for 2050 of Earth's coral reefs was almost $800 billion (Cesar et al. 2003). If pesticides are reducing the productivity of these ecosystems by only 25 percent, the annual economic impact of those pesticides in the ocean would still be $200 billion per year. These critical ecosystems are also stressed by other pollutants, sediment and climate change. Some estimates suggest that under a high greenhouse gas emissions scenario, more than 90 percent of coral reef communities would be lost by 2100 (Speers et al. 2016). Cumulatively, these pose imminent threats to Earth's ocean ecosystems.

3.4 Impacts of Nutrient Pollution

3.4.1 Impacts on ecosystems and marine life

Nutrient pollution, which occurs when anthropogenic sources of primarily N and P are discharged into marine systems, leads to eutrophication, algal blooms, dead zones and fish kills in freshwater and coastal waters. Scientists have estimated that about 80 percent of large marine ecosystems in the world already suffer from serious eutrophication, hypoxia and anoxia in coastal waters (Selman et al. 2008; Diaz et al. 2011; STAP 2011). In addition, related incidences of toxic algal blooms such as 'red tides' have become more frequent (Rabalais 2002). Eutrophication also leads to habitat changes and the loss of species of high value (Heisler et al. 2008).

Many species can be impacted directly or indirectly by nutrients in marine ecosystems as nutrient inputs have altered the abundances and distributions of marine species (e.g. through algal blooms). Eutrophication and oxygen depletion (often referred to as 'dead zones' when affecting a large area) have direct adverse effects on coral reefs, seagrass beds, fish and shellfish (Bouwman et al. 2011). Diaz et al. (2011) identified more than 770 eutrophic and hypoxic coastal systems worldwide, where 70 percent of the areas had documented hypoxia and almost 30 percent were developing hypoxia. The dead zone in the Gulf of Mexico resulting from agricultural runoff into the Mississippi River has been studied extensively, but there is less data on these zones in developing countries, so these estimates are likely conservative.

One example of the direct impact of increased nutrients in the ocean is the world's largest macroalgal bloom, which was recorded from 2011 to 2018 (the most recent data available). Using satellite images, (Wang et al. 2019) showed that since 2011, the free-floating mats of brown macroalgae called *Sargassum* spp. have increased both in density and size, generating a long belt of 8,880 km extending from West Africa to the Caribbean Sea and Gulf of Mexico. *Sargassum* is a naturally occurring seaweed that provides a critical habitat to a diverse array of species in this ecosystem. However, when the *Sargassum* mats overcrowd the coasts, it can impact the movement of some marine species. When the excess *Sargassum* dies and sinks to the ocean bottom in large quantities, corals and seagrasses can be smothered. On the beach, rotten *Sargassum* releases a strong smell, potentially imposing health challenges for people who have asthma. *Sargassum* blooms and their adverse effects could reduce the number of tourists during a bloom. For example, in 2018, Barbados had to declare a national emergency because of a bloom.

The ocean is becoming more stratified, and while there is still some discussion over coastal marine ecosystems being N- or P-limited, (Elser et al. 2007) found that, for coastal systems, N and P limitations play a similar role, implying that reducing the discharges of both N and P is important for alleviating pollution in coastal areas. This is exactly what was shown by (Beman et al. 2005), who found that areas that are nitrogen deficient were especially vulnerable to nitrogen pollution. They also found that agricultural runoff had a strong and consistent influence on biological processes, stimulating algal blooms 80 percent of the time within days of fertilisation in the Gulf of California. They then projected that by 2050, 27–59 percent of all nitrogen fertiliser would be applied in developing regions upstream of nitrogen-deficient marine ecosystems. These ecosystems are especially vulnerable to agricultural runoff and nitrogen pollution impacts (Beman et al. 2005).

3.4.2 Human health impacts

Some important drinking water sources (e.g. Lake Erie) cannot be used during algal blooms, as the toxins either increase the cost of treatment or make it impossible to treat. Other human health impacts come from direct or indirect exposure to toxins resulting from algal blooms—for example, a red tide can cause ciguatera poisoning, paralytic shellfish poisoning, neurotoxic shellfish poisoning (NSP), amnesic shellfish poisoning and diarrhetic shellfish poisoning, which are the five most commonly recognised illnesses related to harmful algal blooms (HABs). Exposure to the toxins from HABs is mediated through the consumption of contaminated fish and shellfish, or through exposure to aerosolised NSP toxins near water bodies where a bloom is occurring (Grattan et al. 2016).

3.4.3 Economic impacts

Attempts to evaluate the monetary impacts of eutrophication have been made over the last two decades. Studies indicate a variety of impacts and costs that are quantifiable fairly directly, for instance, when cities of hundreds of thousands of people are deprived of drinking water for several days. One example is the toxic algal bloom that occurred in the western Lake Erie basin in 2011, which led to a disruption of water supplies for 400,000 people (Watson et al. 2016). In another example, a major and extensive red tide outbreak occurred along the coast of Hong Kong and south China, covering an area of more than 100 km^2. Over 80 percent (3,400 tons) of mariculture fish were killed, and the total loss was over $40 million (Yang and Hodgkiss 2004). On the other hand, integrating all the environmental, health and socioeconomic impacts in the calculations of indirect effects poses more of a challenge.

3.5 Impacts of Antibiotics, Parasiticides and Other Pharmaceuticals

3.5.1 Impacts on ecosystems and marine life

Our understanding of the impacts of emerging contaminants is limited to what has been learned by studying specific instances where they have been found and identified; impacts on the overall marine environment are not well-understood. Pharmaceutical substances have been examined worldwide in surface water, groundwater, tap/drinking water, manure, soil and other environmental matrices. (aus der Beek et al. 2016) reviewed 1,016 articles and found that pharmaceuticals or their transformation products have been detected in the environment of 71 countries covering all continents. Six hundred thirty-one pharmaceutical substances were found at levels above the detection limit of the respective analytical methods employed. Residues of 16 pharmaceutical substances were detected in each of the five UN regions, and the antibiotic tetracycline was detected in wastewater treatment plant effluents in all UN regions. Regional patterns of pharmaceutical leakage to the environment emerged as well: Antibiotics were most prevalent in Asia, analgesics edged out other pharmaceuticals as most prevalent in Eastern Europe, lipid-lowering drugs were highest in Europe and Latin America, oestrogens were found most in Africa, and the 'other pharmaceutical' category was predominant in Western Europe (aus der Beek et al. 2016).

Research presented at the 2019 annual meeting of the Society of Environmental Toxicology and Chemistry found that of the sites monitored, 65 percent of them contained at least one of the 14 most commonly used antibiotics. These sites were located in rivers in 72 countries across six continents. The concentration of one antibiotic, metronidazole, found by the researchers at a site in Bangladesh was 300 times the 'safe' level. (The AMR Industry Alliance recently established 'safe' levels of antibiotics in the environment, ranging from 20 to 32,000 nanograms per litre depending on the antibiotic.) Ciprofloxacin, a general antibiotic used to treat various bacterial infections, most frequently exceeded safe levels, surpassing the safety threshold in 51 places. Geographically, 'safe' limits were most frequently exceeded in Asia and Africa (to the greatest degree in Bangladesh, Kenya, Ghana, Pakistan and Nigeria), but sites in Europe, North America and South America also had levels of concern, showing that antibiotic contamination is a global problem. Sites with the highest risk of contamination were typically adjacent to wastewater treatment systems and waste or sewage dumps and in areas of political turmoil, including the Israeli and Palestinian border (University of York 2019).

Benzophenone-2 (BP-2) is an additive to personal-care products and commercial solutions that protects against the damaging effects of ultraviolet (UV) light. BP-2 is an 'emerging contaminant of concern' that is also often released as a pollutant through municipal and boat/ship wastewater discharges and landfill leachates, as well as through residential septic fields and unmanaged cesspits. Although BP-2 may be a contaminant on coral reefs, its environmental toxicity to reefs is unknown. This poses a potential management issue, since BP-2 is a known endocrine disruptor as well as a weak genotoxicant (Downs et al. 2014).

There is concern over the impacts of commonly used organic UV filters, including oxybenzone (benzophenone-3), 4-methylbenzylidene camphor, octocrylene and octinoxate (ethylhexyl methoxycinnamate), on the marine environment. Oxybenzone, octocrylene, octinoxate and ethylhexyl salicylate have been identified in water sources around the world, and are not easily removed by wastewater treatment plant techniques (Schneider and Lim 2019). Oxybenzone has been specifically linked to coral reef bleaching. In addition, 4-methylbenzylidene camphor, oxybenzone, octocrylene and octinoxate have been identified in various species of fish worldwide, which has possible consequences for the food chain (Schneider and Lim 2019). Danovaro et al. (2008) found that even low concentrations of sunscreens caused bleaching of corals. The organic UV filter induces the lytic viral cycle in symbiotic zooxanthellae with latent infections. Therefore, sunscreens may be playing an important role in coral bleaching by promoting viral infections in areas with high recreational use by humans (Danovaro et al. 2008).

> Antibiotic contamination is a global problem. Sites with the highest risk of contamination were typically adjacent to wastewater treatment systems and waste or sewage dumps and in areas of political turmoil.

3.5.2 Human health impacts

Wastewater treatment plants are a main source of antibiotics released into the environment. An overabundance of antibiotics in wastewater may generate antibiotic resistance genes and antibiotic resistant bacteria. Some scientists are concerned that wastewater treatment plants are becoming hot spots for resistant genes and bacteria, which has implications for human health should people get infections that are then resistant to typical antibiotics (Rizzo et al. 2013).

3.6 Impacts of Industrial Chemicals Including Persistent Organic Pollutants

3.6.1 Impacts on ecosystems and marine life

Polybrominated diphenyl ethers (PBDEs) and POPs are toxic, are not easily degradable in the environment, bioaccumulate in the food chain and undergo long-range transport (European Environment Agency 2019). Many industrial chemicals and POPs are known to be poisonous and to damage the environment and the organisms living in the affected ecosystems. These pollutants have become distributed throughout the ocean and have been found in seemingly pristine environments. These pollutants also bioaccumulate in marine organisms such as fish and invertebrates such as corals, which can lead to various physiological impairments, varying from subcellular changes such as direct effects on DNA (deoxyribonucleic acid) to metabolic stress (Logan 2007; van Dam et al. 2011).

3.6.2 Human health impacts

POPs and PBDEs can cause cancer and toxicity in the liver, kidneys and reproductive system (Qing Li et al. 2006). The main impacts of industrial pollution to human health are derived from making direct contact with contaminated water. The direct contact with polluted water puts people at risk when the toxins are heavy metals. The chemical content in the water, whether carcinogenic or not, may nevertheless play a role in contributing to cancer mortality risk (Hendryx et al. 2012). Bathing in contaminated water increases the risk of respiratory disease and skin problems.

Human consumption of marine organisms that have been contaminated with polluted water is one major impact of industrial pollution on humans. Many of the fish that are a primary food source for the indigenous people in the Canadian Arctic are heavily contaminated by POPs (Dewailly 2006). While some persistent organic pollutants have started to decrease in humans and food in monitored Arctic locations because of international restrictions, levels of oxychlordane, hexachlorobenzene, polybrominated diphenyl ether and perfluorinated compounds are not decreasing (Abass et al. 2018). Greenland has some of the highest concentrations of POPs in humans in the Arctic—with the exception of PBDEs, Greenland populations had the highest measured levels of POPs than any other Arctic country (Gibson et al. 2016).

3.6.3 Economic impacts

Studies indicate a variety of economic impacts from industrial pollution. The tangible economic impacts include those that occur during pollution incidents as well as from activities undertaken to prevent, mitigate, manage, clean up or remedy pollution incidents. The global economic cost related to the pollution of coastal waters is $16 billion annually, largely due to human health impacts (UNEP 2006). An additional source of cost is the loss of earnings caused by damage to natural resources. The intangible costs are the loss of marine biodiversity and the provision of other environmental services caused by industrial pollution.

3.7 Impacts of Heavy Metals

3.7.1 Impacts on ecosystems and marine life

Exposure to heavy metals can increase the permeability of the cell membrane in phytoplankton and other marine algae, leading to the loss of intracellular constituents and cellular integrity, and inhibiting metabolism (Sunda 1989; González-Dávila 1995; Hindarti and Larasati 2019). High trace element burdens in marine mammals have been associated with lymphocytic infiltration, lesions and fatty degeneration in bottlenose dolphins, and decreasing nutritional states and lung pathologies in other marine mammals (Siebert et al. 1999). In addition, cadmium, lead and mercury are potential immunosuppressants; of particular concern is the buildup of mercury, which marine mammals tend to accumulate in the liver.

3.7.2 Human health impacts

Mercury and Arsenic: Methylmercury is a neurotoxic compound responsible for microtubule destruction, mitochondrial damage, lipid peroxidation and accumulation of neurotoxic molecules such as serotonin, aspartate and glutamate (Patrick 2002). Consumption of contaminated aquatic animals is the major route of human exposure to methylmercury (Trasande et al. 2015). Seafood contaminated by heavy metals or metalloids such as mercury and arsenic can contribute to human health risk (Harris et al. 2014; Gao et al. 2018). One unforgettable case was the mass poisoning of people in Minamata, Japan, in the 1950s, when 2,252 people were impacted by the contamination and 1,043 died (Harada 1995).

Cadmium and Lead: Consuming fish containing to cadmium and lead can cause major diseases in humans such as renal failure, liver damage and symptoms of chronic toxicity in the kidney (Bosch et al. 2016; Gao et al. 2016).

Chromium: Because of its mutagenic properties, hexavalent chromium is a carcinogen that humans can get exposed to through soils, sediment and surface waters, as well as some fish (Copat et al. 2018; Tseng et al. 2019).

3.7.3 Economic impacts

Heavy metal pollution results in substantial economic impacts to the fishing sector. Bioaccumulation of metals in fish limits the species that can be safely eaten and the frequency that those fish can be eaten, and as a result can limit imports and exports. For example, in 2006, European Commission Regulation 1881/2006 established the maximum levels for cadmium, lead and mercury in food products. High quantities of heavy metals in fish are one of the principal reasons why fish are detained at EU borders and the main problem that importers from non-EU countries must address. The economic losses deriving from EU border detentions amount to hundreds of millions of euros each year (FAO n.d.).

3.8 Impacts of Oil and Gas

3.8.1 Impacts on ecosystems and marine life

Oil spills tend to disproportionately impact sea birds, which can be harmed and killed by exposure to oil. Individual birds become unable to swim or fly and nervous system abnormalities can occur. Population-level effects of oil toxicity on aquatic birds occur through the loss of egg viability. Because it is inherently poisonous, oil in the marine environment has the potential to harm any creature that comes in contact with it. This includes larger animals such as sea turtles, which are sensitive to chemical exposure at all stages of life and lack an avoidance behaviour, and seals, which can become blind, as well as smaller organisms, such as zooplankton and larval fish. Oil spills, and their associated responses, can be particularly damaging to fragile but vital marine ecosystems such as coral reefs and mangroves, but are believed to damage life throughout the water column. Heavier oils settle and can coat and smother benthic areas. In areas impacted by oil spills, bottom-feeding fish have developed carcinomas and papillomas on their lips, as well as changes in their cell membranes. Spilled oil can persist in the environment, continuing to injure and kill marine life. More research is needed to fully understand the less obvious impacts of oil spills on the marine environment (NOAA OR&R 2019).

3.8.2 Human health impacts

A 2016 review article on the human health impacts of oil spills looked at mental health effects; physical and physiological effects; and genotoxicity, immunotoxicity and endocrine toxicity. While there exist a number of obstacles to calculating human health impacts—such as challenges to determining exposure levels and the level of effectiveness of personal protective gear as well as a reliance on self-reported health symptoms and variations in genetic sensitivities to chemical exposure—the authors concluded that there is sufficient evidence to establish a relationship between exposure to oil spills and the development of adverse health effects in exposed individuals (Laffon et al. 2016).

3.8.3 Economic impacts

Oil spills can be very costly to the responsible companies as well as to the fishing and tourism industries affected by the spill. For example, BP's Deepwater Horizon spill in the Gulf of Mexico is estimated to have cost the company $61.6 billion in penalties and fines; cleanup and remediation; and payments to affected companies, communities and individuals (Mufson 2016). The sinking of the Prestige oil tanker in November 2002 off the coast of Galicia, Spain, resulted in estimated losses to the Galician fishing sector of €76 million by December 2003 (Surís-Regueiro et al. 2007). Kontovas et al. (2010)

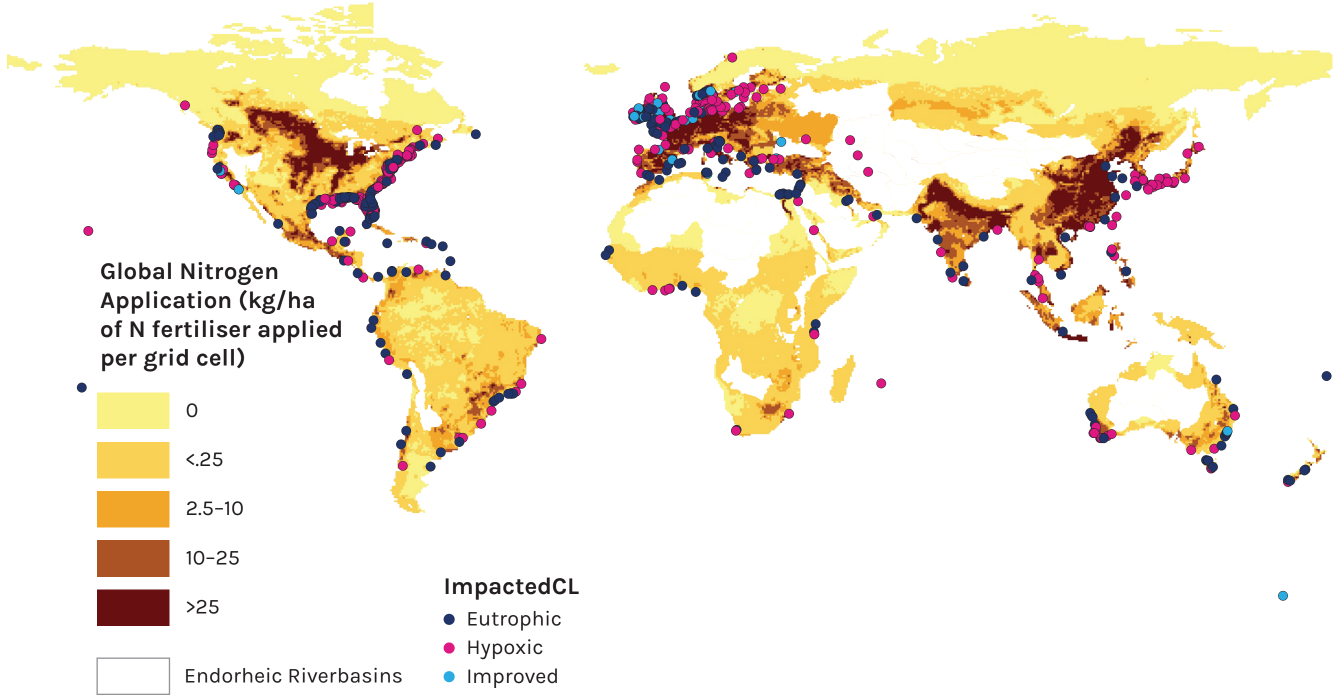
calculated a per metric ton cost for oil spills based upon a regression of 38 years of oil spill and cost data—the average value being $4,118 per metric ton in 2009.

3.9 Impacts Summary

Inputs lead to impacts

Based upon the literature reviewed for this Blue Paper, it is evident that all pollutants discussed in this report are concerning to our ocean, though some may be more urgent or easier to address than others. In addition, multiple pollutants can act synergistically, creating a greater effect on the ocean than the sum of their individual impacts. Exploring the present and future impacts, as was done in this section, is one way to start to prioritise which pollutants to tackle first. At this moment, the plastic pollution crisis is very salient—the issue is tangible and understandable, and countries around the world are working on solutions because of marine ecosystem and economic impacts. It is also evident from this work that nutrient pollution is of great concern to the ocean. Nutrients contribute to harmful algal blooms and create low-oxygen hypoxic zones and stratification, ultimately impacting the health of marine life and humans. Without changes to either of these two pollutant input systems in a business-as-usual trajectory, the impacts from them will get only worse as populations grow and economies continue to develop. Figure 3 provides a global map showing nitrogen use, along with the drainage basins and the impact of this drainage by showing hypoxic areas in the ocean. Urgent action is needed to protect the ocean from further impacts from pollution.

Figure 3. Global Nitrogen Use and Hypoxic Areas in the Ocean



Note: Mismanaged nitrogen use on land and incidences of eutrophication and hypoxia.

Sources: Data compiled from Potter et al. 2011a; World Resources Institute 2013. Map created by A. Brooks.

4. Human Dimensions

The issue of pollutants leaking into the ocean is entirely a consequence of human decisions and behaviours. It is determined by individuals, communities, companies and politicians, to name but a few of the actors within the social-environmental system (Pahl and Wyles 2017; SAPEA and Academies 2019). These actors have varying perceptions, goals and values that motivate existing practices (and can also be harnessed for change). For example, a farmer might decide to employ a pesticide to increase yield and be willing to accept adverse effects on wildlife. A cosmetics company might decide to replace natural ingredients with plastic microbeads to save money and reduce allergens in their products.

Within the social and behavioural sciences' research on environmental pollution, the focus has been on principles of risk perception and determinants of behaviour (Pahl and Wyles 2017). In other words, how does a person or community decide that a pollutant poses a risk, and what factors motivate behaviour change (including not just individual actions but also demand for legislation and policy change)?

Researchers have found that how experts assess risk is different from how non-experts assess risk (see (Böhm and Tanner 2013). Experts apply scientific methods of risk assessment that focus on specific thresholds or outcomes such as fatalities or concentrations, whereas non-experts judge risk levels using a wide range of factors such as moral evaluation of the issue, perceived fairness, perceived control and positive and negative emotions such as dread and pride. These discrepancies can contribute to conflict between stakeholders. Mental model approaches are useful in this context because they can illustrate different expectations about the sources, pathways and impacts of pollution, which can provide triggers for change. However, it has also been noted that perception of risk in itself is not strongly linked to action, and if too strong, could even undermine action (Peters et al. 2013). However, when the risk is associated with an emergency event such as a natural disaster, this may encourage people to take action, depending on personal agency, community capacity and resilience (Brown and Westaway 2011). It is important to understand risk perception differences among stakeholder groups because they can influence how media reporting is interpreted, and should be taken into consideration when policies and interventions are developed.

Behavioural practices can contribute to pollution but are rarely quantified. For example, the dosage of fertilisers and timing of applications might vary according to practices and knowledge available to farmers, and fine-tuning practices could greatly reduce environmental (and health) impacts. Behaviour is determined by a range of factors beyond mere knowledge. To illustrate, most people understand healthy lifestyles but few eat very healthily and regularly exercise. This is similar in the environmental domain, where knowledge is one factor that can motivate behaviour change, but other factors are more powerful, including perceived control, social approval and moral norms, among others. In addition, contextual factors, such as the accessibility and design of the waste disposal system and availability of materials, are important. For example, if there is no recycling bin nearby, a person needs to have a strong motivation to recycle to put in the extra effort to find one (Pahl and Wyles 2017; SAPEA and Academies 2019).

To change perceptions and behaviours, a multipronged approach can target actors individually. Laws, bans and restrictions are powerful tools that can signal a social norm of undesirable behaviour. While outlawing a particular substance can be the most powerful tool, some materials, such as plastics, are so widespread that a simple ban would fall short or could be applied only to certain products. Education and public outreach campaigns are necessary to accompany policy change and are powerful instruments in their own right. Good campaigns build on behavioural science insights and integrate key elements that have been shown to work, e.g. empowering individuals, making specific suggestions for behavioural solutions that are effective and socially acceptable. It is important not to crowd out intrinsic motivation but rather to build on personal norms and values and develop a pro-environmental identity as this could spill over into other domains and behaviours. Effective interventions link to the target group's understanding of the issue and to their motivations and concerns, and build on existing social networks and channels. Often, there is initial reluctance to change (e.g. introduction of seat belts, smoking bans), but early adopters may forge the path. Trusted members of a community can trigger wider change and could be empowered as change agents. Change can happen top down and bottom up; to target plastic pollution, for example, there are many examples of community-led actions, voluntary efforts in the retail sector (e.g. bans on plastic bags) and nonprofit initiatives.

5. Opportunities for Action

Over the last several years, marine plastic pollution has captured the world's attention and inspired hundreds of commitments from governments, businesses and nongovernmental organisations (NGOs); dozens of innovation challenges; hundreds of start-up companies seeking to create solutions; and millions of citizens taking action, whether as citizen scientists, as part of a beach clean-up or by changing their own consumption choices.

It is extremely challenging, at least with available data, to weigh the damage done by marine plastic pollution against the harmful impacts of nonplastic pollution from municipal, agricultural, industrial and maritime sources, though the latter group has been more exhaustively studied. A more helpful question to ask, however, might be this: How can action to address plastic pollution be leveraged to maximise the benefits across as many other ocean pollutants as possible? If plastic pollution is uniquely able to catalyse action on solutions, how can we prioritise and design solutions to also stop the flow of other pollutants into the ocean?

The seven approaches developed from this research and presented below begin to address these questions. Each approach includes recommendations for interventions and actions to address ocean pollution through four levers: infrastructure, policy, mindset and innovation. These levers consider actions that may be taken by companies large and small, by elected officials and policymaking staff, by citizens and by innovators. There is likely a role for some form of voluntary collective action from the biggest producers and users of plastics. In fact, hundreds of companies have signed on to frameworks such as the New Plastics Economy, facilitated by the Ellen MacArthur Foundation, and/or have set goals regarding how they will address the problem of plastic pollution. This paper does not speculate about the precise paths companies will take, but rather focuses on the specific actions most likely to move the needle on plastic and other types of pollution reaching our ocean. After the details of the approaches are introduced, they are then summarised and compared based on their breadth of mitigation across pollutants and sectors.

In this section, the list of key interventions and actions are mapped to the following:

- Sectors: Municipal (M), agricultural (A), industrial (I), maritime (Mar)
- Types: Infrastructure, Policy, Mindset and Innovation
- Pollutants: Sourced from Table 1. Given below each corresponding intervention table
- Relevant UN Sustainable Development Goals (SDGs)

IMPROVE WASTEWATER MANAGEMENT			
INFRASTRUCTURE	**POLICY**	**MINDSET**	**INNOVATION**
i. Create or expand wastewater treatment capacity (M) ii. Add tertiary treatment for nutrients and microplastics (M) iii. Install toilets (wet or dry) where needed to prevent open defecation (M) iv. Install septic tanks where access to municipal wastewater systems is limited (M) v. Ensure industrial wastewater is appropriately treated, whether through municipal or other infrastructure (I)	i. Ensure supporting policies for wastewater improvements and sustainability of infrastructure over time are in place (M)	i. See wastewater as a natural resource, especially in water-constrained regions (M)	i. Develop washing machine filters for microplastic fibres (M) ii. Innovate ways to remove pharmaceuticals and antibiotics from wastewater effectively and affordably (M)

Sectors: *Municipal (M), industrial (I)*
Pollutants: *Macroplastics; microplastics; other solid waste; nutrients; antibiotics, parasiticides and other pharmaceuticals; heavy metals; and industrial chemicals and POPs*
SDGs: *6.2, 6.3*

IMPROVE STORMWATER MANAGEMENT			
INFRASTRUCTURE	**POLICY**	**MINDSET**	**INNOVATION**
i. Use natural filters such as berms and clay to minimise runoff into the ocean (A, M) ii. Implement stormwater and storm drain filtration and river mouth trash collection (M)	i. Set total maximum daily loads (TMDLs) for trash (M) ii. Impose regulatory limits, TMDLs for discharge (I) iii. Employ stormwater permitting (M) iv. Regulate animal waste lagoons that have the potential to discharge into the ocean (A) v. Regulate use of pesticides, herbicides and nutrients for residential and commercial use (M) vi. Require nutrient management plans and pesticide management plans (A) vii. Require reporting of and/or limit usage of nutrients and pesticides (A)	i. Change cultural norms around having manicured lawns to reduce the use of pesticides, herbicides and fertilisers used for residential and commercial landscaping (M) ii. Create a culture of responsibility regarding picking up dog feces (M) iii. Change habit of washing with excessive soap, shampoo and products that contain high levels of nitrogen and phosphorus (M)	i. Conduct research and development in stormwater and other treatment systems (M, A, I) ii. Change crops, seeds and farming practices to minimise nutrient application prone to leakage (A)

Sectors: *Municipal (M), agricultural (A), industrial (I)*
Pollutants: *Macroplastics; microplastics; other solid waste; pesticides; nutrients; antibiotics, parasiticides and other pharmaceuticals; heavy metals; industrial chemicals and POPs; oil and gas*
SDGs: *None*

ADOPT GREEN CHEMISTRY PRACTICES AND NEW MATERIALS			
INFRASTRUCTURE	**POLICY**	**MINDSET**	**INNOVATION**
i. Construct treatment facilities with ‘green engineering’ principles (M) ii. Develop infrastructure for the production of new or alternative materials	i. Ban or limit the use of chemicals of concern and hazardous materials (I) ii. Ban hard-to-manage materials (M) iii. Require tracking/ manifest of chemicals of concern (I)	i. Adopt green chemistry principles as a practice for companies (I) ii. Change cultural norms around having manicured lawns to reduce the use of pesticides, herbicides and fertilisers used for residential and commercial landscaping (M)	i. Develop new materials that maintain the desirable performance characteristics of plastics but not the problematic ones, e.g. true biodegradables (M, A) ii. Develop alternative cleaning products, e.g. phosphate-free soap and detergents (M) iii. Use fish waste or seaweed to make biopolymers for fishing gear (A) iv. Support research and development in green chemistry and alternative chemicals (I) v. Reduce and prevent tire wear and tire dust by using new materials or other mechanisms vi. Use new materials for fishing gear, e.g. biodegradable components (Mar) vii. Support the development of products and services that do not use any chemicals of concern (I)

Sectors: *Municipal (M), agricultural (A), industrial (I), maritime (Mar)*
Pollutants: *Macroplastics; microplastics; other solid waste; pesticides; heavy metals; industrial chemicals and POPs*
SDGs: *3.9, 12.4*

PRACTICE RADICAL RESOURCE EFFICIENCY

INFRASTRUCTURE	POLICY	MINDSET	INNOVATION
i. Enable the development of circular business models through shared infrastructure, for example, reverse logistics or commercial washing services for reusable foodservice items (M)	i. Impose fees on single-use or other high leakage items (M) ii. Encourage industry voluntary contributions to reduce fossil-fuel-based plastics (M, A, I, Mar) iii. Support policies that allow personal container use in shopping and dining (M) iv. Enable treatment and use of food and human waste in appropriate applications (M, A)	i. Change cultural norms around waste generation/consumption and reuse, in particular to reduce the use of single-use plastic items (M)	i. Design zero-packaging grocery stores or include ‘packaging free’ or ‘plastic free’ aisles in regular grocery stores (M) ii. Develop new purchasing models that end reliance on single-use plastics (e.g. packaging as a service, reuse models) (M) iii. Pricing structure/business model for nutrients and pesticides to optimise outcomes and minimise waste (A) iv. Require fishing gear tracking (Mar)

Sectors: *Municipal (M), agricultural (A), industrial (I), maritime (Mar)*
Pollutants: *Macroplastics; microplastics; other solid waste; pesticides; nutrients*
SDGs: *8.4, 12.2, 12.5*

RECOVER AND RECYCLE THE MATERIALS WE USE (FORMAL AND INFORMAL SECTORS)

INFRASTRUCTURE	POLICY	MINDSET	INNOVATION
i. Implement systems for compliance with bale contamination standards in exported/imported waste (M) ii. Deploy technology for advanced waste drop-off facilities (M) iii. Use materials that are recyclable and retain value (M) iv. Improve technology used at recycling facilities (M) v. Use equipment and processes to recover and recycle chemicals and materials (I)	i. Implement extended producer responsibility laws (M) ii. Provide incentives for waste segregation and recycling (M) iii. Strengthen markets for recycled plastics (e.g. mandate use, secure demand, create price premiums) (M) iv. Implement Fishing for Litter programmes (Mar)	i. Change cultural norms around proper sorting and recycling (M) ii. Expand home composting (M) iii. Promote and expand commercial composting infrastructure (M)	i. Invest in tracking technology to combat illegal dumping (M) ii. Develop and scale on-demand waste collection (M)

Sectors: *Municipal (M), agricultural (A), industrial (I)*
Pollutants*: Macroplastics; microplastics; other solid waste; nutrients; industrial chemicals and POPs*
SDGs: *8.3, 8.8, 11.6, 12.2, 12.5*

IMPLEMENT COASTAL ZONE IMPROVEMENTS

INFRASTRUCTURE	POLICY	MINDSET	INNOVATION
i. Provide for sediment/dredge material removal and treatment (I, Mar) ii. Conduct sediment remediation with in situ mats (Mar) iii. Improve wastewater and solid waste management on ships (Mar) iv. Build ships and rigs to prevent and minimise oil spills (Mar) v. Improve infrastructure at ports to manage waste generated from ships, including making waste management affordable (M, I, Mar) vi. Land solid waste where infrastructure is available (Mar)	i. Enforce international dumping agreements (M, Mar) ii. Strengthen oil spill prevention policies (M) iii. Restrict locations and types of coastal and open-ocean aquaculture (A)	i. Engage people to adhere to MARPOL to reduce illegal discharge (Mar) ii. Ensure that shipping/ maritime developments prioritise marine protection (M, Mar) iii. Operate and manage oil rigs and ships to minimise oil spills (I) iv. Encourage participation in beach clean-ups, Adopt-a-Beach programmes and clean beach certifications such as Blue Flag and Project Aware (M) v. Use citizen science apps such as the Debris Tracker to engage citizens on pollution issues (M)	i. Innovate equipment and methods for managing wastewater and solid waste on ships (Mar) ii. Develop new oil spill prevention technology (Mar) iii. Conduct research and development in individual pollutant cleanup systems (I, Mar) iv. Shift to land-based aquaculture systems (A)

Sectors: *Municipal (M), agricultural (A), industrial (I), maritime (Mar)*
Pollutants: *Macroplastics; microplastics; other solid waste; pesticides; nutrients; antibiotics, parasiticides and other pharmaceuticals; heavy metals; industrial chemicals and POPs; oil and gas*
SDGs: *None*

7. Build Local Systems for Safe Food and Water

INFRASTRUCTURE	POLICY	MINDSET	INNOVATION
i. Expand drinking water infrastructure (M) ii. Develop municipal composting systems to support local food production (M, A)	i. Ensure adequate drinking water standards (M)	i. Use technology to raise awareness and provide practical solutions, e.g. Fill it Forward and apps to locate water fountains (M) ii. Encourage local sourcing of food (e.g. people, restaurants, government) (M) iii. Encourage people to bring their own packaging to purchase local food (M) iv. Use sustainable methods of food production (both on land and aquaculture) and minimise pesticide and nutrient use (A)	i. Use multitrophic aquaculture production—'waste' from one aquatic species becomes food for another (A) ii. Farm mussels, sea grass or other nutrient-absorbing species for nutrient equilibrium (A)

Sectors: *Municipal (M), agricultural (A)*
Pollutants: *Macroplastics; microplastics; other solid waste; pesticides; nutrients; antibiotics, parasiticides and other pharmaceuticals; heavy metals; industrial chemicals and POPs; oil and gas*
SDGs: *6.1, 6.B. 2.1, 2.3*

For comparison purposes, the scope of each intervention approach is presented in Table 3. As the data do not exist today to quantitatively compare the value of one approach versus another, this table focuses on showing the reach of each intervention by sector for each pollutant and those directly related SDGs.

Table 3. Summary of Interventions and Pollutants Addressed across Sectors and SDGs

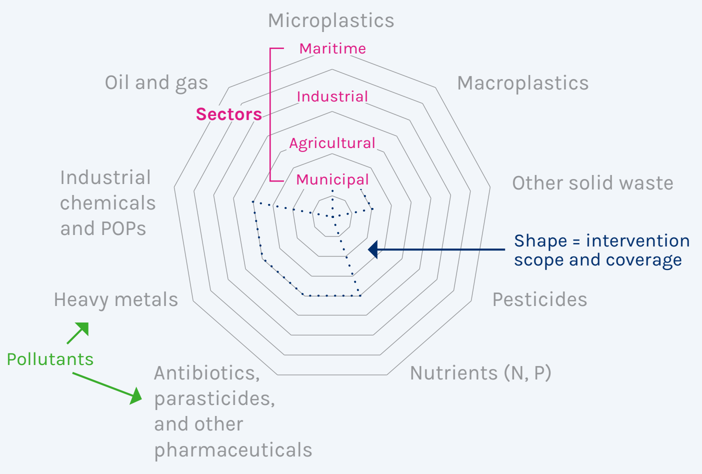
	(1) IMPROVE WASTEWATER MANAGEMENT	(2) IMPROVE STORMWATER MANAGEMENT	(3) ADOPT GREEN CHEMISTRY PRACTICES AND NEW MATERIALS	(4) PRACTICE RADICAL RESOURCE EFFICIENCY	(5) RECOVER AND RECYCLE	(6) IMPROVE COASTAL ZONES	(7) BUILD LOCAL SYSTEMS FOR SAFE FOOD AND WATER
SDGS	6.2, 6.3	NONE	3.9, 12.4	8.3, 8.8, 11.6, 12.2, 12.5	8.3, 8.8, 11.6, 12.2, 12.5	NONE	6.1, 6.B, 2.1, 2.3
Microplastics	**M**	**M**	**M, A**	**M, A, I, Mar**	**M, A, I, Mar**	M, Mar	M, A
Macroplastics	**M**	**M**	**M, A, Mar**	**M, A, I, Mar**	**M**, A, **Mar**	M, Mar	**M, A**
Other solid waste	**M**	**M**		**M**	**M, A, Mar**	M, Mar	M, A
Pesticides		**A**	**M, A**	M, **A**			**A**
Nutrients (N, P)	**M,** A	**A**		M, **A**	M, A	**A**	**M, A**
Antibiotics, parasiticides, other pharmaceuticals	M, I	A				**A**	**A**
Heavy metals	**M**, I	**M**, A, I	**M**, A, **I**, Mar			**A, I,** Mar	**A**
Industrial chemicals and POPs	M, I	**M, A**	M, **A, I,** Mar		I	**I**	
Oil and gas		**M**, A, I		I, Mar	I	**M, I, Mar**	

Notes: Sectors are municipal (M), agricultural (A), industrial (I), maritime (Mar)
Bold sectors are the primary scope of influence, non-bold are secondary; cells are shaded progressively darker as more sectors are impacted.

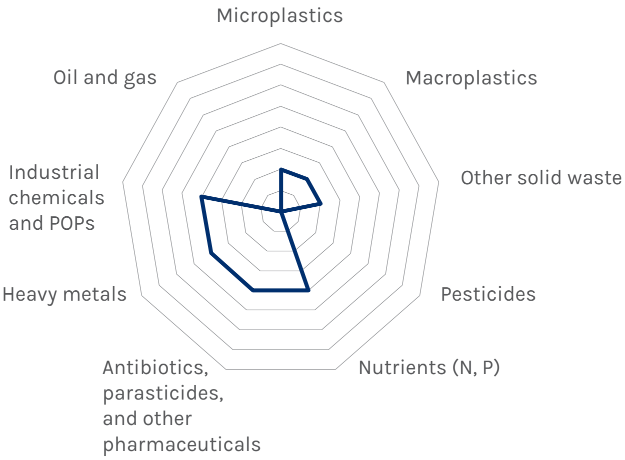
Source: Authors.

Figure 4 presents spider graphs of each intervention to visually compare their effects on each class of pollutants across the sectors. These graphs do not illustrate a score for each intervention, but show the extent to which they impact pollutants across single or multiple sectors (depicted by how far the shape spreads outward). In general, the overall impact increases as more pollutants and sectors are impacted, but the metrics of mass quantities, discrete counts and values, as well as risk and impact, are not able to be taken into account in these illustrations. However, synergies in addressing other pollutants while addressing plastic pollution are illustrated.

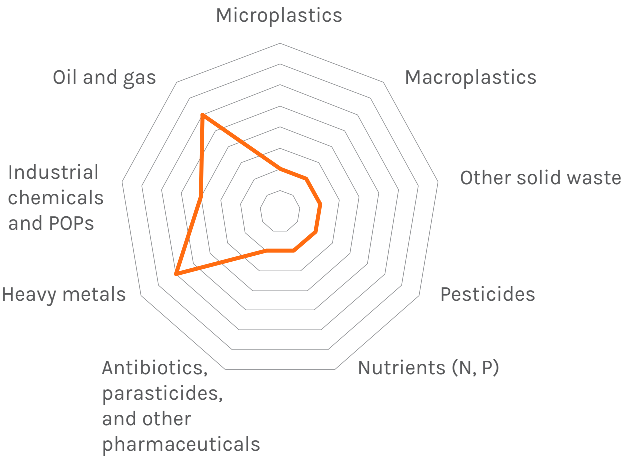
Figure 4. Spider Graph Illustrations of Approaches 1–7 by Pollutant and Sector



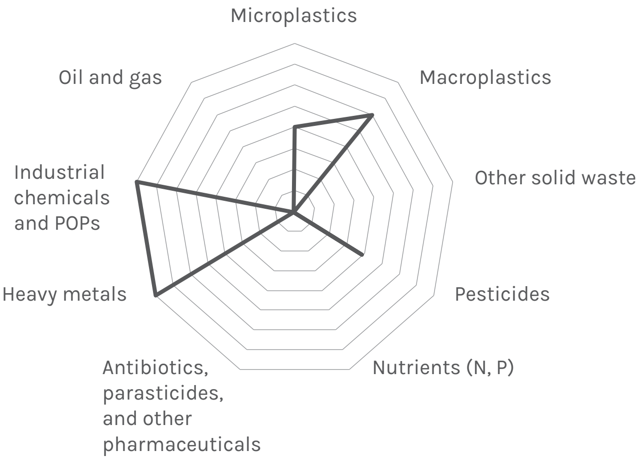
How to read these graphs



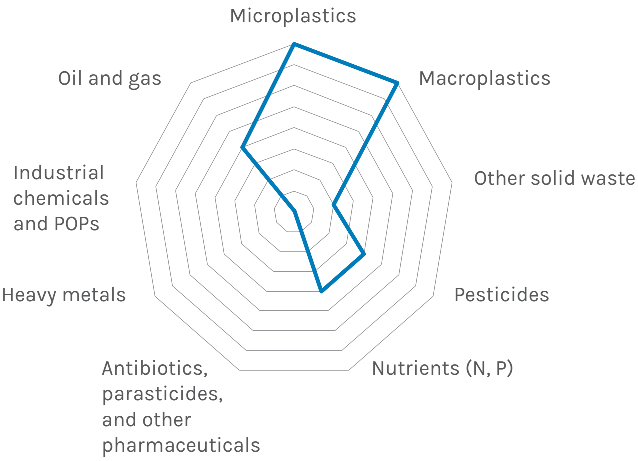
Improve waste water infrastructure



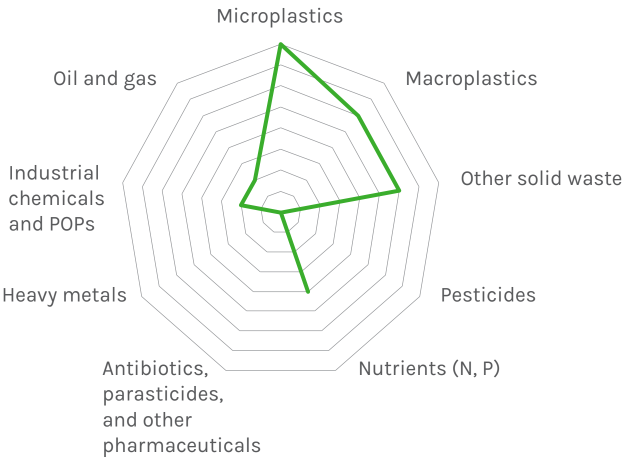
Improve storm water infrastructure



Adopt green chemistry practices and new materials

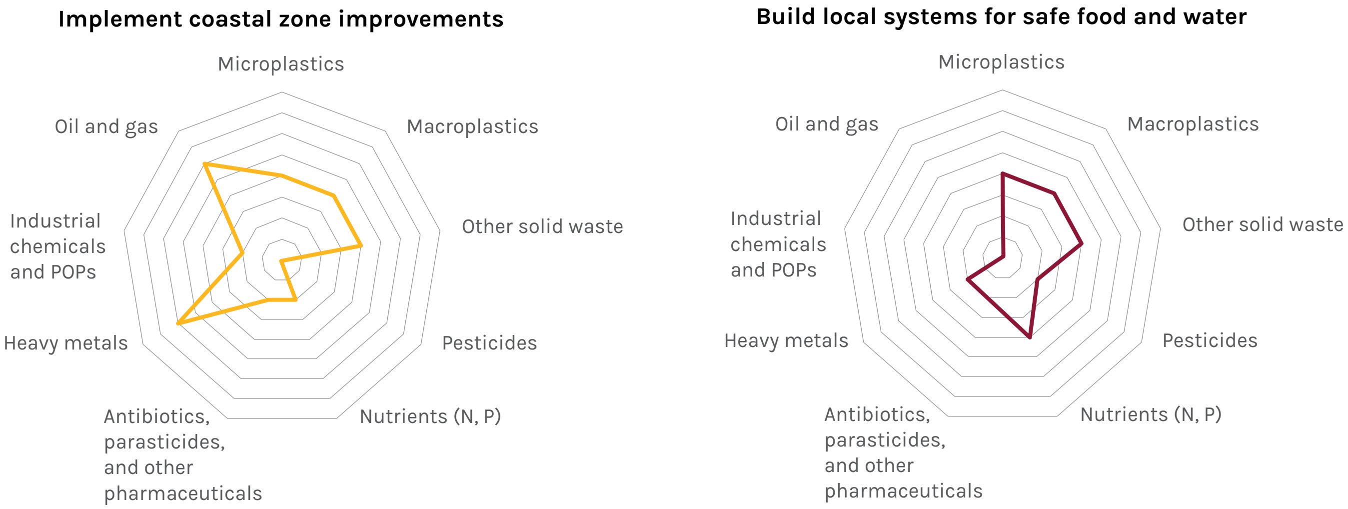


Practice radical resource efficiency



Recover and recycle the materials we use

Figure 4. Spider Graph Illustrations of Approaches 1–7 by Pollutant and Sector



Source: Authors.

Governments, together with businesses, investors, individuals, communities and NGOs, can have a major impact on changing the trajectory of pollution discharges into the ocean—with the opportunity to address other intersectional social and environmental challenges in the process. Solutions will come from innovative policies, support for research and innovation, investment in wastewater and solid waste infrastructure and shifting mindsets and behavioural practices. Many companies that are facing increased costs—or are taking responsibility for costs that they have historically imposed on others—will inevitably claim that these actions will only result in a loss of jobs, profits and economic prosperity.

It is important that we don't confuse the minimisation of harmful pollution with a reduction in quality of life, livelihood opportunities or economic success. In fact, the reality can be quite the opposite. Pollution in the ocean is already negatively impacting human health, economic prosperity for ocean-based businesses and marine ecosystems on which humans depend for essential ecosystem services. Solutions to ocean pollution can create jobs, reduce costs to many businesses and governments and improve the health and prosperity of millions of people.

Pollution is an externality of a linear economy. In creating an economic system where product costs nearly always exclude the environmental impacts for those products (whether during their creation, useful life or end of life), we have effectively designed our economies to maximise pollution, in service of maximising profits. We have invented the idea of 'throwing things away'—and the vastness of the ocean has enabled this fiction to persist for a very long time.

Alternative economic systems, such as the circular economy or regenerative economy, begin with the premise that there is no such thing as waste; that in a closed system like that of Earth, there is nowhere for damaging pollution to go that won't end up harming ecosystems, plant and animal life and, ultimately, human life. The branding of an economic model is less important than this fundamental premise: There is no 'away,' so we must design our economic system to recognise complete life cycle costs. Once the boundaries of the economic system are fixed, the machinery of the economy itself will be very effective at finding the most efficient ways to stop the problem of pollution.

How one place can make a difference

While no single community or country can solve the problem of ocean pollution alone, a single country can be a first mover in adopting innovative policies and solutions that show the way for others to follow. One barrier innovators face is helping to bridge the imagination gap between today's and tomorrow's realities. A community, country or region can bring the vision of a pollution-free future to life and make it easier for others to begin to adopt the same solutions.

Regional strategies

Smaller communities and countries can consider adopting regional strategies to help achieve critical mass for certain types of innovations, investments and infrastructure. For example, regions that align their requirements for companies to innovate around packaging, end-of-life responsibility and other issues can make it more compelling and less complex for multinational companies to comply.

Global collaboration

The ocean is a global resource impacted by all actions everywhere. Given this, it would be appropriate and effective to organise a global compact or commitment to improving the health of the ocean so the ocean can better support all life. International treaties have had success in the past at reducing some impacts on the ocean (e.g. Montreal Protocol, Stockholm Convention). As communications and technologies make the world feel like a smaller place and emphasise the interconnectedness of humanity and our environment, there may be openings to build global support for such an agreement. At a minimum, current declarations from the G7 and G20, as well as United Nations Environment Assembly of the United Nations Environment Programme and other UN initiatives, can be built upon.

Further research

While much has been learned about the scope, scale and impacts of marine plastic pollution in recent years, there remain significant gaps that could help inform and prioritise solutions. There are multiple significant research efforts underway that were not published in time to be referenced in this paper. It is the authors' hope that these studies will be completed and released as soon as possible as they are expected to contribute significantly to the state of knowledge on this topic. Ongoing research on ocean plastic is also needed, and would be greatly facilitated by the creation of open data protocols to aggregate and share data globally for scientific scholarship.

Finally, just as we see synergies in the solutions to ocean plastic and other pollutants in the ocean, more research is needed to understand their other interactions in the ocean as well as their implications.

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