National Oceanography Centre

SOURCES, AMOUNTS & PATHWAYS OF PLASTICS ENTERING THE GLOBAL OCEAN

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Executive summary

Plastic pollution is a growing global issue, yet despite public and political concern, the manufacture and use of plastics continues to increase year-on-year. This is primarily due to the versatile and low-cost nature of plastics, enabling them to be used for a wide variety of different purposes. This low cost, however, is only evident during the production, manufacture and sale of plastics, while the environmental impact of plastic waste is more difficult to measure.

It is now well-known that large masses of plastics enter the environment every year, with a large amount of this plastic ending up within the ocean. Depending on the source of the information gathered, and the calculations or model simulations carried out, different figures have been produced to quantify this contamination. Estimates of plastic inputs to aquatic systems (including rivers and the ocean) currently range from 4-23 million metric tonnes per year. However, the actual amounts of plastic lost to the environment each year are difficult to define, as some key information, for example on waste mismanagement, is difficult to access or accurately quantify.

Our understanding of the principal sources and pathways of plastic waste into the ocean is extremely limited, although continues to develop, and some trends stand out. The key sources of plastics to the ocean across multiple studies are found to be tyre particles, textile fibres, pellets, and surface coatings and paints. Other sources may be significant, but have not yet been quantified or included in global plastic budgets, for example industries which use significant quantities of plastic such as construction, sports and leisure, and electricals. Rivers are believed to be a significant pathway for plastics into the ocean, transporting millions of tonnes of plastics from land-based sources into the ocean per year. Nonetheless, direct input of plastics to the ocean is also an issue, in the form of shipping losses, discarded fishing gear, and degradation of marine paints and coatings.

The characteristics of plastics are key in influencing their fate and behaviour once within the ocean. Factors such as polymer type, aging and degradation will all affect an item's density, thus determining whether it will sink or float. It has only recently become understood that plastics in the ocean are distributed throughout the water column and seafloor, not just at the surface, which is a fundamental leap in our understanding of the distribution of plastics throughout the ocean. Furthermore, item characteristics such as particle shape, size and chemical composition can all influence their toxicity to marine organisms and wider ecological effects. These characteristics are thus important to consider when developing models and predictions for understanding the long-term fate and implications of plastics within the ocean.

It will be necessary to tackle the problem of plastics in the environment from multiple different angles; however, cleaning up or otherwise mitigating the existing plastic debris at any practical and successful scale is unlikely to be feasible, and thus future action requires preventing further plastics from leaking into the environment. The most effective strategies will therefore be top-down. Target areas should include policy change, industry action to change or modify manufacturing processes, improved global waste management and publicity and societal change in the approach to disposable plastic use. These approaches will all have significant challenges in their implementation and will not be quick fixes but will be key to long-term solutions.

Contents

1 | Meet our scientists

Dr Alice Horton
Principal Investigator – Anthropogenic Contaminants

Alice is a research scientist with over 7 years' experience in plastic pollution. She has published on issues including microplastics in UK rivers derived from road runoff and drainage, microplastics in treated and untreated wastewater and potable water, ingestion by fish, associations with organic chemicals and ecotoxicology. Alice leads a number of projects for NOC, funders of which include UK Water Industry Research (UKWIR), United Nations Environment Program (UNEP), and the EU Horizon 2020 programme.

Dr Mike Clare
Principal Researcher – Ocean biogeosciences

Dr Mike Clare is an expert in the onshore to deep-sea transfer of particulate material, including plastics. His recent study in Science found the highest recorded concentrations of microplastics on the deep-seafloor. These pollution hotspots were created far from their original source as a result of deep-sea currents. Mike joined NOC as a Research Scientist in 2015, prior to which he worked for ten years as a consultant to a range of offshore industries. He provides evidence on ocean science-related topics to organisations such as the OSPAR Commission, UN, and EU Council Working Party on the Law of the Sea.

Professor Richard Lampitt
Ocean Biogeochemist

Richard has a wide range of research and management experience in oceanography. He set up the NOC Microplastics Research Group 6 years ago which he now leads. His primary focus of research over the past 25 years has been in the downward flux of particles in the ocean and so brings significant insight into the ways in which particulate material in the ocean is transformed and transported by physical, chemical and biological processes.

Dr Isobel Yeo
Research Scientist – marine mapping and geochemistry

Isobel is a marine geologist and geophysicist with interests in dispersal and sink stability of particles in the oceans, seafloor and habitat mapping and physical and geochemical characterisation of deposits. She has more than 15 years' experience working in the marine sciences and works across projects spanning topics as diverse as ocean dispersal, habitat characterisation, deep sea mining, seafloor monitoring and geohazards. She also sits on a number of international committees, including the European Marine Board Working Group on Marine Geohazards.

Dr Katsia Pabortsava
Research Scientist – Pelagic Ecosystems Group

Katsia is a marine biogeochemist with over 6 years' expertise in marine plastic contamination. She examines temporal and spatial variations in microplastic abundance and downward fluxes in the ocean using advanced imaging spectroscopy tools. She has participated on ten research cruises and led the collection, processing and chemical analysis of naturally occurring- and plastic particles.

INTRODUCTION

2 | General background

The issue of plastic waste in the ocean is one of growing magnitude and concern. Plastics have been observed across a wide range of locations, spanning different site characteristics and influences. One of the key challenges in understanding and preventing the spread of plastic pollution lies in the diversity of the materials and sources that plastics comprise, meaning that multiple different strategies will be required. Despite the knowledge that our growing use of plastic is contributing to widespread environmental contamination, plastic usage and production is set to continue increasing over the coming decades. In order to manage this effectively, we must ultimately understand what mitigation strategies, policy and laws regarding production, use, and disposal will most effectively target marine plastic pollution.

The mass production of synthetic plastics began in the 1950s, enabling a shift from primarily reusable containers to single use packaging [1]. Plastics are durable, versatile, lightweight and inexpensive, resulting in an increase in the proportion of municipal solid waste in middle- and high-income countries from 1% in 1960 to 10% in 2005 [2]. Since production began, compound annual growth of 8.4% has resulted in the production of an estimated 8300 million metric tons of virgin plastics [1] (Table 1). Key plastic producers include China, Europe, North America and the rest of Asia (excluding China)[3] (Figure 1). Of this production, the primary uses are for packaging, building and construction, the automotive industry, electrical and electronic industry, sports and leisure, and agriculture [4]. The polymer type in highest demand in Europe is polypropylene (PP), which accounted for 19.3% of production in 2017 [4] and is widely used in plastic packaging, among other uses.

Globally, humans are already struggling to manage plastic waste [5]. As a result of waste mismanagement [6,7], including poor management or degradation of landfill, erosion of coastal landfill sites, inadequately controlled emissions from industry, wind-blown debris and direct release into coastal areas [8] much of the plastic waste we generate will end up in the ocean. It is estimated that 75% of all marine litter is plastic [9] and plastic waste accumulation has been reported on beaches [10], floating on the sea surface [11], on remote islands [12], in the deep sea [6,13] and even within Arctic sea ice [14]. Despite current multiscale commitments aiming to reduce plastic emissions into the environment, including Goal 14.1 of the United Nations Sustainable Development Goals ('By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution'), the promotion of zero-waste lifestyles, levies on single use consumer plastics, and attempts to remove plastics from the environment, approximately 19-23 million metric tonnes (Mt) of plastic waste entered rivers, lakes and the ocean in 2016 [15]. If current waste trajectories continue, plastic waste reaching the ocean could reach 90 Mt per year by 2030. Even in ambitious future scenarios that include existing global commitments to reduce plastic emissions [16–19] models predict an input of 20 – 53 Mt per year by 2030, with increased waste management capacity unable to keep pace with projected growth in plastic waste generation [15] (Figure 2).

"Despite multiscale committments aiming to reduce plastic emissions into the environment...and attempts to remove plastics from the enviroment, approximately 19-23 megatonnes of plastics waste enertered the acquatic system in 2016"

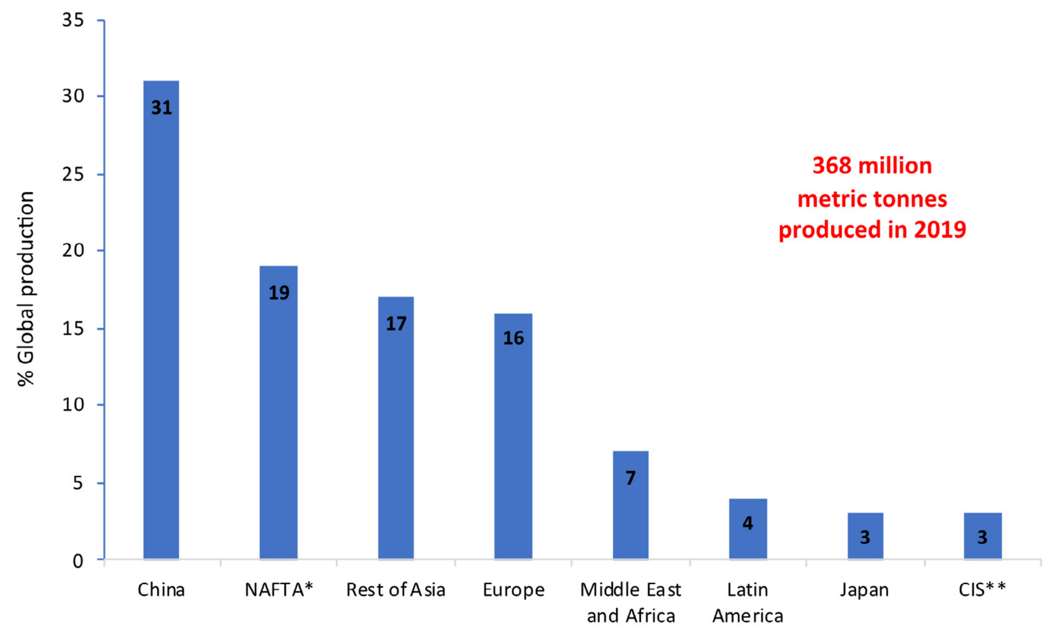

Figure 1: Distribution of global plastic materials production in 2019, by region[3]. *North American Free Trade Agreement ** Commonwealth of Independent States.

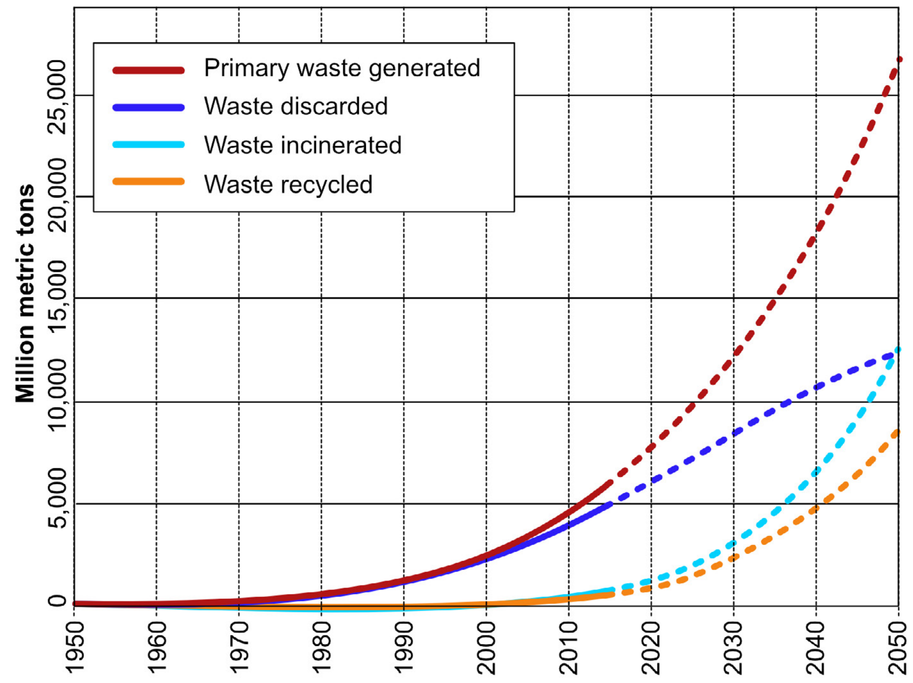

Figure 2: Cumulative global plastic waste generation and disposal (in million metric tons) modified from Geyer et al 2017 [1]. Solid lines show historical data from 1950 to 2015; dashed lines show projections of historical trends to 2050.

Polymer	Global production (Mt)	Share of total production
Polypropylene (PP)	16.9	16%
Low density polyethylene. Linear low-density polyethylene (LDPE, LLDPE)	45.7	12%
Polyvinylchloride (PVC)	43	11%
High-density polyethylene (HDPE)	40.4	10%
Polyethylene terephthalate (PET)	18.8	5%
Polystyrene, expanded polystyrene (PS, EPS)	18.8	5%
Polyurethane (PUR)	16.1	4%
Other thermoplastics	10.8	3%
Acrylonitrile butadlene styrene, acryonitrile styrene acrylate, styrene-acrylonitrile (ABS, ASA, SAN)	8.1	2%
Polycarbonate (PC)	2.7	1%
Polyamide (PA)	2.7	1%
Elastomers (non-tyres)	7.9	2%
Thermosets	33.7	9%
Adhesives	9.4	2%
Sealants	1.8	0.5%
Coatings	2.8	0.1%
Marine coatings	0.5	0.2%
Road marketing coatings	0.6	8%
PP fibres	30.1	5%
PA fibres	4.4	1%
Elastomers (tyres; mainly styrene-dutadlene rubber)	7.1	2%
Bioplastics (e.g. polyactic acid)	2.1	0.5%
Total	388.2	100%

Table 1: Global plastic production and share of total production, divided into different polymers. Data from Ryberg et al (2019) 20.

3 | Report objectives

This report was produced to provide a science-based report on ocean plastics, to enable a better understanding of the current extent of ocean plastic contamination and how this links to specific sources. This report will cover:

Categories of polymers in the world ocean
In this section we will define what is meant by 'ocean plastics' and the definitions of different plastic types by size, shape and chemistry.

Key sources of ocean plastics and their contributions
In this section key sources of ocean plastics will be linked to specific use types, and further broken down into polymer types and the forms in which these are found in the ocean. Losses to the environment will be covered, in addition to plastic movements, interactions with marine processes, and the processes affecting their transport, accumulation and degradation.

Current scale of the issue
This section will cover the current knowledge on the abundance and extent of ocean plastics in relation to regional inputs, sources and polymer types. This will also cover the differences between coastal and deep waters.

Ecotoxicology and ecological effects
This section will give a short outline of the current understanding of negative environmental and ecological impacts due to plastics, and key considerations with respect to particle chemistry, size and shape.

Solutions and mitigation strategies
Tackling ocean plastics is a multifaceted challenge which will require multiple approaches. Here we detail some of the many ways in which plastic pollution is being addressed, which strategies might be the most effective, and why.

Data gaps and challenges
Ocean plastic research has made substantial advances in recent years but many knowledge gaps remain. This is compounded by the fact that the research is, by its very nature, tackling a global situation and that plastic is viewed as a single contaminant, although there are very many plastic types. In this section we will highlight areas major relevant gaps and suggest broader areas where relevant research could be undertaken.

Conclusions
In the final section we will synthesise the data presented in these different sections, to provide a short overview of the current state of marine ocean plastic pollution research, with a view to informing decision making.

CAETEGORISING PLASTICS

4 | Chemistry of plastics

The term ‘plastic’ covers a wide range of synthetic and semi-synthetic polymers with a variety of uses that can be moulded or shaped. There are thousands of types of plastics with different polymer compositions, additives and characteristics that may be classified in different ways including based on their chemical composition, application and thermosetting properties.

The physical characteristics of plastics can broadly be divided into two categories: 1) thermoplastics (which can be remelted and remoulded) and 2) thermosets (which cannot return to their original state once set). Additives within plastics give them their inherent properties, but are not chemically bound to the polymer’s chemical structure and can thus leach out over time, changing the properties of the plastic as it ages. Some polymer types are used much more commonly than others, including high density polyethylene (HDPE), polyvinyl chloride (PVC), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET) (Table 2) and polyethylene (PE). Other types commonly produced include: polycarbonate (PC), acrylic (polymethyl methacrylate), PMMA), acetal (polyoxymethylene, POM), nylon (polyamide, PA), and acrylonitrile butadiene styrene (ABS).

Code	Abbreviation	Name	Common uses	Recylced uses	Polymer density (g/cm3)
1	PET	Polyethylene terephthalate	Clear drinks bottles, plastic food trays, textiles (polyester)	Fabrics (fleece), strapping, carpets	1.29-1.40
2	HDPE	High density polyethylene	Milk bottles, personal care and cleaning product bottles	Garden furniture, litter bins, pipes, milk bottles	0.94-0.97
3	PVC	Polyvinyl chloride	Window and door frames, pipes, clothing, toys, some drinks bottles	Often recycled into the same product	1.3-1.58
4	LDPE	Low density polyethylene	Carrier bags, some bottles/containers, 6-pack holders, lamination	Bin bags	0.89-0.94
5	PP	Polypropylene	Butter/margarine tubs, bottle tops, waterproof clothing, carrier bags	Clothing fibres, industrial fibres, food containers, dishware	0.89-0.91
6	PS	Polystyrene	Yogurt pots, cushioned packaging, take away containers/cups	Polystyrene pallets	1.04-1.08
7	OTHER	Acrylic Nylon Polymer composites	Perspex Fishing nets, clothing Various applications	Various	Various

Table 2: Main 7 plastic code divisions in the UK 21

Plastics are very versatile in terms of their physical and chemical properties, making them ideal materials for a range of applications. In addition to being beneficial while products are in use, the distinct physical and chemical properties of plastics play an important role in determining the extent and rate of transformations (e.g. fragmentation, degradation, aggregation) and interactions (biofouling, ingestion, sorption of other pollutants) for different plastics in the ocean, and thus their persistence and impact on the biota within it.

The importance of a polymer-specific assessment of microplastics in environmental samples has been highlighted by several studies [22–24]. Pabortsava and Lampitt [22] demonstrated the importance of tailoring the methods for microplastic sampling and analysis to specific polymer types, with a consideration of their likely abundance in the environment. As such, targeted sampling and extraction of polymer types of interest, pre-concentrating them by filtering larger volumes of water and scanning larger image areas on the filter were suggested as ways to reduce the uncertainty in quantification especially when studying relatively rare plastic types [22].

Presence or absence of specific chemical constituents may be an indicator of the origin and source of plastic debris. Yet, in practice, tracing the source of plastics based on the presence or absence of certain additives is currently challenging as the chemical composition of the virgin (not degraded) plastic particle must be known. Leaching of additives or other constituents from plastics is further complicated by the absorption of different organic and inorganic compounds from the surrounding environment. For example, in addition to their intrinsic heavy metals, plastic particles can also attract the same or other heavy metals from seawater [25–27]. These adsorption/desorption processes occur naturally for all types of particles including plastics, and they are complex and highly variable [28]. Therefore, confidently linking plastics to their precise sources remains a challenge.

Plastics can act as vectors for transporting other harmful substances, but the processes involved are not well understood. The mechanistic nature of leaching, adsorption and desorption of co-contaminants from and onto microplastics is very poorly understood, but are speculated to include hydrophobic interactions, pH variations, the ageing of particles, and polymer composition. The rates of these processes are unknown and can be driven by numerous intertwined factors such as composition and physical structure of the plastic particles themselves (e.g. level of roughness/weathering, porosity, or biofilm coverage) [29,30] and by the environment in which they are present (e.g. temperature, salinity, pH, entrainment in the marine snow or faecal pellets) [28].
Regardless of the provenance of plastics and their co-contaminants in the environment, it is increasingly recognised that there are a number of potentially harmful effects for ocean life. The impacts on biota and the ecosystem will depend on their composition, concentration, routes and time of exposure, as well as the state of organisms exposed (e.g. age and level of nutrition), all of which require intensive in situ and laboratory-based assessments, as they are currently at the very early stage of being quantified and understood.

“Regardless of the provenance of plastics and their co-contaminants in the environment, it is increasingly recognised that there are a number of potentially harmful effects for ocean life.”

5 | Size and shape categories

Plastic debris is described in many different ways, most commonly by shape (beads/ spheres, pellets, fibres, fragments and films) [31] and/or size, where they are usually classified as macroplastics (20 mm diameter and larger), mesoplastic (5 mm - < 20 mm), microplastic (1 μm – < 5 mm) or nanoplastics (1 nm – < 1 μm) [8], although consensus has still not been reached on size classification across all studies. While we commonly hear about the risks of microplastics, all sizes of marine plastic waste may pose a risk to ecosystems [32]. We now briefly outline the different sizes of plastic waste.

Macroplastics

Macroplastics are the most visible form of ocean plastic waste, with accumulation reported widely since the 1990s [33]. Their larger size, usually formed of whole or partial items, means it is often possible to categorise the original function and source of these items with some confidence. Their visually identifiable nature makes macroplastics a primary target for clean-up campaigns and citizen science initiatives, as they can be most easily found, recorded and collected.

Microplastics

Marine microplastics were first reported in the 1970s [34,35] although the term microplastic did not become widespread until the 2000s; first being used to describe plastic fragments of a few microns in diameter [7] and now commonly used as a catch-all term for plastic particles < 5 mm (although several studies define this threshold as < 1 mm) [36]. Microplastics may be either primary (manufactured at microscopic size), produced as pellets which act as the raw feedstock for the manufacture of plastic items, or by grinding or extrusion to be used in manufacture, cleaning products and cosmetics, or secondary, produced by the fragmentation and degradation of larger plastic items during their use [9]. Due to their widespread use, the exponential increase in particle numbers as large items fragment, and the ease by which they are transported microplastics are now widespread throughout the global marine environment.

Nanoplastics

Nanoplastics are particles between 1 nm to 1 μm in size and may also be primary or secondary [37], with sources including paints, adhesives, coatings, 3D printing [38], as well as being produced from cutting or grinding of plastic products [39] or by degradation. They are of particular concern as their very small size allows them to potentially pass-through biological membranes where they may affect cell function [38]. Identification and quantification of nanoplastics in the ocean is even more challenging than for microplastics, due to the limitations of currently available analytical techniques, and providing estimates of nanoplastic occurrence is challenging [37]. Given the ongoing uncertainties regarding the environmental abundance of nanoplastics, for simplicity within this report nanoplastics will be included within the definition of microplastics, unless specifically stated.

6 | Key sources of plastics & their contributions

In 2019, global plastics production reached 368 Mt annually. Of this, 58 Mt were produced in Europe [40]. Estimates of plastic input into the ocean vary hugely. In 2015, an estimate stated that between 4-13 Mt plastic are input to the ocean per year [2]. A subsequent study published in 2020 estimated that in 2016, an increased value of between 19-23 million tonnes of plastic entered wider aquatic systems (rivers, lakes and the ocean). Furthermore, they predicted that under a business-as-usual scenario, annual inputs could reach nearly 90 Mt by 2030, or 53 Mt even with ambitious reduction measures [41].

Marine plastic waste is derived from a huge variety of different sources reflecting the widespread and diverse uses of plastics. According to a recent study commissioned by the EU, the greatest sources of microplastics to the marine environment are:

- tyres (48%)
- pellets (28%)
- textiles (fibres released during laundering, 8%)
- road markings (7%) 42

These proportional sources vary slightly in terms of the proportional sources to those presented in a 2017 IUCN report, also specifically on microplastics [43]; however, the dominant sources (textile fibres and tyres) generally remain the same. The key difference is for pellets which, in the IUCN calculations, make up only 0.3% microplastic inputs to the ocean. This discrepancy in the estimated relative contributions of different plastic types underlines the current uncertainties in linking waste sources to waste accumulations in the ocean. These and other significant contributors are explored in the following subsections.

Litter and mismanaged waste

Litter and mismanaged plastic waste are commonly identified as the primary source of marine plastic pollution when considering plastics of all sizes. While overall estimates suggest between 1.7 and 4.8% of total plastic waste generated in coastal countries eventually enters the ocean, the regional variability in plastic waste is controlled both by the population and by the percentage of this waste that is poorly managed [2]. As a result, 16 out of the top 20 marine plastic pollution producers are middle-income countries, where waste management infrastructure is failing to keep pace with fast economic growth and, in many cases, with imports of plastic waste from abroad. In low-income countries, waste mismanagement is likely high, however waste production per capita is comparatively low, while in high income countries waste mismanagement is comparatively proportionally lower, but waste production per capita is much higher [2]. Waste mismanagement primarily concerns open dumping (often in uncontrolled sites), open burning of waste fractions and insufficient controls on leachates or losses from disposal sites as well as the poor management of derelict sites, which enable them to lose plastic to the environment [44] (Figure

3). Not all of the plastics lost will inevitably or immediately enter the ocean, as terrestrial environments may also retain plastics across a range of temporal scales, and plastics may accumulate and be retained within soil for a long time, especially in areas with limited anthropogenic or erosive influences [45], as they are protected from degrading factors. However, with increasing populations and development, and over 70% of waste being inappropriately manged even in higher-income regions [46], only vast global investment in improving waste management practices is likely to have a meaningful impact on marine plastic pollution.

"Estimates of paint-related plastic inputs to the environment are reasonably consistent and sit around 10-11%"

Textiles

Estimates of textiles as a source of microplastics, as a result of microfibre loss during use or laundering, range from 8% - 35% of the total microplastic waste entering the ocean annually [42,43] (Figure 4). Microfibres are often the dominant particle type found in surveys of marine microplastics. Synthetic microfibres are typically composed of polyester, polyethylene, nylon, or acrylic, and are generated as a result of fibre shedding or abrasion during wear or laundering. They are often too small to be removed by washing machine filters or traditional sewage processing methods and can therefore be discharged into waterways and the ocean with treated water [67]. Although wastewater treatment has been shown in many cases to be > 99% efficient in removing microplastics in general from treated wastewater (instead accumulating in sludge), the remaining ~1% can still cumulatively account for large quantities of microplastics released [47]. The worst fabrics for microfiber shedding are thought to be polyester fleece materials, averaging almost 85 times the number of fibres released during washing than other fabrics [48].

Figure 3: Photograph taken in April 2019 of a legacy landfill site on the coast of Walney Island, UK (54.065°N, 3.227°W) showing plastic loss to the ocean as a result of coastal erosion of a now derelict waste site. Inset shows the location of the site on the island. Image credit: National Oceanography Centre ©

"Not all of the plastics lost will inevitably or immediately enter the ocean, as terrestrial environments may also retain plastics across a range of temporal scales, and plastics may accumulate and be retained within soil for a long time"

Fishing gear

Fishing equipment is often made of synthetic textiles, in particular nylon, PE and PP, which when discarded can become a direct contributor to marine plastic and microplastic waste [49]. Fishing waste is commonly known as ALDFG (Abandoned, Lost, or otherwise Discarded Fishing Gear) and may be lost by accident, due to snagging or adverse weather, or may be deliberately discarded when it reaches the end of its useful life. There is no universally accepted figure for the contribution of ALDFG to marine litter, and loss rates from fisheries are highly variable, although most estimate it at less than 10% [41,50], although 5.7% of fishing nets and 29% of fishing lines are estimated to become ALDFG [51]. Once in the environment, fishing-derived plastics may float or sink and will be degraded (predominantly by abrasion on rocky seafloors and/or UV exposure) [50].

Paints and surface coatings

Less well-known than other sources, but also important as a microplastic source, are paints and surface coatings, both derived from land and sea. Estimates of paint-related plastic inputs to the environment are reasonably consistent and sit around 10-11% [42,43]. Plastic polymers are often used as binders in paints and antifouling agents, and may be liberated by corrosion, wear and tear and by the process of open blasting used to maintain marine surfaces, which usually have a low degree of waste collection and recycling. Marine coatings are thought to represent at least 60,000 tonnes per year of plastic input into the ocean, although the actual figure is likely to be much higher, as the 100-year estimated paint life used in coming to this figure is optimistic. Over six million tonnes of paint are applied to steel vessels and structures every year. There are few studies on the extent of coating-derived microplastics, however one detailed study in the North Sea found that in estuarine and central regions the microplastics bore a strong signature of antifouling coatings (i.e., abraded chlorinated rubber-, acryl-styrene-, and epoxide binder-containing particles) as opposed to coastal regions, which were strongly dominated by plastic packaging [52,53].

Tyre and road wear particles (TRWP)

Also related to transport, tyre and road surface wear is capable of generating significant emissions of microplastic particles [54]. However, despite being documented in marine environments, once again, there is limited data available on the types, locations and proportional contributions of these processes to ocean microplastics. Existing studies suggest emissions from car tyres are substantially higher than those of other associated sources of microplastics,

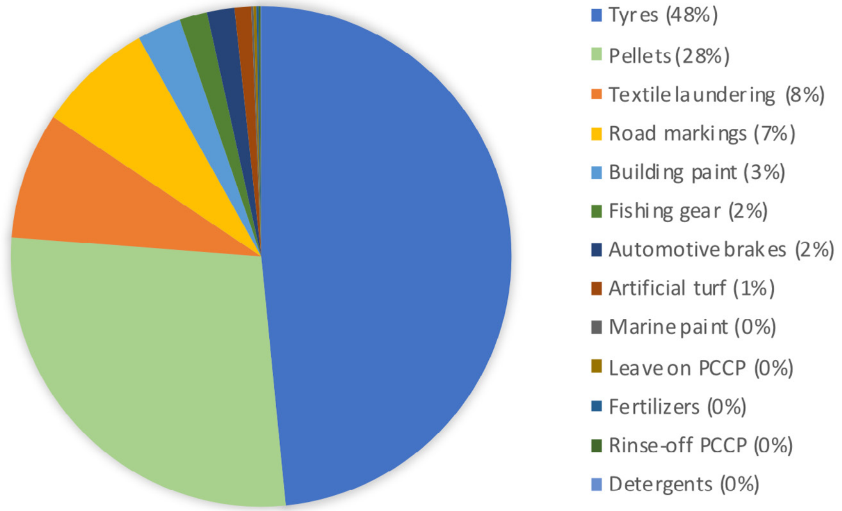

Figure 4: Proportional input of different plastic sources to surface waters (freshwater and marine). Created using data from 42. Those with 0% were not truly 0, but negligible compared to the other sources.

such as airplane tyres, brake wear and road marking wear [54]. Existing research shows large variability in the particle sizes produced by tyre wear e.g. 50 - >100 µm [55], 0.5-20 µm [56], 20 -80 nm [57] and 30 – 60 nm [58], that are then deposited on or by the road and removed by runoff, or, for the smallest fractions, may become airborne and be transported by wind [59]. A small, but significant proportion (around 10%) is small enough to become airborne. TRWP are also highly variable in their form, size and density and have a range of polymer compositions (natural rubber (polyisoprene), butadiene rubber, styrene butadiene rubber, pentaerythritol resin, EVA, PMMA, epoxy, styrene butadiene styrene, PP, PE) [59]. In the UK, it is thought that tyre wear will have accounted for up to 350,000 tonnes of ocean microplastic by 2030, with an annual generation of 63,000 tonnes per year [54].

Pre-production pellets

Microplastic pellets, also known as nurdles, are industrially produced as a convenient way to trade and then transport plastic products to manufacturers for final moulding. They are spherical and around 4 mm in diameter. Pellet spills are not uncommon and can be on a huge scale (for example the case of 87 containers of nurdles lost in the Indian Ocean in May 2021). The concentration of plastic pellets is often regionally controlled, with lower concentrations in regions with generally better management and fewer accidental losses. However, in some regions nurdles comprise the primary microplastic found in beach deposits, making them a notable, yet often localised pollutant. Estimates of losses to surface waters range between 0.3-28% [42,43].

Personal care and cosmetic products (PCCPs)

Another source of primary microplastics are PCCPs containing microbeads [60–63]. While these have been banned in wash-off products in the UK since 2018, these remain within many 'leave-on' products. Furthermore, despite some bans, globally sales of PCCPs containing microbeads remain high, with over 70% of PCCPs sold in some regions of China containing microbeads [62]. PE tends to be the most common constituent, along with nylon, PMMA, PET and PP and many products will contain more than one polymer as a constituent [62,64]. Approximately 10% of modelled microplastics exported by rivers into the oceans are PCCPs [64], although this ballpark estimate is based on assumptions about the density of particles and discharge rates based on fairly sparse available data.

Construction materials

The construction industry is the second largest consumer of plastics (after the packaging industry), at over 300 Mt produced annually [65], and some estimates suggest as much as 20% of plastic waste may originate in the construction sector [66]. Plastic's versatility and durability make it hard to replace in many building applications, although a number of construction companies (e.g. The Diringer & Scheidel Group [67], Mace [68], Multiplex [69]) have announced efforts to reduce plastic waste generation and increase recycling, primarily focussed on those plastics that are thrown away, rather than those used in 'permanent' installations. However, there is some research that suggests some plastics, particularly micro- and nanoplastics, could be shed from installed plastics too. For example, synthetic plastic pipes, including those made from PE (including low, medium and high density), PVC and PP have been used in widespread applications all over the world, including in drinking water distribution systems. These pipes are likely to be negatively impacted by disinfectants, including chlorine, chloramine, and chlorine dioxide (common drinking water additives), which produce a strongly oxidative environment potentially capable of prematurely ageing plastic pipes [70,71]. This can lead to changes in their mechanical, surface and morphological characteristics, increasing the likelihood of micro- and nanoplastics shedding from aging pipes. Construction may also represent a possible future sink for plastic waste, with recycled plastic building materials, such as plastic bricks, increasing in popularity.

The categories above cover some of the main known sources of marine microplastic pollution, but sources are as diverse as plastic usage (Figure 4). Some other likely but unstudied sources which therefore cannot currently be quantified include wear of shoe soles, degradation of artificial surfaces, including Astroturf, artificial sports pitches with rubber crumb infill, other paints, any process involving grinding or sanding plastics, for example in cosmetic nail procedures. Without many more detailed studies of the types, location and volumes of microplastics in aquatic environments it is likely many sources are currently

missed or underrepresented from the presented budgets, and inclusion of these would change our understanding of the proportional inputs from different sources.

Pathways of plastics into the ocean

Between 0.5 – 3 Mt plastics entering the ocean annually are believed to be transported via rivers [23,72,73], with other routes (not included in these figures) including direct input from land, and dumping or accidental loss at sea. The variability in these estimates highlight that there is still a large degree of uncertainty in these numbers, as few calibrated measurements have been made. Recent studies suggest that some of this plastic entering aquatic systems may actually be retained within river systems themselves, and may not reach the ocean [74]. While plastic waste generation tends to be primarily predicted as a function of population size, the existence and efficacy of waste management infrastructure also strongly influences waste output [2].

Once they enter the ocean, plastics are redistributed by a range of wind, ocean currents, biological processes and sinking [75–78]. Models of plastic distribution produce highly variable results, particularly those for microplastics, as a result of knowledge gaps in microplastic sources, degradation and sinks [79], the physical behaviour of plastic particles, and the effects of biological modification and interactions [80]. Furthermore, models rarely take into account 3D distribution (i.e. distribution with ocean depth) [81], instead predicting surface transport only, making predicting the fate and impacts of microplastics on the environment challenging. The majority of Lagrangian particle tracking studies assume positively buoyant particles, or else vertical settling, and thus do not account for lateral movement other than by surface currents (e.g. [82]). It is thus a common assumption in models that the majority of plastics float and thus accumulate on the ocean surface; however, recent studies have shown this is not necessarily the case. Supposedly buoyant plastics such as polyethylene and polypropylene, can be distributed widely at various depths throughout the water column and on the deep seafloor [22,83,84].

Ocean plastics life cycles and sinks

The fate of plastics once they reach the ocean is difficult to predict, as there are a huge array of factors influencing their behaviour. The specific gravity (or density) of plastic material (subject to numerous polymer types and formulations) relative to their surrounding water is a key factor determining the ability of plastic debris to sink or float (Table 2).

Other factors will all determine the behaviour, fate and the impact of plastic contaminants in the ocean, such as:

- Morphologies of plastic debris (size, shape)
- Sources and pathways of plastics to and within the ocean
- Their various temporary or permanent sinks (ingestion, sequestration into sediments)
- Interactions (biofouling, aggregation, incorporation into zooplankton faecal pellets)
- Transformations (fragmentation and degradation)
- Timescales over which all these processes operate.

Based on observations within the environment, predicted global figures for ocean surface debris accumulation range from hundreds to thousands of metric tons [79,85,86]. However, debris that can be measured on the ocean surface represents only a very small fraction of estimated annual plastic emissions into the marine environment, leaving the remainder unaccounted for [6,22,74,87–89]. One explanation for this 'missing' fraction is that a large proportion of polymers are inherently denser than seawater and so will sink (Table 2). Additionally, plastics sink as a result of biological interactions such as biofouling, or incorporation into faecal pellets. A positive correlation observed between surface chlorophyll-a concentrations and abundance of microplastic in the deep-sea sediments suggests that microplastics may travel downward through entrainment into the sinking marine aggregates [90,91]. The existence of this mechanism, known as ballasting (e.g. [92]) for microplastics has been shown in laboratory conditions [90,93] but is yet to be demonstrated in situ. These factors mean that many plastics are present within the water column below the surface [22], within sediments or, alternatively, become stranded on coastlines [86].

Macroplastic distribution by age is also variable, with most buoyant plastic (79%) in the coastal surface layer originating from objects less than 5 years old. Whereas, in the offshore surface layer, where older objects have more time to accumulate, plastic younger than 5 years accounts for only 26% of the buoyant plastic mass and macroplastics older than 15 years contribute nearly half of the total mass (47%) [86].

Due to the propensity for plastics to become dense and sink, plus the fact that once in the deep-sea plastics are unlikely to return to the ocean surface, the deep ocean is considered the ultimate sink for plastics, including microplastics [6,94]. Yet, the direct measurements of plastics in the open ocean are very sparse and have been mostly focussed on microplastic particles collected in the surface waters or seafloor [87,95,96]. The vast ocean interior remains severely under sampled for microplastics. However, the limited research in the open ocean has shown that microplastics at greater depths are abundant and can contribute significantly to plastic mass within the oceans. Pabortsava and Lampitt [22] quantified the loads of three common plastics (PE, PP, PS) in the top 200 m of the Atlantic Ocean from 35 samples at 12 sites. Through extrapolating their depth-resolved polymer-specific data they showed that the combined mass of just PE, PP and PS microplastics of 32-651 um size category could balance, or even exceed, the estimated bulk plastic inputs into the Atlantic Ocean since 1950. Full-depth assessments of microplastic concentrations have also been done in the Arctic Central Basin [97] and at three locations in the West Pacific Ocean and East Indian Ocean 98. Other studies on vertical abundance of microplastics were conducted predominantly in the coastal waters sampled, at most, 300 m below the surface [99–102].

Of the estimated annual inputs of 4-12 Mt of plastic from the coastal municipal waste and rivers, the mass of plastics >300 µm suspended in the surface ocean makes up between 93,000-236,000 tonnes [79,103]. In addition to particles at depth, studies by Enders et al. [104], and Poulain et al. [105] demonstrated that a significant fraction of the 'missing' ocean plastics could in fact be those that are smaller than can be captured by traditional sampling and detection methods (nets and trawls with aperture size >300 µm), likely due to continuous fragmentation of larger plastic items in situ [87,106,107]. In the study mentioned above, Pabortsava and Lampitt [22] measured particles > 25 µm, smaller than the majority of studies to date, revealing a critical importance of very small, sub-surface microplastics for the oceanic plastic burden, especially relative to larger-sized plastic debris floating in the surface or deposited on seabed [108]. The measurement of these small particles is likely to be a further contributing factor to the large masses of plastics observed in this study. Therefore, small particles can contribute significantly to overall mass budgets. This highlights the importance of including smaller particles in observations.

The dominance of microplastics <100 um in the surface waters and in the ocean interior [22,106,107] indicates that the horizontal dispersal of microplastics and their loss into the ocean interior is a size-selective process (see also [11,38,76,87,109]). High quantities of predominantly 11-25 µm microplastics found in the deep-sea sediment further indicate that the surface load of microplastics is eventually removed to the seabed [91], although the exact processes mediating this transport and the rates at which they occur remain elusive and poorly constrained.

The knowledge gap concerning the amount and location of 22 plastics in the ocean, especially those in smaller size categories (<300 µm) precludes the full understanding of how microplastics interact with oceanic life and processes, given the abundance of microscopic life in the oceans. As such, the estimates

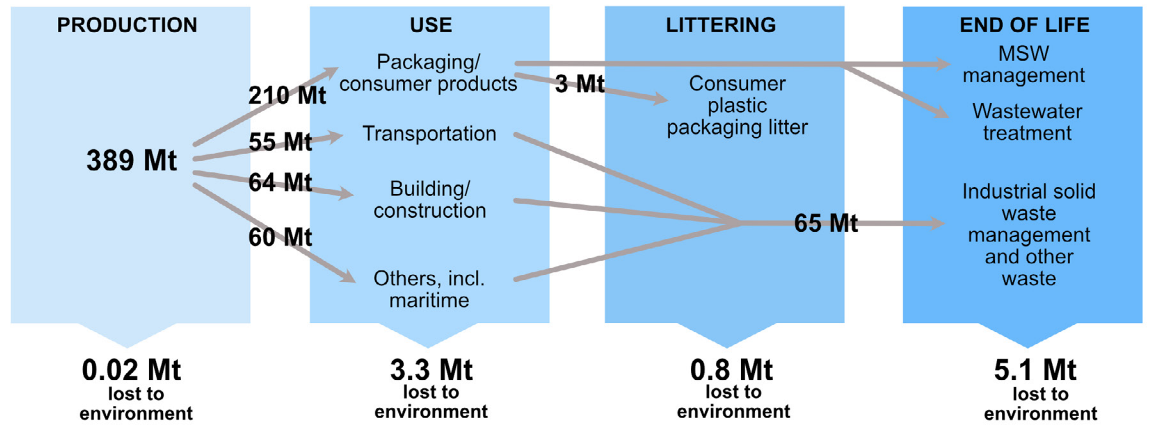

Figure 5: Global plastic value chain and estimated losses to the environment for the year 2015, modified from Ryberg et al (2019) 97. Overview of the plastic value chain showing amounts annually produced, used in different sectors and eventually disposed of (end-of-life stage). Total masses of plastics lost to environment (marine, freshwater, and terrestrial compartments) are shown per life cycle stage. The mass of plastics produced is not equal to the mass of plastics disposed of due to plastic service lifetime extending beyond the year of production. Accordingly, a fraction of the plastic waste disposed of in 2015 was produced before 2015.

of global plastic load in the near-surface ocean and the inputs from the land-based plastic waste are challenging to reconcile and thus the persistence of microplastics in the ocean remains virtually unknown. This is concerning with respect to understanding the long-term implications of this contaminant in the marine environment, given that these smallest organisms, such as plankton, play a fundamental role in the trophic food web and nutrient cycling.

Plastic losses in production and transport

Global plastic production is relatively well quantified, and regional consumption can be estimated using per capita plastic consumption statistics, alongside population. Data for plastics used in different applications is harder to achieve, but can be estimated [1] and subdivided further where more detailed data is available. Losses can be estimated using existing data alongside statistical models as required [20]. The overall global plastic life cycles and losses calculated using these methods are shown in Figure 5.

The life cycle model (Figure 5) shows that just over half of plastic production (54%) is used for packaging and consumer products with the next largest con-

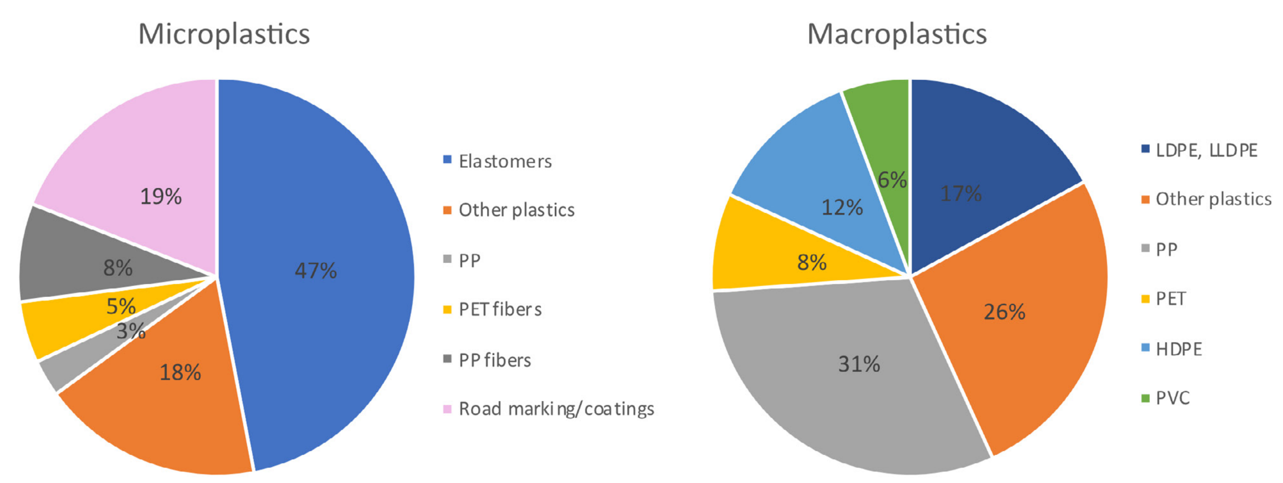

Figure 6: Losses of microplastics and macroplastics to the environment (marine, freshwater, and terrestrial compartments) by polymers and plastic applications (when exact plastic (or polymer) types cannot be identified). Modified from Ryberg et al (2019) 20.

sumer being building and construction (16%). As a result, by far the largest quantified waste generation also comes from packaging and consumer products.

Across the plastics life cycle, the largest losses of occur in the Use of Plastic Products and End of Life (EoL) stages, which account for ca. 36% and 55% of total plastics losses to the environment, respectively [20]. In general, about 90% of microplastic losses are related to the use stage and about 77% of macroplastic losses are from the EoL stage. Geographic distributions suggest that, in line with the highest losses, mismanaged waste disposal is the primary source of plastic loss, with higher losses in low-income countries where open-dumping of waste is permitted (although this should be considered in light of foreign plastic imports where appropriate).

The distribution of polymers lost to the environment is shown in Figure 6. Microplastic losses are dominated by elastomers (likely derived from tyres), with lesser contributions from road markings. Overall, microplastic losses seem to roughly correlate with overall regional plastic consumption [20]. Macroplastic losses correlate with polymers commonly used in packaging including LDPE, HDPE and PP, and those most commonly produced overall (Table 2).

The overall plastic loss totals from this study both have fairly large error bars and differ considerably from some other studies e.g. [2], thus undoubtedly more research is needed to reduce the errors and improve loss estimates. However, the overall conclusions of similar studies, that losses occur primarily during use and disposal, and that plastic packaging, consumer products, clothing fibres, tyres and road markings are the main sources of macro and micro-plastics, are common to most studies of plastic waste outputs [20,43,66,110–113].

Plastic aging and degradation

The aging of plastic items and particles will significantly alter their behaviour and fate due, for example, to loss of plasticisers and other chemical additives, fragmentation and degradation, and biofouling. Loss of additives can lead to change in colour, altered shape and embrittlement of plastics, ultimately leading to their degradation. At near-ambient temperatures chemical degradation typically involves either oxidation (involving O_2) or hydrolysis (involving H_2O), both of which can be accelerated by microbial action, heat and light [37,114,115].

There are three important processes that impact the extent and speed of marine plastic degradation [116]:

1. Bacterial and other organism colonisation of the surface of plastic particles will both physically degrade the particles (Scanning electron microscopy images of weathered plastics show pits and grooves that conform to the shape of certain microorganisms [117]) as well as generate biofilms [118–120] which may produce enzymes that also erode the surface [121].

> "The aging of plastic items and particles will significantly alter their behaviour and fate due, for example, to loss of plasticisers and other chemical additives, fragmentation and degradation, and biofouling"

2. Abiotic hydrolysis of functional groups, like esters, carbonates, and amides, can sever the large macromolecules which make up polymers, reducing their molecular weight [116,122].

3. Exposure to UV radiation and oxygen causes photodegradation [123,124], also reducing molecular weight, causing cracking that produces microplastics, eventually degrading into nanoplastics [125]. This process produces aldehydes and ketones, further encouraging the development of biofilms [126]. Finally, the higher surface areas produced by physical weathering will also enhance interactions with organic pollutants [127], potentially making them more hazardous.

While being an indicator of potential harm associated with exposure to microplastics, compositional variation of additives in microplastics can also suggest the source of different plastic types in the ocean, the extent of their degradation/weathering, and residence time [128]. For example, a study that assessed the UV degradation of PET, PP and PS in air, freshwater and seawater demonstrated an enhanced chemical weathering of PP compared to other plastics (though all were increasingly degraded with time) [129]. This differing rate of degradation is important to consider when thinking about the abundance of plastics within the environment, as the rate of degradation will determine the longevity of different types of plastics. This will also determine the rate at which they will degrade to microplastics, nanoplastics, and ultimately remineralise into their constituent elements. Therefore, when examining marine plastic waste, it is crucial to understand not only the sources and pathways of plastics, but also the chemistry of the plastics involved. Furthermore, the sorption of pollutants onto plastic particles is not the same across different types of plastics [130].

7 | Current scale of the issue

Regional plastic contributions and variability

While plastic pollution is globally widespread, it is by no means evenly distributed, with some areas being significantly more contaminated than others. In this section we discuss some of the controls on the global variations in release of plastic waste to the natural environment. According to a review by IUCN 43 , the largest regional microplastic releases from land occur in South Asia and India (18.3%) and North America (17.2%), with other significant releases in Europe and Central Asia (15.9%), China (15.8%) and East Asia and Oceania (15.0%). The lowest releases occur in South America (9.1%), Africa and the Middle East (8.7%). When considering combined microplastics and macroplastics, China (11.3%), Africa (10.5%), and South America (11.4%) become the most significant contributors. Nonetheless, higher income regions such as Europe and Central Asia, and North America, still contribute not-insignificant amounts (8.1% and 5.9% respectively) 20. The drivers for these variable concentrations generally relate to a combination of population density, plastic production and use, and mismanagement of waste such that it enters the natural environment 73,131.

Large populations in low- to middle-income regions that have limited access to wastewater treatment result in the greatest releases of microplastics, which accounts for the particularly high proportions in South Asia and India. However, wastewater treatment is commonplace in Europe and North America. Instead, in these higher income regions, the large releases are linked to them having per capita losses that are larger than the global average 43. Rates of plastic consumption also continue to rise in higher-income countries, and these countries lack the capacity required to recycle the huge volumes of plastic waste being produced. As a result, even though recycling is usually promoted as a solution to plastic waste in reality more than half of the waste recycled in higher-income nations that is destined for 'recycling' is exported overseas 132. Until recently this waste was primarily sent to China 132, but China banned the import of most non-industrial plastic waste in 2017, resulting in a shift to poorer countries, including East Asian and Pacific nations 133 (in 2016 they received 70% of affluent OECD countries' plastic waste). The Chinese ban on non-industrial plastic waste imports has also increased the cost of recycling, resulting in stockpiling or incineration of plastic earmarked for recycling across many richer nations 133.

Some lower-income nations choose to import plastic waste as a source of income, either through subsidies

or through the provision of raw materials 134. However, the countries that are most incentivised to import plastic waste are often not those with advanced waste management systems, meaning they commonly become overwhelmed by waste, resulting in excessive plastic leakage into the environment 133. To further understand the role of the international plastic waste trade on management and loss, it would be valuable to consider quantities of plastics export from higher to lower income countries, and how this is changing over time. However, such analysis is outside the scope of this report. Thus, while large proportions of plastic waste may be attributed to low- or middle-income countries, much of this waste may well have started its life in richer countries, with the money and resources to export it elsewhere, and thus any framing of the sources of marine plastic waste should be considered with this in mind. Furthermore, the export of plastic waste from the place it was created results in an artificially clean environment, reduces the perceptions of plastic pollution and waste mismanagement, and may indirectly influence consumers to purchase or use more plastic products in these regions 133.

Robust quantification of plastic emissions worldwide remains a challenge and must consider a wide range of socio-economic and behavioural issues. Recent studies have attempted to make first-order estimates of the global distribution of plastic emissions to the natural environment based on empirical relationships between these factors (i.e. population density, plastic management practices), calibrated with observational data acquired at several locations worldwide, but it is also worth stressing that many regions remain un- or sparsely-sampled (e.g. 73,131). One study also attempted to determine how those plastic emissions may be transferred by rivers that drain to the ocean, concluding that more than 1000 rivers account for 80% of the global annual emissions of plastic to the ocean via rivers, which ranges between 0.8 and 2.7 million metric tonnes per year 73. Small urban rivers were found to be the most polluting, in contrast to the large rivers that have previously been identified as the main culprits 2.

Plastics can also be released due to a range of offshore activities, including shipping and fishing, which are not included in the land-based estimates. It is estimated that marine sources account for approximately 20% of the plastic pollution in the ocean; however, much uncertainty surrounds this estimate, and it is also highly geographically variable 135. Commercial fishing is the main contributing activity, which can account for the dominance of ocean plastic pollution in some regions. It is estimated that 640,000 tonnes of discarded fishing gear is added to the ocean every year, and may make up as much as 10% of the total plastic budget in the ocean 136. In areas where intense deep-sea trawling occurs, particularly in submarine canyons, remote seamounts, and ocean ridges, seafloor surveys have revealed that accumulations of litter may be almost entirely dominated by fishing gear 137,138. Floating plastic on the ocean surface also often contains large amount of fishing-related litter. Indeed most (approx. 65%) of the plastic debris in the so-called Great Pacific Garbage Patch in the North Pacific Ocean relates to fishing. This 'garbage patch' consists of a suspension of large and small plastic pieces floating at or beneath the ocean surface.

The physiography of a region can further compound the focusing of plastic pollution. For example, the Mediterranean Sea features elevated plastic concentrations due to its enclosed nature, which effectively traps the resultant plastic emissions within the basin. It also has a number of diverse sources that include highly populated coasts and geographically variable efficiency of waste management, combined with tourism, intense fishing, and maritime traffic and shipping. Therefore, the accumulation of plastics within any given region is a result of a range of different factors, which include sources, but also depend upon the physical (e.g. rivers, ocean currents, waves, wind etc.) and biological (e.g. ingestion, excretion) processes that may disperse them further afield, locally concentrate them, or even transfer them back to shore or into the atmosphere (in the case of nano and microplastics).

To date it is believed that polar seas are among the least impacted by plastic pollution. This is due to the fact that the Arctic, and especially the Antarctic, are subject to far lower population pressures than other global regions, and plastics must undergo long-range transport to reach these areas. Nonetheless, plastics are detected at most locations that are sampled 139–142. Shipping, fishing and tourism are all activities that can contribute to local inputs of plastics to even these remote regions, but perhaps more important are the currents and winds that can transport plastics from more populated lower latitudes. The Arctic is highly connected with adjacent sea and this provides pathways for plastic litter transfer into the Arctic 141. Plastics have been reported in sea surface waters around the Antarctic Peninsula and in seafloor sediments 143,144. Sea ice itself may also trap and/or transport microplastics 145.

Oceanic distribution and abundance by source

As the same polymers may be used to produce a multitude of different products for different uses, it is challenging to use the chemistry of plastic particles alone to identify their original use. For macroplastics, it is sometimes possible to physically identify the source by sampling and examining the plastic as whole items, however, these studies are time consuming and therefore relatively sparsely distributed. Comparing studies may also be challenging because the definitions of sources are variable and inconsistent, and because environmental processes may sort plastic waste by shape and size, biasing some regions to certain sources.

The Great Pacific Garbage Patch is one of the best studied regions of floating ocean plastic accumulation. In this region 52% of the plastic waste found and examined is attributed to plastic lines, ropes and fishing nets, 47% is hard plastic sheet and film, 0.5% is pre-production plastic pellets and 0.05% was plastic foam [131]. The lines, ropes and nets were primarily large particles, with over 90% > 50 cm in size. By mass, 86% were fishing nets. The hard plastics were more mixed, with around 50 % of plastics > 5 cm (macroplastics), around 10% mesoplastics, and the remaining material all < 1.5 cm.

Compared to the open ocean, the proportions of different types of plastic are often very different in coastal areas. For example, in coastal and beach regions in the Philippines, plastic waste was dominated by sachets and wrappers (29%), disposable cups and plates (17%), plastic bags (15%), straws and stirrers (8.9%) and sacks (3.9%) (data given by number of objects not mass) [146]. This agrees with other studies that have suggested that land-based sources of plastic packaging form the majority of waste in rivers, with fishing and aquaculture products dominating in the ocean, suggesting that pollution pathways between rivers and ocean may not be as strongly coupled as has previously been suggested [147].

Oceanic distribution and abundance by polymer

Studies that attempt to quantify the abundances of polymer types are hampered by very low and irregular sample spacing density. There are also differences in how data are analysed and reported. For example, many studies attempt to identify plastic pollution in terms of its source use (e.g. plastic packaging, fishing equipment, etc.) rather than in terms of specific polymers. In order for plastic waste polymer types to be identified, plastic material must first be sampled and then geochemically characterised, typically using Infrared Spectroscopy and being careful to avoid environmental contamination (specifically when studying microplastics) that may bias the results [31]. Extraction methods may also bias studies towards one or more particle or polymer types [148]. Because of these requirements comparing data across multiple studies, conducted by multiple scientific researchers or groups can be challenging.

For oceanic distribution of polymers, here we show studies where the polymer types reported correlate with the seven main plastic divisions used in the UK (Table 2). One of the primary issues with this data is that much detail is lost in the 'Other' plastic category, particularly nylon. As the primary component of most fishing nets, nylon is potentially a very important polymer to understand in the context of marine plastic pollution. With this synthesis the findings were variable (Table 3) and the small number of datasets makes it hard to draw broader conclusions. However, some general environmental differences can be identified:

- For plastics floating on the sea surface, the primary polymers were PET and HDPE with low levels of PVC and PS.
- PET was also common on beaches and intertidal areas, but these regions showed an increased proportion of PP and Other polymers (O).
- Subtidal/Epipelagic areas were similar, with slightly increased levels of O proportional to PET than intertidal regions.
- The water column was dominated by O category polymers, with an increase in the proportion of PET at depths > 200 m.
- Marine sediments were regionally variable, but commonly contained PET, PP, PS and O.

Study	Year	Intertidal/beach							Subtidal/ Epipelagic							Sea surface						
		PET	HDPE	PVC	LDPE	PP	PS	O	PET	HDPE	PVC	LDPE	PP	PS	O	PET	HDPE	PVC	LDPE	PP	PS	O
Schwarz et al., 2019.	2019	53%				26%	5%	16%	67%				20%	12%	1%							
Erni-Cassola et al., 2019.	2019	27%				7%	10%	57%	16%				26%	10%	47%	51%				31%	6%	12%
Suaria et al., 2016.	2015															52%		3%		16%	3%	26%
Enders et al., 2015.	2016																					
Brignac et al., 2019.	2019	12%	7%	4%	8%	42%	6%	22%	15%	5%	2%	3%	2%	6%	67%	19%	55%		10%	2%		14%

Study	Year	Water column							Water > 200m							Water < 200m						
		PET	HDPE	PVC	LDPE	PP	PS	O	PET	HDPE	PVC	LDPE	PP	PS	O	PET	HDPE	PVC	LDPE	PP	PS	O
Schwarz et al., 2019.	2019															40%				13%	12%	35%
Erni-Cassola et al., 2019.	2019	27%				3%	1%	88%								2%				4%		94%
Suaria et al., 2016.	2015																					
Enders et al., 2015.	2016	27%		5%		9%	2%	57%	56%		2%		12%	6%	26%							
Brignac et al., 2019.	2019																					

Table 3: Compiled data from a number of studies showing the distribution of polymers in plastic pollution in different marine (saltwater) zones. Note the large variability between studies, which results from differences in location as well as sampling and analytical techniques. Note, different aquatic environments are also often not uniformly distinguished. Here we follow the definitions used in Erni-Cassola et al. 144 who distinguish water types marine zones (intertidal, subtidal, sea surface, water column, deep water > 200 m and deep sediments > 200 m) and Schwarz et al. 143 who distinguish freshwater beaches, epipelagic zones and sediments, although this level of subdivision is not available for all studies. Greyed out boxes indicate regions that were not covered by the study.

Microplastic concentrations in the ocean

Despite the growing number of studies and increasing amount of data on plastics and microplastics within the ocean, our knowledge of the abundance, fate and sinks of microplastics is not yet well-constrained. This is primarily due to the challenges of collecting, processing and analysing microplastics in an accurate and repeatable way. This especially applies to the size of particles analysed; while microplastics can be defined as any particle between 1 μm and 5 mm, the lower size limit collected varies across studies, for example 10 μm [106], 25 μm [22], 335 μm [149] 500 μm [150] depending on available equipment and analytical capability. It is known that smaller microplastics are proportionally far more abundant within the environment, hence this difference in sampling techniques and analytical methods used for detection significantly influences the number of particles reported, and makes comparison across studies difficult [22,140]. For example, a study directly comparing techniques that collect different sizes of particles found a tenfold increase in the number of particles reported when a 100 μm mesh net was used compared to a 500 μm mesh net [151].

Observational and modelled estimates of the mass of microplastics in the surface waters of the ocean range from 93,000 and 490,000 metric tons, equivalent to 15 to 51 trillion (15-51 x 10^{12}) particles in the surface ocean [79,152]. This mass is predicted to increase 50-fold to 2.5×10^7 to 1.3 × 108 tonnes (best-case and worst-case scenario, respectively), equivalent to 9.6 to 48.8 particles /m3, (3.48×10^{20} – 1.77×10^{21}, within the top 5 m of the ocean) by 2100 [152]. While broad data on the global ocean are useful, it is important to note that global estimates are a generalisation of the state of the ocean, and concentrations are heavily location dependent. For example, hotspots exist in the Eastern Mediterranean and the Yellow Sea; in 2014 concentrations in these locations were estimated to reach over 40,000 and 50,000 microplastics /m^3 respectively, while measured concentrations in other regions are highly variable [152]. For example, in the Arctic, one study found surface water concentrations to range from 0.004-0.19 microplastics /m^3, varying depending on location and season [153].

8 | Ecotoxicity & ecosystem effects of plastics in the ocean

Numerous studies have shown the interactions of organisms with plastics, from charismatic higher trophic organisms such as whales, seals and turtles ingesting or becoming entangled in macroplastics 154,155, or ingesting microplastics 156, all the way down to microplastic ingestion by lower trophic zooplankton and fish larvae 157,158. There is also evidence to suggest that microplastics can be transferred up the food chain via trophic transfer 159,160, leading to biomagnification (an increased internal burden in higher trophic organisms, as a result of ingesting microplastics at a faster rate than they can be excreted). While the effects of entanglement can be clear to see (inhibited movement, restricted growth, suffocation), the effects of ingestion and accumulation tend to be more subtle, and can therefore be less obvious over short timescales.

> "different species are differently sensitive to stressors. Thus what might kill organisms of one species, might have little or no effect on another"

The difficulty in understanding the effects of plastics, and especially microplastics, is primarily due to the large diversity of the materials, comprised of many different polymer types, chemical additives, found in a range of shapes and sizes. All of these factors will influence the hazard posed by the plastic to organisms. Furthermore, different species are differently sensitive to stressors. Thus, what might kill organisms of one species, might have little or no effect on another 152. More commonly observed in experimental studies than outright mortality are sub-lethal effects, i.e. those which can alter an organism's life history, such as growth, health and reproduction 161. These effects might not be immediately obvious upon exposure to microplastics, but can especially occur given chronic exposure, and are important to consider in the context of persistent environmental contamination. Such effects may have knock-on impacts with the potential to alter the health, functioning or interactions within entire ecosystems 162,163. Some of the specific factors influencing acute and chronic toxicity are discussed in further detail in the following subsections.

Chemical toxicity

Plastics are a complex mixture of chemicals; one single plastic item has the potential to contain thousands of chemicals 164. However, the knowledge-base on the chemicals that are associated with plastic debris found in the environment, or so-called plastic co-contaminants is currently extremely limited 165. Plastic materials contain numerous additives, which are added to plastic formulations upon production to achieve or improve their properties (colour, flexibility, durability). Additives contained in plastic include inert or reinforcing fillers, plasticizers, antioxidants, UV stabilizers, lubricants, dyes, flame-retardants, adhesives, heavy metals, and more. In most cases, additives are not chemically bound to the polymer chain and hence can readily leach out when plastic particles enter the new surrounding (e.g. seawater or animal guts/tissues) 166. This is commonly observed in the form of embrittlement as plasticisers, which enable flexibility, are lost.

The combinations of additive chemicals in products are usually commercially confidential, i.e. are not declared or publicly available by the manufacturer. Research is ongoing to assess the different compositions of various consumer products, and the toxicity of these, with evidence to date suggesting that many plastic additives can be highly toxic, persistent and bioaccumulative. Some examples of these include Bisphenol A (BPA) and phthalates, which are used to make household products and food packaging, can disrupt the endocrine system when ingested or inhaled 167,168. Phthalates and BPA have both been found within the tissues of marine mammals 169,170. Additives have also been shown to lead to oxidative stress in the bacterium Aliivibrio fischeri 164, and reduced reproduction and survival in the crustacean Daphnia magna 171. Heavy metals (e.g. Pb, As, and Cd), which are used as colorants and stabilisers for plastics, in high enough doses can lead to cancer and hormonal disruption.

Size-dependent toxicity

Numerous studies report that the size of microplastic particles may influence the degree of their toxicity, although as with all microplastics research, this cannot be presented as a simple black and white statement. In general, smaller particles are more bioavailable to a wider range of organisms – at its most basic, an organism cannot eat a particle if the particle is larger than the organism's mouth 161,172. Thus, the smaller the particle, the greater the range of organisms that will be able to ingest the particle, whether intentionally or unintentionally. Smaller particles also have greater surface area to volume ratios, which increases their exposure to the surroundings and their ability to attract and absorb contaminants 96,173–177. Further, smaller particles, for example those < 10 μm, and down in the nanoplastics range (< 1 μm), have the potential to cross membranes, passing from the gut content into the tissues or circulatory system of the organism 178,179. This has been observed in a range of organisms from crustaceans (shore crabs, Carcinus maenus) 160 to various species of fish 180,181. It should be noted, however, that simply because small microplastics are ingested does not necessarily mean they will be translocated 181, and if they are, the occurrence can be very low. A study on European seabass (Dicentrarchus labrax) juveniles found that approximately 1 microplastic particle (1-5 μm) reached the muscle tissue for every 1.87×10^7 particles ingested 182. Nonetheless, reduced particle size has been shown significantly to increase toxicity in a number of cases 183,184, or at least to differently affect the toxic mechanism 185. Again, it should be noted that this is not a consistent trend, as some other studies show no effect of size, or may even find in some instances that larger particles are more acutely toxic 186.

Shape-dependent toxicity

The shape of microplastics has been shown to be significant in influencing their toxic effects. For example, polypropylene fibres were found to have significantly greater effects on growth, and reproduction than polyethylene fragments 187, although recognising that these are different polymer types. However, another study showed that even when the same polymer type was used (PP), fibres were significantly more toxic than fragments under identical controlled experiment conditions 186, highlighting that this difference was not a polymer-specific effect. This toxicity may be a result of increased retention time of fibres, which has been shown both for the freshwater amphipod, Hyalella Azteca 187, and for the earthworm Lumbricus terrestris 188, and entanglement, whereby even at this proportionally smaller scale, zooplankton can become entangled in microfibres in the same way that large fauna become entangled in fishing lines 189. This can lead to deformities and a knock-on effect on growth and reproduction.

9 | Solution & mitigation strategies

Public plastic risk perception – the power of the people

Public awareness and risk perception of marine plastics has greatly increased over the last decade, primarily as a result of an increase in scientific focus and resulting media attention. Risk perception is the subjective assessment of the likelihood and consequences of a negative event, and is driven by a number of factors 190. The increase in frequency of scientific reports from the 1970s onwards led to political discussions and initiatives around ocean plastics, but did not really capture public imagination until scientific studies (e.g. 191) discovered plastic accumulation in the centre of the North Pacific Gyre. Nicknamed 'The Great Pacific Garbage Patch' this discovery and its linguistic framing resonated with the public, resulting in an increase in awareness of plastic pollution in the ocean. However, the lack of an immediate and disastrous impact coupled with the remoteness of the problem resulted in relatively little long term media coverage and the public perceived risk remained fairly low 190. Through the next decades, however, it became increasingly apparent that marine plastic pollution was a global phenomenon and by the early 2000s it was beginning to become a focus of academic research. This was followed by increasing international media attention and political directives. Denmark placed a levy on plastic bags in the early 1990s, while Bangladesh was the first country to ban single use carrier bags in 2002 and they have been followed by other governments around the world, with 127 countries adopting some form of legislation to regulate plastic bags as of 2018 192.

Public perception of plastic risk also tends to be guided strongly by media coverage or public-facing policy or campaigns. For example, microbeads, typically used in cosmetics and personal care products as exfoliants, contribute a small percentage of overall plastic production and waste (it is estimated that only around 2% of microplastics entering the ocean are microbeads) 43, yet have become extremely exposed in the media. The resulting public outcry and numerous campaigns and petitions advocating for banning or restricting microbead usage has resulted in a ban on the sale of wash-off products containing microbeads in the UK since 2018 and similar bans or restrictions in many other countries. A subsequent public campaign to ban plastic drinking straws (which make up less than 0.03% of plastic waste) led to a ban on the sale of plastic drinking straws, in addition to cotton buds and drink stirrers in England from July 2021 (with caveats).

While bans on unnecessary single use plastics are steps in the right direction, these objects do not account for the largest sources of plastics entering the ocean. Therefore, the public lobby, while powerful, is often not focussed on, or even aware of the greatest marine plastic pollution sources. While microplastics are currently receiving a relatively high degree of media coverage, there is in general a poor public understanding of what microplastics are, how they reach the ocean, what the risk to the environment and humans might be. Perhaps most importantly there is very little recognition of how an individual's own behaviours might contribute to microplastic generation, with responsibility for plastic pollution and microplastics assigned to a wide range of stakeholders, including governments, industry and specific nations 193. Furthermore, the success of reactionary campaigns focussed on specific products has made many plastic product producers wary of engaging with scientific studies on marine plastic, not wanting either their company or their product to be singled out or become the focus of the next campaign. This is an unfortunate side effect of well-intentioned campaigns, because scientific and industry partnerships can often be the best way to quickly identify problematic plastic sources and develop workable solutions to remove or minimise their impact.

Looking up the chain – need for large-scale action

Without substantial changes in the amount of plastic waste society generates and how and where it is disposed of, the amount of plastic in the marine environment will continue to increase, while existing debris will continue to degrade and fragment into microplastics. While clean-up operations are a good way of raising public awareness and grassroots action, in reality these will not make any significant dent in the amount of plastic present within the global environment, regardless of the scale of the operation. Even well-funded, high-profile marine clean up initiatives have found it challenging both to operate in the open ocean and to collect enough plastic to have a significantly beneficial impact on plastic contamination when compared to the plastic influx from land and rivers. This is especially the case for microplastics, which will be impossible to remove from the environment.

Instead, actions at the top of the chain will be required to prevent further loss of plastic to the environment. Linked to this, understanding and predicting the current and future abundances of microplastics from different sources in the environment is essential to prevent these losses, and predict possible ecological effects when losses do occur.

Life Cycle Assessments (LCAs)

One way to make the plastic production and waste management cycle more sustainable, and to prevent unnecessary losses, is using Life Cycle Assessments (LCAs), based on the life cycle model presented earlier. These can be used to quantify and compare the impacts of different processes to enable more informed decision making. For plastics, LCAs would typically involve compiling an inventory of energy/material inputs and environmental outputs, assessing the environmental impacts associated with these inputs and outputs, and calculating performance indicators, which can be used to objectively inform decisions. However, the effectiveness of LCAs depends heavily on how it is being used and the questions it is required to answer, for example, if it is only asked a limited or ill-informed question, the answers it produces will also be limited and therefore LCAs must be set up carefully and interpreted accordingly.

A number of recommendations for plastics have been made based on LCAs. In order for these LCAs to be accurate and useful they tend to focus on one or a subset of plastic products and make specific recommendations, however across all products they conclude that multiple actions across the life cycle of plastic products are needed and a range of policy interventions should be employed to reduce environmental impacts. The UN reports all discourage the idea of replacing a single use item with another single use item, instead advocating for a different way of using materials within an economy. Circular economy approaches are based on the principle of keeping products and materials in use for longer, in order to reduce their overall consumption. Typically, this will mean reusing a product multiple times, but it also includes recycling or repurposing objects in order to keep them in the economy. Thus, in order to reduce plastic loses to the environment, it is necessary to quantify the production of different plastic polymers and their uses (Table 2) and plastic losses to the environment from the different stages in value chains and locations.

European and UK policy

Globally there are an array of national and international policies that aim to target prevention of ocean plastics and in many places we are beginning to see policy moving away from banning specific products towards looking at the full plastic value chain, with increasing importance given to developing a circular economy framework, in which resources are used more efficiently and retained in use for as long as possible [190]. Up until recently, plastic waste was primarily managed under general waste regulations, like the EU waste framework directive. The first packaging waste directive (Directive 85/339/EEC) was adopted in the mid-1980's and has been amended multiple times since: in 1994, 2003, 2004, 2013 and 2015, with the most recent revision including Directive (EU) 2015/720, on reducing the consumption of lightweight plastic carrier bags [194]. The Waste Framework Directive brought together more specific directives related to specific waste streams. These include sewage, construction and demolition and a number of others, many of which contain plastics. The December 2019 European Commission Green Deal and Circular Economy Action plan include further policies and directives aimed at reducing plastic waste addressing how products are designed and promoting sustainable usage and circular economy processed to minimise waste and keep resources within the economy for as long as possible [195].

The UK has set specific targets to reduce the generation of plastic waste and, by proxy, the UK's contribution to marine plastics. The 2018 Resources and Waste strategy led to consultations on packaging producer responsibility, plastic packaging taxes, deposit return schemes and recycling, several of which are now included in the Environment Bill 2021-2022. Additionally, the UK Plastics Pact [196] is a voluntary pledge that sets out several key targets to achieve by 2025:

1. To eliminate problematic or unnecessary single-use plastic packaging through redesign, innovation, or alternative delivery models (such as reuse),
2. All plastic packaging should be reusable, recyclable, and compostable,
3. 70% of plastic packaging should be recycled, reused, or composted
4. 30% recycled content across all plastic packaging.

The UK government has also recently published a target that avoidable plastic waste should be eliminated by 2042, while Scotland has committed to introducing a deposit return scheme by July 2022.

European and UK policy is less clear on microplastics, to date typically including them in general plastic policy documents than as a separate entity. In December 2017 the UK, along with a further 192 UN member states, signed resolution UNEP/EA.3/Res.7 on Marine Litter and Microplastics. This agreement, which recognises other resolutions such as the Marine Plastics Debris and Microplastics technical report [197] reaffirms a commitment to reduce marine debris, lays out a number of commitments to reduce waste and improve waste management and commits to continue to work in the area through the formation of an ad-hoc working group of experts [198].

On a broader European scale, the European Chemicals Agency (ECHA) have proposed a radical ban on all intentionally-added microplastics, extended from wash-off cosmetics to include medical devices and products, agricultural applications, cleaning products, coatings and paints, among other uses. This would be the world's most comprehensive ban on microplastics to date, preventing the loss of tens of thousands of tonnes of plastics to the environment annually [199]. However, it is worth noting that this is still only a small proportion of the microplastics released, the majority of which are lost to the environment more widely through shedding and degradation of larger items. The decision on the restriction and its scope will be made by the European Commission with the EU Member States, but the result has yet to be announced.

10 | Data gaps & challenges

It is known that plastics have been entering the environment for decades, with annual inputs steadily increasing in line with plastic production (Figure 1). Despite this, it is difficult to measure the exact amounts (i.e. by mass or number of items) of plastics released, due to the complex interacting factors that influence the release of plastics to the environment. For this reason, models are widely used to produce estimates based on available data, including plastic production, national/regional use, population density, waste mismanagement etc. Different models use different calculations, and all must make some assumptions, therefore different models will produce different results for the same queries (Table 4). Furthermore, the data that is input to models significantly influences the output. This is important to consider when interpreting model outputs (and demonstrated by the variability of outputs covered in this report) and using such figures to support further research, given how significantly the underlying data used can influence the output. This uncertainty means that models cannot be used to accurately predict exact environmental scenarios but can be useful tools for predicting and interpreting current and future trends alongside measured data. Overall, the greater the amount of reliable data available as a result of field and experimental studies, the better the predictions will be.

One parameter that is commonly included in models to predict losses of plastics to the environment is that of waste mismanagement. Waste mismanagement may be one of the most difficult parameters to measure accurately, as mismanagement by its nature is usually not planned or intended, and can thus be difficult to predict or monitor. This is especially the case in developing countries, where waste management systems are often not well-developed or in some places may be non-existent, and thus large volumes of waste will be released directly to the environment without any capacity to measure it. Understanding waste mismanagement is not only key to parameterising models, but also to prevent these losses, as losses cannot be targeted without knowing the extent and scale of the problem.

A key challenge currently, is that the rapid influx of new data is continually changing our understanding of the plastic waste issue. This is enormously beneficial but it does mean that information becomes outdated quickly. For example, a commonly stated statistic is that of the 'missing plastic' from a study in 2015, based on how we could account for only 1% of the predicted ocean plastics, as a result of existing measurements at that time [79]. Since that study, a publication in 2020 has highlighted that the missing plastics were in fact likely not missing at all, but had simply been omitted in measurements. This includes particles below the ocean surface (i.e. within the water column down to the ocean floor) and also very small microplastics i.e. > 25 μm [22], as opposed to the commonly reported sizes of > 150 or > 330 μm, as are commonly measured from the surface using manta net trawls [79]. It is known that smaller particles exponentially outnumber larger particles within the environment [202], and thus, any measurements omitting these smallest particles (> 10 μm) will be missing a large proportion of what is present. This example highlights the crucial importance of ongoing research in this field and the importance of keeping stated 'facts' up to date as new evidence becomes available.

"A key challenge currently, is that the rapid influx of new data is continually changing our understanding of this issue"

One of the primary factors affecting the recent proliferation of data in this field is related to the development of novel techniques for sampling and analysis,

and the increased availability of reliable analytical methods and equipment. This is improving the ability of many laboratories to carry out plastics and microplastics research. However, the techniques are also becoming more varied, meaning that methods may analyse different particle sizes, may measure by count (microscopic and spectroscopic techniques) or by mass (chemical analysis). This makes comparability between different datasets, and comparison with historical studies, more difficult [203–205]. For example, an apparent increase in concentration in a certain location may be a result of a real environmental increase, or an improvement in analytical sensitivity. Such factors must be carefully considered when interpreting data.

While the challenges in this field are many, the final one to note here is that of trying to unravel the long-term ecological implications of marine ecosystem exposure to plastics. As highlighted above, the term 'plastics' comprises a huge diversity of different material types, characteristics and additives, all of which will impact on organisms and ecosystems differently. Furthermore, different species will be differently sensitive to environmental perturbation as a result of contaminants, including plastics [162]. Despite this variation, plastics are rarely shown to provide benefits for local ecosystems, instead often modifying individual or community health, structure, function or diversity to produce a non-natural effect [206,207]. If directly negative effects are not seen, plastics tend to produce no overall impact rather than providing benefits [208]. Even where plastics may be perceived to be beneficial, for example providing a substrate for organisms to colonise, it is often non-native or harmful species which colonise plastics, and can subsequently be transported [209–211]. Given that plastics continue to increase in abundance and tend to have subtle sub-lethal effects associated with chronic exposure rather than causing outright mortality, it could be that long-term effects on ecosystems will not be evident until harm is already irreversible.

Study	Comments	Annual plastic emission
Council, N.R., 1975. Assessing Potential Ocean Pollutants: A Report of the Study Panel on Assessing Potential Ocean Pollutants to the Ocean Affairs Board, Commission on Natural Resources, National Research Council. National Academies.	-	45 Kt
Jambeck, J. R., Andrady, A., Geyer, R., Narayan, R., Perryman, M., Siegler, T., et al. (2015). Plastic waste inputs from land into the ocean. Science 347, 768–771.	Modelled from usage	4.8-12.7 million Mt
Sherrington, C., Darrah, C., Hann, S., Cole, G., Corbin, M., 2016. Study to support the development of measures to combat a range of marine litter sources. Rep. Eur. Comm. DG Environ. 410.	-	6.5-22.6 Mt
Lebreton, L.C., Van Der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A. and Reisser, J., 2017. River plastic emissions to the world's oceans. Nature communications, 8(1), pp.1-10.	Modelled river emissions	1.15-2.41 Mt
Schmidt, C., Krauth, T., & Wagner, S. (2017). Export of plastic debris by rivers into the sea. Environmental science & technology, 51(21), 12246-12253.	Compilation of measured global plastic data.	0.41-4 Mt
Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. 7, eaaz5803.	River emissions	0.8-2.7 million Mt
Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A. and Eriksen, M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science, 369(6510), 1515-1518.	-	19-23 Mt
W. W. Y. Lau, Y. Shiran, R. M. Bailey, E. Cook, M. R. Stuchtey, J. Koskella, C. A. Velis, L. Godfrey, J. Boucher, M. B. Murphy, R. C. Thompson, E. Jankowska, A. Castillo Castillo, T. D. Pilditch, B. Dixon, L. Koerselman, E. Kosior, E. Favoino, J. Gutberlet, S. Baulch, M. E. Atreya, D. Fischer, K. K. He, M. M. Petit, U. R. Sumaila, E. Neil, M. V. Bernhofen, K. Lawrence, J. E. Palardy, Evaluating scenarios toward zero plastic pollution. Science 369, 1455–1461 (2020).	Microplastic river emissions	1.2 Mt
Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.-F., Estournel, C., Constant, M., Kerhervé, P., 2021. The missing ocean plastic sink: Gone with the rivers. Science (80-.). 373, 107–111.	Microplastic river emissions	6.2 Kt

Table 4: Estimates of annual plastic (blue) and annual microplastic (green) inputs to the ocean 2,15,23,41,72–74,189,190.

11 | Conclusions

Plastic pollution is a relatively new field of research, meaning that despite the recent rush of attention and publications, there are many research questions remaining. Uncertainties are a common feature of any new scientific field, and plastics are no exception, however our knowledge of this issue continues to develop rapidly, and we have a far better understanding than we did even five years ago.

The sources of plastics are diverse and so are their routes to, and transport pathways within, the environment. While the knowledge and understanding of some of these sources and pathways are improving, many of them are yet to be quantified. The capacity for industrial production and waste management may drive the regional differences in plastic emissions to the environment. The highest regional contributions correlate with large-scale plastic manufacture and use, and/or inadequate waste management, with the extent of these influences varying depending on the region. This highlights that the regional strategies for tackling plastic loss to the environment will necessarily be different depending on industrial, economic and social factors.

While local sources may influence local contamination, plastic debris is also spread far away from its source by ocean currents and air masses. This makes it difficult to trace the origins of plastics found within the environment, especially once they have started to degrade such that the original item becomes unrecognisable. Numerical models can help to identify processes that influence the inputs and transport of plastics and point to the potential sources of their origin. The chemical and morphological characteristics of plastic debris influence their behaviour, fate and toxicity, highlighting the importance of understanding not just 'plastics' as a whole, but different types, shapes, sizes and uses of synthetic polymer materials.

Based on the diversity of plastic waste, it will not be possible to manage or mitigate plastic pollution with one strategy alone. Understanding the key sectors, sources and pathways into the environment will be crucial to stopping the problem at source, rather than the much greater and more futile challenge of trying to mitigate the impacts of existing debris. It will not be possible to tackle them all simultaneously so the biggest culprits should be targeted, with a focus on industry action and policy enforcement.

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