FIRST DRAFT OF 2020 ASSESSMENT ON SOURCES, PATHWAYS AND HAZARDS OF LITTER INCLUDING PLASTIC LITTER AND MICROPLASTIC POLLUTION

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PREFACE

The growing problem of marine litter and microplastics is being addressed by the United Nations Environment Assembly through key resolutions adopted at its four meetings. These include: UNEP/EA.1/Res.6: Marine plastic debris and microplastics (2014); UNEP/EA.2/Res.11: Marine plastic litter and microplastics (2016); UNEP/EA.3/Res.7: Marine litter and microplastics (2017); and UNEP/EA.4/Res.6: Marine plastic litter and microplastics (2019).

In 2016, UNEP prepared a report *"Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change* (UNEP 2016) in response to UNEP/EA.1/Res1.6.
The report focussed on:

- identification of the key sources of marine plastic debris and microplastics;
- possible measures and best available techniques and environmental practices to prevent the accumulation and minimize the level of microplastics in the marine environment;
- recommendations for the most urgent actions;

areas especially in need of more research, and other relevant priority areas

The United Nations Environment Assembly, at its fourth session in March 2019, requested the Executive Director of the United Nations Environment Programme (UNEP), in resolution UNEP/EA.4/Res. 6 paragraph 2, to:

"…immediately strengthen scientific and technological knowledge with regard to marine litter including marine plastic litter and microplastics, through the following activities:

> *(b) Compiling available scientific and other relevant data and information to prepare an assessment on sources, pathways and hazards of litter, including plastic litter and microplastics pollution, and its presence in rivers and oceans; scientific knowledge about adverse effects on ecosystems and potential adverse effects on human health; and environmentally sound technological innovations;*

This shall hereinafter be referred to as the "Assessment".

In response to this request, the Executive Director of UNEP has begun preparations for this Assessment, and has convened a Scientific Advisory Committee to guide and inform the implementation of paragraph 2, and in particular guide the development of the Assessment requested in subparagraph 2(b).

Executive Summary

Key Messages

SECTION 1: SOURCES AND DRIVERS OF MARINE LITTER AND MICROPLASTICS

1.1 PLASTIC IN THE MARINE ENVIRONMENT

Plastic have substantially outpaced any other manufactured material in terms of production, because of their low cost, durability, versatility and resistance to degradation. Demand for plastic is increasing worldwide, especially in emerging economies, where a threefold increase is expected by the middle of the century (Lebreton and Andrady 2019; Geyer 2020).

Today, plastic represent roughly 80% of all marine litter (Carney et al. 2019). They potentially pose a significant threat to the environment, because the properties that make them so successful also make them difficult or impossible to be assimilated by nature. They are also pervasive. Floating plastic can be observed in all oceans and a wide variety of aquatic organisms, from small zooplankton, molluscs and fishes, are becoming entangled or ingesting them. The levels of plastic ingestion can be very high; for example, in highly mobile oceanic species such as turtles, plastic was found in 80-85% of the marine litter ingested by count and 45 and 95% of total mass (Pham et al. 2017). Birds are also affected. In the North Sea 95% of fulmars were found to have ingested plastic, a pattern repeated around the globe (Provencher 2019).

Plastic can not only influence the oceans today but also for many decades to come due to their durability and potential cascading effects on ecosystems (Bergman et al. 2015). In a recent academic editorial (Borja and Elliott 2019) thus caution against treating marine litter and microplastics in isolation and as a short-term issue, and recommend that more holistic approaches be adopted to find solutions which take into account climate change, habitats and biodiversity loss, overfishing, interactions of different pollutants, and cumulative impacts of different human pressures.

In studies of marine beach litter, the non-plastic components (comprising 15-20%) are often inert (e.g. construction material) or biodegradable (e.g. paper, wood) and therefore have a lower environmental impact. But about half of identifiable plastic pieces in marine litter are ‘single use plastic’ (e.g. crisps packets, cotton bud sticks etc.) and abandoned fishing gear. Together these two categories constitute nearly 84% of marine litter (European Commission 2018).

There are ten commonly found single use plastic items that account for 86% of the categories found in beach litter around the world. The list includes drink bottles, caps and lids; cigarette butts; cotton bud sticks; crisp packets / sweet wrappers; sanitary applications; plastic bags; cutlery, straws and stirrers; drinks cups and cup lids; balloons and balloon sticks; and food containers including fast food packaging. The major items of fishing gear include nets, ropes, buoys, static pots and aquaculture platforms.

Without effective management strategies for end-of-life plastic, billions of metric tons of plastic waste materials will continue to accumulate across all the Earth’s major terrestrial and aquatic ecosystems.

There are essentially three different fate pathways for plastic waste. First, it can be recycled, using mechanical and chemcial processes. or reprocessed into a secondary material; to date recycling has primarily been for non-fibre plastic. This can help to avoid future plastic waste generation when it displaces primary plastic production, but the counterfactual nature of this process means that the volumes are extremely difficult to determine. Contamination and the mixing of polymer types generate secondary plastic of limited or low technical and economic value. Second, plastic can be destroyed thermally by incineration with or without energy recovery. There are also emerging technologies, such as pyrolysis, which extract fuel from plastic waste, but these are still limited. The environmental and health impacts of waste incinerators strongly depend on the design, management and use of Best Available Technologies and Best Environmental Practices. Finally, plastic can be discarded and either contained in a managed system, such as sanitary landfills, or left as mismanaged solid waste in open dumps or as litter in the natural environment.

Microplastics in the marine environment come from multiple sources. Primary microplastics, nurdles or pre-production pellets and resin beads, enter the environment as particles that are already 0.05-5mm in size. They are manufactured for a variety of industrial uses such as film formation, viscosity regulation, skin conditioning, emulsion stabilizing, industrial scrubbers for air-blasting technologies and in personal care and cosmetic products such as soap, shampoo, deodorant, toothpaste, creams, exfoliators, sunscreen lotion, facial masks, lipstick and eye shadow. Secondary microplastics are the result of larger pieces of plastic breaking down or fragmenting into smaller pieces due to exposure to sunlight or normal wear and tear e.g. tyres, road surfaces, clothing. Earlier studies by Eriksen et al. (2014) and van Sebille et al. (2015) estimated that 93 to 268 ktons of microplastics are currently floating in the oceans. Other microplastics such as acrylic and fibres are denser than seawater and likely to accumulate on the ocean floor where they are ingested by deep sea organisms (Taylor et al. 2016).

Nanoplastics (< 1 μm) arise as a byproduct of fragmentation of microplastics and have recently been confirmed to be present in the North Atlantic Subtropical Gyre (Ter Halle et al. 2017). Little is known about the adverse health effects of nanoplastics in organisms including humans, but due to their small size, nanoplastics can cross cellular membranes and affect the functioning of cells.

1.2 UNDERLYING DRIVERS OF PLASTIC IN THE MARINE ENVIRONMENT

The underlying drivers leading to plastic accumulating in the oceans are complex, with several factors at work to constitute to the current situation. The major driver is the demand for plastic across all economic sectors and the link to -attitudes amongst the general consumer, where the lack of awareness of the impacts of marine litter and microplastic, means that choices are made that lead to increased volumes of plastic litter in the environment. Others relate specifically to maritime operators including shipping and fisheries and aquaculture.

In a recent study of attitudes to marine litter by Hartley et al. (2018), members of the public were found to be more likely to blame the global marine litter crisis on retailers, industry and government. However, they have less faith in those agencies' motivation and competence to address the problem, placing greater trust in scientists and environmental groups to develop effective and lasting solutions. It also showed more than 95 per cent of people reported having seen litter when they visited the coast, and such experiences were associated with higher concern and a willingness to adapt personal behaviour to address the problem. There was - growing appreciation and concern about the threat litter poses to wildlife within the marine environment, vastly outweighing other fears such as the impact on tourism and the fishing and shipping industries.

Below are examples of the drivers of the top ten single use plastic that the EU identified when determining solutions for their disposal pathways (European Commission 2018).

i) Wide availability of plastic as a cheap and convenient option. The purchase of plastic is easy and convenient, and often there are only a few or less convenient alternative options available. In the case of fishing and aquaculture, plastic materials have been essential in reducing production costs, improving product quality and hygiene as well as producers' health and security.

ii) Consumer convenience. We live in a throwaway society, where convenience is valued highly and an on-the-go trend favours convenient single use plastic. The result is increased consumption of short-lived or disposable items rather than reusable alternatives, even where they exist and are environmentally preferable.

iii) Market fragmentation. Countries are adopting different approaches and establishing separate initiatives, which make it harder to operate effectively in the plastic waste arena.

iv) Market failure. The externalities of litter in the environment are not internalised into the costs of items, especially single use plastic and fishing gear. As a result, there is limited economic incentive to develop or choose items with a better environmental footprint. For example, the cost of collection and transport of end-of-life fishing nets could be reduced or spread out more evenly if organised with the involvement of materials producers, as well as on a regional or national basis. At present that cost is mostly left to the ports, which are often small-scale, and often overly dependent on or even exclusively limited to fishing.

v) Lack of market incentives for the effective participation in separate collection (such as ‘pay as you throw’ schemes) or for the return of (beverage) containers in the form of deposit return schemes. These schemes can encourage better waste management, especially for complex products or packaging formats not designed for recyclability.

vi) Poor waste management infrastructure. For example, there may be insufficient number of bins, or infrequent emptying (especially in tourism hotspots during high season), or, improper treatment of waste which then ends up as marine litter (for example, plastic released through storm overflow basins). Despite the potential value of some of the fishing gear, recycling is very limited and left to a few innovative operators.

vii) Consumer behaviour. This contributes to marine litter through the purchase of plastic (especially single use plastic), and the act of littering. For some plastic products, citizens have little knowledge whether they will end up as marine litter or whether they are made of plastic that will not bio-degrade in the environment. For example, most people who throw away a cigarette stub do not know that the filter is made of plastic (rather than paper), and people flushing a cotton bud down a toilet probably assume it will either degrade or be captured in the wastewater treatment. Fishers may be not fully aware of the long lifetime and lasting impact of gear lost at sea.

viii) Potential harm as marine litter and its associated slow disintegration. Biodegradation in the marine environment is particularly challenging. For the time being, there is no recognised method to test biodegradation of plastic in the extremely varied conditions of the coastal and marine environment.

ix) Abandoned or discarded fishing gear. Even though full implementation of existing rules such as MARPOL or the EU Control Regulation would imply that fishing gear should not be abandoned or discarded intentionally, there is evidence that this is happening at a significant scale, including because of lack of incentives to handle gear waste differently. This is mostly an issue of cost, of the burden of bringing broken gear back, and of retrieving lost gear. Given the near impossibility of controlling whether gear is discarded or abandoned, improvements through incentives and/or facilitation are likely to be needed.

x) Accidental loss of fishing gear. Gear conflict, adverse weather, vandalism and theft may result in loss of gear. Gear conflict is the contact of passing vessels with active or even passive gear. Re-locating gear at sea can be difficult because of damage by marine organisms, gear becoming snagged, removal of marker buoys and entanglement. Even though loss of fishing gear that is in good shape is a significant financial loss, which fishermen try to avoid, retrieving accidentally lost gear, may be perceived as too time and cost intensive.

xi) Lack of standardised monitoring, retrieval and locating systems for abandoned or lost fishing gear. Fishermen from different flag states fish in the same waters. Information exchange and cooperation of authorities to effectively target and retrieve their lost gear is lacking.

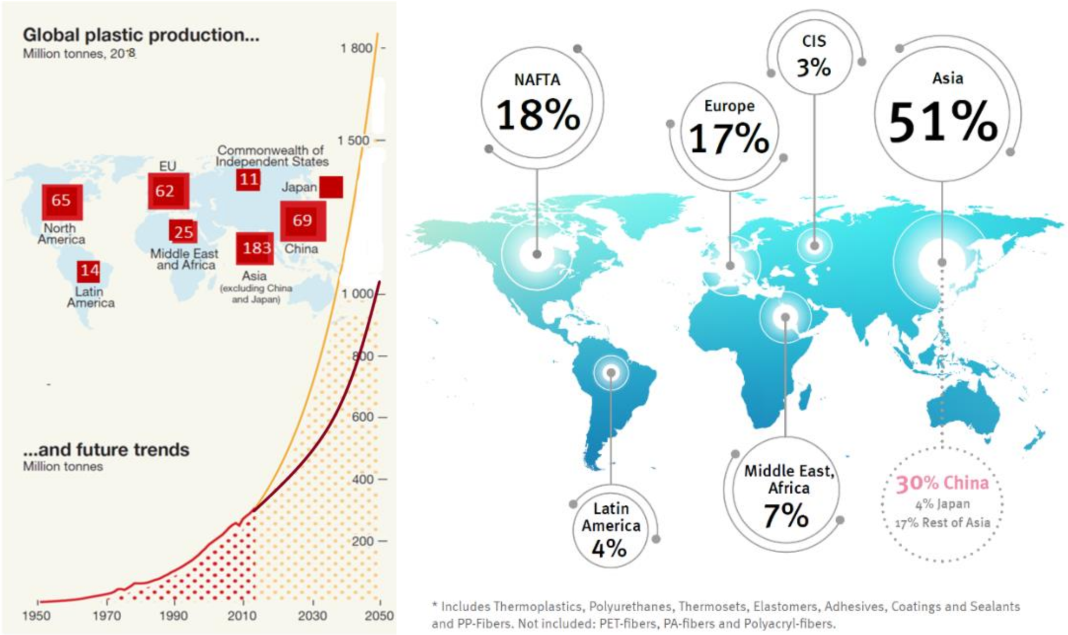
xii) Fishing gear is expensive to recycle. Fishing gear is often built-up material that needs to be dismantled before entering waste management or recycling. Resources are not made available for the dismantling, cleaning, and sorting needed before recycling.

1.3 GLOBAL PRODUCTION AND DEMAND FOR PRIMARY PLASTIC

Trends in global production

The increasing volumes of plastic litter and microplastics entering the oceans is a reflection of global trends in production and demand. The increase in the global cumulative production of primary plastic, from 1950 to 2017, is now estimated at 9.2 billion metric tonnes (Geyer 2020). Half of this has been generated in the last 13 years (Figure 1). From 2012 – 2019 global production increased by 38%, with packaging as the dominant market sector for plastic use (39.9%), followed by building and construction (19.7%) and automotive (10%) (PlasticsEurope, 2019). However, there are significant regional differences in production volumes. From 2012-2018, there were increases in Europe (13.6%), China (15%), North America (13%), Middle East and North Africa (19%) and Asia (37%), with declines in CIS (22%) and no change in Latin America (Table 1) (PlasticsEurope 2019). These differences reflect both user demand and the price of feedstocks. In Europe, single use plastic food packaging which is difficult to recycle because it is made of multiple materials, makes up a large part of the plastic used for packaging (Schweitzer et al 2018). The significant investment in the USA of over USD 200 billion since 2010 in new plastic and chemical plants, has been spurred by the low cost of raw materials from access to low-cost natural gas from shale formations (American Chemistry Council 2019).

The latest global production forecast is 1.1 billion metric tonnes in 2050 (Figure 1) compared to the earlier estimate (UNEP 2016) of 1.8 billion tonnes (Geyer 2020). This new estimate reflects a change in the calculation and the decline in growth in Europe, with a drop of 5% in 2019 on 2018. Nevertheless, this global figure represents a significant increase in the overall volume of plastic in the world.



* Includes Thermoplastics, Polyurethanes, Thermosets, Elastomers, Adhesives, Coatings and Sealants and PP-Fibers. Not included: PET-fibers, PA-fibers and Polyacryl-fibers.

Figure 1 Regional plastic production 2018 and global trends. Sources: PlasticsEurope (2019); Geyer (2020).

Year	Global	Europe	China	North America	Latin America	Asia	Middle East, Africa	CIS
2011	279	58	56					
2012	288	57	60	57.3	14.11	133.3	21.5	13.7
2013	299	58	62	57.1	14.4	136.3	21.8	8.6
2014	311	59	73	59.1	15.6	143.1	21.8	9.33
2015	322	58	75	59.6	14.2	157.1	23.5	8.4
2016	335	60	78	60.3	13.4	167.5	23.45	6.7
2017	348	64.4	81	61.6	13.9	174	24.7	9.05
2018	359	61.8	69	65	14	183	25	10.7
2019	≈ 400							

Table 1 Global and regional plastic production (million tonnes) 2011 – 2019. Source: PlasticsEurope (2019).

Today plastic materials are produced from a variety of sources, to meet a wide range of product requirements (Figure 2). They can have a fossil origin (crude oil, gas, etc.), a biomass base (sugar cane, starch, vegetable oil, etc.) or a mineral base (salt). Biosourced materials include agro-polymers such as polysaccharides (starches, ligno-cellulose, pectins, gums and chitosans) and animal and plant proteins and lipids (casein, whey, collagen, gelatin; spya, gluten); micro-organisms such as polyhydroxy-alkanoates (PHA); biotechnology synthesis of polyactides. Petrochemical sourced materials from synthetic monomers include (polycaprolactone, polyesteramides, aliphatic and aromatic co-polyesters). Eight polymer groups now make up 95% of global plastic production, with polyethylene (PE) as both high density (HDPE) and Low density (LDPE) and polypropylene (PP) resins alone making up 45% of total production.

Figure 2 Common uses of different plastic polymers.

Plastic can be biodegradable or non-degradable, regardless of the nature of their raw materials, which means that if properly collected and treated together with organic waste, they can even become compost (Table 2). However, the biodegradability of plastic in the marine environment is still not well understood. For example, recent studies on the breakdown of biodegradable plastic show that there are significant differences between different polymers, for example PHA and PLA and when exposed to different microbial communities (Dussud et al. 2018).

Origin/End of Life	Biosourced	Petrochemical sourced
Biodegradable (as a minimum under conditions of industrial composting)	starch or cellulose-based polymers PHA (polyhydroxy-alcanoates) PLA (polyactic acid) bio-PBS (polybutylene succinate)	PCL (polycaprolactone) PBAT (polybutylene adipate-co-terephthalate) PBS (polybutylene succinate) - copolymers
Non-biodegradable	bio-PE (bio-polyethylene) bio-PET (ethylene bioterephtalate) bio-PTT (trimethylene biopolyterephthalate) bio-sources polyamides (PA) and polyurethanes (PUR)	PE (polyethylene) PET (ethylene terephthalate) PS (polystyrene) PP (polypropylene) PVC (polyvinyl polychloride) PA (polyamides) PUR (polyurerthane)

Table 2 [Near here] Examples of different plastic types according to origin (biosourced or petrochemical based) and end-of-life (biodegradable or not).

In 2018, global production of biosourced and/or biodegradable polymers was estimated at 2.11 million tonnes, representing less than 1% of all plastic produced annually, and using an estimated 0.81 million hectares of land (Figure 3). Of these, 43 % were biodegradable, 30 % of which was both biosourced and biodegradable (European Bioplastics 2018). The bioplastics market is still driven by bio-based PET (non-biodegradable), (27%), and biodegradable starch-based blends (18%), followed by biosourced PA (non-biodegradable), PLA (biodegradable into industrial compost) and biosourced PE (non-biodegradable) (10%). Packaging alone accounts for 65% of the outlets for these materials, ahead of textiles, consumer goods, automobiles and transportation or construction. Global bioplastics production capacity is expected to increase by 24% by 2023 to 2.62 million tonnes (European Bioplastics 2018).

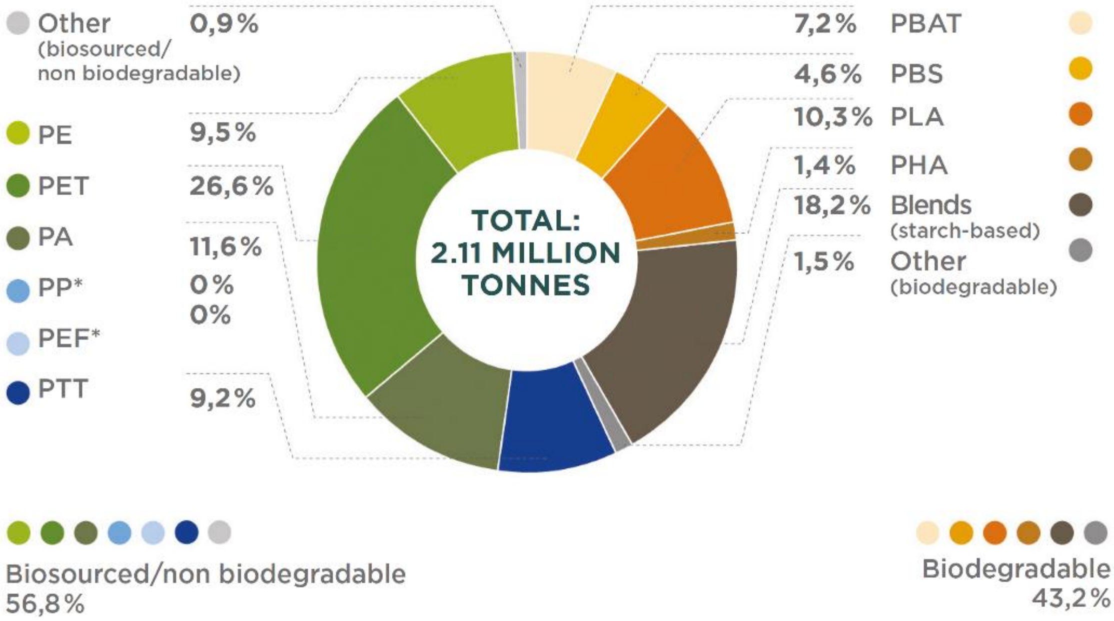


Figure 3 Global capacities for bioplastics production. *Biosourced PP and PEF are under development with marketing set for 2023. Source: European Bioplastics (2018).

In addition to the chemical composition of the hundreds of types of plastic, different shapes and sizes are also manufactured. Primary microplastics, nurdles or pre-production pellets and resin beads, particles of 0.05-5mm in size (Andrady 2011), are manufactured for a variety of industrial uses such as film formation, viscosity regulation, skin conditioning, emulsion stabilizing, and in personal care and cosmetic products such as soap, shampoo, deodorant, toothpaste, creams, exfoliators, sunscreen lotion, facial masks, lipstick, eye shadow, children's bubble bath, etc. and nanoplastics (Thompson and Napper 2019). Microplastics beads have been recognised as persistent, potentially harmful materials, and a number of countries have taken action to control or ban their use.

1.4 GLOBAL TRADE IN PLASTIC WASTE

Sources of primary and secondary plastic waste

The greatest volumes of primary waste are generated by the packaging, consumer and institutional products and textiles sectors (Figure 4). The building and construction sector which in 2017, took up 16% of all global plastic production (resin, fibres, and additives) while only generating 4% (14 Mt) of the global plastic waste. The packaging sector consumed 36% of global plastic production but produced 46% of total plastic waste generated (Geyer 2020).

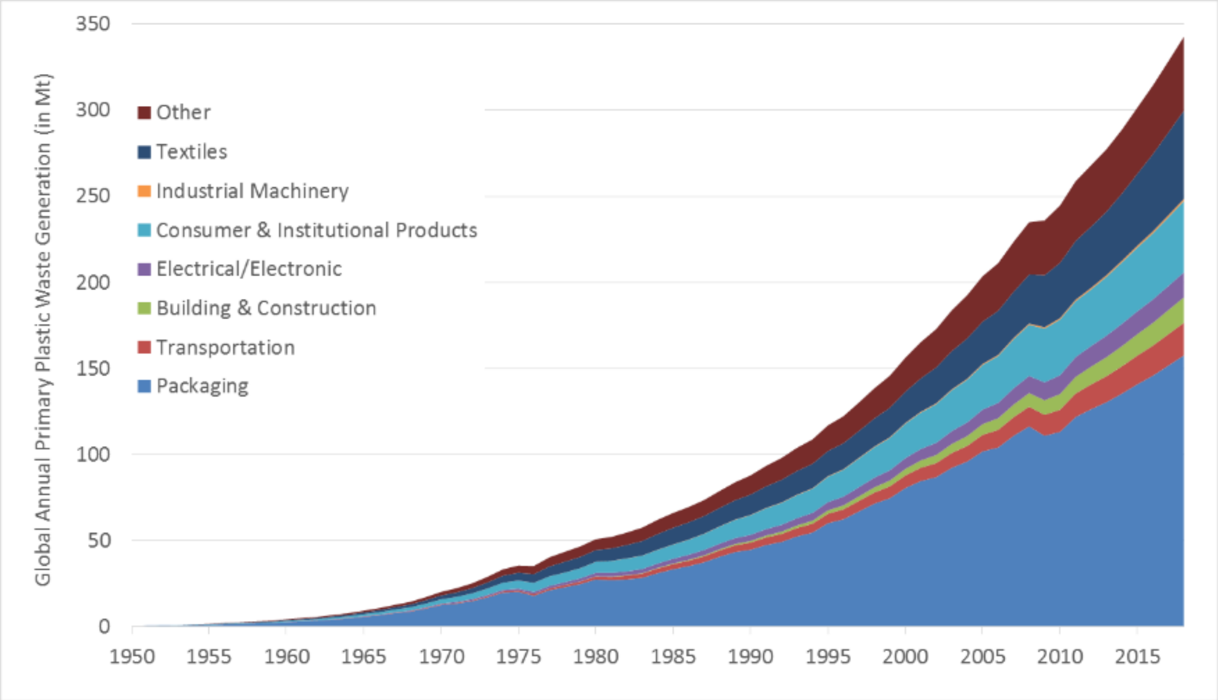


Figure 4 Global annual primary plastic waste generation (in Mt) by sector (1950 to 2018). Source: (Geyer 2020).

The current plastic economy is still widely based on a linear value chain, of "extract-manufacture-dump", making it difficult to determine the real impact of recycling on primary material production. Of the 6.9 billion tonnes of plastic waste generated up to the end of 2018, 10% was recycled, 14% was incinerated, 26% went to landfills and 50% ended up in the environment as a consequence of littering, illegal dumping and a lack of effective waste management (Geyer 2020) (Figure 5).

Worldwide, 14% of plastic packaging is collected for recycling. However, the majority of this is transformed into applications of lower value that are not recyclable after use. In 2017, status quo industry figures for packaging indicated that 93 % of global plastic used was virgin, 7 % was recycled, of which 98% was downgraded and only 2% ending up in a closed loop (IMPEL 2019). If the losses which occur during sorting and reprocessing are factored in, only 5% of the value of materials is retained for subsequent use (Ellen MacArthur Foundation 2016). These losses can be significant. For example, since 2006 in post-consumer packaging, after a short-term cycle of use, the loss of value of packaging waste each year has been 80 – 120 billion USD.

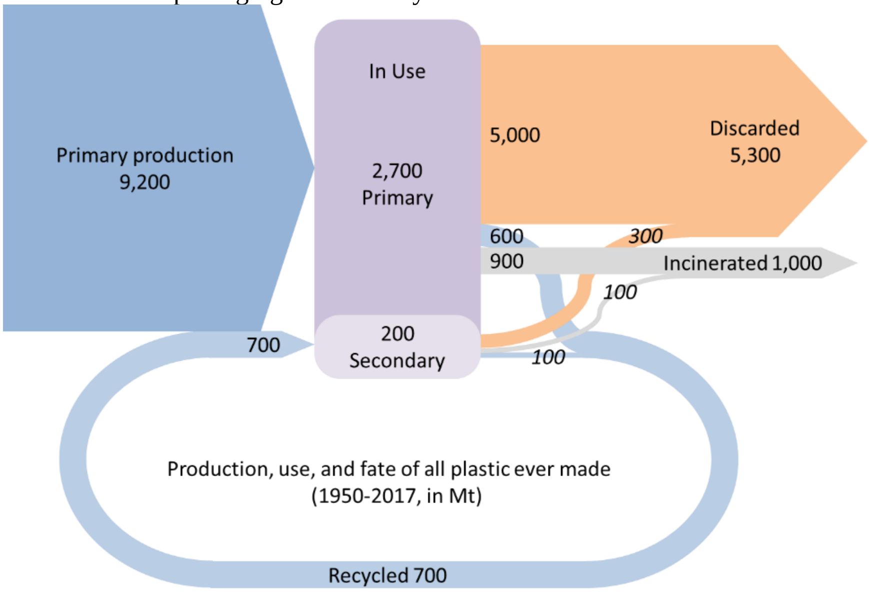


Figure 5 Production use and fate of all plastic made 1950 -2017, Mt. Source: (Geyer 2020).

The composition of plastic waste differs from that of plastic production in any one year because of the different mixes of polymers and lifetime distributions in different consuming sectors. This makes recycling of plastic difficult and leads to secondary materials of reduced technical and economic value due to contamination and the mixing of polymer types. Plastic recycling as a whole is less than plastic packaging and falls well below global recycling rates for paper (58%), iron (70%) or steel (98%) (Geyer 2020).

Different forms of plastic are found in plastic-related solid waste streams; in 2018 there were 5.6 billion tonnes of polymer resin, 0.9 billion tonnes of polymer fibres and 0.4 billion tonnes of additives (Figures 5 and 6). Using a top-down methodology for the estimation of waste that combines plastic production data with lifetime distributions of the plastic-containing products, Geyer (2020) has been able to show that the generation of primary plastic waste, i.e. primary not recycled material, is lagging behind primary plastic production (Zink et al 2018). In 2017, for example, 438 Mt was added to the in-use stock, while only 328 Mt left it as waste; in other words, 110 Mt of plastic was added to the stock in use.

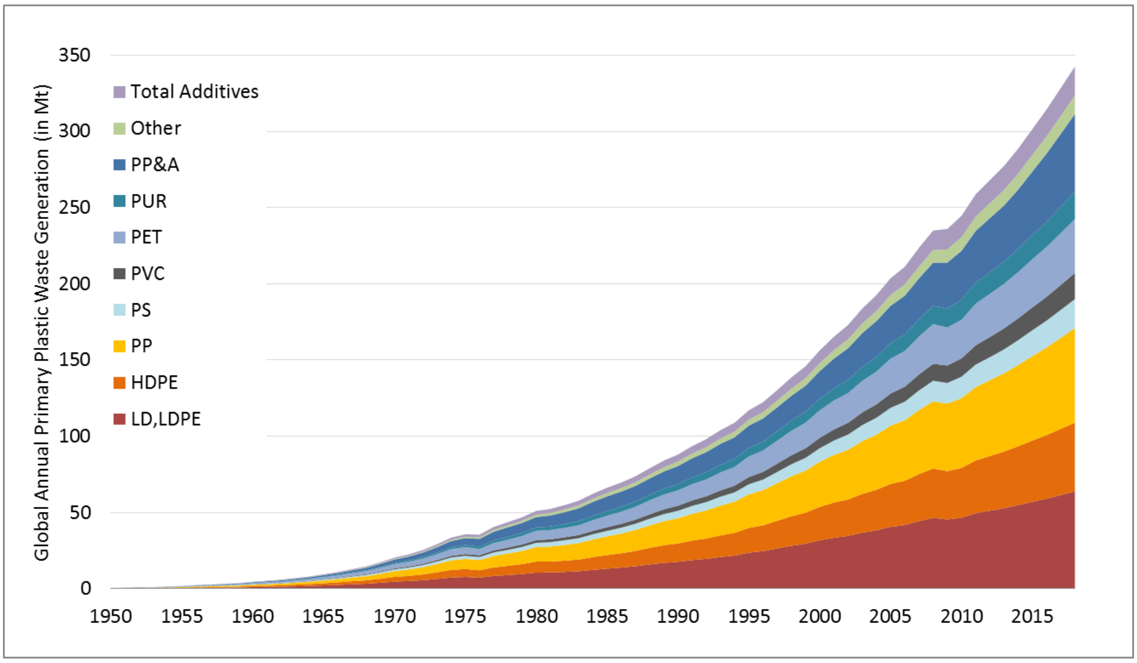


Figure 6 Global annual primary plastic waste generation (in Mt) by plastic type (1950 to 2018). Source: (Geyer 2020)

Global trade and the recycling of plastic waste

The cumulative global trade of plastic waste exports and imports from 1988-2016 is valued at 163 billion USD (Brooks et al. 2018). It is covered by the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, on the prevention of deposits of toxic wastes imported from abroad. For plastic waste, the Basel Convention applies when shipping materials considered hazardous across country borders, in which case shipments of waste may be subject to prior informed consent. There is an eased process for certain wastes (green-list waste), that do not pose any likely risk to the environment when shipped for recovery, and for which shipment can start without prior informed consent. Under certain circumstances, plastic waste can be shipped under the green list if considered sufficiently uncontaminated. Norway's amendments to the Basel Convention that require prior informed consent for shipment of plastic wastes, except for uncontaminated single-polymer plastic comes into forec in 2021. For secondary plastic raw materials that have ceased to be waste, waste shipment regulation does not apply. However, if the importing country disagrees on the end-of-waste status, the Basel Convention may still apply (EEA 2019).

The main problem in the global plastic trade is the loss in quality and cross-contamination of plastic waste streams; this is causing million of tonnes of plastic waste to be shipped thousands of kilometres only to be burned at the destination (UNEP 2019). Using commodity trade data for mass and value, by region and income level Brooks et al. (2018) showed that higher-income countries have been exporting plastic waste (70% in 2016) to lower income countries in East Asia and the Pacific for decades. However, this dynamic is now changing because of the recent banning of plastic waste imports by China and the Basel amendment. This has led to a shift towards imports by many smaller countries, making it much harder for large exporting regions such as Europe to establish sustainable export markets and ultimately mismanaged waste. The main difficulties include getting a clear picture of all the different local regulations and procedures, uncertainties as to how the plastic waste is being handled, especially in countries with less developed infrastructure and legislation; differences in enforcement for the same type of waste shipment; out-of-date information on policies in importing countries; lack of knowledge in the importing countries about exporter's procedures, including notifications; lack of clarity in the definition of clean waste leading to incorrect cargo codes being used to avoid problems with respect to the Basel Convention (EEA 2019). The ban by China will displace an estimated 111 million metric tonnes by 2030, which historically has consisted of 90% polymer groups used in single use plastic food packaging.

Globally, 168 million tonnes of recyclable plastic waste were produced from 1988-2016. Geyer et al. (2017) produced a forecast based on historical data and trends in disposal rates showing that if production was to continue on the same curve, by the end of 2050, 26,000 metric tonnes of resins, 6000 metric tonnes of polyphthalamide fibres, and 2000 metric tonnes of additives will have been produced. Assuming consistent use patterns and projecting current global waste management trends to 2050, 9000 metric tonnes of plastic waste will have been recycled, 12,000 metric tonnes incinerated, and 12,000 metric tonnes discarded into landfills or the natural environment compared to 5000 metric tonnes today (Figure 7).

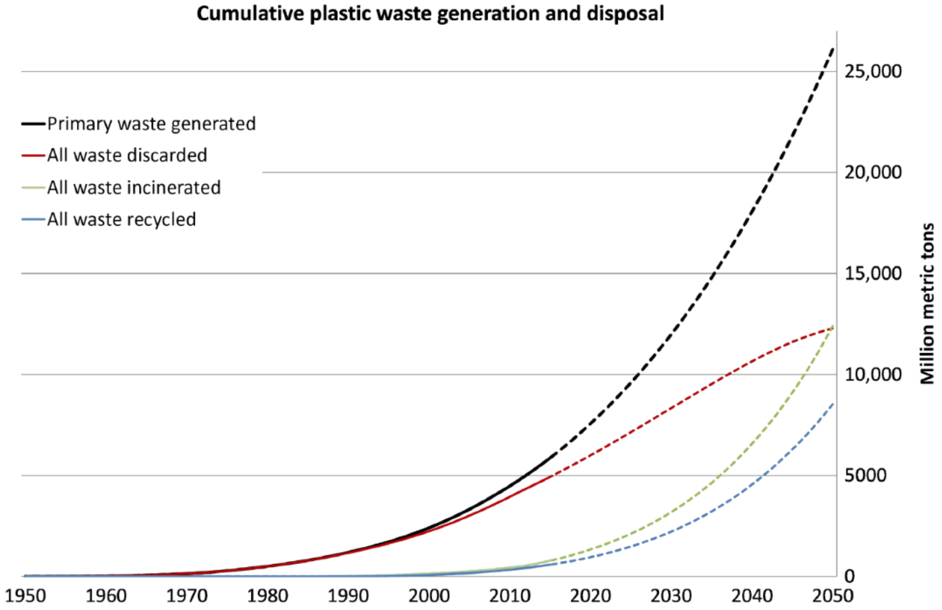


Figure 7 Cumulative plastic waste generation and disposal (in million metric tons). Solid lines show historical data from 1950 to 2015; dashed lines show projections of historical trends to 2050 Source Geyer et al (2017).

Recycling potential depends upon the chemical constituents of the plastic (Mutha et al. 2006; Geyer et al. 2016; Zink et al. 2018). Thermoplastics, such as polyethylene (PE) of different densities, polyethylene terephthalate (PET), polypropylene (PP), polyamide (PA), polyvinyly chloride (PVC), polystyrene (PS) and expanded polystyrene (EPS), can be melted when heated and hardened when cooled and reheated, reshaped and frozen repeatedly. Thermosets, such as polyurethane (PUR), vinyl ester and a range of resins, undergo a chemical change when heated, meaning that they cannot be re-melted and reformed. Additives, such as phthalates used as softening and anti-cracking agents (e.g. DBP, DEP, DEHP) or flame retardants (HBCD, PBDEs) can alter the recycling potential of plastic and as legacy substances may restrict recycling or reuse under the Stockholm Convention due to the likely release of hazardous chemicals into the environment (Hansen et al 2013; Stockholm Convention on Persistent Organic Pollutants 2017).

Within the life cycle of plastic, the largest amount of plastic recycling is done via mechanical recycling of thermoplastics (Figure 8). This involves re-granulation of sorted materials, but the potential of this high price segment is often limited by product quality requirements and high standards of feedstock quality. Energy recovery is a form of thermal recycling, using the low value segment and producing both high and low calorific substitute fuels. Chemical recycling, which depolymerizes the plastic waste back into its monomers, is currently still very limited and potentially uses a lot of energy in the process. Without landfill restrictions or energy conversion infrastructure, post-consumer plastic waste can go directly into the environment and becomes lost to the circular economy.

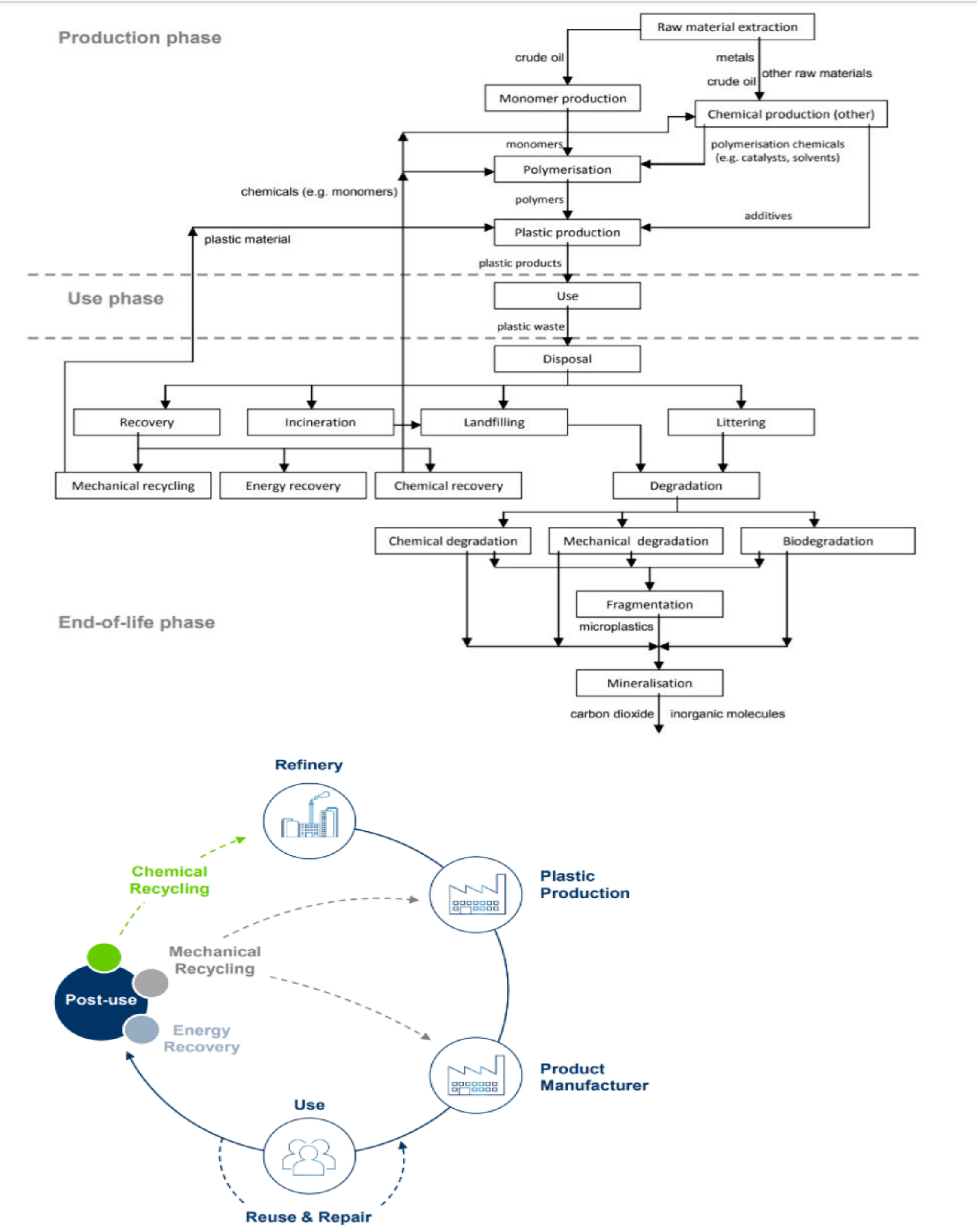


Figure 8 Life cycle of plastic and the recycling processes for post-use plastic

Polymers derived from chemical depolymerisation of plastic materials and articles as well as unused plastic production offcuts can be reused, even for food packaging. However, recycled plastic for food packaging is highly restricted; for example, under the EU regulation (EC No 282/2008) the recycling process must be authorised and managed by an appropriate quality assurance system guaranteeing the quality of the recycled materials. One concern in recycling plastic is that they contain a range of additives, widely used as plasticizers, flame retardant and fillers; many of these are listed under the Stockholm Convention as persistent organic pollutants. Production data for additives are sparse and typically omitted in plastic production statistics, but there is evidence to suggest that non-fiber plastic contain, on average, around 93% polymer resin and 7% additives by mass. This implies that a substantial fraction of finished plastic are additives rather than the actual polymer.

Although there are several hundred published standards relating to plastic within the International Organization for Standardization (ISO), only 13 of them deal with plastic recycling. Four in particular are of relevance for marine litter and microplastics (Figure 9). ISO 15270:2008 provides guidance covering plastic waste recovery, including recycling options for recovery of plastic waste arising from pre-consumer and post-consumer sources. A new working group for plastic recycling was established in late 2018 to review and develop new and existing standards. In the 2019 European Union work programme for European standardisation, the European Commission proposed the development of standards addressing the procedural and infrastructure issues for recycling.

Figure 9 ISO standards relating to plastic waste

1.5 SOURCES OF MARINE LITTER AND MICROPLASTICS

Land-based sources

The major land-based sectoral sources of marine litter and microplastics are retail (packaging, household and consumer goods), food and beverages (single use plastic products), households (packaging, household and consumer goods) tourism (packaging, household and consumer goods), plastic recyclers (packaging, household and consumer goods), construction (expanded polystyrene, packaging), agriculture (films/sheets, pots, pipes), and terrestrial transportation (tyres, end-of-life vehicles) (Figure 4).

Around 40% of all plastic production is used for packaging, including single use plastic used in the food and beverages sector. In agriculture, plastic is used in irrigation pipes, protective meshes and sheets, containers, fencing, in pellets for the delivery of chemicals and fertilizers and used in plastic mulching. The construction industry uses plastic in pipes, flooring and roofing and sealants, which can also be a diffuse source of hazardous chemicals.

Sectoral sources of primary microplastics include plastic producers (plastic pellets), households (personal care products and cosmetics), ship cleaning and buildings (abrasive powders) and manufacturing (powders for injection moulds and 3D printing). Sources of secondary microplastics include ratial (fragmented packaging, household goods, consumer goods), households (fragmented packaging, household goods, consumer goods), textiles and fashion (mechanical washing of fabrics), transportation (tyre, roads), plastic recyclers (fragmented packaging, household and consumer goods), construction (fragmented expanded polystyrene, packaging), and agriculture (fragmented films, sheets, containers, pipes). In addition to these, there are known to be microplastics in leachates from landfill sites, in bio-sludge from wastewater treatment plants and in agricultural run-off (He et al. 2019; Mahon et al. 2017; Li et al. 2018; Sun et al. 2019). Analysis of the presence of microplastics in soils provide new evidence of significant contamination of soils by sewage sludge application (Nizzetto et al. 2016). The authors estimate that microplastic loadings to agricultural soils in Europe and North America represent an environmental reservoir that is potentially larger than the marine environment.

Plastic from land-based sources are distributed across three fractions: plastic products in use, post-consumer managed plastic waste, and mismanaged plastic waste, which includes urban litter, and inadequately contained waste such as open dumps where waste can be transported via runoff and wind (Geyer et al. 2017). Some mismanaged waste may be collected by street sweepers and concerned citizen groups and re-introduced in one of the two first categories. Managed waste is accounted for and is typically disposed of by incineration or landfilling. Generally, per capita use of plastic and the population density at a given location can be used to determine the local plastic demand by consumers, reflected in the in-use fraction. The former generally scales with the local gross domestic product (Hoornweg et al. 2013; Lebreton and Andrady 2019) with more affluent countries using as much as over 100 kg/pp/ year (Waste Atlas 2016). But in populous countries such as India or China, a relatively low per capita use of plastic coupled with a high population density can still yield large tonnage of plastic waste.

The study by Jambeck et al. (2015 to be updated) based on a World Bank dataset (Hoornweg and Bhada-Tata 2012) on country specific waste generation and management, concluded that the fraction of this waste reaching the oceans was 4.8 to 12.7 million metric tonnes of plastic in 2010 from populations living within 50 km from the coastline. In a new study using self–reported levels of inadequate disposal, Lebreton and Andrady (2019) estimated that approximately 80 million metric tonnes of waste were inadequately disposed of, a figure representing 47% of the global annual municipal plastic waste generation. The proportion varied amongst regions; in Asia it was estimated that 52 metric tonnes were released through mismanaged waste, in Africa 17 metric tonnes, Latin America and Caribbean 11 metric tonnes, Europe 3 metric tonnes, North America 0.3 metric tonnes and Oceania 0.14 metric tonnes.

The practice of importing waste, especially e-waste, from developed nations, is to a large part responsible for the high levels of mismanaged waste in developing countries (Schmidt, 2006). When imports of plastic are combined with population growth and socio-economic development, the scenarios of Lebreton and Andrady (2019) suggest that mismanaged plastic waste at the level of watersheds in Africa and Asia will continue to be a significant driver of marine plastic into the latter half of the 21st century.

Sea-based sources

Marine litter from sea-based activities is significant as the major industries have become reliant on plastic materials to provide affordable, lightweight and durable equipment. Sectors that are sources of plastic and microplastics include fisheries (fishing gear, sealants, storage boxes, packaging), aquaculture (buoys, lines, nets, structures, sealants, storage boxes, packaging), shipping and offshore operations (shipping packaging, cargo) and ship-based tourism (packaging, personal goods). Primary microplastics can be introduced through loss of cargo and from personal care and cosmetic products in ship-based tourism. Secondary microplastics will arise in the marine environment from wear and tear of fishing gear such as polypropylene ropes and aquaculture operations.

The largest component of sea based marine litter comes from abandoned, lost and otherwise discarded fishing gear and some aquaculture installations. Whilst on average the overall amounts of plastic waste discharged at sea are small compared to mismanaged waste on land, plastic waste lost from marine transport, offshore platforms, recreation, fishing or aquaculture enters the marine environment directly. Examples of causes of discharging litter at sea include accidental and sometimes irretrievable loss of discarded fishing gear; limited life-span of some items used at sea; mismanagement of waste, e.g., dumping at sea due to the high cost of waste handling in ports, inadequate facilities for waste handling at sea; inadequate reception and storage facilities for waste and consignment; lack of operators to handle waste or gear; lack of incentives to recycle or reuse gear. In the revision of the EU Directive on Port Reception Facilities, it was noted that up to 30% of the waste from ships, including fishing vessels and recreational craft, that should be delivered to ports is not, potentially ending up being discharged at sea. There is no evidence that dumping of rubbish from ships at sea has decreased.

Coastal and sea-based tourism remains a significant source of plastic waste from intentional or accidental littering of shorelines (Arcadis 2014). There are few direct quantitative estimates of the overall volumes of plastic waste introduced by tourists, but Hartley et al. (2018) showed that members of the public perceived direct releases into the sea as the problem rather then plastic waste entering via overflows from water treatment or landfill sites. When asked about the key factors contributing to the problem, people attributed it predominantly to the use of plastic in products and packaging, human behaviour when disposing of litter, and the single use nature of plastic.

Fishing gear is the largest single category of beach litter. Surveys of beach litter suggest that netting from fisheries and aquaculture makes up 39% and 14% respectively (European Commission 2018); the rest being made up of buoys, pots, feed sacks, gloves, boxes etc. The proportion of items from sea-based activities on beaches increases with stronger tides, suggesting that the proportion of litter in the water may be even higher. At sea, 10% of all floating marine debris is lost or discarded fishing gear (Stelfox et al. 2016); in the great garbage patch 46% of the waste is fishing nets (Lebreton 2018). What has been brought up in fishing nets in western Atlantic and the Baltic indicates equal numbers of items coming from single used plastic as fishing gear, whereas the majority of plastic found in Arctic waters derives primarily from fishing (Vlachogianni et al. 2016).

Surveys in areas close to shore with high concentrations of aquaculture show significant concentrations of plastic in the form of cages, longlines, poles and other floating and fixed structures used for the culture of marine animals and plants. There are no reliable estimates of the contribution of aquaculture to marine litter and the types of material lost depends on the type of culture systems, construction quality, vulnerability to damage, and management practices and could be nets and cage structures (for marine fish cages), lines or floating raft structures (for seaweed systems) or poles, bags, lines, and plastic sheeting (for mollusc farming). Because many of these items are expensive, aquacultural operators are likely to take considerable care to avoid losses.

A Canadian study showed that greater concentrations of microplastics were measured in farmed mussels than in wild mussels, which may be a result of farming practices that use polypropylene lines to anchor the mussels, or it may be due to differences in microplastic concentrations in the different locations from which the farmed mussels and wild mussels originated (Mathalon and Hill 2014). On beaches located along the coastline of the Adriatic and Ionian Seas mussel nets were the seventh most frequent items found (Vlachogianni et al. 2016), while in the seafloor surveys litter from aquaculture accounted for 15% of total items recorder (Spedicato et al. 2019). Given that global aquaculture production accounts for more than 50% and marine aquaculture of fish and molluscs for nearly 15% of global seafood production, the contribution of the aquaculture sector to marine litter is likely to rise.

Using a complementary approach to beach counts and counts following retrieval actions from the sea floor, EU sectoral statistics from the PRODOM database[1] were used to calculate the fishing gear contribution to waste and to marine litter (European Commission 2018). The total loss of plastic waste (netting and non-netting) from fishing gear and aquaculture is estimated at 11,000 tonnes per year (Unger and Harrison 2016; European Commission 2018; Ingeborg and Gabrielson 2018). By comparison, the input from single use plastic were estimated at 15,604 tonnes per annum.

Other sea-based sources of marine litter include end-of-life recreational boats. A yachts' average lifespan has been estimated at 30 years, although in some instances this may stretch to 40-45 years. This lifespan has been increasing over time with the use of stronger materials, such as fibre reinforced polymer. It is thought that between 1% and 2% of the 6 million boats kept in Europe, in other words at least 80,000 boats, reach their end-of-life each year. However, only around 2,000 of those are dismantled (European Commission 2017). A significant number of the remaining boats are left abandoned, potentially ending up in the ocean and becoming marine litter.

1.6 SUMMARY

i) Plastic of all sizes make up at least 80% of all marine litter around the world. Evidence shows that plastic is being ingested by all forms of marine life, including birds. Single use plastic and fishing gear represent 84% of marine litter globally. There is no conclusive evidence on the concentration or extent of uptake of micro(nano)plastics in the marine environment.

ii) Due to its pervasive nature, tackling marine litter and micro(nano)plastics should not be undertaken in isolation but holistically across the drivers, pressure, state, and impacts including both based and sea-based sources.;

iii) Globally, production of plastic reached 9.2 billion tonnes (1950-2017), an increase of 38%; in a revised estimate this is projected to rise to 1.1 billion tonnes by 2050. Twelve major drivers of plastic production have been identified, ranging from its properties, price and convenience.

iv) Plastic are made from fossil and non-fossil-fuel based materials; 8 polymer groups make up 95%. Today, less than 1% of the total plastic produced are biomass based, using 0.8mllion hectares of land.

v) The three major fate pathways of plastic are recycling, pyrolysis and managed or mismanaged disposal. Up to the end of 2018, 6.9 billion tonnes of plastic waste were generated, 5.6 billion tonnes of plastic, 0.9 billion tonnes of polymer fibre and 0.4 billion tonnes of additives. Of the total, 10% was recycled, 14% was incinerated, 26% went to landfills and 50% ended end up in the environment as a consequence of littering, illegal dumping and a lack of effective waste management. The latest estimate of inadequately disposed waste is 80 million metric tonnes, representing, 47% of the global annual municipal plastic waste generation.

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[1] Eurostat PRODuction COMmunautaire provides statistics on the production, exports and imports of manufactured goods in the EU https://ec.europa.eu/eurostat/statistics-explained/index.php/Industrial_production_statistics_introduced_-_PRODCOM

vi) Demand for plastic mainly comes from packaging (37.9%) building and construction (19.7%) and the automotive industries (10%). In the packaging sectors 14% is recycled, with 93% of plastic used as virgin and 7% recycled plastic. These recycling rates are far less than for paper (58%), iron (70%) or steel (98%).

vii) The loss of value since 2006 in post-consumer packaging alone, after a short-term cycle of use, each year has been 80 – 120 billion USD

viii) From 1988-2016, 168 million metric tonnes of recyclable waste has been generated; the latest forecasts estimate that in 2050, 9000 metric tonnes of plastic waste will have been recycled, 12,000 metric tonnes incinerated, and 12,000 metric tonnes discarded into landfills or the natural environment compared to 5000 metric tonnes today.

ix) The cumulative global trade of plastic waste exports and imports from 1988-2016 is valued at 163 billion USD;

x) Amendments to the Basel Convention on shipping of waste and the banning of imported plastic waste by China will make it more difficult for exporters in the developed world to implement sustainable waste strategies based on waste being shipped to developing countries.

xi) Major problems in recycling come from the mixed nature of plastic waste and the potential relapse of hazardous chemicals post-consumption. Production data on additives is sparse, but there is evidence that for non-fibre plastic additives represent 7% by mass.

xii) There are only a limited number of standards which specifically cover plastic from the perspective of their fate in the marine environment.

xiii) The major land-based sources of marine litter and micro(nano)plastics are from rivers, lakes, and wastewater treatment plants. In addition to the sectors feeding into the major fate pathways, agriculture affects volumes of micro(nano) plastics through use of sewerage and plastic mulching.

xiv) Estimates of land-based volumes going into the seas, based on GDP and plastic production range from 4.8 – 12.7 million metric tonnes from populations living within 50 km from the coastline. (To be updated).

xv) Sources of sea-based marine litter and micro(nano)plastics are predominantly from fisheries and aquaculture, offshore operations and shipping. Coastal tourism and yachting are also potentially important sources, but data on volumes of waste from these are unavailable.

xvi) Beach litter has been extensively analysed from surveys and campaigns. Up to 39 % and 14% of litter comes from fisheries and aquaculture respectively, plus marine debris, and the remaining 50% from 10 types of single use plastic items.

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SECTION 2. PATHWAYS, HAZARDS AND IMPACTS

2.1 PATHWAYS OF LITTER AND MICROPLASTICS INTO THE OCEAN

There are multiple pathways by which all sizes of plastic enter the marine environment: these include run-off from soils, riverine flows, wastewater flows, airborne and direct entry (Figure 10). Storms and natural hazards can also deliver significant volumes of plastic waste into the ocean. Some plastic, such as single use plastic, once littered or flushed down the toilet are likely to be transported via more than one pathway; for example, they can be transported by wind, rivers, sewerage systems or dropped directly into the sea. Similarities have been observed between the composition of riverine and beach litter, underlying how the two are linked. For example, an analysis of floating macro litter from 52 rivers and on marine beaches found signficant overlap amongst 8,599 items (Gonzalez et al. 2016). However, the small number of time series analyses and ecosystem-wide studies that have been undertaken present major challenges in documenting the pathways of plastic.

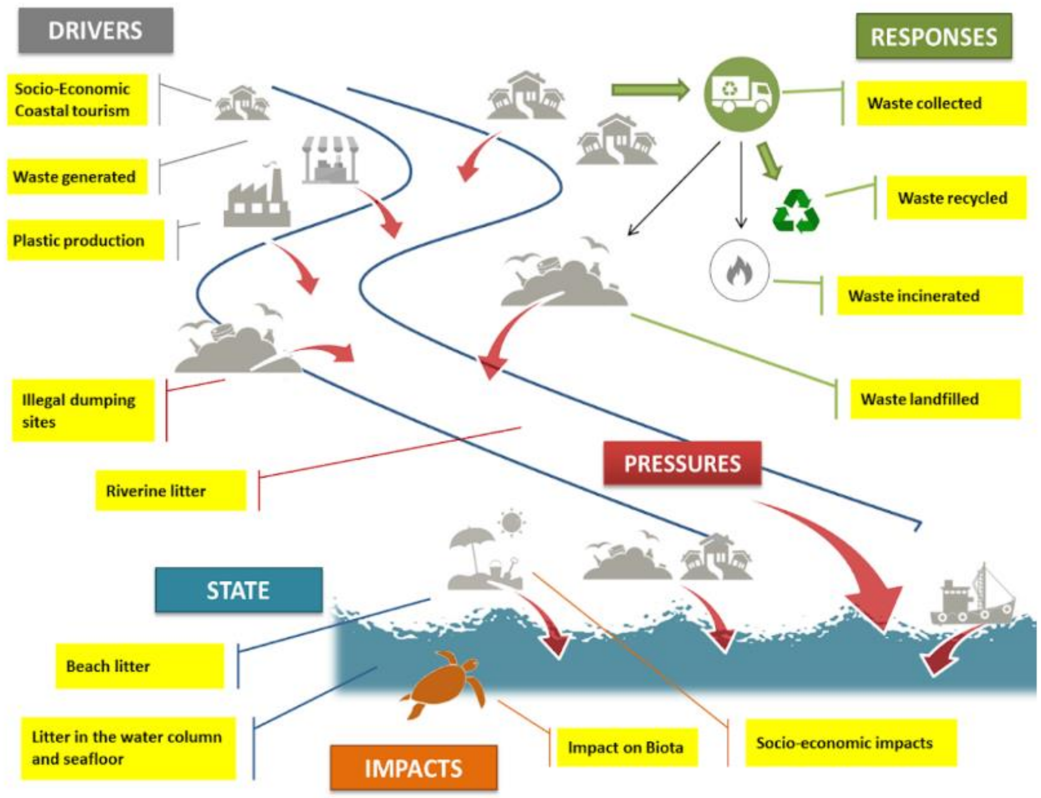

Figure 10 Conceptual diagram of the pathways and Drivers, Pressures, State, Impacts and Responses of marine litter (source Deltares)

The movement of microplastics is harder to monitor. A model-based analysis of the contribution of different pathways to the global release of microplastics into the marine environment showed significant losses from land-based sources such as transportation (66%), wastewater treament (25%) and wind transfer (7%), with only a small percentage from the marine sector (2%) (Boucher and Friot 2017). The distribution of releases in the ocean were different. At the global level, around one third (29.5%) of the population is connected to a wastewater treatment system. Accounting for overflows, this means that for this pathway more than two-thirds (71%) of the microplastics are on average released into the oceans. For road-runoff, only 32% of the losses end up as releases due to the losses going through the sewerage system. All losses occurring in the ocean and all losses transported by wind become releases. Thus, 44% of the releases come from the road runoff pathway, 37% along the wastewater pathway, 15 % are transported by wind and 4% are direct releases to the oceans.

Riverine pathways

Riverine inputs represent a major pathway for marine litter (van der Wal et al. 2013). However, predicting plastic emissions from rivers is challenging given the under-representation of plastic pollution studies in freshwater environments (Blettler et al. 2018). Many factors associated with river morphology, such as bottom type, curvature can create internal river turbulences at different scales, wave action and mixing in the water column, will determine the behaviour of litter and microplastics in the river and its catchment area. Stretches with settled flow are likely to show a pronounced stratification of plastic particles throughout the water column whereas at lower flow rates, more plastic is likely to be found either floating on the river surface or close to one riverbank. Flooding of catchment areas can also reduce microplastic contamination of riverbeds (Hurley et al. 2018).

Estimated contributions of riverine plastic pollution to the marine system vary greatly. Jambeck et al. (2015) estimated that riverine inputs to the oceans from mismanaged solid waste in countries with a coastal border were between 4.8 and 12.7 million tonnes per year [TO BE UPDATED]. Schmidt et al. (2017) estimated that between 88-95% of marine plastic comes from just 10 rivers, whilst Lebreton et al. (2018) report that 67% of all marine plastic entering from rivers comes from 20 rivers. However, there are too few temporal studies to fully understand riverine dynamics and plastic fluxes and the overall impacts of anthropogenic stressors (Schmidt et al. 2017; Best 2019).

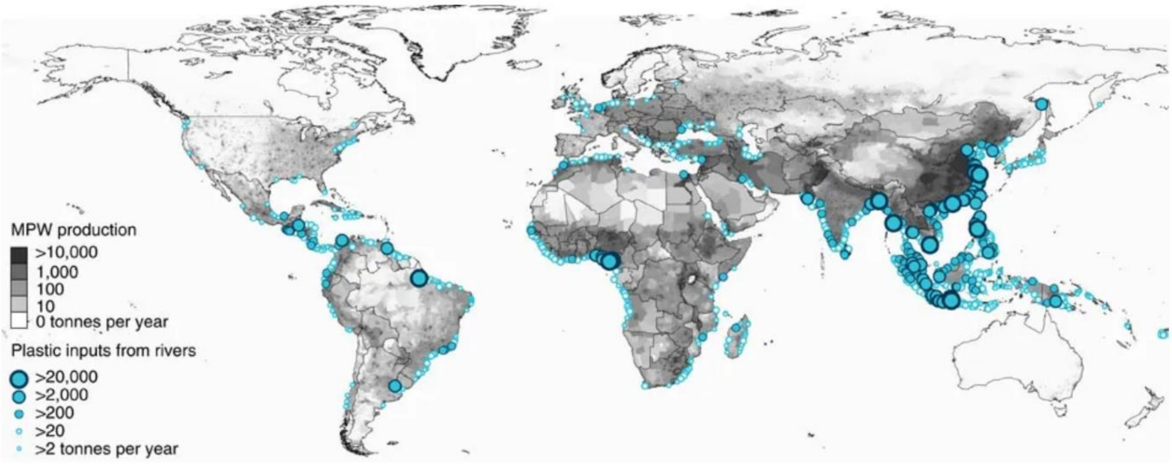

Figure 11 Riverine inputs of Municipal Solid Waste.

One of the three main sources of micro(nano)plastic particles in the marine environment are the biosolids and effluent water coming from wastewater treatment plants (Carr et al. 2016; Karapanagioti 2017). The most abundant nanoplastic particles are the synthetic fibers made from different polymers, which come from washing synthetic cloths; more than 1900 fibers per item per wash end up in sewage (Browne et al. 2017) and because synthetic fibers are not readily decomposed, they concentrate in sewage sludge and are also discharged in effluents.

Riverine inputs of microplastics are difficult to quantify as the majority of freshwater microplastic studies have been conducted at a small number of sites on rivers across Europe, North America, and China, but rarely accounting for river catchments in their entirety (Stanton et al. 2019a). However, there have been studies of litter on the shorelines of some larger rivers, such as the Danube and the Rhine, which have underlined the volumes of plastic debris (Lechner et al. 2014; Klein et al. 2015). Other approaches have been to produce estimates linked to population centres (Eerkes-Medrano et al. 2015; Peters and Bratton, 2016; Horton et al. 2017; Tibbetts et al. 2018) and wastewater treatment plants (Murphy et al. 2016; Mintenig et al. 2017; Talvitie et al. 2017; Ziajahromi et al. 2017; van Emmerik et al. 2019). In some cases, microplastic removal from wastewater treatment plants has been found to exceed 99% (e.g. Talvitie et al. 2017), but the volume of water released by wastewater treatment plants means that they still have the potential to release large numbers of microplastic particles into the oceans. Microplastic particles that do not pollute the effluent of wastewater treatment plants are incorporated into the solid products of the wastewater treatment process, forming a component of the sludge (Mahon et al. 2017). Where this sludge is applied to land, microplastic particles are directly introduced to the terrestrial environment, and may subsequently be washed into aquatic environments during periods of rain and erosion (Hurley and Nizzetto 2018; Li et al. 2018).

Freshwater reservoirs, groundwater and drinking water

Plastic pollution is known to pollute freshwater lakes and reservoirs, from the vast water bodies of the North American Great Lakes (Eriksen et al. 2013) to smaller lakes and ponds (Faure et al. 2015; Vaughan et al. 2017). Far less is known about the processes and levels of infiltration of micro(nano)plastics into groundwater from reservoirs. Panno et al. (2019) report on microplastics in karst groundwater systems (karst systems constitute quarter of the world's drinking water sources) found a median of 6.4 microfibres L^{-1}. In terms of drinking water, the World Health Organization (2019) has identified nine studies that report on the abundance of microplastic particles. The average concentration of microplastic particles per litre in these studies ranged from 0.0 (Strand et al. 2018) to 6292 (Oßmann et al. 2018). The methods used to quantify microplastic particles in these drinking water samples vary and some have been found to be inappropriate for microplastic quantification (Stanton et al. 2019a). A small number of studies have identified microplastic particles in bottled water (Mason et al. 2018) showing concentrations as low as 14 ± 14 microplastic particles per litre (Schymanski et al. 2018), but there are too few studies to have a comprehensive understanding of the fluxes of microplastics into the ocean from drinking water supplies (Oßmann et al. 2018; Schymanski et al. 2018).

Snow and ice

Microplastic particles have alsobeen identified in sea ice **(**Bergman 2019). Sea ice can act as a temporary sink for particles (Peeken et al. 2018), but there is also the potential for large quantities of historic microplastic pollution to be released into the marine environment as the sea ice melts (Obbard et al. 2014).

Marine pathways

Once plastic have entered the ocean environment, there are many pathways whereby macro and micro(nano) move through the different zones from rivers to the coast, and from the surface layers into the water. Litter moves through the different compartments from rivers and the land, along the coastline, surface/upper ocean, water column, and then into the sea-bed and biota (Castro-Jiménez et al. 2019; Pedrotti et al. 2016; Kukulka et al. 2012). In each, there are processes which affect the fate and distribution of marine litter and microplastics biota. For example, plastic debris may become trapped in coastal ecosystems, such as mangroves and impact the dynamics of the sediments (Ivar do Sol et al. 2014). Some plastic is more buoyant and so will remain in the upper ocean compared to those such as acrylics with a higher density that will sink. This can provide opportunities for organisms to disperse and even act as sites for ovipositioning (Majer et al. 2012). As organisms become attached to marine plastic litter, it will change the buoyancy, and the pieces of plastic may then sink. The effects of these processes and degradation on the transfer of plastic between compartments is largely unknown.

A visualisation of the surface current distribution of plastic can be seen on the PlasticAdrift open platform (van Sebille 2019 http://www.plasticadrift.org/;Wichmann et al. 2019). Surface currents distribute the floating plastic to all ocean basins. In the subtropical regions there are large gyres recognised as marine accumulation zones of floating plastic debris; but even into the Arctic, these now have been discovered in the nothernmost and easternmost areas of the Greenland and Barents seas where they meet a “dead-end” (Figure 12), (Statista 2019; Cózar et al. 2017). The fragmentation and typology of plastic suggests that the aged debris originated from distant sources and demonstrates how the poleward branch of the thermohaline circulation transfers floating debris from the North Atlantic to the end of the conveyor belt in the Arctic Ocean which then becomes as a sink for plastic debris. Microplastic particles are also known to be present in the deepest parts of the ocean, in the Hadal trenches. (Peng et al. 2020).

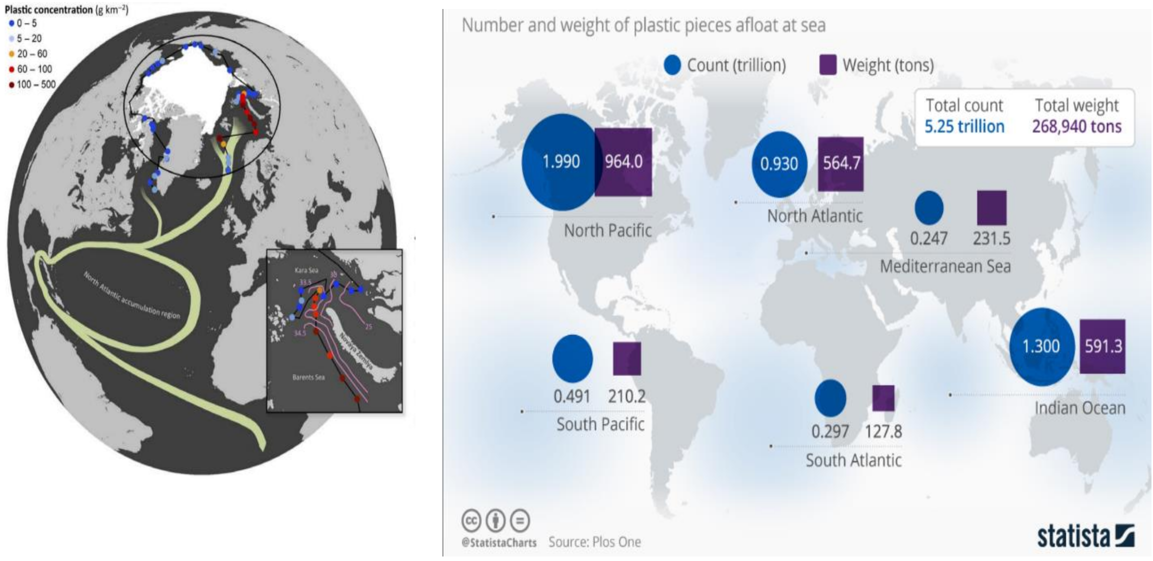

Figure 12 Number and weight of floating plastic pieces; and concentrations in the Arctic Ocean Source: Statista 2018; Cózar et al. 2017).

Airborne transmission

Only a small number of studies have reported microplastic particles in atmospheric deposition. they include Dris et al. (2016), Dris et al. (2017), Cai et al. (2017), Stanton et al. (2019b), Allen et al. (2019), Bergmann et al. (2019), and Klein and Fischer, (2019). They identified microplastic particles in urban (Dris et al. 2016; Cai et al. 2017; Bergman et al. 2019; Klein and Fischer, 2019; Stanton et al. 2019a), and remote atmospheric depositions (Allen et al. 2019; Bergman et al. 2019). However, the sampling regime in these studies have been limited in spatial and temporal extent and so it is difficult to draw any quantitative conclusions.

The abundance of microplastic particles in atmospheric deposition samples is also likely to be influenced by the methods used to collect samples. Concentrations of airborne particulates increase closer to the ground (Prata 2018). Bergman et al. (2019) for example, collected the surface layer of settled snow from different locations. The sampled snow included temporally undefined ‘freshly deposited’ snow, snow that had fallen two days prior to sampling, and snow that was not temporally restrained at all. The potential for ground level contamination of the freshly deposited snow that Bergmann et al. (2019) analysed was not quantified.

Understanding the entrainment (taken into the atmosphere) of microplastics into and transported though the atmosphere is challenging given the variety of shapes, sizes, and densities of microplastic particles. Often sourced from anthropogenic activities such as road traffic and energy production (Keuken et al. 2013), airborne particles with aerodynamic diameters <10 µm are of particular concern to human health, as they are small enough to be inhaled, with particles <2.5 µm having the potential to reach the deep lung (Wright et al. 2019). Although, long-range transport of airborne microplastic particles is possible, mechanisms of microplastic entrainment into the atmosphere are currently largely theoretical.

Chemical and physical properties affecting transmission pathways

The different types of polymers used in plastic have a wide range of properties affecting their behaviour in different environments: these include their density and buoyancy, hydrophobic/hydrophilic properties, and propensity towards biofilm formation and biodegradability. In the marine environment, one of the most important factors is the density of the plastic relative to that of seawater. Densities of common plastic range from 0.90 to 1.39 kg m^{-3}, compared to freshwater with a density of 1.0 for pure water and seawater which can range from 1.020 – 1029 kg m^{-3}, depending on the temperature, salinity and depth. Based on this, only PE and PP would be expected to float in freshwater, plus EPS in seawater. Buoyancy is also affected by entrapped air, water currents and turbulence. This explains why drinks bottles made of PET (1.34 – 1.39 kg m^{-3}) can commonly be found both floating in coastal waters and deposited on the seabed. The buoyancy of plastic polymers can also be affected by the presence of biofilm on the surface (Napper and Thompson, 2019).

Particle size is an important factor for both transport as well as detection. When released into the environment, plastic litter becomes fragmented by both physical and chemical processes into microplastics (<5 mm), (Barnes et al. 2009). Levels of microplastics in seawater and in freshwater were likely underestimated in the UNEP report (2016). More recent analyses using finer mesh (for example 0.45µm) found 3 orders of magnitude more microplastics per litre when compared to commonly used methods (335 µm neuston net tow, bongo nets >500 µm, manta nets >300 µm and plankton nets >200 µm and >400 µm) (Barrows et al. 2017, 2018; Green et al. 2018; Whitaker et al. 2019). Nanoplastics may pose an even greater threat, but as yet there remains significant uncertainty as to their concentrations in seawater.

Airborne particles with aerodynamic diameters <10 µm do not remain airborne for long; the airborne residence times of particles with an aerodynamic diameter of 1-10 µm is reportedly as low as 10-100 hours (Esmen and Corn 1967; Whelpdale 1974), with sea salt particles >50 µm having very short atmospheric lifetimes (Athanasopoulou et al. 2008).

One of the main reasons why plastic have become the biggest form of pollution in the world's ocean (up to 80% of marine litter by mass consists of plastic) is their slow rate of degradation (Gewert et al. 2015; Dussud et al. 2018). Plastic tend to degrade and start losing their original properties at a rate depending on the physical, chemical and biological conditions to which they are exposed. Plastic degradation by exposure to ultraviolet light (photodegradation), results from the weakening, and eventual breaking, of covalent bonds within the structure of the plastic polymers, known as chain scission (Gewert et al. 2015). The chain scission can occur at any point within a polymer's structure, with the potential to cleave monomers from the inert polymer; some of these may be hazardous, such as persistent organic and bioaccumulative pollutants, which can themselves cause environmental harm (Lithner et al. 2011). Overall, degradation is generally slower in aquatic environments compared to on land and may even not occur in environments with limited exposure such as in pelagic (surfacewaters and the water column) and benthic (sedimtary) environments (Webb et al. 2013).

In the environment, biodegradable plastic, specifically biodegradable plastic carrier bags, have been found to have limited biodegradability (O'Brine and Thompson, 2010; Accinelli et al. 2012; Napper and Thompson, 2019). Where biodegradable plastic is not able to biodegrade, they risk fragmenting into microplastic particles in much the same way as conventional plastic (Napper and Thompson, 2019).

The ease with which biofilms form depends on the polymer and surface properties; some materails are very recalcitrant and inhibit the formation of biofilms, for example, the stable aliphatic chains of polyethylene (PE), which dominates the composition of plastic waste in the sea surface (Auta et al. 2017; Tokiwa et al. 2009). Under different conditions, various bacteria can degrade OXO-biodegradable and hydro-biodegradable plastic (Vázquez-Morillas et al. 2016; Eyheraguibel et al. 2017; Dussud et al. 2018). Surface properties of plastic are important in the development of biofilms; weathered plastic may increase biofilm growth due to their increased surface area compared to non-weathered plastic (Rummel et al. 2017). At sea, plastic is almost immediately coated by an inorganic and organic conditioning film which is then rapidly colonized by microorganisms that form a biofilm on their surfaces embedded within an exopolymeric substance matrix. These natural assemblages act as a form of protection, nutritive resource, offer metabolic cooperativity, and an increase in the possibility of gene transfer among cells.

The bacterial communities accumulated on plastic surfaces differ from those in the seawater indicating clear niche partitioning between bacteria living on plastic versus surrounding seawaters, with the primo colonizers, representing <0.1% of the bacterial diversity found in the surrounding seawater. (Sogin et al., 2006), (Zettler et al. 2013; Amaral-Zettler et al. 2015; Dussud et al. 2018). The latest results on bacterial colonisation (Pedrós-Alió 2012; Sauret et al. 2014) apply particularly well to the plastisphere in general and that the bacterial communities living on plastic, although rare in the seawater, prove to be opportunistic species able to grow and to become the "core species" living on plastic (McCormick et al. 2014; Dussud et al 2018).

Pathogenic bacteria, such as *Aeromaonas salmonicida* and *Vibrio parahaemolyticus* have also been found to colonise microplastic particles collected from the marine environment (Kirstein et al. 2016, Viršek et al. 2017). In laboratory studies, plasmid transfer in bacterial assemblages has also been found to be higher in communities that colonise microplastic particles when compared to free-living communities (Arias-Andres et al. 2018).

Regarding biodegradability, the latest results show that differences in the bacterial communities and the oxidation degree of the polymers, under different environmental conditions, will be important factors in understanding how quickly different types of plastic are likely to biodegrade in marine environments and could help explain the lack of mineralization of preoxidized OXO in marine water (Alvarez-Zeferino et al. 2015) or clear biodegradation in other environments (Eyheraguibel et al. 2018). Harrison and co-authors conclude that current standards and test methods are insufficient in their ability to realistically predict the biodegradability of plastic in aquatic environments (Harrison et al. 2018).

2.2 HAZARDS AND IMPACTS OF MARINE LITTER AND MICROPLASTICS

Marine litter causes enormous harm to ecosystems: impacts include mortality or sub-lethal effects on plants and animals through entanglement, physical damage, smothering, ingestion of plastic by animals such as turtles or birds, facilitating the invasion of alien species and altering community structure. Microplastics have the potential to accelerate accumulation of chemicals throughout the food chain, with potential negative impacts on human health. However, empirical data and modelling efforts show that microplastic and microbead concentrations are very low in relation to their toxicity to humans and environmental organisms. This seems to hold true not only for direct particle effects but also for effects of microplastic-associated chemicals as well as nanoparticles (Backhaus 2019). This does not mean that there is no risk, rather that more evidence needs to be gathered beyond the exploratory ecotoxicological studies to date.

Hazards can be classified according to the level of adverse effects they can have on an organism, ecosystem or community when exposed to it (UNEP 2016). Because of their chemical nature, durability and pervasiveness, marine litter and microplastics are potential risk multipliers. For example, entanglement, and eventual strangulation and drowning of iconic species can damage a sensitive habitat, with cascading effects on economic livelihoods. Physical changes in sediment structure caused by macroplastics can induce changes in local temperatures that are detrimental to heat-sensitive organisms which are exacerbated by exposure to hazardous chemicals, such as persistent organic pollutants and legacy substances (banned substances), transported or released from plastic as they degrade. However, exposures to plastic and micro(nano)plastics are difficult to determine especially in the aquatic environments (Adam et al. 2019); in some studies, plastic additives, specifically phthalates, have been used as a proxy for plastic exposure in large marine organisms including whales with unknown impacts for the wider assessment of exposures (Fossi et al. 2012; 2014) and sharks (Fossi et al. 2014).

Marine litter and microplastics by the very nature of their production are linked to significant levels of greenhouse gas emissions, associated with plastic production and recycling and hence to global climate hazards created as a consequence.

Other hazards that arise in dealing with marine litter relates to its disposal, especially if it is collected through an informal waste scheme and then disposed of through uncontrolled or incomplete combustion. Legacy substances in plastic products need to be managed in a safe manner and prevented from being recycled into new products. To support recyclers in Europe, the European Chemicals Agency has been required to introduce a database of articles containing substances of very high concern, and to make the information available to consumers and recyclers. Plastic may also contain persistent organic pollutants (POPs), which according to the Stockholm Convention and EU Regulations, must not be recycled. Waste containing POPs above the regulated limit values must be irreversibly destroyed and must not be recycled. Examples of possible POPs in plastic are some brominated flame retardants and short-chain chlorinated paraffins. Plastic containing newer POPs may not necessarily be classified as hazardous waste.

Impacts on human health

Marine litter can pose a problem to human health if it is collected from beaches and then burnt in open pits where the fumes can be inhaled. A recent study undertaken on eggs in two locations in Indonesia contaminated by plastic waste, showed high levels of a range of hazardous chemicals including dioxins and dioxin-like PCBs (IPEN 2019).

The other potential impact on human health of marine litter and microplastics is likely to be through consumption of seafoods rather than direct exposures, especially in communities and indigenous groups who rely entirely on in marine foods for their proteins (European Environment Agency 2013). Although the polymeric materials that make up marine litter and microplastics are biochemically inert, they often include additives to meet the requirements of the final product; these include flame retardants, colourants, plasticizers, plus other hazardous chemicals and persistent organic pollutants. Most of these additives are of small molecular size and are not chemically bound to the polymeric materials, so they are susceptible to leaching into the surrounding environment. However, there are still insufficient data regarding the actual, measured presence and effects of these materials, and current methods for sampling and reporting of data are not standardized or replicated. This significantly limits the validity of the data and their statistical significance concerning the marine enviroment (Costa 2018).

Although microplastics have been found in the guts of marine species (including samples taken from commercial markets) that humans consume as food (e.g. shellfish, fish), it is unknown whether this presents any measurable hazard to humans at current levels of contamination, particularly given the many other sources of exposure to toxic chemicals in modern life (food, air, and water). Human ingestion of plastic via seafood is probably more common for shellfish and small fish that are eaten whole, including the gut, and less frequent for large fish of which generally only the flesh is eaten.

More recently the potential risk of nanoplastics (<100 nm in at least one dimension) in seafood has been raised. Compared to microplastics, nanoplastics have an increased mobility in the tissues of living organisms and their larger surface to volume ratio increases the potential concentration of harmful chemicals they can absorb. However, as indicated in the recent review by Ferraira et al. (2019) the marine distribution and impact of plastic nanoparticles are relatively unknown. This presents an unknown risk to marine organisms as well as to humans who consume seafood.

Impacts on ecosystem health

The physical impacts of large pieces of plastic waste, such as fishing nets, on specific ecosystems, include enmeshment, strangulation and drowning. Microplastic particles have the potential to alter the water retention and temperature of some sediments. This includes beaches, where the consequences of temperature fluctuation can influence the development of organisms whose sex is influenced by temperature, such as the eggs of sea turtles (Carson et al. 2011).

Once accumulated in the benthic environment, plastic debris and microplastics have the potential to alter the structure and composition of macro and microfaunal and bacterial assemblages (Goldstein et al. 2016). This effect has been demonstrated using field experiments with both rigid (Katsanevakis et al. 2007) and flexible (Green et al. 2015) large, plastic debris. Outdoor mesocosm experiments using natural flowing seawater and intact sediment cores have been used to assess the impacts of conventional or biodegradable microplastics on invertebrate assemblages from three different habitats (Green 2016; Green et al. 2017). In sandy habitats, dominated by flat oysters (*Ostrea edulis*), the addition of (80 $\mu g\ L^{-1}$) of either conventional (HDPE) or biodegradable (PLA) microplastics caused a reduction in the number of species and in the overall abundance of organisms (Green 2016). Similarly, in a follow-up experiment, in muddy sediment dominated by flat oysters, the addition of (25 $\mu g\ L^{-1}$) of the same types of microplastics resulted in a shift in community composition whereby opportunistic oligochaetes became dominant and predatory polychaetes declined (Green at al. 2017). The mesocosm bags labelled as biodegradable did not biodegrade in the marine systems, even after 3 years (Napper et al. 2019).

The same changes were seen in freshwater experiments where biodegradable polyhydroxybutyrate and non-biodegradable polymethylmethacrylate microplastics both led to a decrease in biomass of the freshwater amphipod *Gammarus fossarum* (Straub et al. 2017). Although the effects of anthropogenic plastic debris have been studied in freshwater ecosystems (Holland et al. 2016) very little is known about the behaviour and break-down of biodegradable microplastics in aquatic habitats. A recent study found that secondary nanoplastics released from PHB microplastics persist and have negative effects on freshwater organisms including water fleas, cyanobacteria and microalgae (González-Pleiter et al. 2019).

In terrestrial experiments, polylactic acid, commonly used as an alternative to PE, has been shown to have an effect on soil stability by decreasing the germination and growth of plants, led to a lack of growth in annelids and affected soil structure by reducing the formation of macroaggregates (Boots et al. 2019). Microplastics can also have effects on important aspects of ecosystem functioning and structure, e.g. in fungal communities (Kettner et al. 2017). Experiments in marine sedimentary habitats found that conventional or biodegradable microplastics (Green et al. 2017), decreased the flux of inorganic nutrients (including ammonium and silicate) from the sediment and reduced the biomass of microphytobenthos (microscopic primary producers in sediment). There is now some evidence that plastic is having an impact on the carbon cycle in the oceans (Cole et al. 2016; Porter et al. 2018) as well as on primary producers in marine, freshwater and terrestrial habitats (Yokota et al. 2017; Prata et al. 2019).

The latest review on evidence of the impacts of nanoplastics in marine ecosystems shows that the research is still limited, making it unclear what health risks nanoplastics represent for marine organisms (Ferreira et al. 2019). The available data show some evidence that once ingested, these particles can pass from the intestines into an animal’s circulatory system and generate an immune response. In one laboratory experiment nanoparticles were able to pass into the food web, from algae, to zooplankton and then to fish, where they entered the brain and incited behavioural disorder. There are some data in the review showing a high potential for bioaccumulation and biomagnification along marine food chains but the lack of standardised methodology for nanoplastics detection makes this a challenge. In nature, animals are likely exposed to low concentrations of plastic nanoparticles during their whole life-time. The studies showed that different phyla react differently and so it is difficult at this stage to predict the ecological risks of nanoplastics to the marine environment.

2.3 SUMMARY

i) There are multiple pathways for plastic to enter the ocean, including soil run-off, riverine and wastewater flows, airborne transmission and direct inputs. However, there are too few published data sets from monitoring programmes or studies of individual rivers or at the catchments level, to make it impossible to derive time series analyses or estimate accurately the volumes of these flows.

ii) Analyses of micro(nano) plastic in freshwater and groundwater systems are too limited and the methods are not standardised to estimate the concentrations or sources.

iii) Microplastics have recently been recorded in samples of snow and ice from different locations and from airborne particles, however, the methods used are not standardised making it difficult to compare results from the different studies.

iv) Movement of floating plastic in the marine environment can be seen from visualisations of surface currents. Results for the Arctic were confirmed by field observations which found floating plastic stranded in dead-ends in the north-western reaches.

v) The chemical and physical proeprties of plastic determine their bouyancy and density and hence propensity for movement in surface waters and the water column, and fluxes between marine compartments. Recent analyses have shown that different types of polymers are more likely than others to encourage formation of biofilms and bacterial growth, which affects the density of plastic particles.

vi) Studies have shown that the size of particles is important, especially for airborne transmission into the ocean from land-based sources. Surveys of freshwater and seawater using very fine filters indicate that concentrations of microplastics could be three orders of magnitude higher than previously recorded. However, measurements of the concentration of nanoparticles are absent.

vii) Pathogenic bacteria have been found to colonise microplastic particles. Bacterial communities on plastic particles differ from the ambient community; these proto communities appear to encourage plasmid and pathogenic bacteria to grow. Bacterial communities, along with oxidation potential of the waters, determine the rate of degradation. However, many of these processes are not well articulated, making current tests insufficient for the prediction of biodegradability under real-world conditions.

viii) Amongst the greatest hazards of plastic to marine organisms are the lethal and sub-lethal effects of entanglement, smothering and accumulation of plastic through ingestion, which can in turn alter the structure of ecosystems and put key species at risk. For this reason, plastic are risk multipliers through the emissions of greenhouse gases during producton and their potential impacts on primary production in the oceans, plus the release of legacy chemicals during degradation processes, some of which are defined as substances of very high concern.

ix) Human health issues have arisen through contamination of land-based foods resulting from open-pit burning of plastic collected from beaches and coastal areas. There is also the potential for micro(nano)plastics to affect human health via consumption of seafood; however, there is no confirmatory evidence of high concentrations of microplastics from field sampling.

x) Ecosystem health effects of plastic debris and microplastics occurred in mesocosm experiments on biodegradability where in the community species were altered, and assemblages restructures and biodiversity declined. Fungal and sedimentary invertebrate communities were also affected. Nanoplastics released during the experiments affected aquatic invertebrates; however, the data are too limited to draw any comprehensive conclusions on the hazards posed by micro(nano)plastics on marine ecosystems.

xi) Biodegradability is slower in marine environments compared to on land; experiment in mesocosm bags of biodegradable plastic showed that there was no degradation even after three years.

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SECTION 3. MONITORING, INDICATORS OF MARINE LITTER AND TRACEABILITY

3.1 MONITORING, BASELINES AND INDICATORS

Monitoring of plastic litter has become an imporant part of determining the health of the oceans. However, there is as yet no commonly agreed set of methodologies or indicators to assess the impacts of different forms of plastic. There is also very little published information about prevention programmes and their effectiveness.

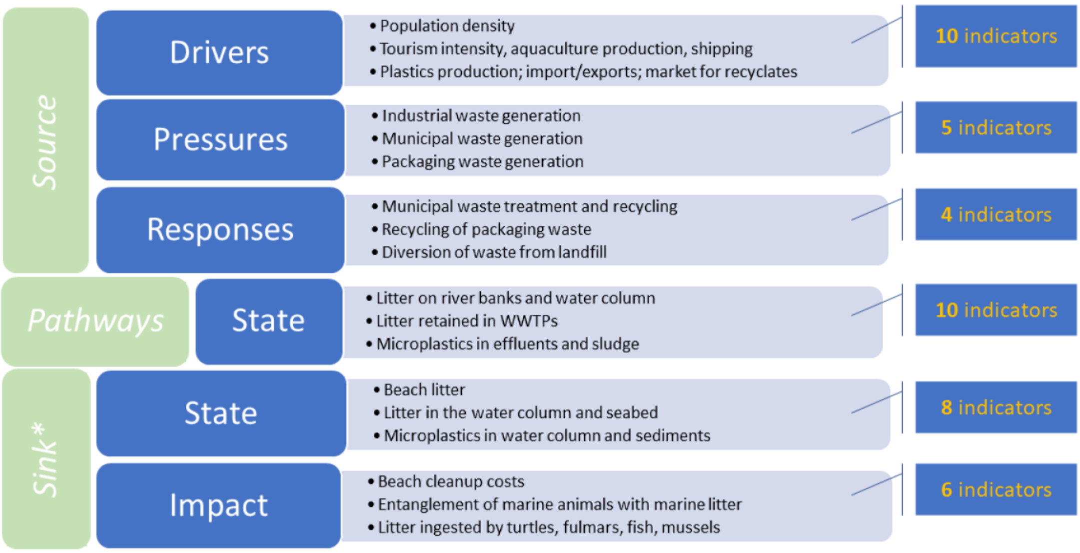
Assessing the issue of marine litter and microplastics holistically means linking how societies are using, reusing and recycling plastic materials and how effective they are in preventing leakages of valuable resources into the environment from source to sea and across the life cycle. Such an approach recognises the importance of rivers, transportation, agriculture and wastewater as major sources of marine and microplastics as well as mismanaged waste, and that developing monitoring efforts on rivers will generate important data on inputs of waste from land-based sources and on the measures intended to prevent them.

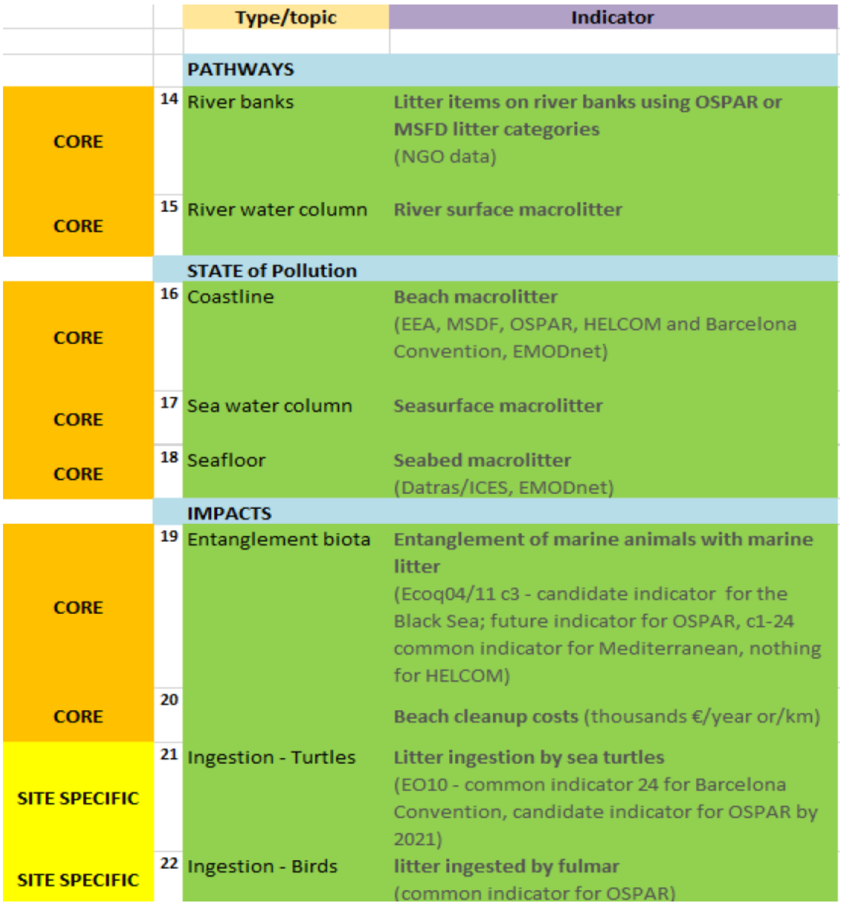
Baselines and Indicators

What is to be monitored, where and how often will depend on the policy or operational questions being addressed. Establishing commonly agreed indicators, baselines and methodologies is becoming increasingly urgent to enable governments and citizens to fully understand and compare the volumes, distribution and fate of marine litter and microplastics in different locations. Monitoring baseline volumes and distribution of marine litter requires measurements to be taken using various instruments, technologies and approaches. For this there need to be agreed sets of definitions and methodologies that enable data to be connected along the various transport pathways from lakes and rivers, soil runoff, to shorelines and beaches in the inter-tidal areas, the ocean surface and water column, seabed and biota.

A number of indicator processes are underway to monitor marine litter and microplastics. The UN Sustainable Develop Goal 14, Target 1 states that by 2025, countries should prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including plastic debris and nutrient pollution. The indicator cited is an index of coastal eutrophication and floating plastic debris density, however there is as of yet no internationally established methodology or standards available. The word "floating" will be removed as the proposed methodology would measure more than just floating plastic. Agreed sub-indicators for 14.1.1 by the Inter-agency and Expert Group on SDG Indicators (IAEG-SDGs) include beach litter, floating plastic, plastic in the sea column and on the sea floor and the optional indicator of ingested plastic. Additionally, 14.1.1 includes supplementary indicators related to the source and flow of plastic. One of the aims of the Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean (2019 GESAMP) is to provide commonly agreed methodologies for measurements to generate sub-indicators on sources, distribution and quantities and impacts of marine litter to support the collection of data for the plastic litter indicator.

Indicators, based on the concept of "source-to-sea" concept and the framework of Drivers, Pressures, State, Impacts and Responses (DPSIR), are also being adopted in some regions; for example, in European seas, indicator development is part of the *H2020 Initiative for a cleaner Mediterranean*. Led by the European Environment Agency and implemented together with UNEP-MAP, a set of indicators has been defined and proposed that will potentially enable an integrated assessment to be made of key types of land-based sources of pollution, including solid waste/marine litter (Table 4; Figure 13) (European Environment Agency ETC-ICM 2019). These indicators link with the work of the European Union's Technical Group on an indicator base for monitoring marine plastic (Veiga 2016).





		Type/topic	Indicator
		PATHWAYS	
CORE	14	River banks	**Litter items on river banks using OSPAR or MSFD litter categories** (NGO data)
CORE	15	River water column	**River surface macrolitter**
		STATE of Pollution	
CORE	16	Coastline	**Beach macrolitter** (EEA, MSDF, OSPAR, HELCOM and Barcelona Convention, EMODnet)
CORE	17	Sea water column	**Seasurface macrolitter**
CORE	18	Seafloor	**Seabed macrolitter** (Datras/ICES, EMODnet)
		IMPACTS	
CORE	19	Entanglement biota	**Entanglement of marine animals with marine litter** (Ecoq04/11 c3 - candidate indicator for the Black Sea; future indicator for OSPAR, c1-24 common indicator for Mediterranean, nothing for HELCOM)
CORE	20		**Beach cleanup costs** (thousands €/year or/km)
SITE SPECIFIC	21	Ingestion - Turtles	**Litter ingestion by sea turtles** (EO10 - common indicator 24 for Barcelona Convention, candidate indicator for OSPAR by 2021)
SITE SPECIFIC	22	Ingestion - Birds	**litter ingested by fulmar** (common indicator for OSPAR)

Table 3 (a and b) Example of the proposed EU indicator framework (a) and the specific indicators on *pathways*, state of pollution and impacts of marine litter (b) Source: EEA ETC-ICM

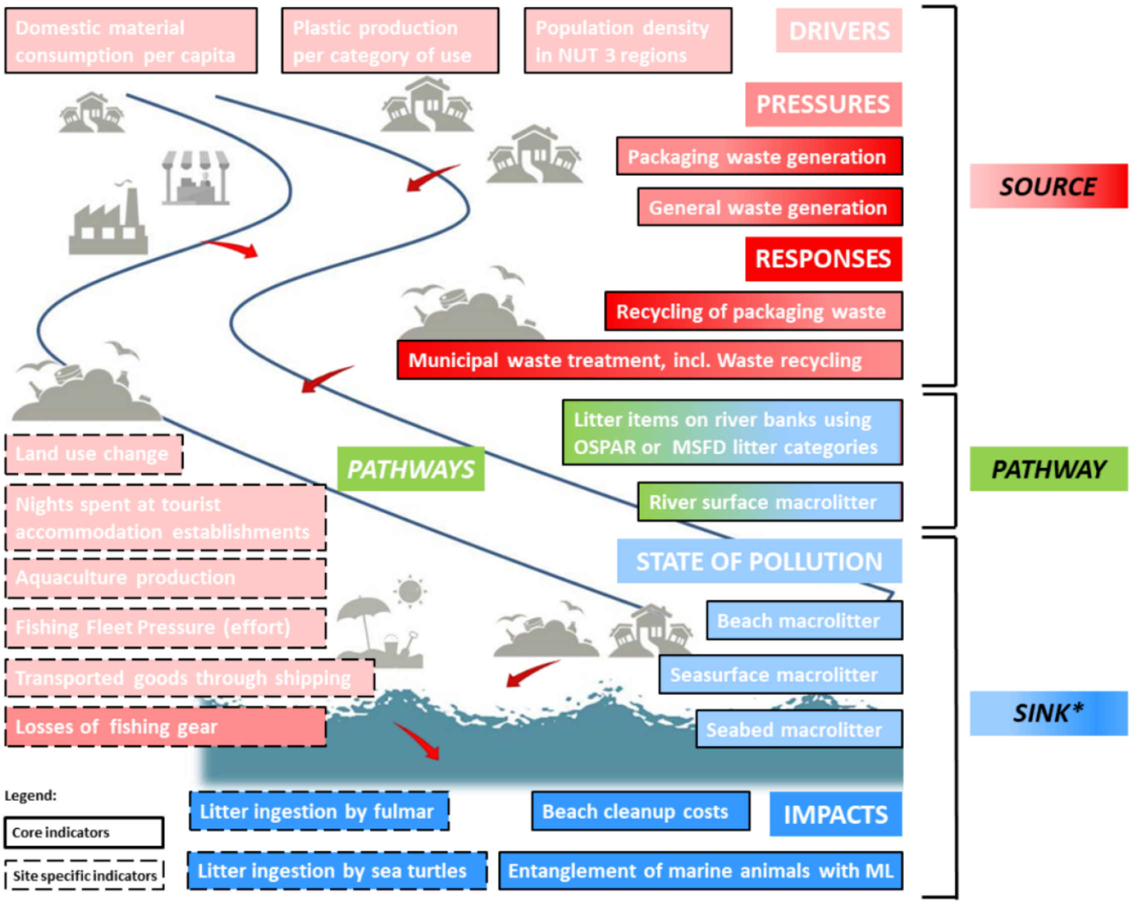


Figure 13 Proposed core set of indicators presented in conceptual framework of Drivers Pressures State Impact Response for marine litter (*the term sink is referring to the final destination of marine litter) (Source of scheme: IWRS; source of background: Deltares). 2-coloured boxes (green-blue) represent both indicators on “state” of river litter and about “pathways”. Source; European Environment Agency ETC-ICM (2019)

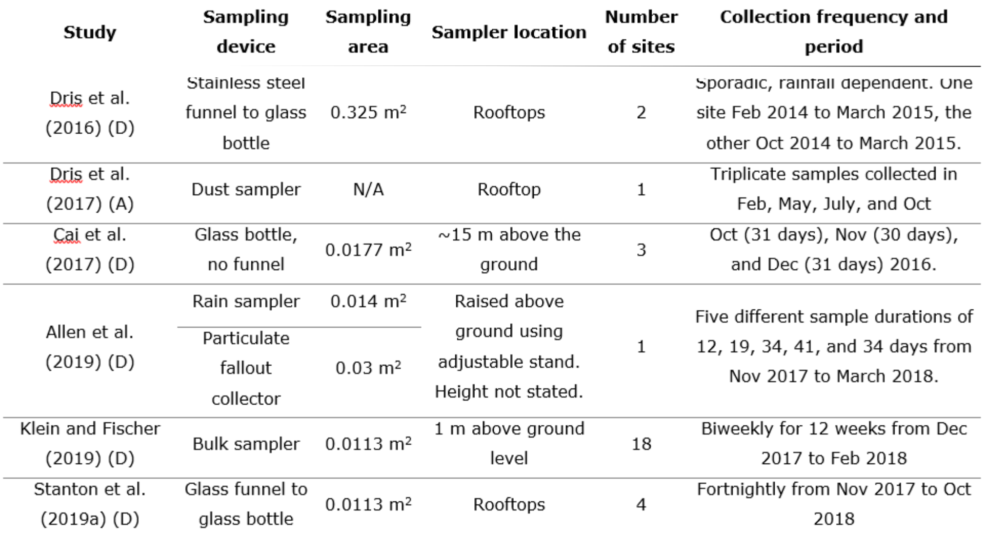
Definitions, guidelines and methodologies

For the marine and coastal environment, GESAMP (2019) provides guidelines for the monitoring and assessment of plastic litter and microplastics and makes a proposal for the series of sub-indicators (see Glossary). For purposes of cross-validation of monitoring and surveys, the definitions used for marine litter and microplastics can be applied to plastic litter on land, in air and freshwater systems; the definitions refer to size, shape and colour.

In terms of macro-litter, it has been common to adopt a hierarchical classification so that users can subsequently compare items with those classified by typologies in other locations. This approach is rooted in the earlier guideline by UNEP/IOC which defines 77 categories of marine litter, based on composition (glass, plastic, metal) form (bottle, bag film, rope etc.) and size (Cheshire et al. 2009; GESAMP 2019). There is now an initiative amongst the Regional Seas Programme in Europe to have a common list based on the UNEP/IOC list to allow for comparability. Other similar classification lists exist, for example in the USA (NOAA MDMAP).

For microplastics, the majority of researchers continue to define these simply as those plastic particles smaller than 5 mm (in their largest dimension). This definition is rooted in Arthur et al. (2009). Some have used more complicated definitions of microplastic particles. For example, Frias and Nash (2019) define microplastics as: *any synthetic particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 µm to 5 mm, of either primary or secondary manufacturing origin.*

There are intrinsic difficulties in determining and identifying microplastic particles in environmental samples, due to their size and varied shape, colour and degree of degradation. This is why efforts to detect the presence of these particles have resulted in different methodologies (da Costa and Duarte 2015; Löder and Gerdts 2015). Currently, there are no standardized methodologies for their correct sampling and identification (Besley et al. 2017), although numerous workgroups have been established with the specific intent of developing such standardized methods e.g. GESAMP (2015), OSPAR (2015) and NOAA (2015). To date these efforts have failed to derive a standardised protocol for the sampling of micro(nano)plastics in the different environmental compartments, including biota. Different units of measurement and quantification are being used by researchers; in some, the data are given per weight of sample, per volume of matrix or sampling area, without information to enable comparisons to be made (da Costa 2018). A variety of methods are also being deployed to collect airborne and deposited microplastic particles (Table 5), with problems arising in the measurements due to entrainment of other particles and contamination (see Section 2) (Stanton 2019 b).



Study	Sampling device	Sampling area	Sampler location	Number of sites	Collection frequency and period
Dris et al. (2016) (D)	Stainless steel funnel to glass bottle	0.325 m^2	Rooftops	2	Sporadic, rainfall dependent. One site Feb 2014 to March 2015, the other Oct 2014 to March 2015.
Dris et al. (2017) (A)	Dust sampler	N/A	Rooftop	1	Triplicate samples collected in Feb, May, July, and Oct
Cai et al. (2017) (D)	Glass bottle, no funnel	0.0177 m^2	~15 m above the ground	3	Oct (31 days), Nov (30 days), and Dec (31 days) 2016.
Allen et al. (2019) (D)	Rain sampler	0.014 m^2	Raised above ground using adjustable stand. Height not stated.	1	Five different sample durations of 12, 19, 34, 41, and 34 days from Nov 2017 to March 2018.
	Particulate fallout collector	0.03 m^2			
Klein and Fischer (2019) (D)	Bulk sampler	0.0113 m^2	1 m above ground level	18	Biweekly for 12 weeks from Dec 2017 to Feb 2018
Stanton et al. (2019a) (D)	Glass funnel to glass bottle	0.0113 m^2	Rooftops	4	Fortnightly from Nov 2017 to Oct 2018

Table 4. A summary of the sampling approaches taken for the collection of airborne microplastic particles (A) and deposited microplastic particles (D) in five of the six studies to report the presence of atmospheric microplastics.

New monitoring approaches and technologies

UNEP (2020) is developing new guidelines for the harmonization of monitoring macroplastics and microplastics in freshwater systems, because of the significant anthropogenic stressors on large rivers (Best 2019) and the large uncertainties about riverine inputs of plastic litter to the sea. Three sources are seen as important for freshwater monitoring; the rivers themselves, reservoirs and wastewater treatment plants. Drawing on the experiences of marine monitoring, the guidelines warn of sample contamination due to the higher particle loading in freshwater systems and provides additional precautionary steps during sample preparation.

Freshwater monitoring programmes should ideally cover the whole size spectrum of plastic. This is because in freshwater systems, microplastics and larger items typically contribute equally to total mass concentration (Schmidt 2017). Damming of rivers, which can also significantly alter downstream transport of plastic debris, especially in large rivers with average discharges of $>1000 m^3 s^1$, can also lead to higher mixtures of plastic building up in reservoirs, from fisheries and aquaculture where they occur.

Different technologies and sampling strategies are needed when monitoring for plastic along a river (Figure 14). Typically, surface nets, manta trawls, underwater pumps and booms have been used to collect water which is then passed through a net or filter, and bottom nets, designed for fishing, to trawl for items (Gonzalez et al. 2016; González-Fernández and Hanke 2017; UNEP 2019). Because river flows can fluctuate significantly on an hourly, weekly, seasonal and multi-year basis, in situ monitoring in different parts of the river may be needed. Automated monitoring using unmanned autonomous vehicles can support a multi-temporal sampling and monitoring approach as well as simple visual protocols for observing rivers from bridges, such as the one developed in the RIMMEL project aimed at harmonising riverine plastic litter data (González-Fernández and Hank 2017). Scaling up of visual observations can also be done using earth observations (satellites and cameras) and Unmanned Aerial Vehicles (UAV) (Martin et al. 2018; Geraeds et al. 2019) and cameras (Kylili et al. 2019).

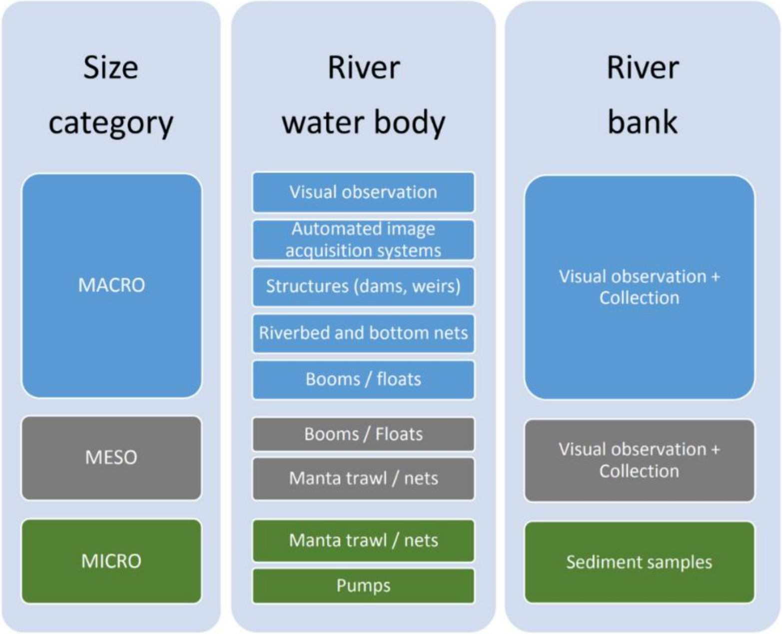


Figure 14 Main methodologies for monitoring litter by size categories in different compartments of a river.

Shorelines, riparian areas and riverbanks are often transient sources of plastic due to water level variations and tides. This may lead to regular depositions as well as additional ones during extreme events. Recent work by Hurley et al. (2018) showed that the flooding across UK catchments decreased plastic concentration along riverbanks by 70 %. Sampling sediments along dynamic banks is unlikely to yield consistent time series data, however studies in estuaries have shown that it is possible to quantify time signals in plastic, although not necessarily estimate transport volumes into the ocean (Sadri and Thomson 2014).

Survey photo-materials of the seabed from 2013 – 2018 were also used in a novel experiment in the Mediterranean to back-date sea-floor macro-litter (Cau 2019). A total of 54 items were identified with their product code, including aluminium cans produced in the 1980s. Items dumped within 5 years were the most numerous and were identifiable macro-litter items, suggesting that the technique could be used on-board fishing vessels for monitoring the seabed for litter.

New data streams from a number of space agencies, in particular the European Commission Sentinel 1 and 2 satellite missions, also represent a potential source of regular monitoring of macro-plastics on riverbanks, surface waters and shorelines. Models using satellite data of surface currents can be deployed to indicate areas where floating plastic are concentrating for more accurate in situ sampling (Wichman et al. 2019 ; van Sebille www.plasticadrift.org).

3.2 DATA SHARING AND CITIZEN SCIENCE

Data sharing arrangements and platforms

The complexity and scale of dealing with marine litter and microplastics requires that data from many sources be shared and integrated. Estimating and forecasting the volumes, distribution and fate of marine litter and microplastics, as well as evaluating the effectiveness of preventative measures will also require expertise from many fields to work together. The easiest way to make this happen is to establish data protocols that can facilitate data exchange. Joint data storage approaches may also help as it would bring in data comparability and enhance harmonisation. For some of the freshwater analyses, only local data might be needed, however, for the marine environment, access to data on a larger scale will be necessary. In contrast to methodologies which deliver an International System of Units traceable result, many of the methodologies used today are operationally defined. This means that protocols on metadata, definitions and ontologies, units, minimum quality standards, and access rights will need to be defined and agreed by relevant organisations such as River Commissions, Regional Sea Conventions and Action Plans, and the UN and be available to everyone. In addition, detailed documentation of sampling and analytical procedures will be needed, especially to address micro(nano)plastics.

The main platform is the Global Partnership on Marine Litter Platform (GPML 2019). Examples of data sharing systems and platforms that can be linked to the GPML platform include the European Marine Observation and Data Network (EMODnet), the Copernicus Data Service for the Sentinel missions and the Africa Regional Data Cube, plus many others at the national level.

The Global Partnership on Marine Litter (GPML) was launched in June 2012 at Rio + 20 in Brazil, under the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) (UNEP 2013) to protect human health and the global environment by the reduction and management of marine litter through a wide range of activities.The partnership is made up of international agencies, governments, non-governmental organisations, academia, private sector and civil society who contribute in the form of financial support, in-kind contributions and/or technical expertise. The GPML is supported by an online platform (GPML 2019) which provides details on projects, enhances cooperation and co-ordination, helps to promote awareness of sources of marine litter, their fate and impacts, and supports knowledge management and information sharing (GPML 2019). Other platforms can connect to the GPML platform, for example, Marine Littter Solutions, (https://www.marinelittersolutions.com/projects/), an open source platform with projects in 17 countries plus the the EU member States.

Citizen science initiatives

The problems surrounding marine plastic, triggered in part by large campaigns such as Clean Seas and the Blue Planet II documentary series (2018) have elicited a wide range of citizen science initiatives. These range from monitoring of litter on beaches and in rivers to tracking and analysing microbeads and pellets in the environment; as citizen science initiatives they are all engaged in collecting data and sharing and disseminating them through online databases and mobile applications.

Examples where the citizen science is directly contributing to monitoring and data collection include: 2minutebeach clean https://beachclean.net/ where citizens monitor beach litter, clean up and record the status on a mobile app.; Beat the Microbead http://www.beatthemicrobead.org/ where citizens use a mobile application to check and scan barcodes of cosmetic products for presence of microbeads; CoastWatch Microlitter http://coastwatch.org/europe/microlitter/ where citizens monitors visible micro litter and fill out a form via a mobile app or online form to produce a microlitter map; Community Beach Clean (UK) https://www.sas.org.uk/our-work/beach-cleans/ where citizens monitor beach macro-litter, and bring communities together to clean up beaches; International Coastal Clean Up https://oceanconservancy.org/trash-freeseas/international-coastal-cleanup/ where citizens monitors beach litter, cleaning up beaches with a “how-to” kit, and provide data through CleanSwell, a mobile app on long-term global data on plastic; International Pellet Watch http://www.pelletwatch.org/ where citizens monitor plastic resin pellets (“nurdles”), collect and send them to a lab for analysis, provide data for global mapping of pellet pollution and help to develop a better understanding of the persistent organic pollutants (POPs) associated with resin pellets; Marine Debris Tracker (US) https://marinedebris.noaa.gov/partnerships/marinedebris-tracker where citizens monitor beach litter activity, clean beaches and use a mobile app to map types of beach litter; Marine Litter Watch (Europe) https://www.eea.europa.eu/themes/water/europesseas-and-coasts/marine-litterwatch where citizens monitor beach litter, clean beaches and contribute to a public database via a mobile app to support European policy making; The Great Nurdle Hunt http://www.nurdlehunt.org.uk/ which monitors plastic resin pellets (“nurdles”), collects them on beaches and generate hot spots maps to inform policy change; OSPAR Marine Litter Monitoring https://www.ospar.org/workareas/eiha/marine-litter where citizens monitor all beach litter on 100m of beach, and all macro litter on 1km of beach 4 times a year using a “How-to” guide and beach questionnaire, and provide data for the analysis of marine litter composition by type for North-East Atlantic; RIMMEL (Europe) https://www.mio.univamu.fr/IMG/pdf/riverine_litter_monitorin g_network_information.pdf where citizens monitor visible macro litter floating on rivers by standing on a bridge, or where the river enters the ocean, record macro litter that you see during set amount of time using a mobile app to provide inputs into building statistical models of the inflow of macrolitter into marine environments from rivers; The Plastic Tide https://www.zooniverse.org/projects/thep lastictide/the-plastic-tide/classify where citizens monitor plastic litter in drone photos, by spotting and tagging plastic litter in online photographs and help to train algorithms to recognise plastic automatically.

3.3 TRACEABILITY

Traceability and access to information

Traceability of products across the life-cycle is vital for the circular economy. For plastic traceability is needed to keep track of constituents such as additives, help reduce loss of materials and value and potentially secure better environmental management of post-consumption waste. Delivering traceability has a long history in the food supply chain and the financial sector, where traceability has become synonymous with blockchain technologies. The plastic industry has recently begun to explore the use of these technologies to establish systems that will enable data exchanges amongst suppliers and producers and providing for traceability and transparency across what is today a fragmented supply chain. The use of blockchain will also help to make it easier for suppliers, processors, manufacturers, moulders and brand owners to choose traceable, sustainable and circular materials. It can also incentivise suppliers and manufacturer to produce traceable, sustainable and circular materials and products and provide critical life-cycle information for reverse logistics, including take-back of products, materials and components. Such approaches are in line with the New Plastics Economy (Ellen MacArthur Foundation 2016), which has a goal to design a system where plastic packaging never becomes waste but can re-enter the economy either as a valuable biological or technical material.

However, disclosures along an industrial supply chain do not necessarily lead to transparency or disclosure about the constituents of a particular product such as additives towards the consumer or other industries. For this, public traceability systems are needed, supported by technologies such as QR codes, that enable consumers to access information about the physical properties of the traced object, the positive or negative effects with which it is associated, the monitoring and certification processes. Consumers of plastic products will also need to be aware of the institutional relations that activate and constrain such traceability systems, so as to be able to have trust in the information they are receiving. Certification and labelling schemes require clear guidance on which aspect of a product they are responsible for verifying or assuring. To date, the major schemes for plastic have focussed on recyclability; however, as more knowledge and research brings to light the impacts of post-consumption plastic traceability schemes will need to be more aware of the full hazards and risks of a product. As yet no such schemes exist.

Transboundary movement of plastic waste

An increasingly important challenge in global governance has been to track the cross-border travels of goods that are associated with positive or negative effects (Muirhead and Porter 2019). The transboundary movement of waste is regulated by the Basel Convention, which prohibits the export of hazardous waste unless the importing state has given its prior consent in writing to the specific import (OECD 2009). It has recently been amended, based on a proposal from Norway, which will come into effect in 2021, extending the current regime to include contaminated, mixed or hard-to-recycle plastic waste (European Environment Agency ETC/WMGE 2019) (see Section 1 Global trade for a discussion on recent changes). This development represents a step change in the global management of plastic waste and places plastic waste within a globally recognised legal standard for the control of international movements of waste, as a category requiring special consideration, and part of the prior informed consent process, which is the cornerstone of the Basel Convention.

Currently, developed countries are able to export lower-quality plastic waste to private entities in developing countries without approval from the importer's government or responsible authority. The new rules mean that contaminated plastic waste, and most plastic waste mixes, will require prior consent from importing countries before they are traded, with the exception of mixes of polyethylene, polypropylene, and polyethylene terephthalate (more commonly known as PET). Importing countries receiving mixed and unsorted plastic waste from foreign sources are expected to have the right to refuse non-compliant shipments — a measure intended to compel exporting companies to facilitate the export of clean, recyclable plastic. The measures are intended to make the global trade in plastic waste more transparent. Part of this transparency involves introducing a level of accountability that is currently lacking in the export/import system. Countries that are not a signatorysignatories to the Convention could still be impacted should they attempt to export plastic waste to a signatory nation.

The implementation of a traceable system for the export and import of plastic waste will aid global traceability and management, though it will be for the individual signatory country to decide how this particular measure is implemented domestically. Careful planning will be required to ensure the operation of a unified, global system accessible by all signatory countries is effectively implemented.

Extended producer responsibility

Extended Producer Responsibility (EPR) has been part of waste policy for a long time, particularly within the OECD countries. According to the OECD, EPR aims to make producers responsible for the environmental impacts of their products throughout the product chain, from design to the post-consumer phase (OECD, 2016; 2019). It also alleviates the burden of public administrations for managing end-of-life products, and if properly designed can incentivising waste prevention and recycling. Implementing extended producer responsibility as a measure towards downstream waste management is currently being examined by the European Commission as part of its work on reducing marine litter through action on single use plastic and fishing gear (European Commission 2018). The OECD is doing much work on EPR, under the auspices of the *Working Party on Resource Productivity and Waste* (OECD, 2016: 2019).

The main challenge to using this measure for marine litter is that after a number of years it has become clear that producer responsibility organisations managing the EPR do not assume the entire cost of managing the corresponding waste flows, and therefore public administrations continue to sustain part of the costs that should be borne by producers and potentially transferred into prices paid by consumers. Secondly, the producer responsibility organisations do not sufficiently incentivise recyclability and eco-design amongst individual producers and thirdly, insufficient transparency makes it difficult for public administrations to assess compliance; amongst others (OECD 2016). Today it is limited to a small number of products i.e. electric and electronic equipment, batteries and accumulators and end-of-life vehicles: marine litter is however made up of a range of products which may make it difficult to implement beyond single use plastic and fishing gear (see Section 1).

Relevant manufacturing and processing standards and product labelling

There are several internationally established and acknowledged standards and certification and verification schemes for the manufacturing and processing of plastic. These cover aspects of biodegradability, the carbon and environmental footprint, recycling and degradation in industrial composting and in the environment. Examples of relevant standards for the marine environment include ISO 15279 Recovery and recycling of plastic waste; ISO 22526 Carbon and Environmental print; ISO/CD 22722 Disintegration of plastic materials in marine habitats; ISO 18830 Biodegradation test (Figure 9) and ASTM D7081 Standard Specification for Non-Floating Biodegradable Plastic in the Marine Environment for biodegradation to occur within 365 days. These and other published standards are used to certify materials and products by several other organizations including DIN CERTCO in Germany, the Japanese BioPlastics Association in Japan, Vinçotte in Belgium, the Bureau de normalisation du Québec (BNQ) in Canada, the Australasian Bioplastics Association in Australia/New Zealand or the Biodegradable Products Institute (BPI) in the U.S. These certification agencies use well-researched and vetted test specifications to establish third-party, peer reviewed programs to confirm the end-of-life performance of bioplastic materials following the requirements of the standard specifications. With the development of new materials, standards and certifications for other end-of-life scenarios are needed; however, in some instances only standard test methods are provided, which may not contain pass or fail criteria to be established by the industry. Little of the testing information is made public and as such no real progress can be made on labelling standards.

Labelling of plastic products has primarily focussed on recyclability and degradability, with little information given on additives or life cycle impacts. This has led consumers to underestimate the impacts of plastic production in terms of greenhouse gas emissions and the impacts of disposal (Hartley et al. 2018). The use of clear labelling and the use of global standards is an important measure that can be taken to reduce the risks of hazards to the marine environment (see Section 4).

3.4 SUMMARY

i) Monitoring of plastic litter has primarily focussed on the marine domain and determining the state and impacts. However, the lack of agreed methodologies and indicators for many forms of plastic, across all environmental compartments, plus the complexity of factors affecting the distribution of litter in the sea, means that the overall impacts of marine litter and microplastics are still not well understood.

ii) Establishing baselines for marine litter and microplastics requires agreements on definitions, what is to be measured, where and how often and a series of indicators. A standard sampling protocol has yet to be agreed. Several indicator processes are underway to support the UN Sustainable Development Goal 14 target 1. Examples include GESAMP, with a focus on the marine component; US MDMAP looking at Marine debris and litter; and the EU looking at indicators that run from source to sea using the Drivers, Pressures, State, Impacts and Responses framework.

iii) New guidelines for monitoring plastic litter in freshwater environments will be helpful in determining flows into the ocean. There are several emerging sampling technologies that will help in large-scale monitoring including Unmanned Autonomous Vehicles, survey photographing, plus a number of new global satellite missions that can provide data on different aspects of litter from multispectral and radar instruments.

iv) The complexity and scale of monitoring marine litter and microplastics requires a greater capacity and willingness to share data and information. Data sharing protocols and open data platforms will be needed; examples of existing platforms that can be linked to the main platform, the Global Partnership on Marine Litter Platform, include EMODnet, the Global Partnership for Sustainable Development Data and regional platforms such as the Africa Regional Data Cube.

v) Citizen science initiatives are playing an increasingly important role in collecting data on marine litter and physically removing litter from beaches, estuaries and coastal environments such as mangroves. A number are listed.

vi) Traceability is vital for tracking constituents and additives across the plastic supply chains, for determining the sources and sinks of plastic in the circular economy, to identify leakages into the marine environment and to enable consumers to check the source and make-up of a product. The recent uptake of blockchain technology in the plastic industry will enable flows of materials across a fragmented supply chain to be tracked.

vii) Traceability in the industry does not necessarily lead to open data and transparency for consumers. Certification and labelling schemes are also vital, but current systems are very limited, not standardised and do not reflect real-world conditions in testing.

viii) Transboundary movement of waste falls under the Basel Convention for a large number of countries. Recent changes in the marketplace and amendments to the convention on which waste can be transported means that improved traceability systems will be needed, to cover waste being shilled to locations where there are high background levels of mismanaged waste.

ix) Extended Producer Responsibility is an important concept and measure that can help in tackling marine litter and microplastics. To date there are only a few numbers of items that have come under the EPR and many manufacturers would not agree to taking on responsibility for the entire life cycle of plastic.

x) There are only a limited number of manufacturing and processing standards for plastic which are relevant to marine litter and microplastics, such as from ISO, but no specific labelling schemes.

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SECTION 4. FUTURE PERSPECTIVES

4.1 TECHNOLOGIES AND MEASURES

Technologies and innovations

Across the range of Best Available Techniques, Best Environmental Practices, Market-based instruments and legislation, it is clear from UNEP (2016) that there are many solutions that exist which have guidelines, and which can already be applied to reduce marine litter and microplastics. By implementing BAT-based policies, governments and industry can deliver a high level of environmental and human health protection and contribute to achieving progress towards Sustainable Development Goals, notably Target 12.4 on the environmentally sound management of chemicals and waste. Enforcement of BAT-based emission standards for example, also ensures a level playing field for industry and fosters more efficient operations (OECD 2018). However, the implementation of BAT or similar concepts generally requires a high level of resources especially in the area of waste management and industrial recycling of plastic materials.

There are a range of sectoral BATs and BEPs associated with waste management for example in incineration, waste collection and composting (see Section 1 and 2) (OECD 2018). However, looking into the future it will be important to see marine litter as part of the larger issue of how to move to more sustainable patterns of consumption and production based on a circular economy. In this context there are five key areas of innovation that will impact on marine plastic pollution. The first is Open Data - there are multiple platforms and groups around the world collecting a, processing and sharing data from locations around the world. The power of data analytics, data visualisation and artificial intelligence is helping to make sense of these huge volumes of information and driving greater awareness in the general public of the health of the oceans. Linked to this are the latest satellite operational and science missions such as the Sentinels which can deliver high resolution on an almost daily basis on marine litter in the surface waters and along shorelines and in rivers and lakes. Using specialised digital infrastructure blockchain technology (see section 3) offers an innovative solution to secure transactions which at one end enables industries to pull together fragmented supply chains and at the other enable consumers to potentially participate in small-scale waste collection and return schemes. These technologies put together, can help provide the evidence base for verifiable information across the plastic life-cycle and start to help uncover points of leakage, sources and sinks in the marine environment.

4.2 RISK REDUCTION APPROACHES

Improving standards

Improving product standards and their certification are important ways of reducing the hazards and risks associated with marine litter and microplastics. For the circular economy, this might mean developing improved standards relating to reuse, recyclability and compostability and labelling for a far wider range of products, especially in the packaging sector. This will require building greater consensus on what should be classed as ‘recyclable’ and the types of packaging that can be placed-on-market labelled as such, and how this can be built into both materials and infrastructure Non-recyclable packaging materials are likely to include PVC and PS in food packaging; in these situations clearer messaging, for example a yes/no labelling system based on the agreed recyclability designations, need to be introduced.

There remains a significant degree of confusion amongst consumers about the meaning of recyclability and biodegradability. Several years ago, plastic described as “degradable,” “oxo-degradable,” “oxo-biodegradable,” and “landfill degradable” (see Glossary) were being used to promote products made with traditional plastic supplemented with specific additives promoting degradability. Today these include film applications such as trash can liners, shopping bags, agricultural mulch films, landfill daily covers and plastic bottles. The term degradable means that the products undergo rapid degradation or biodegradation under many end-of-life conditions; this has built up expectations amongst recyclers and consumers that such products are easily disposed of. However, absence of light and oxygen, for example in landfills or on the seabed, coupled with moisture and very low temperatures can slow the degradation process down to a point where the fragments are likely to remain in the environment for a very long time and thus uncontrollable. There have been serious concerns amongst many plastic composting and waste management experts that these products do not meet expectations and can lead to less effective waste disposal because they cannot be properly managed or contained (Plastics industry Association 2018). In the past, government authorities have ruled against unsubstantiated claims of degradability that go beyond the standard specifications and set requirements for improvements in standard specifications and certification by third parties on the rate, time and amount of biodegradation. The risk remains however that labelling products as biodegradable without the evidence to support such claims leads to confusion amongst consumers and recyclers and may even increase littering. What is needed is a more precise sets of standards that address under real-life conditions of litter and microplastics in both riverine and marine environments and a clear process whereby the results of testing are made public and uploaded to consumer portal.

New waste management approaches

At the same time as stricter standards in products are sought, improvements in the standards of infrastructure need to be addressed. For example, as part of the UK's Plastic Pact 2025 Roadmap (WRAP 2018) there is a commitment to putting in place a comprehensive infrastructure for on-the-go (OTG) packaging. Linking waste infrastructure to smart labelling schemes can support automated pay on return schemes linked to on-the-go infrastructure.

In general, low- and middle-income countries highlight the need to improve collection and disposal techniques especially in island states. With the potential for tighter controls over shipments of waste under the Basel Convention coming into force in 2021, shipments of waste for recycling are forecast to decline for a number of developing countries (see Section 1, 3). This is likely to place a stronger focus on managing domestic waste locally; with the potential to target plastic if required. A range of steps are likely to be needed including development of incentives and infrastructure for recycling, increasing public awareness of the value of waste through education programmes and best available technologies for incineration and other processes (OECD 2018).

4.3 SOLUTIONS AND OPPORTUNITIES

Opportunities arising from the Sustainable Development Goals and Targets

The UN Sustainable Development Goals provide an opportunity for all countries to address the use of plastic in their economies and worldwide through key targets across several goals and well as those relating specifically to marine litter. These include prevention and significant reduction of marine pollution particularly from land-based activities (14.1), enhancing conservation and sustainable use and management of marine and coastal ecosystems (14.2, 14 c), increasing economic benefits in small island developing states (14.7), taking urgent action to reduce the degradation of natural habitats (15.5), sustainable consumption and production (12.1), sustainable use of natural resources (12.2), sound management of chemicals and waste throughout the life-cycle, (12.4) effective treatment of wastewater, and substantial reduction of waste (12.5), (6.3); and reversing adverse environmental impacts of cities through air quality, waste management and water treatment (11.6).

Life Cycle Approaches and Ecodesign

Products bring about impacts not just from their manufacturing, but also from the sourcing of raw materials for their production, their usage and end-of-life, as well as due to logistics for transportation. In moving forward with ecodesigns it is crucial that in the context of sourcing alternatives to some plastic, the full life-cycle impacts of the alternative materials as well as the reuse, and recycling value is also examined. Creating new markets for products made from recycled plastic materials rather than virgin stocks is also key to the success of reducing marine litter. Product design can also be used to reduce the propensity for certain items to be littered. For example, bottle lids could be tethered to bottles. Bottle lids are found more frequently than bottles in litter counts, suggesting they are either more frequently littered or captured by litter clean-up services less effectively.

In developing measures to regulate the use of single use plastic the European Union (2019) undertook a life-cycle analysis on for twelve widely-used single use plastic products and their single use non-plastic alternatives as well as reusable alternatives, with the aim of answering the following question: "If single use plastic products were replaced by either single use non-plastic alternatives or multi-use items, what would the impact be on greenhouse gas and air pollutant emissions?" The life-cycle study involved building life-cycle inventories of the single use plastic and their alternatives. Carbon dioxide ($CO_{2)}$, Methane ($CH_{4)}$ and sixteen types of air pollutants were considered. The criteria for selection of plastic alternatives were that: the materials of which single use non-plastic items were composed of, should avoid the generation of microplastics, alternative products met the same function as the plastic products that they substitute in terms of properties that the materials ensure, multi-use items needed to ensure that use of single use plastic was avoided, alternatives needed to satisfy broadly the same market. The analysis pointed to a number of solutions that could be implemented as part of the package of measures being developed, including ecodesign criteria, extended producer responsibility and certification schemes.

When a plastic product is designed from the beginning with an after-use pathway in industrial composting, for example, its degradation should result in improved compost or soil quality. In other words, the material output should hold value, in this case by ensuring the value of the soil. Additionally, it should be ensured that the fate of the product leads to an industrial composting plant, since the properties of the plastic may have adverse impacts on other recycling options. Not to forget that the degradation of the plastic may cause environmental problems if the product is mistaken as compostable by home composting or littered and expected to disintegrate naturally in the environment.

If the quality of the output materials meets expectations, it is more likely that the materials will be able to hold their value. Challenges originate in the various steps of the value chain. If a product is designed to be suitable for mechanical recycling in the after-use phase so that the output materials are of such quality that they can replace virgin raw materials, then it is reasonable to expect that the material will hold its value even after repeated reycling.

Products designed for mechanical recycling should find their pathways through separate collection schemes. At present, the most prevalent collection schemes for bottles made of PET are good examples of systems that support high-quality recycling where plastic hold value. Some member states use deposit refund schemes which incentivise users to return their bottles to the recycling system. Strong demand for PET compared to a still-limited supply of recycled resin, driven by the brand value of using recycled plastic, explains to some extent the relatively high price of recycled PET (rPET).

For short life-span plastic such as other packaging materials, design for mechanical recycling and systems for returning them to recycling should be preferred for reasons such as value, knowledge about the materials, the demand for recycled materials, and the reduction in environmental footprint. Mechanical recycling faces tough hurdles, such as the rapid increase in complex materials, and the struggle to separate complex materials such as composites, multi-layer materials, and associated adhesives.

Improved materials/waste management across the lifecycle of plastic

A full systems approach starting from design is an essential part of tackling the problem of marine plastic. For this to be implemented, the quality of recycled materials is key. Solutions to make products and packaging recyclable need to be considered in the design phase, when the fate of the products after their use should be determined. For example, which collection systems will be available, and for what kinds of treatment – mechanical recycling, chemical recycling, or industrial composting. Local conditions will also need to be taken into account.

Shifting efficiently from a take-make-dispose society to a circular economy where discarded products could contain materials that are less valuable than novel materials is a major challenge. Materials must retain their value in a second life to gain all the environmental benefits over the longer term, such as preventing waste to landfill, avoiding littering, and reducing emissions. Many types of plastic can technically be recycled several times and safeguarding the conditions that allow this is crucial.

The shift to using products made of bio-based materials, including plastic made of bio-sources, is sometimes presented as a solution in support of a bio-circular economy. However, the challenge with most present-day production technologies is that when the full manufacturing chain and lifecycle are taken into account, current bio-based plastic products may have a larger carbon footprint compared to fossil ones. Another challenge is that many novel bio-based plastic polymers are not necessarily recyclable by existing methods, and so may be lost after their first use

To promote circularity, raw materials from the most sustainable sources must be considered; and these include materials that are waste-based and bio-based. However, fossil feedstock is comparatively cheaper and easier to process, and consequently, has traditionally been considered the most feasible choice for raw material production. Mechanically or chemically recycled materials and bio-based materials must therefore endure fierce competition.

In the case of recycled feedstock from gasification or pyrolysis, those result in simpler chemicals which cannot directly be converted back to plastic. In other words, the resulting feedstock needs to be processed in several steps before becoming new polymers. While the output can theoretically be used very flexibly to produce new polymers, there are difficulties in developing techniques, as well as a lack of infrastructure and capacity. Moreover, new polymer production faces competition from other interests such as fuel production, which cannot be included in the calculation towards plastic recycling targets.

When mechanical recycling is used, the carbon footprint for recycled plastic expressed as Global Warming Potential (GWP) can be up to 10 times smaller and save 1.0–1.5 kg of CO_2/kg of resin compared to using virgin materials, thus supporting the EU’s low-carbon path. The ability to achieve high-quality recycled materials through mechanical recycling relies heavily on external factors upstream in the plastic value chain. Many decontamination technologies in mechanical recycling exist and are able to remove additives and inks, but they have not been widely introduced at scale.

As for chemical recycling technologies, they have the potential to supplement mechanical recycling, but should not be perceived as the silver bullet to deal with mixed waste and contaminated plastic. To achieve systematic change, downstream solutions must work hand in hand with upstream solutions in the plastic value chain.

It is generally acknowledged that low-quality recycling is not a sufficient basis for a circular plastic economy, as significant values are lost. Therefore, it is necessary to ensure the high quality of recycled materials. A clearer understanding of how different forms of recycling such as mechanical, chemical and organic recycling could work together would facilitate the development of systems for recycling plastic with varied compositions

Although there are forthcoming solutions for multi-layer materials that add chemicals to make their components mix better into a composite resin, the materials are not likely to hold their value, as their lifetime is likely to be very short. Avoiding multi-layer materials in the first place when they are unnecessary supports sorting and recycling and the retention of the material's value.

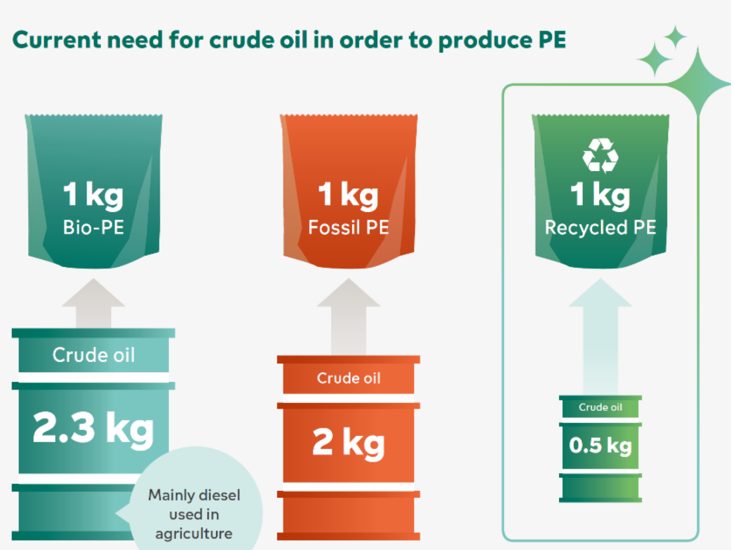

Figure 15 Comparisons of the use of virgin versus recycled plastic and the emissions of CO2 eq**.**

Social processes and community engagement

One of the biggest potential areas to make progress in preventing marine litter is through change in behaviour of consumers. In the first instance, changing behaviour towards shared services will help reduce the number of products that the economy produces overall and the demand for plastic. Information campaigns targeted at consumers use of plastic and the consequences for the oceans have been very effective in raising awareness worldwide. The abundance of plastic carrier bags on the sea floor around Europe has been found to have decreased since the onset of carrier bag charges across Europe, first brought in in 2002 (Maes et al. 2018). However, these campaigns now need to be underpinned by more localised actions and information. For example, campaigns might a) aim to improve consumers' understanding of the impacts of littering with the objective of reducing litter rates through beach clean-ups, or b) aim to reduce the incidence of sanitary items flushed down toilets and drains through visual materials, or c) focus on broader impacts of marine plastic, with the aim of encouraging consumers to take up available single use non-plastic alternatives, or start using multi-use items, instead.

Whilst information campaigns may have a general, population-wide character, mandatory labelling of widely littered items can also help deliver messages more directly to consumers. The effectiveness of such a measure depends on how clearly the message is conveyed, and how much of an impact the message has on those who currently litter the labelled items.

Voluntary actions, commitments and pledges can also be undertaken by consumers and industry alike, to bring about changes without the need for changes in policy. Voluntary agreements can involve a specific industrial sector, or category of producers, with some formal recognition can be given through gaining approval from Public Administration. Examples of the types of voluntary agreements include a) improvements in anti-littering messages on packaging, b) switching material use to alternatives which are demonstrated to degrade in the marine environment, c) supporting the provision of street/beach bin infrastructure, d) supporting litter clean up campaigns, e) implementing refill/reuse schemes in the tourism/hospitality/recreational sector, f) agreeing to offer discounts for those using own coffee cups, or g) funding the sorts of campaigns mentioned above.

Innovative economic instruments

A variety of economic instruments that have been proven to work in other fields have yet to be deployed in the prevention of marine litter and microplastics. These include bring-back/return schemes; withdrawal of perverse instruments; incentivisation of recycling existing materials multiple times; crowd-funding; urban-mining of scarce raw materials from returned products, extended producer responsibility schemes within which there are different charges for products based on their durability, repairability, reusability and recyclability and absence of hazardous substances.

Countries and regions are beginning to develop plastic strategies, in tandem with waste and recycling strategies. For example, the European Commission recognises that current legislation for packaging does not address design for recyclability, and in order to reach the target of 100% easily recyclable and reusable packaging by 2030, adjustments need to be made to the essential requirements for placing packaging on the market.

However, many of these instruments will not succeed unless information about the product components and chemical constituents is made available, so consumers and waste collectors can be incentivsied to return and reuse even very small amounts of materials and items.

Technologies for collection of marine plastic at sea and in rivers

A range of new tagging, tracking and marking of products and waste is being developed to increase traceabilty, accountability and retrieval of plastic (see Section 3). For example, the Ocean Clean Up (https://theoceancleanup.com/oceans/), is trialling a large collector based on long booms filled with air that float on top of the ocean held open by cables to funnel the debris into a central holding tank as well as a river based floating collector known as the Interceptor. Around the world there are many more smaller versions of booms and equipment similar to the Interceptor that are intercepting and collecting floating rubbish in rivers, harbour and ports. These various initiatives are playing a role in both raising awareness but also creating concentrations of waste that can be removed. Dams and reservoirs are also points at which plastic can be collected (see Section 3). The key issue is the post-collection disposal of the waste that has been collected; ideally public administrations should take these into the waste streams that are already being processed.

4.4 SUMMARY

i) There are many solutions amongst the Best Available Technologies, Best Environmental Practices, Market-Based Instruments that can help to tackle marine litter and microplastics. By implementing these, governments and industry can deliver a high level of environmental and human health protection and contribute to achieving progress towards Sustainable Development Goal Target14.1 and Target 12.4 on the environmentally sound management of chemicals and waste. However, the implementation generally requires a high level of resources especially in the area of waste management and industrial recycling of plastic materials.

ii) Looking into the future it will be important to see marine litter as part of the larger issue of how to move to more sustainable patterns of consumption and production based on a circular economy. In this context there are five key areas of innovation that will impact on marine plastic pollution. These include Open Data, data analytics, use of satellite and other tracking technologies, digital infrastructure such as blockchain technologies, linked to physical infrastructure such as on-the-go return and repayment repositories, and life-cycle systems as part of the circular economy.

iii) Risk reduction approaches are necessary. This includes improving product standards and their certification relating to reuse, recyclability and compostability and labelling for a far wider range of products, especially in the packaging sector. This will require building greater consensus on what should be classed as ‘recyclable’ and the types of packaging that can be placed-on-market labelled as such, and how this can be built into both materials and infrastructure. Clearer messaging, for example a yes/no labelling system based on the agreed recyclability designations, need to be introduced.

iv) New waste approaches linked to strategic roadmaps for the development of new intelligent waste infrastructure are needed. Examples include linking waste infrastructure to smart labelling schemes which can support automated pay on return schemes linked to on-the-go infrastructure.

v) Opportunities and solutions have arisen through the UN Sustainable Development Goals, and through the wider deployment of life-cycle analysis in support of the circular economy. Examples include the use of LCE in the ecodesign of alternatives to single use plastic; improved quality and hence value of recycled materials and products; and improved materials for and from recycling processes.

vi) A range of social processes are helping to support the fight against marine litter; public campaigns to improve consumers' understanding of the impacts of littering with the objective of reducing litter rates through beach clean-ups, or to reduce the incidence of sanitary items flushed down toilets and drains through visual materials, or to encourage consumers to take up available single use non-plastic alternatives, or start using multi-use items, instead; mandatory labelling schemes; voluntary actions and agreements.

vii) A variety of economic instruments that have been proven to work in other fields have yet to be deployed in the prevention of marine litter and microplastics. These include bring-back/return schemes; withdrawal of perverse instruments; incentivisation of recycling existing materials multiple times; crowd-funding; urban-mining of scarce raw materials from returned products, extended producer responsibility schemes within which there are different charges for products based on their durability, repairability, reusability and recyclability and absence of hazardous substances.

viii) New technologies for collecting litter and debris in the marine and freshwater environments have also begun to emerge. Whilst these may not be practical for areas in the ocean other than the large concentrations around gyres; collection in estuaries and rivers will help reduce flows into the coastal environments. It is however unlikely that reclaiming plastic from the ocean will be a viable or practical way of reducing plastic and microplastics in the marine environment.

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SECTION 5. KEY RESEARCH AND DEVELOPMENT

5.1 RESEARCH AND TECHNOLOGY

Overview

UNEP (2016) identified a range of key research needs. In summary these were on i) properties of plastic including ways of minimising the use of additive chemicals known to have an impact on the environment, including combinations to reduce the likelihood of desorption once ingested; ii) sources and pathways of marine litter, including quantification of inputs from fisheries and aquaculture and the factors leading to losses of gear, from shipping and offshore sectors, tourism, waste management, and storm sewers through catastrophic events; sources and pathways of microplastics including quantities and relative importance of primary and secondary plastic and the relative contribution of different size, shape and composition, including resin pellets; riverine and atmospheric inputs and wastewater; iii) distribution and fate, specifically the factors controlling degradation, including definitions and specifications of biodegradable products; iv) monitoring specifically the development and use of harmonised monitoring techniques to facilitate intercomparisons, development of automated technologies and modelling to look at patterns of movement and deposition; v) impacts – specifically quantification of the impacts of macro-plastics on biota, population and ecosystem wide effects, use of plastic for rafting organisms, including non-indigenous species; rescue and recovery techniques for entangled species; the effects of micro(nano)plastics and potential risks for food webs and human consumption, clarification of the fate of contaminants on microplastics and identification of hotspots; vi) social impacts including consumer perceptions, behavioural drivers and effective messaging for campaigns; vii) economic impacts – improving the assessment and understanding of the cost of non-action and how to apply this to develop new forms of governance and decision-making; viii) fisheries and aquaculture – quantification of releases of debris and litter, practices and operations, and the potential for gear marking; impacts of ghost fishing, risk assessments for aquaculture operations; assessment f chemical contaminant transfer to seafood; ix) risk assessments – improved integrated, holistic methodologies, including estimates of uncertainties; x) economic dimensions – improved assessments of economic impacts, determination of the value of plastic, of reducing the use and of recycling, elasticity of demand and different incentives.

Since the publication of the 2016 report, a significant number of countries have put in place specific actions to tackle marine litter and plastic including the research needed to address knowledge gaps. The major areas of increased research, technology and knowledge has been on the scale of global production, new materials and eco-designs, the uses of plastic in packaging and post-consumer consequences, on land-based uses in sectors such as agriculture of microplastics, on marine surface distributions of floating plastic, on the pervasiveness of litter and microplastics in the marine environment and potential pathways. However, the published literature contains very limited data on quantifiable measures of harm from marine litter and microplastics to humans and marine organism, on the direct measurements of volumes of litter and plastic from the different sources in the environment, on the life-cycle of plastic and measures needed in terms of moving towards a plastic within a circular economy or on the socio-economic drivers.

Regional perspectives

Global initiatives which provide opportunities for developing a greater understanding of the impacts and ways of preventing marine litter and microplastics are IMO MARPOL Convention through which information on sea-based sources of litter can be derived; the FAO Code of Conduct for Responsible Fisheries which addresses port-reception facilities, storage of garbage on board and the reductions in abandoned, lost or otherwise discarded fishing gear (ALDFG) and The Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), which is the only global intergovernmental mechanism directly addressing the connectivity between marine litter and prevention from land-based sources.

At the G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth, Karuizawa held in June 2019, the G20 Implementation Framework for Actions on Marine Plastic Litter was established and endorsed by the G20 Leaders at the subsequent G20 Osaka Summit. As a common global vision, the Osaka Blue Ocean Vision aims to reduce additional pollution by marine plastic litter to zero by 2050 through a comprehensive life-cycle approach that includes reducing the discharge of mismanaged plastic litter by improved waste management and innovative solutions while recognizing the important role of plastic for society. Under the G20 Implementation Framework, members will share and update information on relevant research.

In 2019, the European Union launched its new Horizon Europe research programme, inspired by the Apollo 11 mission, aimed at delivering solutions in five areas of research and innovation: these include cancer, climate change, healthy oceans, climate-neutral cities and healthy soil and food. Each of these is likely to be touched upon by plastic and its future role in a circular economy.

Marine plastic research is rapidly developing within the 10 ASEAN countries. Indonesia is the most extensive information provider, followed by Singapore and Malaysia. Most of the research is focused on monitoring and surveying of plastic in marine environment and the impact of plastic on marine ecosystems. However, the impact of marine plastic on human health and life has not attracted much attention. Regional countries have organized a series of regional forums and workshops to increase understanding of marine plastic pollution and share and find solutions. In addition, a few regional initiatives have been implemented by regional counties. However, most of the current activities still stay on increasing understanding. The implementation of further movements, such as binding policies, laws and changes in administrative measures, is at early stage. In addition to ASEAN, several other intergovernmental organizations are also promoting actions, plans and research projects in Southeast Asia region. Among them, COBSEA is the leading actor. In terms of public outreach, NGOs have played a key role in this aspect. Overall speaking, countries in ASEAN have recognized the importance of marine plastic pollution. However, both the research and the actions still need further improvement.

5.2 AREAS OF RESEARCH GAPS AND TIME FRAME

Since the release of the UNEP (2016) report, there has been a shift in public perception and government action towards banning single use-plastic and plastic more generally (see section 1). This has opened up new avenues of research needs to better understand the pros and cons of replacing plastic within the global economy in clothing and items such as bags, cups, utensils and a range of personal healthcare and cosmetic products.

Informatics and monitoring

i. Building a global mass balance model estimate for the next decades, to explore scenarios such as zero plastic emission or 100% waste recovery;
ii. Life cycle analysis of plastic including biodegradable plastic that have been commercialized such as starch based plastic, bacteria-based plastic, soy-based plastic, cellulose based plastic, lignin-based plastic and natural fiber reinforced plastic;
iii. Use of blockchain technologies to improve traceability and transparency across the life cycle of plastic;
iv. Improving monitoring methodologies and technologies, data and indicators to assess the impacts of marine litter including:
    - monitoring of litter in freshwater environments, rivers and lakes and the underpinning methods and technologies. Rivers are crucial for understanding the relationship between *sources* and the *sink* of marine litter
    - improvements in laboratory and field assays of microplastics
    - indicators and targets on Wastewater Treatment Plants that measure litter retained or discharged to enable the assessment of specific sources of litter (e.g. disposal in domestic toilets and drainage in the case of combined sewerage systems).
    - specific applications of earth observation technologies and remote sensing (satellites, drones, automated measurements at sea) to provide continuous monitoring of plastic litter on beaches and in surface waters over a broad spatial scale and a short temporal scale and provide data coverage of point and diffuse sources of plastic waste.
    - indicators on socio-economic impacts of marine litter, especially human and wildlife exposures and health
    - comparability of indicators across different land-sea domains. Moving towards a more integrated structure for solutions, will require harmonised monitoring methodologies and efforts.
    - holistic “source-to-sea” framework to enable life cycle analysis of plastic and integrated assessments on the origins, pathways, abundance and effects of marine litter. Marine litter and waste indicators are often expressed in different units (number of items/area or/volume vs mass/year or /capita) which hinders comparison and integration. Solid waste data do not identify plastic items in detail, marine litter is often expressed as number of items.

Materials science

i. New chemistries and materials that provide characteristics such as flexibility and recyclability with low potential post-consumer hazards;
ii. Ecodesign and life-cycle analysis for the use of plastic and their substitutes across sectors.

Toxicology and health

i. Source-to-sea framework for determination of what good status/healthy means for freshwater and marine environments in relation to plastic litter and microplastics;
ii. Health (human and environmental) exposure and impacts of micro(nano)plastics from mismanaged waste, especially on beaches, coastal areas, lakes and rivers, including critical thresholds and most critical exposure pathways
iii. Chemical toxicity of plastic and microplastics during manufacture, which could be released to the environment. Research has identified that many of these chemicals can have toxicological effects on fish, mammals and molluscs, hence a risk could exist if plastic fragments containing these chemicals are ingested by marine organisms;
iv. Effects of microplastics ingested by marine animals;
v. Persistent organic pollutants and the extent to which plastic debris absorbs persistent organic pollutants (POPs) such as PCBs, DDE, and nonylphenols (NP) under field conditions in the oceans.
vi. Micro(nano)plastics and the potential toxicity of different types and sizes of nanoplastics (particles smaller than 100 nm) to marine organisms and consumers. The available data show that nanoplastics may affect negatively organisms from different phyla with reported effects ranging from alterations in reproduction to mortality. Nevertheless, no information on marine vertebrates (e.g. fish) was found. Data show a high potential for bioaccumulation/biomagnification along marine food chains, since they can easily be retained inside organisms. The lack of standardized methodology for nanoplastics detection and the poor or inexistent legislation makes nanoplastics an environmental challenge.

Socio-economics

i. Market mechanisms and economic instruments;
ii. “Power to X” and other options for fossil-fuel-free plastic, including cost and environmental comparisons
iii. Social and behavioural analysis, cost of inaction and co-benefits of different interventions
iv. Smart use of plastic based around
    - product design that enables increased reuse
    - new circular business models for plastic
    - alternative materials for food packaging and on-the-go products

Technologies

i. Technologies to avoid or reduce micro- and nanoplastics in nature
ii. Recycling of plastic including
    - assessment of potential mechanical recycling of consumer and industrial plastic
    - technologies for improved sorting and collection, including AI, robotics, and advanced sensors as well as potential implementation road map
    - technologies to detect, measure, and remove substances of concern from plastic
    - technologies for recycling of complex plastic waste, e.g., chemical recycling
iii. Technology and cost road maps for sustainable bio-based plastic

Short and long-term actions

In the short-term (by 2022) it will be important to undertake research and development to:

- establish the informatics and monitoring frameworks, including standard methodologies for sampling, laboratory testing and data collection to establish the fluxes and flows of plastic into the marine environment and toxicology of microplastics and additives in the environment emanating from plastic waste

- define the core set of indicators, from source to sea, across the DPSIR framework to monitor progress on the reduction of marine litter and microplastics

- establish alternative materials, based on a full life-cycle approach, for the most prevalent single use plastic items and fishing gear found in litter and develop cost road maps for the switch

  - develop open access certification and traceability schemes for all plastic and clear labelling schemes that are linked to them for consumer use

  - raise awareness of the issue of plastic in the marine environment and help to change human behaviours towards those that reduce mismanagement of plastic waste

In the longer-term (by 2024) it will be crucial to have undertaken research and development on:

- building a global mass balance model and life cycle analysis of the use of plastic across all major sectors, especially the maritime sectors, and the establish the impacts on resource use, greenhouse gas emissions, and the potential for moving to zero plastic emissions

- the health and toxicological criteria and testing needed to establish exposure of humans and wildlife to microplastics in aquatic environments

- research solutions for technologies to avoid or reduce micro(nano)plastics in nature across the life-cycle of plastic

- ecodesign principles with major sectors, with a particular focus on the maritime industries i.e. fisheries, aquaculture, offshore operations, shipping and tourism and develop cost road maps.

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SECTION 6. MAIN CONCLUSIONS AND RECOMMENDATIONS

6.1 MAIN CONCLUSIONS

Plastic is found throughout the marine environment, making up at least 80% of all marine litter and are being ingested by all forms of marine life, including birds. Single use plastic and fishing gear represent 84% of marine litter, but there is insufficient evidence as to the concentration or extent of uptake of micro(nano)plastics in the marine ecosystems.

Globally, cumulative plastic production has reached 9.2 billion and is projected to grow to 1.1 billion metric tonnes, rather than 1.8 billion previously forecast. Nearly three quarters of demand comes from packaging, construction and the automotive industries; the drivers of this demand are linked to durability and flexibility of plastic, the low cost and the convenience provided by many consumer products. Less than 1% of production coming from biomass-based sources. Information on the polymers that make up plastic is available but there is little accessible data on the different additives being used, which can represent as much 7% by mass of total production.

Of the three major fate pathways of plastic,10% goes into recycling, 14% into pyrolysis, 26% is disposed of in managed landfills and 50% mismanaged. Today 80 million metric tonnes are inadequately disposed of globally per year. with the forecast for discarded waste rising from 5000 metric tonnes today to 12,000 by 2050.

Over the past 30 years, 168 million metric tonnes of recyclable waste has been generated. Recycling rates of plastic globally remain very low compared to other resources such as paper (53%), iron (70%) and steel (98%). There is a significant loss of value in plastic due the mixed and unknown nature of secondary waste streams; for post-consumer packaging alone these amount to 80-120 billion USD per year. The recent changes to regulatory regimes and national policies will significantly affect the global trade of plastic waste.

The major land-based sources of marine litter and micro(nano)plastics come from mismanaged waste streams, and inputs from agriculture and transportation, via rivers and airborne transport. However, due to inconsistencies in testing procedures and a lack of data little is known about groundwater or aquifer transmission of micro(nano) plastics. The major sea-based sources include fisheries and aquaculture, and shipping. There are no estimates of direct inputs from coastal and sea-based tourism. Beach litter is mainly comprised of ten major items of single use plastic and fishing gear. Estimates of total volumes of waste entering via rivers and mismanaged waste from populations living within 50 km of the coastline range from 4.8-12.7 million metric tonnes.

There are multiple pathways taking plastic into the ocean, including soil run-off, riverine and wastewater flows, airborne transmission and direct inputs. Surveys of freshwater systems using very fine mesh nets indicate that concentrations of microplastics is three orders of magnitude higher than previsouly recorded. However, there are too few published data sets from monitoring prorammes or studies of individual rivers or at the catchments level, to make it possible to undertake time series analyses or estimate accurately the volumes of these flows. Poor testing standards, a lack of standardised laboratory procedures and field measurements make it impossible to determine with any confidence, the fluxes and flows of micro(nano)plastics between compartments, such as from the water column to the benthos and from snow and sea ice in the polar regions into surface waters.

The chemical and physical properties of plastic are vital in determining their buoyancy and density in aquatic systems and hence propensity for airborne transmission, movement in surface waters, the water column and sedimentary compartments. The presence of biofilms and bacterial growth also affects buoyancy and the rate of biodegradation, which is generally slower than on land. In recent mesocosm experiments, biodegradable plastic in the presence of different bacterial communities did not degrade even after three years.

There is evidence that microplastics act as transport media for pathogenic bacteria and that the proto communities on microplastics differ from the surrounding community and encourage plasmid and pathogenic bacteria to grow. It is important to understand the dynamics of bacterial communities as these will determine the rate biodegradation of marine litter and microplastics.

The major hazards of plastic to marine organisms are the lethal and sub-lethal effects of entanglement, smothering and accumulation of plastic through ingestion, which can in turn alter the structure of ecosystems and put key species at risk. Marine litter and microplastics are risk multipliers, not only affecting marine ecosystems directly but also through the greenhouse gas emissions taken to make them and the effects they can have on emissions once in the oceans plus the release of legacy chemicals and substances of very high concern.

Human health issues can arise through contamination of land-based foods resulting from open-pit burning of plastic collected from beaches and coastal areas. There is also the potential for micro(nano)plastics to affect human health via consumption of seafood; however, there is no confirmatory evidence of high concentrations of microplastics from field sampling.

Ecosystem health effects include alterations in species composition, assemblage structure and loss of biodiversity; there is also an indication that fungal and sedimentary invertebrate communities can be affected by nanoplastics. However, the data are too limited to draw any comprehensive conclusions on the overall hazards and risks posed by micro(nano)plastics on marine ecosystems.

Monitoring of plastic litter has primarily focussed on the marine domain and determining the state and impacts. However, the lack of agreed methodologies and indicators for many forms of plastic, across all environmental compartments, plus the complexity of factors affecting the distribution of litter in the sea, means that the overall impacts of marine litter and microplastics are still not well understood.

Establishing baselines for marine litter and microplastics requires agreements on definitions, what is to be measured, where and how often and a series of indicators. As yet standard sampling protocols have yet to be agreed for marine litter and microplastics.

Several indicator processes are underway to support the UN Sustainable Development Goal 14 target 1. Examples include GESAMP, with a focus on the marine component; US MDMAP looking at Marine debris and litter; and the EU looking at indicators that run from source to sea using the Drivers, Pressures, State, Impacts and Responses framework.

New guidelines and emerging sampling technologies will help in catchments and basin-scale monitoring of plastic and marine litter; these include Unmanned Autonomous Vehicles, survey photographing, plus a number of new global satellite missions that can provide data on different aspects of litter from multispectral and radar instruments.

The complexity and scale of monitoring marine litter and microplastics requires a greater capacity and willingness to share data and information. Data sharing protocols and open data platforms will be needed; examples of existing platforms that can be linked to the main platform, the Global Partnership on Marine Litter Platform, include EMODnet, the Global Partnership for Sustainable Development Data and regional platforms such as the Africa Regional Data Cube.

Citizen science initiatives are playing an increasingly important role in collecting data on marine litter and physically removing litter from beaches, estuaries and coastal environments such as mangroves. A number are listed.

Traceability is vital for tracking constituents and additives across the plastic supply chains, for determining the sources and sinks of plastic in the circular economy, to identify leakages into the marine environment and to enable consumers to check the source and make-up of a product. The recent uptake of blockchain technology in the plastic industry will enable flows of materials across a fragmented supply chain to be tracked.

Certification and labelling schemes are also vital, as traceability in the industry does not necessarily lead to open data and transparency for consumers. However, current systems are very limited, not standardised and do not reflect real-world conditions in testing.

Transboundary movement of waste falls under the Basel Convention. Recent changes in the marketplace and amendments to the convention on which waste can be transported means that improved traceability systems will be needed, to cover waste being shilled to locations where there are high background levels of mismanaged waste.

Extended Producer Responsibility is an important concept and measure that can help in tackling marine litter and microplastics. To date there are only a few numbers of items that have come under the EPR and many manufacturers would not agree to taking on responsibility for the entire life cycle of plastic.

There are only a limited number of manufacturing and processing standards for plastic which are relevant to marine litter and microplastics, such as from ISO, but as yet no specific labelling schemes e.g. for microplastics in seafood.

There are many solutions available amongst the Best Available Technologies, Best Environmental Practices, Market-Based Instruments that can help to tackle marine litter and microplastics. However, the implementation generally requires a high level of resources especially in the area of waste management and industrial recycling of plastic materials.

Marine litter needs to be seen as part of the larger issue of how to move to more sustainable patterns of consumption and production based on a circular economy. There are five key areas of innovation that will support this, including Open Data, more public access to data analytics of the plastic industry, use of satellite and other tracking technologies, digital infrastructure such as blockchain technologies linked to physical infrastructure such as on-the-go return and repayment repositories, and life-cycle analysis of products and services.

Risk reduction approaches are necessary. This includes improving product standards and their certification relating to reuse, recyclability and compostability and labelling for a far wider range of products, especially in the packaging sector. This will require building greater consensus on what should be classed as ‘recyclable’ and the types of packaging that can be placed-on-market labelled as such, and how this can be built into both materials and infrastructure. Clearer messaging, for example a yes/no labelling system based on the agreed recyclability designations, need to be introduced.

New waste approaches linked to strategic roadmaps for the development of new intelligent waste infrastructure are needed. Examples include linking waste infrastructure to smart labelling schemes which can support automated pay on return schemes linked to on-the-go infrastructure.

Opportunities and solutions have arisen through the UN Sustainable Development Goals, and through the wider deployment of life-cycle analysis in support of the circular economy. Examples include the use of LCE in the ecodesign of alternatives to single use plastic; improved quality and hence value of recycled materials and products; and improved materials for and from recycling processes.

A range of social processes will be needed. For example, changing behaviour towards shared services will help reduce the amount of products that the economy produces overall and the demand for plastic. public campaigns to improve consumers’ understanding of the impacts of littering with the objective of reducing litter rates through beach clean-ups, or to reduce the incidence of sanitary items flushed down toilets and drains through visual materials, or to encourage consumers to take up available single use non-plastic alternatives, or start using multi-use items, instead; mandatory labelling schemes; voluntary actions and agreements.

A variety of economic instruments that have been proven to work in other fields have yet to be deployed in the prevention of marine litter and microplastics. These include bring-back/return schemes; withdrawal of perverse instruments; incentivisation of recycling existing materials multiple times; crowd-funding; urban-mining of scarce raw materials from returned products, extended producer responsibility schemes within which there are different charges for products based on their durability, repairability, reusability and recyclability and absence of hazardous substances.

New technologies for collecting litter and debris in the marine and freshwater environments have also begun to emerge. Whilst these may not be practical for areas in the ocean other than the large concentrations around gyres; collection in estuaries and rivers will help reduce flows into the coastal environments. It is however unlikely that reclaiming plastic from marine sediments will be a viable or practical way of reducing microplastics in the marine environment.

In the short-term (by 2022) it will be important to undertake research and development to:

- establish the informatics and monitoring frameworks, including standard methodologies for sampling, laboratory testing and data collection to establish the fluxes and flows of plastic into the marine environment and toxicology of microplastics and additives in the environment emanating from plastic waste;

- define the core set of indicators, from source to sea, across the DPSIR framework to monitor progress on the reduction of marine litter and microplastics;

- establish alternative materials, based on a full life-cycle approach, for the most prevalent single use plastic items and fishing gear found in litter and develop cost road maps for the switch;

- develop open access certification and traceability schemes for all plastic and clear labelling schemes that are linked to them for consumer use;

- raise awareness of the issue of plastic in the marine environment and help to change human behaviours towards those that reduce mismanagement of plastic waste;

In the longer-term (by 2024) it will be crucial to have undertaken research and development on:

- building a global mass balance model and life cycle analysis of the use of plastic across all major sectors, especially the maritime sectors, and the establish the impacts on resource use, greenhouse gas emissions, and the potential for moving to zero plastic emissions;

- the health and toxicological criteria and testing needed to establish exposure of humans and wildlife to microplastics in aquatic environments;

- research solutions for technologies to avoid or reduce micro(nano)plastics in nature across the life-cycle of plastic;

- ecodesign principles with major sectors, with a particular focus on the maritime industries i.e. fisheries, aquaculture, offshore operations, shipping and tourism and develop cost road maps.

6.2 RECOMMENDATIONS

Examples of recommendations (to be further developed):

Due to the pervasive nature of plastic in the oceans, tackling the problem of marine litter and microplastics should not be undertaken in isolation but in a holistic manner across the drivers, pressures, impacts, state and response.

Full life cycle analyses across plastic production, and the three major fate pathways of recycling, pyrolysis and managed and unmanaged disposal will help to identify areas and potentially curtail the losses to the value of both primary and secondary plastic waste.

Mismanaged waste from land-based sources is contributing potentially 50% of waste that goes into the oceans; this, together with unknown volumes of micro(nano) plastics arising from wastewater treatment plants, agriculture and transpiration, means that tackling marine litter and microplastics will require a more co-ordinated monitoring and management approach.

Improved standards and real-world testing for biodegradability of plastic and degradable additives are needed, including the rate of biodegradation under different bacterial conditions.

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ACRONYMS

Abbreviations and acronyms

ALDFG	Abandoned, Lost or otherwise Discarded Fishing Gear
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization of the United Nations
FT-IR	Fourier Transform Infrared spectroscopy
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
JECFA	Joint FAO/WHO Expert Committee on Food Additives
PBTs	Persistent, Bioaccumulative and Toxic Compounds
POPs	Persistent Organic Pollutants
SD	Standard deviation
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
WHO	World Health Organization

Common polymers

ABS	Acrylonitrile butadiene styrene
AC	Acrylic
EP	Epoxy resin (thermoset)
EPS	Expanded polystyrene
HDPE	Polyethylene high density
LDPE	Polyethylene low density
LLDPE	Polyethylene linear low density
PA	Polyamide (Nylon) 4, 6, 11, 66
PC	Polycarbonate
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PGA	Poly (glycolic acid)
PLA	Poly (lactide)
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane (also abbreviated as PUR)
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
SBR	Styrene-butadiene rubber
TPU	Thermoplastic polyurethane

Common chemical additives in plastic

BFRs	Brominated flame retardants
BPA	Bisphenol A
BPF	Bisphenol F
BPS	Bisphenol S
DBP	Dibutyl phthalate
DEP	Diethyl phthalate
DEHP	Di-(2-ethylhexyl)phthalate
FRs	Flame retardants
HBCD	Hexabromocyclododecane
NP	Nonylphenol
NPE	Nonyl phenol ethoxylate
PBDEs	Polybrominated diphenyl ethers (penta, octa and deca forms)
Phthalates	Phthalate esters
TBBPA	Tetrabromobisphenol

Common organic contaminants sorbed by plastic

DDT	Dichlorodiphenyltrichloroethane
HCHs	Hexachlorocyclohexane
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated

GLOSSARY OF TERMS AND DEFINITIONS

Biodegradable is when a material can be decomposed under the action of microorganisms (bacteria, fungi, algae, earthworms, etc.). The result is the formation of water, carbon dioxide and/or methane, and by-products (residues, new biomass) that are not toxic for the environment. Biodegradation is influenced by the physico-chemical (temperature, humidity, pH) and microbiological parameters (quantity and nature of microorganisms) of the environment in which it occurs. To be truly meaningful, the term “biodegradable“ must therefore be clarified and linked not only to a duration in time, compatible with a human scale, but also to conditions of biodegradation.

Bacterial biofilms are surface-associated bacterial communities which are embedded within an exopolymeric substance matrix.

Biodegradable plastic is a material that undergoes biodegradation under specified environmental conditions (a process in which the degradation results from the action of naturally occurring micro-organisms such as bacteria, fungi, and algae) and within a specified degradation time as per accepted industry standards. As of 2015, accepted industry standard specifications include, but are not limited to: ASTM D6400, ASTM D6868, ASTM D7081, ISO 17088 and EN 13432.

Bioplastics are materials that are either biosourced, biodegradable or both. It is for this reason that the term “bioplastic“ should never stand alone and why it is necessary to specify, each time this word is used, the plastic’s origin (biosourced or not) and end of life (biodegradable or not).

Biopolymers are natural polymers derived from renewable resources of plants or animals. They can be directly synthesized by plants or animals such as polysaccharides (starch, cellulose, chitosan, etc.), proteins (collagen, gelatin, casein, etc.) and lignins, or synthesized from biological resources such as vegetable oils (rape, soybean, sunflower, etc.). Other biopolymers, such as PHA, are produced by microorganisms (bacteria) through fermentation from sugars and starch.

Biosourced materials are manufactured, in part or in whole, from renewable biological resources, most often vegetable. The sources of raw materials are very varied. We find everything related to biomass, organic matter, in particular starches, sugars and vegetable oils.

Compostable anything that can be composted or be involved in a composting. There is industrial compostability domestic compostability. For industrial composter standards apply: ISO 17088, EN 13432, ASTM 6400.

Composting is an aerobic transformation process (i.e. in the presence of oxygen, unlike methanization which is an anaerobic reaction, i.e. without oxygen) of fermentable materials under controlled conditions. It helps obtain a stabilized fertilizing material, rich in humic compounds, called compost. It is accompanied by the release of heat and carbon dioxide. It is a process widely used, especially in agricultural environments, because compost helps amend soil by improving its structure and fertility.

Degradation of plastic is the partial or complete breakdown of a polymer as a result of e.g. UV radiation, oxygen attack, biological attack. This implies alteration of the properties, such as discolouration, surface cracking, and fragmentation. *Biodegradation* (see Biodegradable); *Mineralisation* in the context of polymer degradation, is the complete breakdown of a polymer as a result of the combined abiotic and microbial activity, into carbon dioxide, water, methane, hydrogen, ammonia and other simple inorganic compounds and *Compostable* (see Compostable); and *Oxo-degradable* (see oxo-degradable).

Marine litter has been defined by UNEP (1955) Environment as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Marine litter consists of items that have been made or used by people and deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; accidentally lost, including material lost at sea in bad weather (fishing gear, cargo); or deliberately left by people on beaches and shores.

Methanization (or anaerobic digestion) is the natural biological process of degrading organic matter in the absence of oxygen (anaerobic). It occurs naturally in some sediments, marshes, rice paddies, landfills, as well as in the digestive tract of some animals such as termites or ruminants. Some of the organic matter is degraded to methane, and some is used by methanogenic microorganisms for their growth. The decomposition is not complete and leaves the “digestate“ (partly comparable to compost), which requires composting in order to be stabilized. Methanization is also a technique used in “methanizers“ where the process is accelerated and maintained to produce usable methane (biogas). Organic waste can thus provide energy.

Microplastics are particles less than 5 mm (Arthur et al. 2009). They are classified as primary or secondary; both types of particles will be subject to similar processes in the ocean and fragment further if subject to UV radiation and mechanical abrasion.

Primary microplastics are purposefully manufactured to carry out a specific function (e.g. abrasive particles, powders for injection moulding, resin pellets for bulk transportation of polymers between manufacturing sites); and

Secondary microplastics represent the results of wear and tear or fragmentation of larger objects, both during use and following loss to the environment (e.g. textile and rope fibres, weathering and fragmentation of larger litter items, vehicle tyre wear, paint flakes).

Monitoring is the intent to measure the current status of an environment or to detect trends in space or time of environmental parameters. Monitoring should be performed systematically by harmonized sampling methods and a consistent data and metadata management procedure.

Oxo-degradable plastic or “fragmentable“, “oxo-fragmentable“, or even “biofragmentable“ or “oxo-biodegradable” are polymers of petrochemical origin containing mineral oxidizing additives that promote their degradation into small pieces (until they become invisible to the naked eye). This plastic can fragment, under certain conditions (light, heat, etc.), but are not biodegradable according to current standards. In addition, these additives seem to contain heavy metals whose environmental effects are currently unknown. The new European Single-Use Plastic (SUP) directive, approved by the European Parliament on March 27, 2019, provides for the prohibition of these oxo-degradable plastic, whatever their use.

Oxo-Biodegradation of plastic is degradation identified as resulting from oxidative and cell-mediated phenomena, either simultaneously or successively. (CEN TC249/WG9)

Plastic is defined as synthetic organic polymers with thermo-plastic or thermo-set properties (synthesized from hydrocarbon or biomass raw materials), elastomers (e.g. butyl rubber), material fibres, monofilament lines, coatings and ropes (GESAMP 2019). Plastic is produced as a mixture of different polymers and various plasticizers, colorants, stabilizers and other additives. Most plastic can be divided into two main categories: thermoplastics (capable of being deformed by heating), which include polyethylene, polypropylene and polystyrene; and, thermoset (non-deformable), which include polyurethane, paints and epoxy resins. About 15% of total synthetic polymer production consists of fibres, such as polyester and acrylic. Another significant component of plastic marine litter is semi-synthetic material, such as cellulose nitrate and rayon, made from biomass (UNEP 2018).

Plastic debris and litter There is no agreed or official text on how to exactly categorise plastic debris and litter, so the terminology used in this report follows that of GESAMP (2019):

Size categories arise out of function. For example, because of the mesh/filter sizes, regulation purposes, or environmental modes of action. Particles less than 5 mm are commonly termed microplastics whereas the terms meso-, macro-, and mega-plastic are used to describe larger particles. (Lusher et al. 2017) propose the following terms: Mega > 1 m; Macro 25 mm - 1 m; Meso 5 mm - 25 mm and Micro < 5 mm.

Shape categories are important indicators for their origin and their state of fragmentation or disintegration. Shape definitions are mainly of importance for particles less than 1 cm in size. Since larger particles often occur as whole items or larger fragments, it is often possible to categorize them as their origin such as bottles, bags or straws. Shape categorization for plastic debris in freshwater can follow the same guidelines given in GESAMP (2019). As with the size categories, there is currently no standardized scheme for the different shapes of plastic debris. The five shape categories used for marine litter, are 1) fragments or irregular shaped particles, crystals, fluff, powder, granules, shavings, 2) fibres/ filaments, microfibres, strands, and threads, 3) beads grains, spherical

microbeads, microspheres, 4) films/sheets, and polystyrene, expanded polystyrene foams 5) pellets resin pellets, nurdles, pre-production pellets, nibs (Lusher et al. 2017).
Colour can provide helpful information about the origin of the particles and their pathways but overall, colour is not regarded as a crucial parameter for categorization of plastic debris (GESAMP 2019, Hartmann et al., 2019).

Polymer refers to a molecule of high molecular weight consisting of a repetitive sequence of a large number of simple molecules called monomers, which may or may not be the same. The number of monomer units constituting the macromolecule is called the degree of polymerization. Polymers are generally polymolecular, i.e. they are composed of blends of molecules of different sizes. Sugars, starch and proteins are natural polymers synthesized by plants, animals or bacteria; these are called biopolymers.

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