Primary Microplastics in the Oceans:

a Global Evaluation of Sources

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FOREWORD

The invention of plastic based on a synthetic polymer in 1907 changed our lives forever – for better and for worse. Plastic is one of the most versatile materials ever produced and has revolutionised the way we package, eat, travel and dress.

The plastic revolution has however come at a cost. Plastic pollution in our marine environment is taking place on a staggering scale with 9.5 million tonnes of new plastic waste flowing into the ocean each year. This is impacting our planet's precious biodiversity and damaging the fragile ecosystems upon which we all depend. The widespread contamination of our oceans is also fast becoming a worldwide human health risk as plastic enters our food and water supplies.

Despite a growing body of work on plastic debris and a heightened global awareness of its global impact, remedial efforts to combat this pollution have been hamstrung by a lack of research and knowledge surrounding the original sources of the waste matter.

Primary Microplastics in the Oceans : a Global Evaluation of Sources helps fill this knowledge gap and provides an important reference point for decision makers as they design and implement the transformative policies and production practices we need to transition towards a circular global economy.

Following in the footsteps of the IUCN "Close the plastic tap" project and the "Plastic debris in the ocean" publication, this report provides a global estimate and mapping of the sources and quantities of primary microplastics – plastics that enter the oceans in the form of small particles released from household and industrial products.

Although mismanaged plastic waste is still the main source of marine plastic pollution globally, this report shows for the first time that, in some countries, more plastic may be released from our driving and washing activities than from the mismanagement of our waste.

Tackling the multitude of sources of marine plastics requires a holistic approach that addresses the problem at its source. The findings in this report must drive new thinking around the way we design, produce, consume and dispose of plastics. Action to turn off the plastic tap could come in the form of new engineered materials and smart design, such as clothes that shed fewer fibres or washing machines equipped with filters. These efforts must be supported by legislation and on-the-ground policies that force real change.

This report also reminds us that, as consumers of plastic, we have a responsibility to educate ourselves and adapt our behaviour in order to protect our blue planet.

We have a major challenge ahead. But with a collaborative global effort, we can reverse the grim forecasts for plastic pollution, and return to a world with healthy oceans.

Inger Andersen,
IUCN Director General

This report owes its existence to the outstanding support from *MAVA Fondation pour la Nature*. The *Swedish Postcode Foundation* and the *Gallifrey Foundation* are also acknowledged for supporting the launch of this report.

1. Abstract

Plastic has penetrated everyday life: from clothing to coatings and from transport vehicles to cleaning products. Plastic is cheap, durable, lightweight and malleable, resulting in a practically unlimited number of possible applications. The disadvantages of plastics however are becoming more and more visible. Large quantities of plastics leak into rivers and oceans, with adverse effects to marine ecosystems and related economic activities.

Plastic wastes include all size residues, from large visible and easily removable items, to small invisible particles. This report investigates the sources of primary microplastics i.e. microplastics that are directly released into the environment as small plastic particles (< 5 mm size). This contrasts with secondary microplastics that originate mostly from the degradation of large plastic waste into smaller plastic fragments once exposed to the marine environment. Primary microplastics can be a voluntary addition to products such as scrubbing agents in personal care products (shower gels, creams, etc.). They can also originate from the abrasion of large plastic objects during manufacturing use or maintenance such as the erosion of tyres when driving or the abrasion of synthetic textiles during washing.

This report is one of the first of its kind to quantify primary microplastics leakage and to demonstrate that these primary microplastics are globally responsible for a major source of plastics in the oceans. The model developed for this analysis enables us to conclude that between 15 and 31% of all of the plastic in the oceans could originate from primary sources. This is a significant but as-of-yet unrecognised proportion. In some countries benefitting from advanced waste treatment facilities, primary microplastics releases even outweigh that of secondary microplastics.

The global release of primary microplastics into the ocean was estimated at 1.5 million tons per year (Mtons/year). The estimate ranges between 0.8 and 2.5 Mtons/year according to an optimistic or pessimistic scenario. The global figure corresponds to a world equivalent per capita release of 212 grams or the equivalent of one empty conventional plastic grocery bag thrown into the ocean per person/per week worldwide.

The overwhelming majority of the losses of primary microplastics (98%) are generated from land-based activities. Only 2% is generated from activities at sea. The largest proportion of these particles stem from the laundering of synthetic textiles and from the abrasion of tyres while driving. Most of the releases to the oceans are occurring from the use of products (49%) or the maintenance of products (28%). The main pathways of these plastics into the ocean are through road runoff (66%), wastewater treatment systems (25%) and wind transfer (7%).

The study reviewed seven regions – Africa and Middle East, China, East Asia and Oceania, Europe and Central Asia, India and South Asia, North America, and South America. It revealed comparable releases per region in absolute value – ranging from 134 to 281 Ktons/year. The per capita releases, however, are very different between regions – ranging from 110 to 750 grams/person/year. Further, most regions are expected to have increased releases of primary microplastics in the next decades. This is due to improvements in per capita income without improvements in systems to prevent the releases.

Importantly this report is based on modelling sources and leakages from economic and household activities, using exclusively publicly available data and not on field measurements. The model could be further improved by using available fee-based proprietary data on regional plastic quantities. It could also be further strengthened by improving underlying regional assumptions on behaviours. Furthermore, confrontation of our predictive model with empirical data from the field would be beneficial in order to validate the model. This is however not feasible yet, given the status of literature and lack of adequate experimental set-up to perform this comparison. Nevertheless, the range of pessimistic/optimistic scenarios considered throughout our study allows for sufficient confidence in the orders of magnitude we put forward.

This report stresses the contribution of primary microplastics to the plastic pollution of oceans on a global scale. It opens the way to a new stream of actions to tackle the issue of plastics in the ocean beyond the traditional focus on waste management. Shaping these solutions will require approaches based on product eco-design and lifecycle thinking, as well as the involvement of key stakeholders from the private (e.g. textile and automotive industry) and public (water treatment and urban infrastructure planning) sectors.

2.

Introduction

Nowadays plastics have penetrated all aspect of everyday life from clothing to coatings and from transport vehicles to cleaning products. Plastic is a cheap, durable, lightweight, malleable material. It has a practically unlimited number of possible applications.

The disadvantages of plastics however are becoming more and more visible. Large quantities of plastics are released into rivers and oceans with various adverse effects to ecosystems and related economic activities.

Littering and mismanaged wastes are often referred to as the main source of plastics entering the ocean. However behind the headlines primary microplastics are becoming another major source of concern. Their release is much less visible, resulting from the voluntary addition of microbeads in products such as cosmetics or from the abrasion of larger plastic items such as textiles or tyres.

The purpose of this report is to provide one of the first global estimate and mapping of sources and quantities of primary microplastics released into the world ocean. It aims to provide new information to decision-makers and stakeholders to help them shape actions to close the plastic tap.

2.1 Plastics & microplastics contaminate the world ocean

Marine environments all over the world are contaminated with plastics (GESAMP, 2015). Plastics can be encountered in two forms: large plastic wastes, and small plastic particulates below 5 mm in size named microplastics (Thevenon et al., 2014).

Recent studies place the total amount of plastic produced since its invention at 8.3 billion tons (Geyer et al., 2017). Of this, an estimated 9% has been recycled (Geyer et al., 2017). Between 4.8 to 12.7 million metric tons of plastic waste are estimated to enter the ocean each year (Jambeck et al., 2015). Given these recent estimations and attempts to accurately quantify the problem, it is vital to understand the relationship between macro and microplastics when citing these numbers.

The estimate of between 4.8 to 12.7 million MT of plastic entering the ocean each year is an estimation of macroplastics (Jambeck et al., 2015). This is based on the mass of waste generated per capita annually, the percentage of plastic waste within that, and finally, the percentage of mismanaged plastic waste that has the potential to enter the ocean as plastic pollution. Therefore, the figures discussed in this report about primary microplastics are *in addition* to the estimations made in the Jambeck report, putting the overall quantity of both micro and macroplastics in the ocean at higher than the average and commonly-quoted value of 8 million metric tons.

Large plastic waste is readily visible. Studies have demonstrated negative social, economic and ecological impacts. These range from the ingestion, injury, entanglement or suffocation of wildlife to economic drawbacks for tourist areas and maritime industries (GESAMP, 2015; Raynaud, 2014). For a review of the many potential negative impacts of plastics on ecosystems, see Thevenon et al. (2014).

Microplastics are not easily visible to the human eye. While potential negative impacts are less obvious, their release into the oceans may also have far reaching consequences. Human health concerns are suspected through the accumulation of microplastics in the food chain and/or sorption of toxicants to plastic while traveling through the environment (Eriksen et al., 2014).

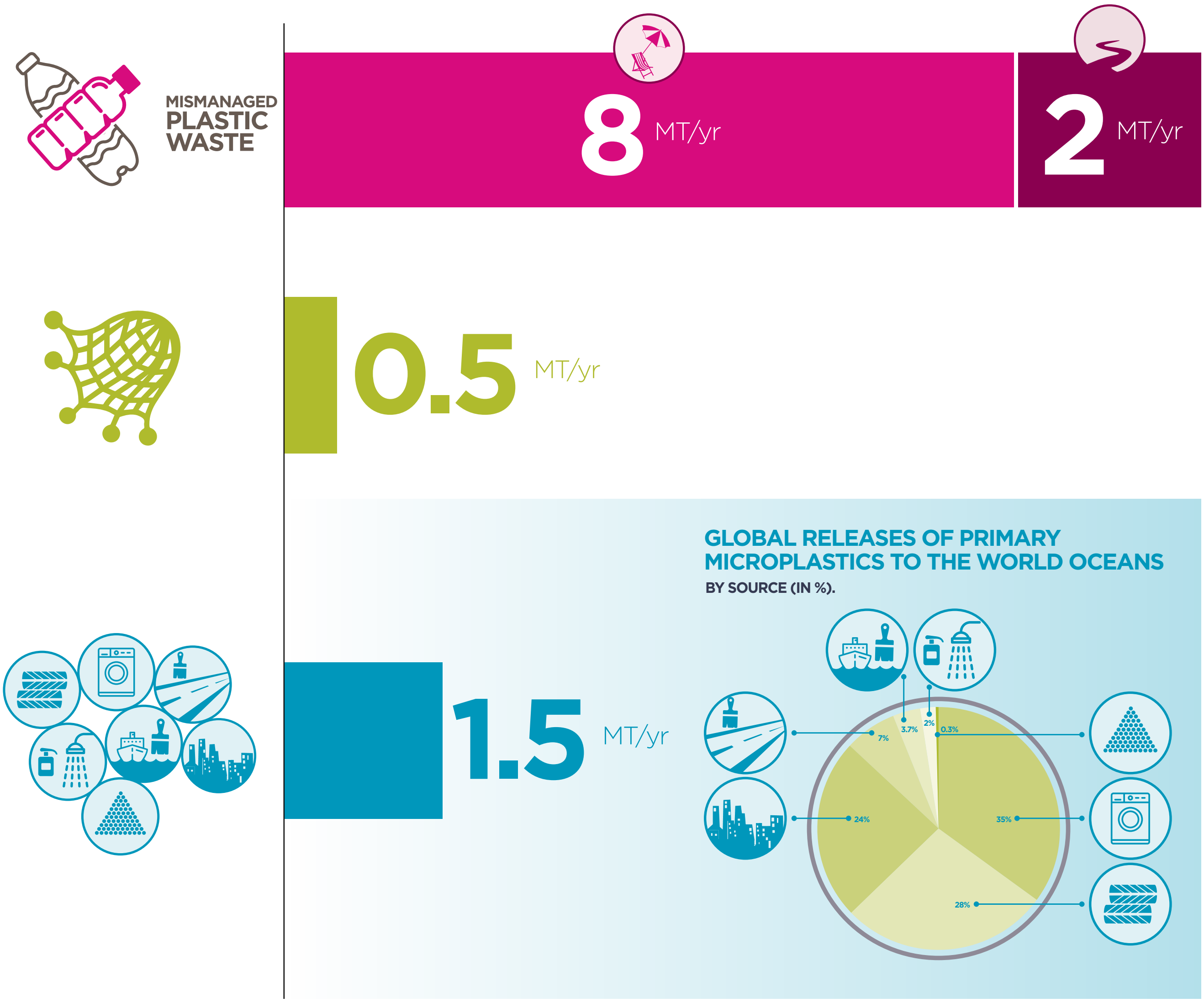
Two types of microplastics are contaminating the world ocean: primary and secondary microplastics. Different definitions have been used in the literature (Lassen et al., 2015) and we adopted the following as proposed by a Norwegian study (Sundt et al., 2014):

- **Primary microplastics** are plastics directly released into the environment in the form of small particulates. They can be a voluntary addition to products such as scrubbing agents in toiletries and cosmetics (e.g. shower gels). They can also originate from the abrasion of large plastic objects during manufacturing, use or maintenance such as the erosion of tyres when driving or of the abrasion of synthetic textiles during washing.

- **Secondary microplastics** are microplastics originating from the degradation of larger plastic items into smaller plastic fragments once exposed to marine environment. This happens through photodegradation and other weathering processes of mismanaged waste such as discarded plastic bags or from unintentional losses such as fishing nets. Given that the origins of secondary microplastics are difficult to trace given their degradation, it is difficult to meaningfully assess how much of the figures of macroplastics have now converted to microplastics. It is for this reason that the report seeks to focus on quantification of primary microplastics, as it is achievable within current data sets.

Once in the oceans, microplastics can either float or sink. Microplastics lighter than seawater such as polypropylene will float and disperse widely across the oceans. They eventually accumulate in gyres resulting from oceanic currents. Eriksen et al. (2014) and Sebille et al. (2015) estimate that 93 to 268 ktons of these microplastics are currently floating in the oceans. Other microplastics such as acrylic are denser than seawater and most probably accumulate on the ocean floor, which means that a significant amount of microplastics may eventually accumulate in the deep sea (Woodall et al., 2014) and ultimately in food chains (Seltenrich, 2015).

This ubiquitous contamination of oceans by microplastics is becoming a major concern. Given the magnitude and uniqueness of this global ocean contamination, some refer to the current period as the *plasticene* (Reed, 2016) and describe the world's ocean as a *plastic soup*[1].



2.2 Knowledge gaps about microplastics releases

There is a common belief that most of the plastics contaminating the world's ocean originate from mismanaged plastic wastes. Most recent reports on microplastics focus almost exclusively on the quantification of these secondary sources and on waste reduction and management (EUNOMIA, 2016a; Jambeck et al., 2015; McKinsey & Company and Ocean Conservancy, 2015; World Economic Forum et al., 2016). Jambeck (2015) reported that between 4.8 and 12.7 Mtons of plastic are released globally into the oceans every year because of mismanaged waste.

Knowledge about the global releases of primary microplastics into the world ocean is howeve rgenerally lacking. While many sources of primary microplastics have been identified in the literature, the global quantities released yearly have not yet been assessed. Consequently, the relative importance of primary versus secondary sources of microplastics is still unknown, and the plastic debate generally does not look outside of the waste management arena.

1 See: http://www.plasticsoupfoundation.org

The discovery of high levels of microplastic in the lakes and rivers in Europe, North-America and Asia (Eerkes-Medrano et al., 2015) might indicate that primary sources represent a significant release of microplastics into the oceans. One study showed that plastic abundance in the Austrian Danube was even higher than that of drifting larval fish, mostly in the form of industrial raw materials such a pellets and flakes (Lechner et al., 2014). Two other studies found that much of the plastic found in surface water originates from cosmetic products such as facial cleaners or from textiles (Browne et al., 2011; Driedger et al., 2015). In the recent assessments performed at country scale in Europe, Essel et al. (2015), Lassen et al. (2015), Magnuson et al. (2016), RIVM (2014), Sundt et al. (2014) identified and quantified around fifteen sources of primary microplastics. Tyres are often cited as the main contributor to the releases.

2.3 Rapidly increasing use of plastics

Today plastic is a common material that can be found in almost all parts of everyday life. This includes packaging, buildings and construction, vehicles, electrical and electronic equipment, agriculture production, clothes and footwear, householder and personal cleaning products. A practically unlimited number of applications are possible thanks to its unrivalled properties of durability, malleability, lightweight and low cost.

Plastic use has increased exponentially since synthetic organic polymers were developed in the mid-20th century. Over 300 million tons of plastic are currently produced yearly to manufacture objects in plastic. This quantity contrasts with only 1.5 million tons produced in 1950. The long-term average annual growth rate has been roughly 4% (PlasticsEurope, 2015). We can then add the plastics for other uses that are not accounted in these statistics[2] such as synthetic fibres for textiles (37.2 million tons) or synthetic rubber for tyres (6.4 million tons)[3]. Also, according to PlasticsEurope (2015), plastic production requires around 4% of the world's annual petroleum production while a similar amount of petroleum is used to provide the energy for plastic manufacturing.

Plastic use varies widely across regions. In North America and Western Europe, for example, the average plastic consumption *per capita* for plastics objects reached approximately 100 kg per year in 2005 and was expected to increase to 140 kg by 2015. In Asian countries, the individual consumption for plastics objects is much lower. It was about 20 kg per year per person in 2005 with an estimated increase to 36 kg by 2015. It is even lower in Africa with an estimation of 16 kilos *per capita* by 2015 (PlasticsEurope, 2009).

Due to the excellent functional properties of this material, it seems clear that plastic use will increase in the future, particularly in lower income regions as their economies grow. Solutions are thus required to close the plastic tap and to reduce the detrimental effects of plastic use on the world environment and potentially human health.

2.4 Objective of this report

The objective of this report is to provide one of the first global quantitative assessments of the direct releases of primary microplastics of petrochemical origin into the world's ocean. This report seeks to contribute to a better identification and prioritisation of the sources and pathways of microplastic pollution. With this information, decision-makers and key stakeholders can make informed decisions and undertake targeted actions to address the problem.

2 Other uses than plastic products are not accounted by plastic branch associations (personal communication from Plastics Europe).

3 References are provided in the methodological appendix.

3.

Description of issues & methodology

Seven major sources of primary microplastics are identified and evaluated in this report: Tyres, Synthetic Textiles, Marine Coatings, Road Markings, Personal Care Products, Plastic Pellets and City Dust. Losses in the environment and releases to the world ocean are quanitifed and presented in the following three scenarios: optimistic, central and pessimistic, and for 7 geographic regions.

3.1 Literature review of key sources

Plastics are used in many activities performed by businesses and by households on land or at sea. The main known primary microplastic sources are reported and classified in Table 1, based on data recently published from Denmark (Lassen et al., 2015), Sweden (Magnuson et al., 2016), Norway (Sundt et al., 2014), and Germany (Essel et al., 2015).

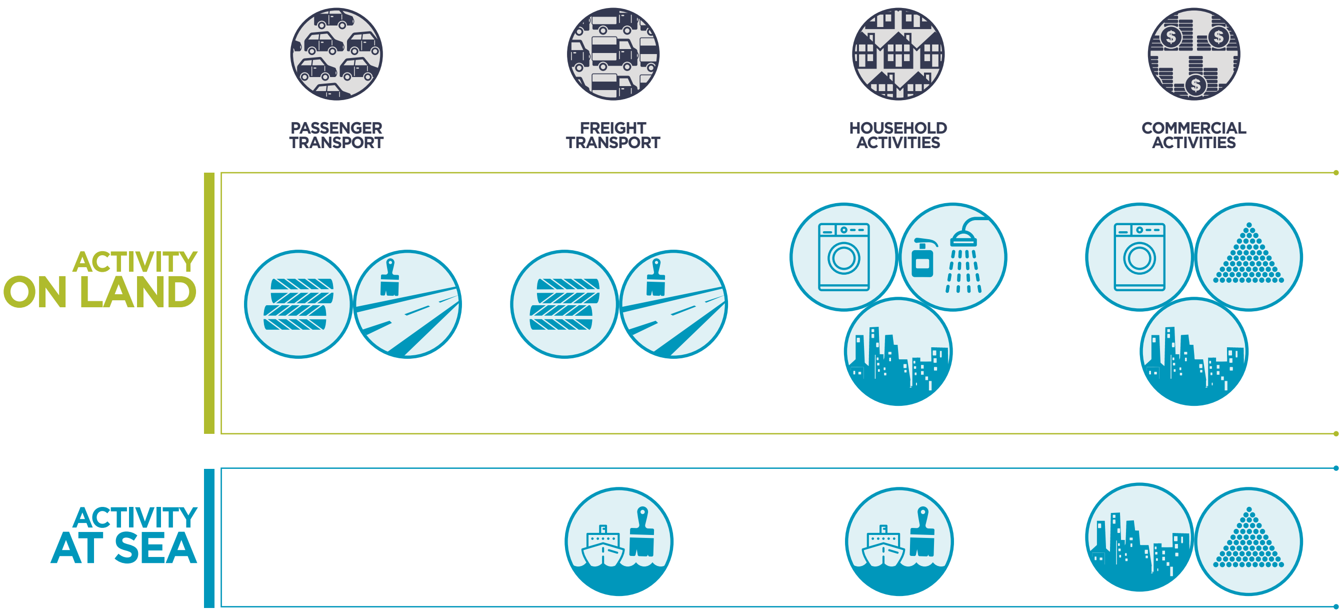
In our study losses and releases of primary microplastics are quantified at global scale for the seven sources identified as dominant in preceding studies. These are as follows:

These different sources stem from different household or commercial activities both on land and at sea, as presented in Table 1.

Table 1

MAIN SOURCES OF PRIMARY MICROPLASTICS

IDENTIFIED IN THE LITERATURE



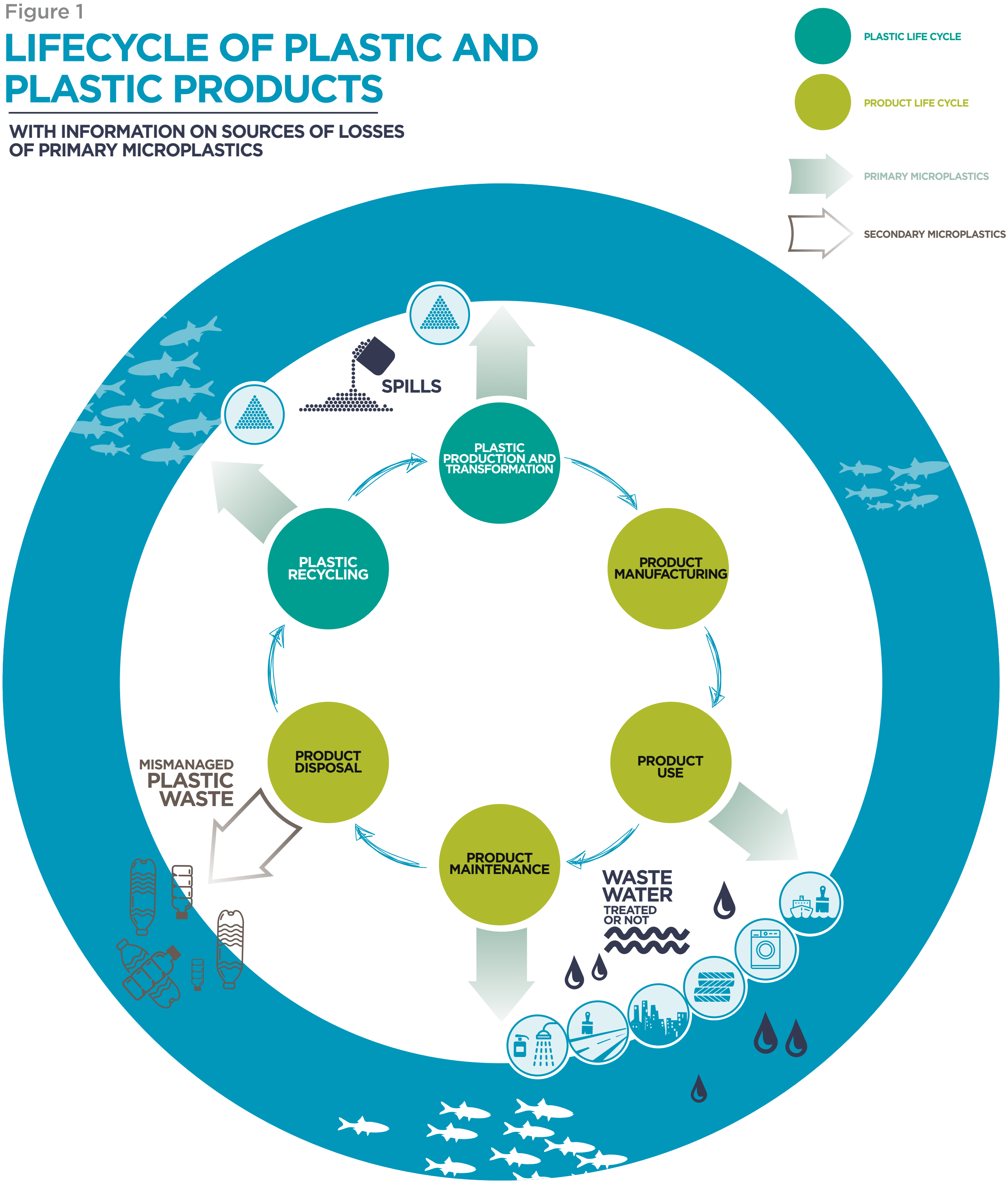
3.2 A lifecycle perspective of losses

Losses of primary microplastics occur at various stages of the lifecycle of plastic and plastic products (Figure 1). Plastic pellets are the only losses occurring during the production, transport or recycling stages of plastics. Most losses mainly occur during the use phase of products containing plastic such as driving a car or during their maintenance such as washing clothes. This contrasts with secondary microplastics that mostly originate from mismanaged waste during the disposal of products containing plastics.

Figure 1

LIFECYCLE OF PLASTIC AND PLASTIC PRODUCTS

WITH INFORMATION ON SOURCES OF LOSSES OF PRIMARY MICROPLASTICS



3.3 Description of seven key sources

The microplastic sources considered in this report stem from a global consumption of plastics of just over 300 Mtons, as presented in Table 2. Main uses are for plastic products which start their life as pellets (85%), for synthetic textiles (12%), and for synthetic rubber in tyres (2%).

Losses from Personal Care Products are the only losses that can be considered as *intentional losses*. The former is intentional because a product containing primary microplastics is poured on purpose into wastewater. By contrast other sources generate *unintentional losses* through abrasion, weathering or unintentional spills during production, transport, use, maintenance or recycling of products containing plastic.

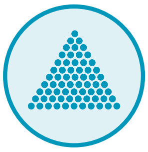
Table 2

CONSIDERED SOURCES

YEARLY WORLD CONSUMPTION AND TYPE OF LOSS

SOURCES	WORLD CONSUMPTION KTONS / YEAR OF PLASTIC	INTENTIONAL LOSS	REFERENCES
PLASTIC PELLETS	257,000	NO	Plastics Europe (2007)
SYNTHETIC TEXTILES	42,534	NO	FAO/ICAC (2013)
TYRES	6,431	NO	ETRma (2010)
ROAD MARKINGS	588	NO	Grand View Research, Inc. (2016)
MARINE COATINGS	452	NO	Coatings world (2012)
PERSONAL CARE PRODUCTS	42	YES	Leslie, H.A. (2015)

1. Plastic Pellets: incidents during manufacturing, transport and recycling



In their primary form, many plastics are in the form of pellets – typically 2-5 mm in diameter – or powders. Pellets are transported to plastic transformers that generate the plastic products. During manufacturing, processing, transport and recycling, pellets can be spilled into the environment through small or large incidents along the whole plastic value chain (Essel et al., 2015). Many field studies are reporting the occurrence of plastic pellets in the environment. These are also known as nibs, nurdles or mermaid tears (Sundt et al., 2014).

Type of loss: unintentional
Lifecycle stage: primary plastic production, primary plastic transport, plastic recycling

2. Synthetic Textiles: abrasion during laundry

Washing synthetic textiles, in industrial laundries and households creates primary microplastics through abrasion and shedding of fibres. Fibres are then discharged in sewage water (Browne et al., 2011) and potentially end up in the ocean (Magnuson et al., 2016).

Significant amounts of these textile fibres have been observed in many *in situ* sampling studies both in open water and marine sediments (Browne et al., 2011). These fibres are typically made of polyester, polyethylene, acrylic or elastane (Essel et al., 2015).

Type of loss: unintentional
Lifecycle stage: product maintenance

3. Tyres: abrasion while driving

Tyres get eroded when used. The particles are formed from the outer parts of the tyre and consist of a matrix of synthetic polymers, namely Styrene Butadiene Rubber (approximately 60%), in a mix with natural rubber and many other additives (Sundt et al., 2014). Tyre dust will then either be spread by the wind or washed off the road by rain. In this study, losses of synthetic rubber are considered but losses of natural rubber are not.

There is no reliable information on the transfer of microplastics from tyres to the world's oceans. Both Norwegian and Swedish researchers have pointed out that a large fraction of particles found in the sea seem to originate from car tyres (Essel et al., 2015; Sundt et al., 2014).

Type of loss: unintentional
Lifecycle stage: product use

4. Road Markings: weathering and abrasion by vehicles

Road markings are applied during the development of road infrastructure and its maintenance. Different types of markings (paint, thermoplastic, preformed polymer tape and epoxy) are applied, with a global dominance of paint (45%) (Grand View Research, Inc., 2016). In most European countries, thermoplastics are the most commonly used material (Lassen et al., 2015).

Loss of microplastics may result from weathering or from abrasion by vehicles. As for tyres dust will either be spread by wind or washed off the roads by rain before reaching surface waters and potentially the oceans.

Type of loss: unintentional
Lifecycle stage: product use

5. Marine Coatings: weathering and incidents during application, maintenance and disposal

Marine coatings are applied to all parts of vessels for protection including the hull, the superstructure and on-deck equipment. They include solid coatings, anticorrosive paint or antifouling paint. Several types of plastics are used for marine coatings including mostly polyurethane and epoxy coatings and also vinyl and lacquers (OECD Series on emissions documents, 2009).

Primary microplastics are released from commercial and leisure boats during building, maintenance, repair or use. The key activities that may lead to releases are surface pre-treatment, coating application and equipment cleaning (OECD Series on emissions documents, 2009).

Type of loss: unintentional
Lifecycle stage: product use, maintenance and disposal

6. Personal Care Products: pouring during product use

Plastic microbeads are used as ingredients in personal care and cosmetic products for a variety of purposes such as sorbent phase for delivery of active ingredients, exfoliation or viscosity. Some products contain as much plastic added as ingredients as the plastic in which they are packaged (Leslie, 2015). These represent up to 10% of the product weight and several thousand microbeads per gram of product (Lassen et al., 2015).

Classical use of personal care products results in the direct introduction of the plastic particles into wastewater streams from households, hotels, hospitals, and sport facilities including beaches. Microbeads from cosmetics have been observed in field studies in different areas of the world (Driedger et al., 2015).

Type of loss: intentional
Lifecycle stage: product use

7. City Dust: weathering, abrasion and pouring

City Dust is the generic name given to a group of nine sources identified in recent country assessments, that are most often occurring in urban environments (Essel et al., 2015; Lassen et al., 2015; Magnuson et al., 2016; Sundt et al., 2014). City Dust includes losses from the abrasion of objects (synthetic soles of footwear, synthetic cooking utensils), the abrasion of infrastructure (household dust, city dust, artificial turfs, harbours and marina, building coating) as well as from the blasting of abrasives and intentional pouring (detergents). These sources are grouped together because their individual contribution is small. However together they account for a considerable amount of losses in the country studies. In contrast to other sources that have been subject to specific and regionalised modelling, city dust assessment is based on more basic extrapolation from the Nordic countries studies (Lassen et al., 2015; Magnuson et al., 2016; Sundt et al., 2014).

Type of loss: mainly unintentional but partly intentional
Lifecycle stage: product use or maintenance

3.4 Modelling activities, losses & releases

This report is based on modelling sources and leakages from economic and household activities, using exclusively publicly available data. This report is not based on field measurements.

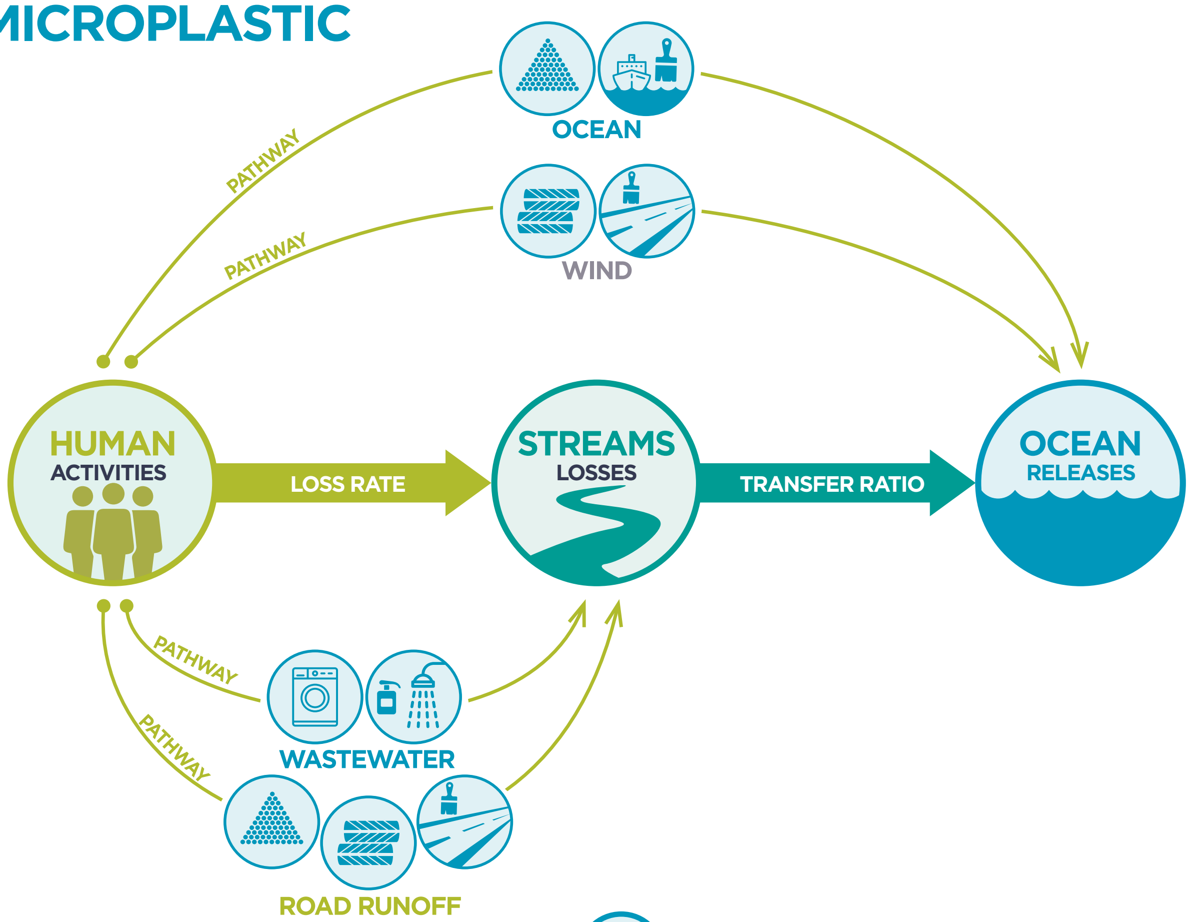
A general description of the approach applied to compute activities, losses and releases is presented in Figure 2. The detailed approach and references are presented in the methodological appendix of this report.

For each activity, the quantity of plastic used has been first computed at global and regional scales. Then the quantity of microplastics entering the environment – the "losses" – has been quantified by applying loss rates specific to each activity and region. In a final step, the fraction of the loss ultimately released into the oceans – the "releases" – has been computed applying appropriate transfer ratios. Transfer ratios are based on four different pathways presented below, and are also specific for different activities and regions:

- Ocean: when losses occur in the ocean (Plastic Pellets, Marine Coatings), 100% of the losses become releases.
- Wastewater: when losses are to wastewater streams (Synthetic Textiles, Personal Care Products) the transfer ratio depends on the regional coverage and efficiency of the wastewater treatment system.
- Road runoff: when losses are on roads (Plastic Pellets, Tyres, Road Markings), a share of the loss is transferred by wind while the other goes through road runoff. In the last case, the transfer ratio depends on the regional shares of roads connected to a separate sewer and to a combined sewer (hence treated in the wastewater treatment system).
- Wind: once the microplastics have been lost, they may be released into the oceans by wind.

Figure 2:

GENERAL DESCRIPTION OF THE MODELLING OF ACTIVITIES, LOSSES AND RELEASES OF PRIMARY MICROPLASTIC



The computations of activities, losses and releases have been performed in an iterative way. In a first step, the global relevance of each of the sources has been estimated at a regional scale. For all sources except City Dust, the estimation is based on the multiplication of generic loss and transfer ratios with regional populations and GDP (Gross Domestic Product).

For City Dust a global value has been estimated for losses based on existing quantified country studies (Lassen et al., 2015; Magnuson et al., 2016; Sundt et al., 2014). This global value has then been distributed to each region proportionally to previously computed losses. Different approaches for modelling have been tested and compared as described in Appendix 1, and allowed for testing the robustness of our model.

In a second step refined computations have been performed applying more detailed data and at the country level when available. A larger set of assumptions has also been tested to generate minimum and maximum bounds for the results using two complementary approaches: a first one based on yearly activities and a second one based on a lifecycle perspective.

3.5 Geographic regions considered

The grouping of countries has been done according to a classification in 7 regions: Africa and Middle East, China, East Asia and Oceania, Europe and Central Asia, India and South Asia, North America, and South America, as detailed in Appendix 3.

3.6 Three scenarios for presenting the results

In this report, the results are presented using three scenarios – optimistic, central and pessimistic – for each of the seven sources both at global and regional scales.

These scenarios correspond to the most credible set of results based on the application of an extended set of assumptions during the study (cf. Appendix 1). The optimistic and pessimistic scenarios are built by selecting the minimum and maximum results after getting rid of extreme and unrealistic combinations of assumptions. The central scenario corresponds to a central value based on the distribution of remaining results.

4.

Results & Analysis

The global release of primary microplastics in the world ocean was evaluated in the order of 1.5 Mtons/year. i.e. between 0.8 and 2.5 Mtons/year. This global figure corresponds to a world equivalent per capita of 212 g or a plastic quantity equivalent to every human tossing one conventional light grocery plastic bag per week into the ocean.

From these results we conclude that between 15% and 31% of all plastic in oceans could originate from primary sources. This is a significant but as-of-yet unrecognised proportion. In higher income countries benefiting from adequate waste treatment facilities, the primary microplastics represent the main contribution to plastic release into the oceans.

The overwhelming majority (98%) of the losses of primary microplastics are generated from land-based activities. Only 2% is generated from activities at sea. The largest proportion of these particles stem from the laundering of synthetic textiles and from the abrasion of tyres while driving.

4.1 Primary microplastics are a significant source of plastic in the oceans

We estimate the following scenarios of releases into the oceans:

- Optimistic – 0.8 Mtons/year
- Central – 1.5 Mtons/year
- Pessimistic – 2.5 Mtons/year

These releases are a fraction of the estimate losses of primary microplastics into the environment presented below:

- Optimistic – 1.8 Mtons/year
- Central – 3.2 Mtons/year
- Pessimistic – 5.0 Mtons/year

The gap between losses and releases under the central scenario means that around 48% of the losses of primary microplastics from activities are released into the world ocean. The remaining primary microplastics are presumably trapped in soil, or sewage sludge. Their fate and effect over time is unknown and depends on conditions and practices in each region.

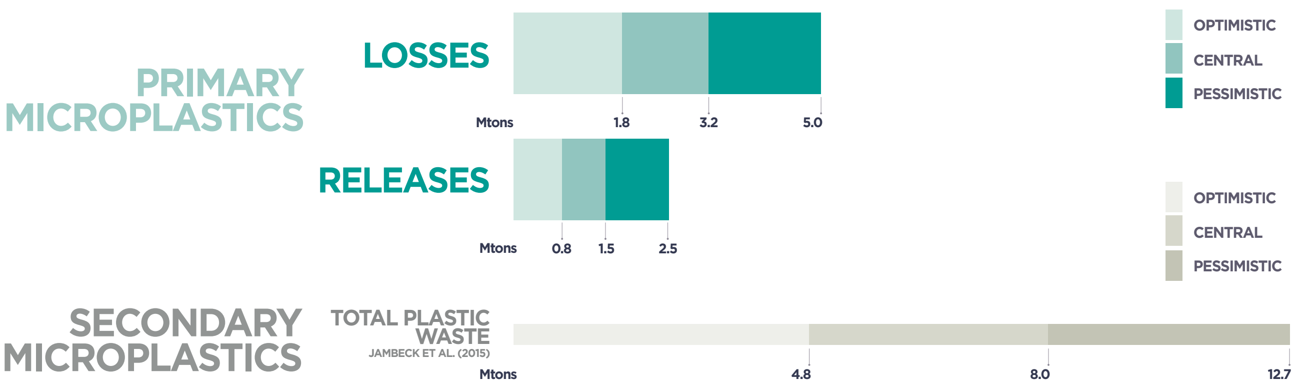
Comparing these releases of primary microplastics to known sources of secondary microplastics – i.e. from plastic waste and from lost fishing nets – indicates that the contribution of primary sources might be significant. The contribution of primary microplastics largely outweighs that of lost fishing nets[4] (0.6 Mtons/year) (Circularocean, 2015; Macfadyen et al., 2009). Considering values from Jambeck (2015), the potential releases from plastic waste range from 4.8 Mtons/years to 12.7 Mtons/year with an average value of 8.0 Mtons/year. This means that between 15% and 31% of the microplastics could be from a primary source, comparing central values in the first case and the pessimistic value from this report with the lowest bound for waste in the second one.

We have decided throughout the study to report microplastic losses and releases exclusively for microplastic from petrochemical origin. Plastics such as natural rubber are not accounted for. Extending the definition and assuming, as in some studies for Europe (Essel et al., 2015; Lassen et al., 2015; Magnuson et al., 2016), that natural rubber is also a concern for the world ocean, global releases from primary microplastics would increase by 45%, 33% and 26% respectively for the three scenarios. The resulting central value for releases would thus be 2.0 Mtons/year and the potential contribution of primary microplastics sources could be up to 37%.

Figure 3

GLOBAL RELEASES OF MICROPLASTICS TO THE WORLD OCEANS:

PRIMARY AND SECONDARY SOURCES (IN KTONS)



4 This value is the only one available but has not been scientifically validated. It should thus be taken with caution.

Our results are consistent with a recent research performed by Eunomia applying a very basic extrapolation of European releases of primary microplastics (from a former proprietary Eunomia report) scaled to a global level using GDP *per capita* in Purchasing Power Parity. Eunomia estimates that primary microplastics releases are between 0.5 and 1.41 million tons/year with a central value of 0.95 million tons/year annually (EUNOMIA, 2016b).

4.2 Two-thirds of the releases are from the erosion of synthetic textiles & tyres

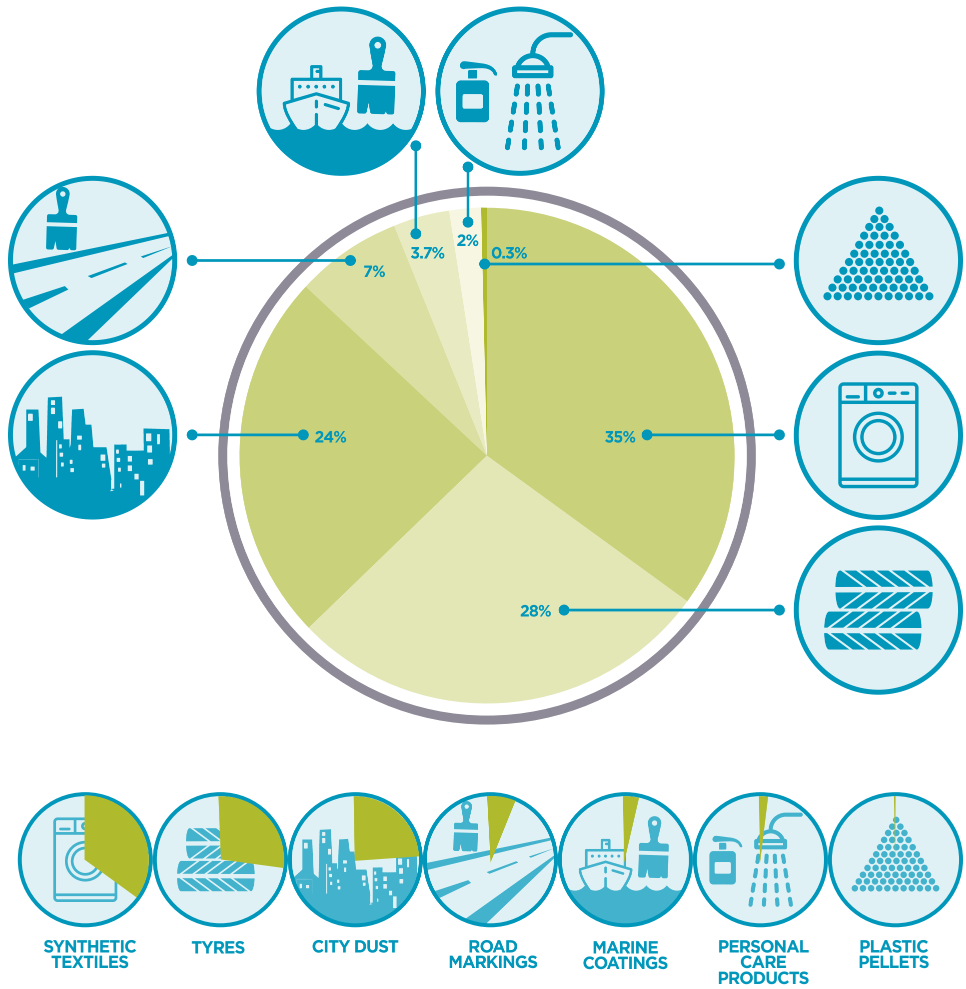
As shown in Figure 4 for the central scenario, close to two-thirds (63.1%) of the releases are due to first the laundry of synthetic textiles (34.8%), and second to the erosion of tyres while driving (28.3%). The order is the same in the pessimistic scenario. In the optimistic scenario the joint contribution is similar but tyres erosion dominates (38%). Note again that these results only consider synthetic rubber. Should natural rubber be considered the erosion of tyres would contribute to almost half of the releases (46.2%) in the central scenario.

The third important contribution (24.2%) is the source City Dust which has been computed with a simplistic approach. Further research should be performed on City dust to better understand the contributions per region. Personal care products only account for 2% of the global release of primary microplastics to the world ocean.

Figure 4

GLOBAL RELEASES OF PRIMARY MICROPLASTICS TO THE WORLD OCEANS

BY SOURCE (IN %).



Textiles

The yearly consumption of fibre for apparel amounts to 69.7 million tons globally – around 11.0 kg *per capita* (2010). Synthetic fibres represent almost two-thirds (60.1 %) of this consumption (FAO/ICAC, 2013).

The global yearly consumption of fibres for apparel has steadily increased over the last two decades (+79.3% between 1992 and 2010). This growth is almost exclusively due to the increased consumption of synthetic fibres with an increase close to 300% (from 16 to 42 million tons) over the same period (FAO/ICAC, 2013).

The majority (62.7%) of synthetic fibres are nowadays consumed in developing economies. In these economies, consumers buy a larger proportion (68.0%) of synthetic textiles than in developed economies (48.2%).

Averaging at 6.1 kg globally, the *per capita* consumption patterns vary largely between regions: going from 0.7 kg *per capita* in Africa and 5.7 kg in Asia, and up to 17.8 kg in North America, i.e. a 25 times range (FAO/ICAC, 2011).

Tyres

Around 1,412.6 million vehicles are in use globally – around 0.3 vehicle *per capita* (2010) (ETRma, 2011). More than two-thirds (71.2%) of these vehicles are personal cars and light commercial vehicles, 25.6% are motorbikes and 3.1% are medium and heavy commercial vehicles. This global vehicle count has steadily increased over the last fifteen years (78%) between 2000 and 2015. Most vehicles are in Asia (36%), with 13% in China, in Europe (27%) and in North America (21%) (ETRma, 2011).

To equip these vehicles with tyres, rubber is needed. Synthetic rubber in tyres represents around 57% of all synthetic rubber uses in 2010. The global consumption of synthetic rubber has increased by 27.3% between 2002 and 2010, mainly driven by China. This is a lower increase than the growth of the global consumption of natural rubber over the same period (+41.2%) (ETRma, 2009).

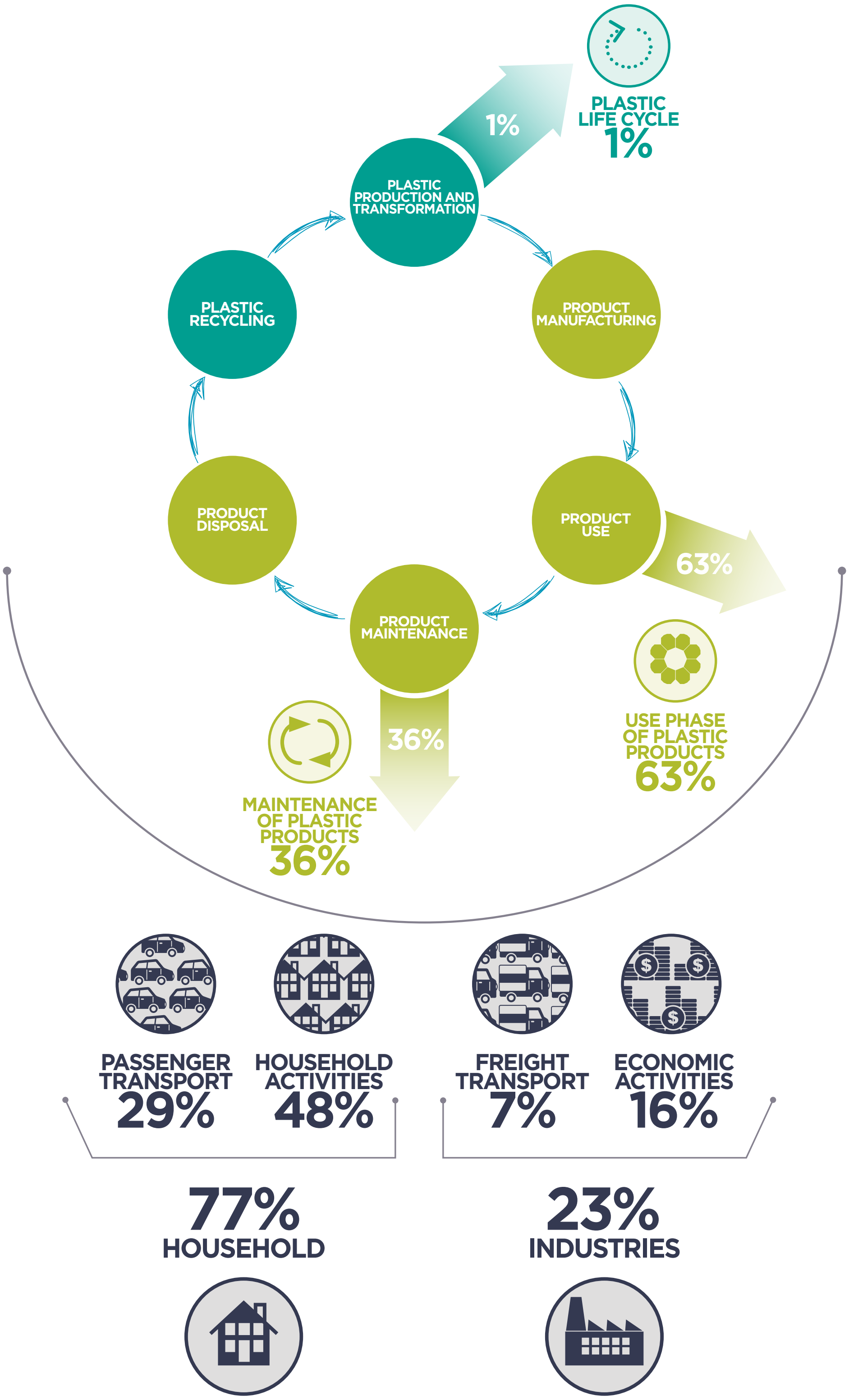
The yearly sales of rubber for tyres were around 13.9 Mtons in 2010, of which 46% (6.4 Mtons) was synthetic rubber (ETRma, 2011). Averaging at 0.93 kg of synthetic rubber globally, the *per capita* consumption patterns vary largely between regions.

4.3 Household activities generate almost three quarters of the releases during the use phase and maintenance of plastic products

Figure 5

GLOBAL RELEASES OF MICROPLASTICS TO THE WORLD OCEANS:

SPLIT PER TYPE OF ACTIVITIES AND LIFECYCLE STAGES



As shown in Figure 5 households generate directly through their activities about three quarters (77%) of the microplastics releases. The rest are generated by economic activities. Most of these household releases occur during the use phase of products (49%) and the rest (28%) during the maintenance of products. Transportation activities correspond to one third (38%) of the sources of households' releases (passenger transport)[5] due to tyres and road markings, i.e. mainly due to the use of personal cars. In Europe for example 90% of the total driven distance is with personal cars (EU JRC/NL PBL, 2010). The rest (62%) of the sources are related to other household activities – laundry of synthetic textiles, use of personal care products and leisure boats coatings.

Releases from economic activities are thus much lower (23%) than releases from households. Most of those are also occurring during the use phase of products and the share due to the plastic part of the lifecycle only accounts for around 0.5% to 1.5%. The share of releases due to commercial transport is similar but slightly lower (30%) than the share due to transportation by households. The road transportation system by itself is thus generating around one third (35.1%) of the total releases.

4.4 Two-thirds of the losses are through road runoffs

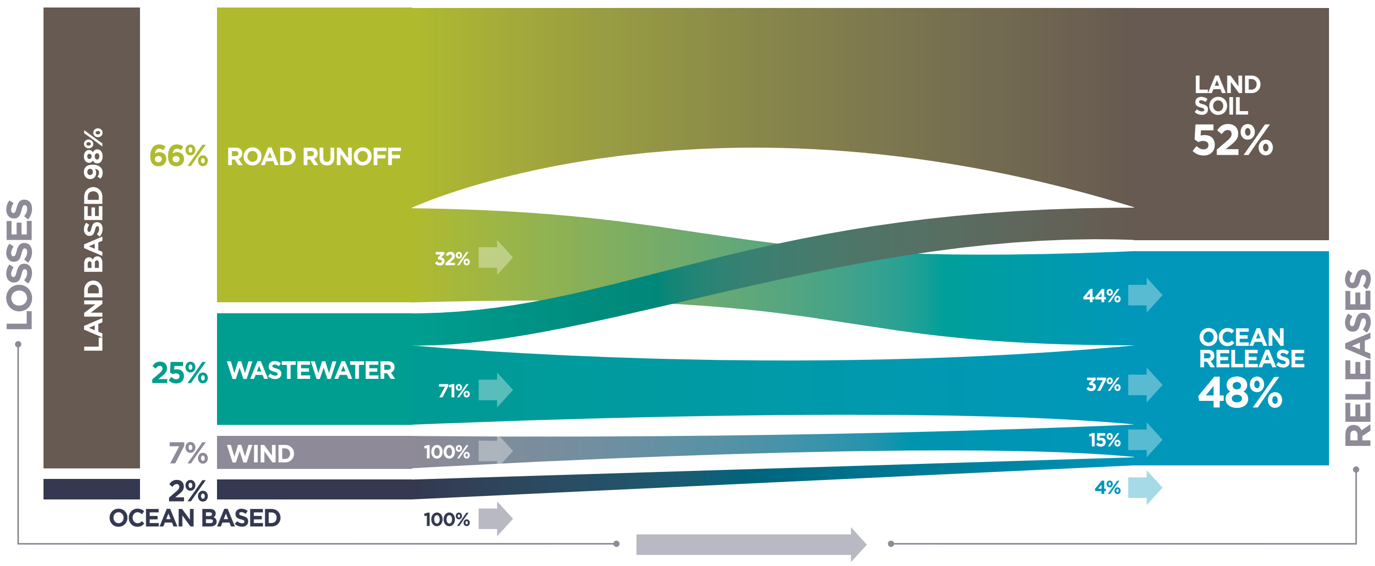
The overwhelming majority (98%) of the losses of primary microplastics are generated during land-based activities. As illustrated in Figure 6, the main pathway is road runoff (tyres, road markings and pellets incidents on land) (66%) followed by wastewater treatment systems (25%) and by wind transfer (7%). Marine activities only generate around 2% of the losses.

The distribution is slightly different in terms of releases. 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 to the oceans. For road-runoff, only 32% of the losses end up as releases. This concerns mainly the losses going through separate sewers. All losses occurring in the ocean and all losses transported by wind become releases[6]. Thus, 44% of the releases are along the road runoff pathway, 37% along the wastewater pathway, 15 % are transported by wind and 4% are direct releases to the oceans.

Figure 6

GLOBAL RELEASES TO THE WORLD OCEANS:

CONTRIBUTION OF DIFFERENT PATHWAYS TO THE RELEASE OF MICROPLASTICS



5 For tyres erosion and for road markings, the split of the global values between households and commercial activities is based on the global driven distance per type of vehicle.

6 The proportion of particules transported by wind to soil is not known.

4.5 All regions contribute significantly to releases

The regional distribution of releases of primary microplastics, regional GDP and population, are presented in Figure 7. All regions contribute significantly to the releases. The largest regional releases are in India and South Asia (18.3%) and North America (17.2%), followed closely by Europe and Central Asia (15.9%), China (15.8%) and East Asia and Oceania (15.0%). Releases are lower in South America (9.1%) and Africa and the Middle East (8.7%).

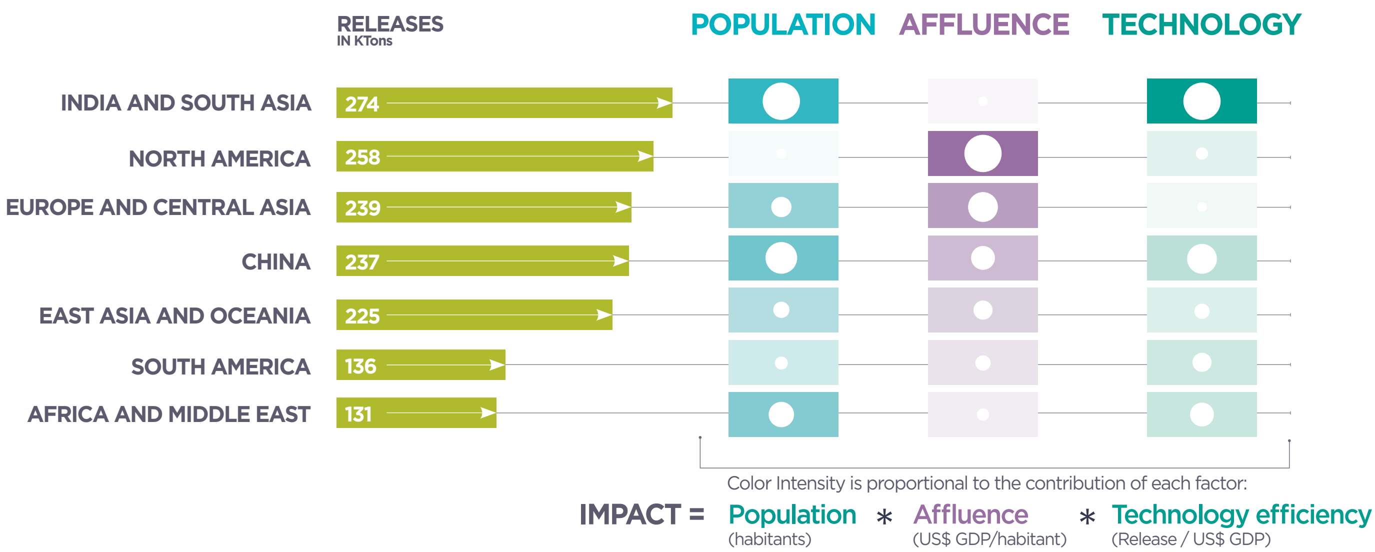
Releases can be explained with a combination of three factors according to the classical IPAT (Impact = Population x Affluence x Technology efficiency) formula (Ehrlich and Holdren, 1971), i.e. in our case the size of a population, the portfolio of activities generating losses (GDP *per capita*), and the capacity of the treatment systems to catch the losses.

In India and South Asia, China and Africa and Middle East, *per capita* losses are below the global average (212 grams/year *per capita*). Large populations combined with a low share of population connected to wastewater treatment systems, e.g. 6.2% in India and South Asia, results in significant releases. Significant releases also occur in Europe and Central Asia as well as North America, but for the opposite reason. In these regions *per capita* losses are larger than the global average, but a relatively smaller regional population is combined with a high share of the population connected to wastewater treatment systems, e.g. 71.4% in North America. South America and East Asia and Oceania sit somewhere in-between.

Figure 7

GLOBAL RELEASES TO THE WORLD OCEANS:

CONTRIBUTION OF THE DIFFERENT REGIONS OF THE WORLD

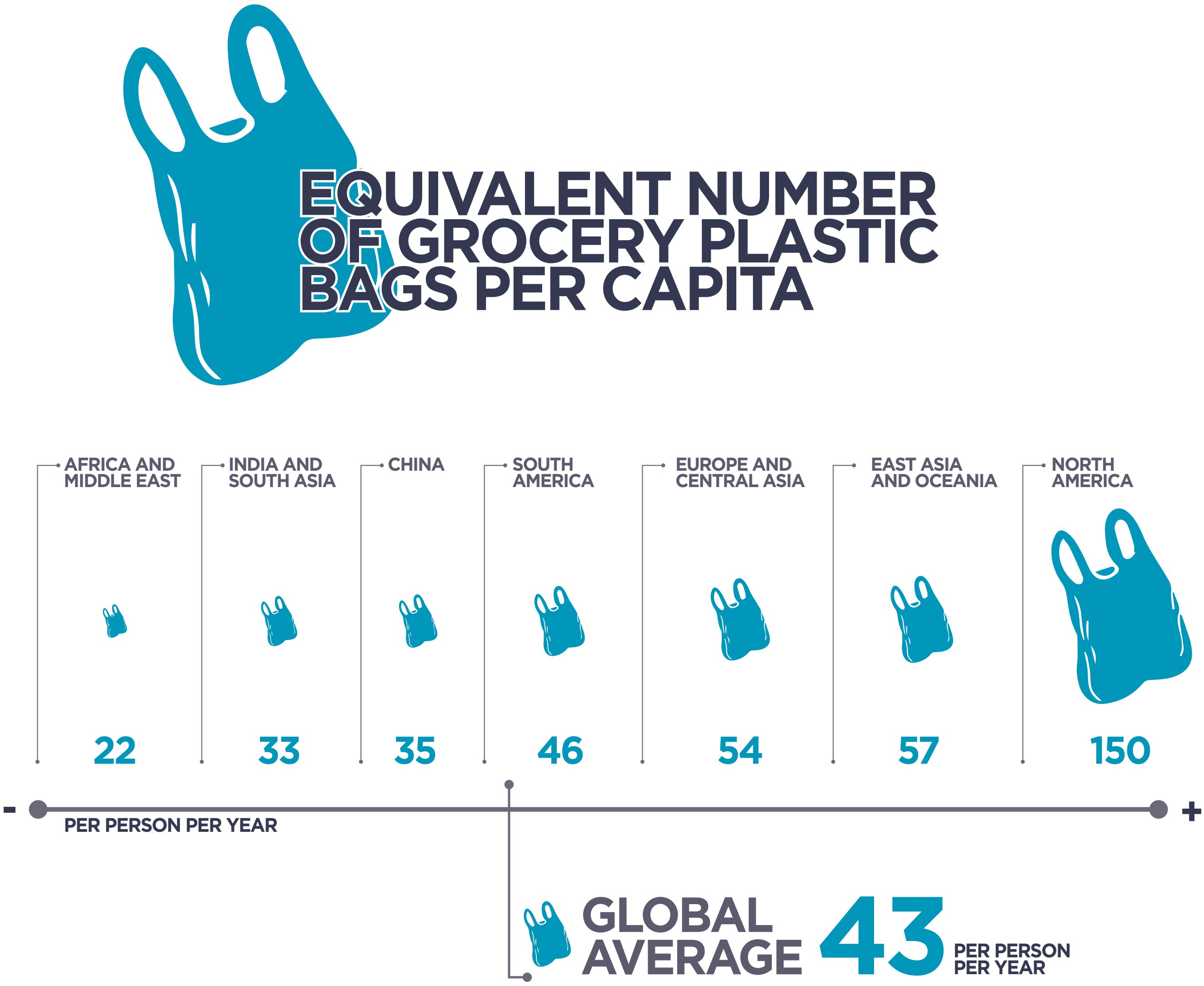


4.6 Releases average one plastic bag per person per week

The release of 1.53 Mtons/year of primary microplastics corresponds to an average release of 212 grams/year *per capita*[7]. This is equivalent to 43 light plastic grocery bags[8] thrown into the world ocean per person or roughly one per week.

This number varies however widely across regions as shown in Figure 8. Going from 22 equivalent grocery bags *per capita* in Africa and the Middle East, this goes up to 150 bags in North America – a seventh fold difference.

Figure 8



7 Global population for 2012.

8 Assuming a weight of 5 grams per grocery bag.

4.7 Key sources of releases differ among regions

The global importance of each regional source is shown in Figure 9. Synthetic textiles are the main source of primary microplastics in Asia, Africa and the Middle East. In these regions the share of synthetic clothes is larger than the global average, the share of the population connected to wastewater treatment systems is lower than the average and the distance driven are lower than in the Americas and in Europe and Central Asia.

In the Americas, Europe and Central Asia tyres dominate. In these regions regional distances driven are much higher than in the rest of the world. Moreover wastewater treatment systems are more common, thus capturing a higher share of the microplastics going through non-runoff or wind pathways, e.g. from synthetic textiles. For Europe, these results are coherent with the results already reported from Northern European countries where tyres dominate losses and releases (Essel et al., 2015; Lassen et al., 2015; Magnuson et al., 2016; Sundt et al., 2014).

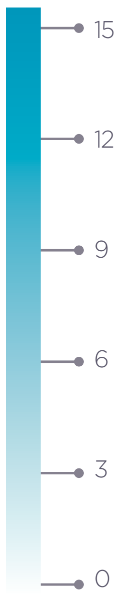
At global scale, the key issues are, by order of importance (in % of global releases, without the source City Dust): textiles in India and South East Asia (15.9%), tyres in North America (11.5%), textiles in China (10.3%) and tyres in Europe and Central Asia (10.3%).

Figure 9

GLOBAL RELEASES TO THE WORLD OCEANS:

KEY SOURCES AMONG REGIONS (TOTAL AMOUNT TO 100%)

INDIA AND SOUTH ASIA	15.9	1.1	0.3	0.1	0.8	0
NORTH AMERICA	2.6	11.5	1.9	1	0.1	0.1
EUROPE AND CENTRAL ASIA	4	8.6	2.4	0.6	0.2	0.1
CHINA	10.3	2.5	1.3	1.2	0.5	0
EAST ASIA AND OCEANIA	6.3	5.3	1.6	1.5	0.3	0
SOUTH AMERICA	2.9	5.1	0.9	0	0.2	0
AFRICA AND MIDDLE EAST	4	3.2	0.6	0.4	0.5	0



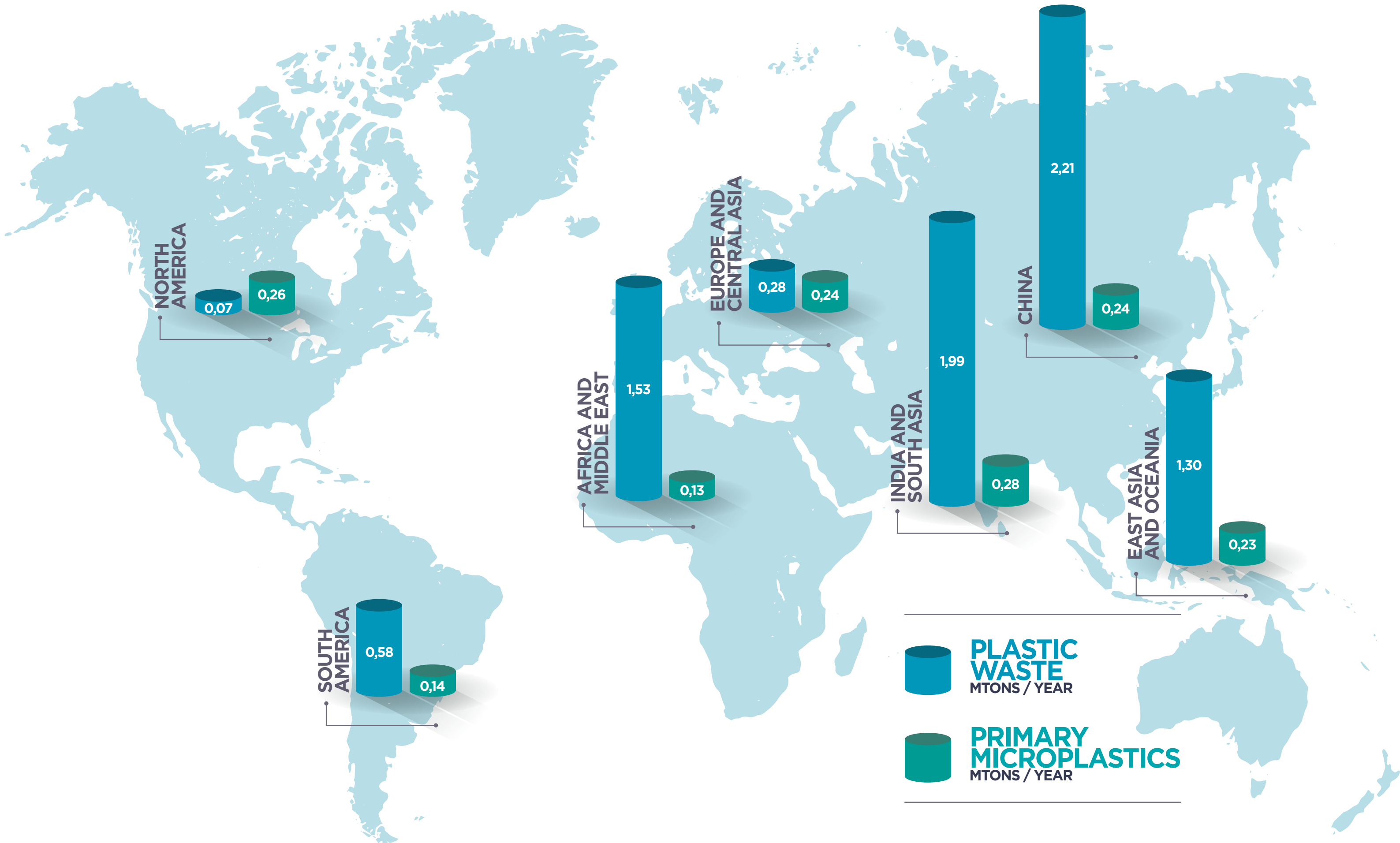
4.8 Microplastic releases are high in Europe & North America

Outside of the dominance of primary microplastics from tyres in the Americas, Europe and Central Asia, the second characteristics of these regions is that releases from primary microplastics are equivalent or outweigh that of secondary microplastics from mismanaged waste for Europe and North America (Figure 10). Such is not the case for the other regions.

Figure 10

GLOBAL RELEASES TO THE WORLD OCEANS:

COMPARISON WITH PLASTICS ORIGINATING FROM MISMANAGED WASTES



4.9 Closing the plastic tap requires different sets of solutions

The present study clearly demonstrates that primary microplastics are a globally significant source of plastics into the oceans. Consequently actions to close the plastic tap should focus not only on implementing better waste management in some regions, but also on finding solutions to reduce diffuse loss over the lifecycle of some products. Depending on the region, priority setting could thus be very different.

For the regions where plastic releases are dominated by mismanaged wastes, priority should be given to implementing better waste management and behaviours. Beyond a classical end-of-pipe approach, reducing the quantity of plastic waste generated (e.g. optimizing, reducing and re-using packaging) as well as increasing the recycling rates (e.g. by increasing the value of plastic waste) could be valid options.

For the regions where primary microplastic releases equal or overweight secondary microplastics from wastes, very different set of solutions should be designed either focusing on product design, infrastructure design, consumer behaviours, or all the three together:

- In the case of intentional losses, such as for personal care products, solutions could be based on finding substitutes to the plastic microbeads and removing them for the product. Several countries and brands are currently in the process of phasing out these microbeads, which hopefully will cancel this source of plastic release into the oceans within a few years.[9]

- In the case of diffusive loss during use phase or maintenance of the product, solutions should be developed through a dialogue between the many actors of the lifecycle of the products, from product designers to water infrastructure engineers. Examples for textiles and tyres are given below.

Potential solutions to reduce microplastic releases from synthetic textiles
Plastic transformation and product manufacturing (chemist/designer): design textiles/textiles fibres to reduce the shedding of fibres
Product manufacturing (designer): pre-wash textiles to reduce heavy loads from first wash
Product maintenance (designer of washing machines): install filtering devices on washing machines
Water infrastructure: understand and increase treatment efficiency.
Product use (consumer): Reduce the share of synthetic textiles by changing individual behaviours or purchasing policies. Note that using recycled fibres instead of virgin fibers may reduce the number of fibres shed. Indeed, using recycled fibres and repurposing wasted plastic for a useful purpose can potentially prevent some mismanaged waste from entering the ocean.

Potential solutions to reduce microplastic releases from tyres
Plastic transformation and product manufacturing (chemist/designer): Ecodesign of rubber polymers and tyres to reduce abrasion
Product use (road/asphalt designer): design road pavement to reduce abrasion
Product use (water infrastructure designer): Ensure water run-off collection and appropriate separation of plastics
Water infrastructure: understand and increase treatment efficiency.

9 Regarding the UK, for example, see: http://www.bbc.com/news/uk-37263087

5.

Conclusion

This study is one of the first to demonstrate that primary microplastics are globally a major source of plastics into the oceans with between 0.8 and 2.5 Mtons/year global releases (central value 1.5), regionally outweighing that of secondary microplastics from mismanaged wastes.

If reducing mismanaged plastic waste remains a priority at global scale, for many regions and sectors, solutions need to be found to also reduce primary microplastic releases. Shaping these solutions require a systemic lifecycle management approach rather than a purely waste management approach. Eco-design of the product and dialogue with all stakeholders from product design to urban infrastructure planning both from private and public sectors will be key to close the plastic tap.

5.1 Take home messages

It is very likely that:

- Losses of primary microplastics from commercial and household activities into the environment is in the order of 3.2 Mton/year.
- The greatest contributors to these losses are abrasion of tyres while driving and abrasion of synthetic textiles while washing, i.e. diffusive losses during use/maintenance phase.
- Release of primary microplastics is a significant source of plastic into the ocean.
- In high income countries with adequate waste management, primary microplastic release equals or overweighs the releases from mismanaged plastic wastes. However in lower income countries plastic releases from mismanaged wastes still is the main source of plastic release into the oceans.

It is more likely than not that:

- Releases of primary microplastics from commercial and household activities into the oceans is in the order of 1.5 Mton/year. This represents 48% of the losses ending up in the ocean.
- The losses and releases from primary sources are going to increase in next decades, due to high population and increasing living standard (affluence) in Asiatic and African countries, unless action is taken to reduce loss rate (Impact = Population * Affluence * Technology efficiency) (Ehrlich and Holdren, 1971). While waste management practices are being improved worldwide, the contribution of primary microplastics for less developed countries may thus increase.
- Main pathways are through sewage water and urban run-off waters, from which microplastic transit to the oceans through rivers.
- About 52% of the microplastic loss is trapped in soils when waste water treatment sludge is used as fertilizer and / or when particulates are washed from the road pavement. Fate and effect of these microplastics in soils is still unknown.

5.2 Shaping action to close the plastic tap

If at global scale reducing mismanaged plastic waste remains a priority, for many regions and sectors, solutions need to be found to reduce primary microplastic releases also.

Reducing mismanaged plastic waste mainly requires implementing adequate infrastructure and waste management practices as well as educating behaviours of consumers. Technologies are readily available and the challenge is more a political and financial one.

Solving the primary microplastic release into the world's oceans requires a very different set of solutions. Apart from personal care products, where microbeads are included intentionally in the product (and thus easy to remove or ban as the trend shows), most losses are unintentional, diffusive losses that cannot be easily solved with end of pipe solutions. The losses are from product use and maintenance, mostly from households, and must be tackled with a global producer-consumer perspective. The banning of microbeads from cosmetics is an illustrative action but will not solve the wider problem. Attention must be paid not to overlook other sources, such as textile and tyres, as our study shows that cosmetics only contribute for 2% of the releases of primary microplastics to the ocean at global scale.

Closing the plastic tap will require design and implementation of both technological, behavioural and policy solutions considering plastics and products over their whole lifecycle to reduce plastic losses during production, use, maintenance or end of life of products and releases to the world ocean.

This eco-design approach requires a systemic lifecycle management approach and dialogue with all stakeholders from product design to urban infrastructure planning both from private and public sectors, as already well documented elsewhere (UNEP SETAC, 2009).

Based on the principle that you can improve only what you can measure, metrics and indicators should be developed to set targets and monitor progress. This should include integration in target settings frameworks and policies (e.g. Sustainable Development Goals), as well as in more operational tools such as Life Cycle Assessments. This is the way business developers and product designers will have the microplastic issue under the radar.

5.3 Next steps

An immediate next step is to further develop the analysis presented in this study. This will require additional data collection and a more in depth understanding of regional and sectorial impacts. We also need to better understand the cumulative implication of these releases over time. Furthermore, confrontation of our predictive model with empirical data from the field would be beneficial in order to validate the model. This is however not feasible yet, given the status of literature. Adequate experimental set-up should be developed in order to perform this comparison.

While further research is underway, this study can play a very critical role in opening discussions about how to address primary microplastics beyond traditional plastic waste management approaches. The growing presence of microplastics in the oceans requires new thinking about how to mitigate both primary and secondary releases across the supply chain.

Several organisations including IUCN have started multi-stakeholder dialogue processes to explore how we can close the plastic tap. We need now to ensure that the issue of primary microplastics is not being overlooked in these processes vis-à-vis plastic from mismanaged waste origin. This will require engaging new stakeholders and developing innovative life cycle management approaches.

6.

Appendix 1: Sources

The assumptions for the computation of the optimistic, central and pessimistic scenarios are presented here per source in descending contributing order. These scenarios represent the most credible selection among an extended set of results in this study. The complete set of assumptions, scenarios and results will be published elsewhere.

6.1 Synthetic textiles: abrasion during laundry

Activities and losses are computed in two ways. The first approach combines the estimated number of wash cycles per region with reported losses of microplastics per wash as measured in the effluent of washing machines. The second approach combines data on yearly global and regional synthetic textiles sales with the typical losses over the lifecycle of a synthetic textile cloth.

Approach 1

Activities: Annual number of laundry cycles *per capita* (55), and load per standard wash (4 kg) derived from Pakula and Stamminger (2010). Regional population (2007) from (UNDP, 2015). The regional synthetic shares are from the own-computed regionally-extended dataset based on (FAO/ICAC, 2011) (see approach 2).

Losses: Pessimistic/optimistic: 300/1500 mg of microplastics loss per kg of synthetic textiles per wash, as reported in (Lassen et al., 2015). The central value is set to 900 mg/kg.

Releases: See wastewater pathway in appendix 2.

Approach 2

Activities: Global and regional consumptions (2007) of textiles from (FAO/ICAC, 2011). Data correction and extrapolation to sub-regions based on *per capita* consumption and on population from UNDP (UNDP, 2015).

Losses: Optimistic/pessimistic: 0.74/5% of microplastics loss over the lifecycle (Essel et al., 2015; Lassen et al., 2015). The central value is set to 2%.

Releases: See wastewater pathway in appendix 2.

Comparison of the two approaches

Releases in the optimistic scenario based on the low value for losses in approach 1 match the lower value applied in approach 2 (± 13%). The central scenario is based on an average of the central scenarios in approach 1 and 2: both approaches differ at global scale by only ± 9% but result in different distribution across regions.

6.2 Tyres: abrasion while driving

Activities and losses are computed in two ways. The first approach combines the estimated driven distance covered by all vehicles in a region with reported particulate matter emissions from tyres per km per type of vehicle. The second approach combines data on yearly global and regional sales of synthetic rubber for tyres with the typical particulate matter emissions over the lifecycle of a tyre.

Approach 1

Activities: Annual distance driven in countries (2011) for goods and for people traffic from OECD (OECD, 2013). Extrapolation of distance to other countries based on a linear regression model (OLS) using carbon emissions from transportation (2005) (EU JRC/NL PBL, 2010). The share of goods traffic outside of OECD countries is set to the OECD average (13%). Share of heavy trucks (vs light trucks) in goods traffic: optimistic: 0%, central: 50%, pessimistic: 100%. The selected share of synthetic rubber share per tyre is equivalent to the global share of synthetic rubber in tyres in 2010 (46%) (ETRma, 2011). The urban/rural split is 50% (optimistic scenario) or based on the urban share of the population (central and pessimistic scenarios) from UNHSP (United Nations Human Settlements Programme, 2016).

Losses: Optimistic/central/pessimistic: 0.033/0.051/0.178 gram per tyre-km for cars, light and heavy trucks from (GRPE, 2013; Lassen et al., 2015; Sundt et al., 2014).

Releases: See road runoff pathway in appendix 2.

Approach 2

Activities: Global consumption of synthetic rubber for tyres in 2010 from (ETRma, 2011). Allocation to regions based on (a) the number of vehicles per type (motorcycles, cars and light commercial vehicles, medium and heavy commercial vehicles) per region in 2010 from (ETRma, 2011), (b) the number of wheels per type of vehicle, respectively 2, 4 and 6 and, (c) an average tyre weight per type, respectively 10, 16 and 50 kg (selected values based on literature), and (d) a 25% share of rubber (tread pattern only) per tyre (WRAP, 2006). The proportion of synthetic rubber per tyre is like approach 1.

Losses: Optimistic/pessimistic: 10/25 % of microplastics loss over the lifecycle (Essel et al., 2015; Magnuson et al., 2016; Sundt et al., 2014). The central value is set to 20%, which is equivalent to the global apparent loss of rubber (quantity of synthetic rubber losses computed in approach 1 over the global sold quantity of synthetic rubber for tyres).

Releases: See road runoff pathway in appendix 2.

Comparison of the approaches for the selected scenarios

Releases in the optimistic scenario based on the low value for losses in approach 1 match the lowest value applied in approach 2 (± 1.5%). In the central scenario, based on the central values for losses in approach 1, releases match the central value applied in approach 2 (± 9%). In the pessimistic scenario, the high value for losses in approach 1 are 37% lower than when applying the high value in approach 2.

6.3 City dust: spills, weathering & abrasion

City Dust has been modelled in a different and less specific manner than other sources.

City Dust is the generic name given to a group of nine sources, identified in recent country assessments that are most often occurring in urban environments (Essel et al., 2015; Lassen et al., 2015; Magnuson et al., 2016; Sundt et al., 2014). These sources are grouped together because their individual contribution is small but they account together for a considerable amount of losses in the country studies.

Activities: City Dust includes losses from the abrasion of objects (synthetic soles of footwear, synthetic cooking utensils), the abrasion of infrastructure (household dust, city dust, artificial turfs, harbours and marina, building coatings) as well as from the blasting of abrasives and intentional pouring (detergents). In contrast to other sources that have been subject to specific and regionalised modelling, for city dust assessment is based on more basic extrapolation from the Nordic countries studies. A more detailed assessment should be undertaken in the future to precise the relevance of this source.

Losses: Losses from other sources were extrapolated (+ 29% at global scale) from (Lassen et al., 2015; Magnuson et al., 2016; Sundt et al., 2014) proportionally to the losses computed for the six key sources.

Releases: 50% roadrunoff pathway and 50% wastewater pathway (own hypothesis)

6.4 Road markings: weathering and abrasion by vehicles

Activities and losses are computed by combining data on yearly global and regional consumption of traffic road marking coating with the typical plastic content per segment of paint (paint, thermoplastic, preformed polymer tape, epoxy) and reported loss rates from existing studies.

Description: The global traffic road marking coating consumption is around 1'200 ktons (2014). The use of road marking coating is related to the development of the road infrastructure, its maintenance and to security aspects. The largest market is Europe (31.9%) followed by the USA. Different types of paints (paint, thermoplastic, preformed polymer tape) are applied, with a dominance of paint (44.7%) (Grand View Research, Inc., 2016).

Activities: Global, US and EU consumption (2014) of marking paint for road from (Grand View Research, Inc., 2016). Allocation to other regions, i.e. 43% of road marking paints, based on GDP from (The World Bank, 2016). Global share of segment 'paint' from (Grand View Research, Inc., 2016). Proportion by types of segments of road marking paints for USA from (Grand View Research, Inc., 2016). Proportion of plastic per segment of paint: 10.5/40% for the optimistic/central and pessimistic scenarios (Lassen et al., 2015; Sundt et al., 2014), 25% for thermoplastics (Lassen et al., 2015; Sundt et al., 2014) and 100% for the other segments (tape). The share of the segments is based on the US shares and respect the global 'paint' share. The urban/rural split is based on the urban population (United Nations Human Settlements Programme, 2016).

Losses: Optimistic/central/pessimistic: 23/43/100% from Grand View Research (2016) of microplastics loss (Sundt et al., 2014) (Lassen et al., 2015).

Releases: See road runoff pathway in appendix 2.

6.5 Marine coatings: weathering, application & maintenance

Activities and losses are computed based on the global and regional quantities of marine coatings applied yearly accounting for the plastic content of the paint and reported losses over the whole lifecycle of boats from existing studies.

Activities: Global and regional applications of marine coatings (2012), as well as global shares per type of boats (containers, leisure, commercial) and per reason of application (new build or maintenance, repair and overhaul) from (Wright, 2009). Regional split between types of boats based on (Wright, 2009) and complemented for Asia based on GDP (The World Bank, 2016) and on the number of boats in US and in EU[10] for leisure (Laaksonen, 2012). Proportion of plastic in paint: 50% from (Lassen et al., 2015).

Losses: Optimistic/central/pessimistic loss rates for commercial boats: 3/6/9% based on (OECD Series on emissions documents, 2009) for the central value. Optimistic/central/pessimistic loss rates for leisure boats in developed economies (North America and Europe): 10/30/50%. Optimistic/central and pessimistic loss rates for leisure boats in developing economies 50/90% derived from (Sundt et al., 2014).

Releases: See ocean pathway in appendix 2.

10 http://www.europeanboatingindustry.eu/facts-and-figures. Accessed on 23/08/16.

6.6 Personal care products: loss during use

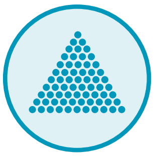
Activities and losses are computed based on regional populations combined with yearly losses *per capita* in Europe reported in existing studies.

Activities: Regional population from (UNDP, 2015).

Losses: Optimistic/central/pessimistic: 1/6/13g *per capita* per year from (Gouin et al., 2015; Leslie, 2015; Essel et al., 2015).

Releases: See wastewater pathway in appendix 2.

6.7 Plastic Pellets: manufacturing, transport & recycling



Activities and losses are computed based on the global and regional quantities of primary plastics produced yearly and accounting for the losses due to production, land and water transport as well as end-of-life of plastic and plastic products as reported in existing studies. Releases are allocated to the region using the plastic products, i.e. based on a consumer perspective (plastic footprint).

Activities: Global and regional production of primary plastics (2007) from (PlasticsEurope, 2009). Allocation of primary plastics to sub-regions and countries is based on GDP. Computation of regional footprints (consumption perspective) using an extended global Multiregional Input-Output Model (MRIO) based on Exiobase 2.0 (Tukker et al., 2014).

Losses: Losses are computed at four stages: production of primary plastics, manufacturing of plastics, transport on land (for domestic uses of plastics products) and water (for interregional trade of plastics products), as well as plastic end-of-life. Optimistic/central/pessimistic: 0.00003/0.0001/0.001 % of microplastics losses per stage from (Cole and Sherrington, 2016).

Releases: Land transport of primary plastics and plastics for domestic use: see wastewater pathway in appendix 2. Sea transport of imported primary plastics and plastics: see ocean pathway in appendix 2.

7.

Appendix 2: Pathways

The assumptions for the computation of the pathways from losses to releases are presented here. For each of the six main sources once activities are computed a loss rate is applied to estimate the primary microplastics losses. Then losses become so-called “releases” into the world ocean through four possible pathways.

7.1 Road runoff pathway

Where: land-based losses and releases
Sources: tyres, road markings, plastic pellets on land

When losses are on roads, part of them is transferred by wind (see wind pathway). The remaining part is washed by rainwater. In rural areas, it is considered that few roads are connected to sewers: A global average value equivalent to 3.5% of losses in rural areas is assumed to end up in the oceans (Lassen et al., 2015; Ten Broeke et al., 2008). In urban areas, two cases are possible: a drain to a separate sewer or a drain to a combined sewer. In the first case, 80% of the releases are assumed to end up in the oceans (Lassen et al., 2015). In the second case, releases depend on an additional assumption, the share of roads connected to a combined sewer. For the optimistic scenario, it is assumed that 50% of roads are connected. For the central and pessimistic scenarios, it is assumed a proportionality between the proportion of the population connected to wastewater treatment systems and the proportion of the roads with a sewer system to collect water from roads. See more on the wastewater pathway below.

7.2 Wastewater Pathway

Where: land-based losses and releases
Sources: synthetic textiles, personal care products, plastic pellets on land

When losses are to wastewater streams, the release ratio depends on the regional coverage and efficiency of the wastewater treatment system. It is assumed that the share of water treated is proportional to the proportion of the population connected to wastewater treatment systems. The regional share of the population connected to wastewater treatment systems is based on an own-computed dataset extending data from UNSTATS (UNSD, 2011) for missing countries and for missing regions with data from the literature. Global treatment efficiency is set at 85%. This number accounts for the non-retained share of microplastics in wastewater treatments systems (3-6%) for fibres according to Lassen et al. (2015) and for overflows (10%) in Europe according to Phillips et al. (2012). Overflow is probably much higher for some developing economies but values are scarce.

7.3 Wind Pathway

Where: land-based losses and releases
Sources: tyres and road markings

When losses are on roads, a part of them is spread by the wind. This part is set at 10% based on Wang et al. (2015). 100% of these losses become releases.

7.4 Ocean Pathway

Where: sea-based losses and releases
Sources: plastic pellets, marine coatings

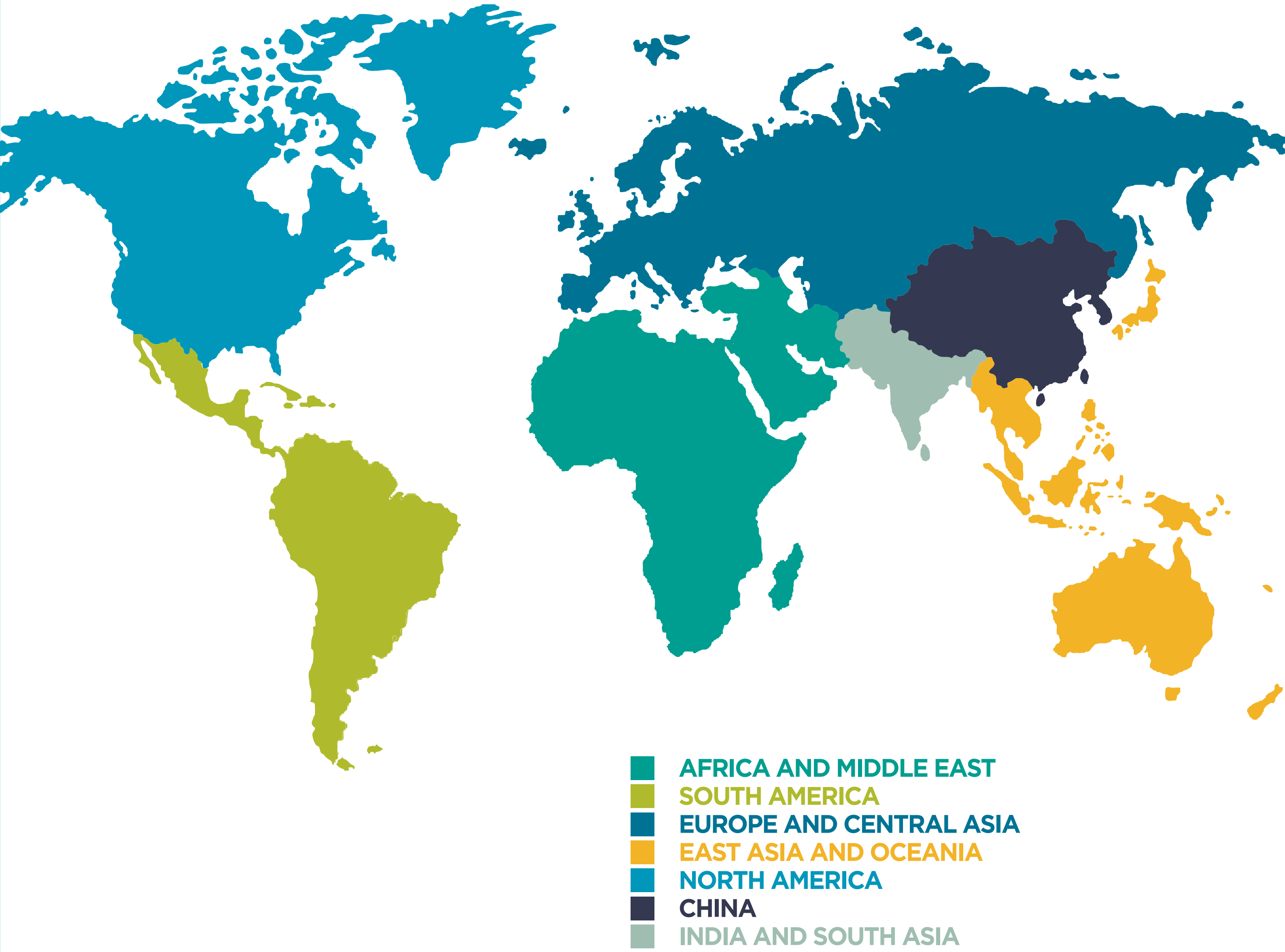
When losses occur in the ocean, 100% of the losses become releases.

8.

Appendix 3: Regions

The grouping of countries has been done according to a classification in 7 regions: Africa and Middle East, China, East Asia and Oceania, Europe and Central Asia, India and South Asia, North America and South America.

THE SEVEN REGIONS CONSIDERED THROUGHOUT THE STUDY



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