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IMPACTS OF PLASTIC POLLUTION IN THE OCEANS ON MARINE SPECIES, BIODIVERSITY AND ECOSYSTEMS

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Marine ecosystems already dealing with multiple stressors are now facing an additional stressor in plastic pollution.

Polar bear investigating plastic items stranded on a beach on Svalbard.
Date: 11.08.2021. Location: Spitzbergen, Lomfjorden, De Geerbukta. © Andreas Alexander

1. Executive Summary

Current plastic pollution
Since the advent of the widespread commercial production and use of plastics (see Glossary) after the Second World War, the rate of production and the associated emission of plastic waste into the world's oceans has grown significantly. In recent decades, much of the plastic pollution came from single-use items.

Annual emissions of plastic into the oceans were estimated at 19–23 Million tons in 2016.

Annual emissions into the oceans were estimated at 19–23 MMT (see "Metric ton" in the Glossary) in 2016. Another important feature of plastic pollution is that, once in the environment, the larger macroplastic items break down into ever smaller fragments, becoming microplastics, which become nanoplastics. Because of this fragmentation process, concentrations of microplastics and nanoplastics will continue to rise for decades even if all plastic emissions cease now.

Increasing scientific and public interest
The last decade has seen an unprecedented increase in research findings coupled with a growing interest in the media and rising concern in the public sphere. Pictures of beautiful tropical beaches and coral reefs choked by plastic waste, of dying animals caught up in abandoned fishing nets and throwaway plastic items, and of birds with stomachs full of plastic waste have played a prominent role in raising awareness of this issue to gain public attention globally.

Meanwhile, scientists have worked on more and more questions related to plastic pollution, with thousands of studies now covering many different aspects of this pervasive environmental problem. In this report, we review the scientific literature to summarise and evaluate the current state of knowledge on the effects of plastic pollution on marine populations, species and ecosystems.

Spatial distribution
One important result from this research is that plastic pollution is now ubiquitous. It has reached every part of the ocean, from the sea surface to the deep ocean floor, from the poles to coastlines of the most remote islands and is detectable in the smallest plankton up to the largest whale.

Once in the oceans, plastic spreads very unevenly among marine regions.

Once in the oceans, plastics spread very unevenly among marine regions, species and ecosystems. There are only a few areas where little to no plastic pollution has been detected, in most areas it has and some hotspots are already severely polluted. Such accumulation 'hotspots', are, for example, the five big ocean gyre systems, areas near major source points, like long polluted rivers and ecosystems such as coral reefs, mangrove forests and deep-sea canyons. Moreover, certain regions, such as parts of the Mediterranean, East China and Yellow Sea are considered pollution hotspots.

While median (see Glossary) pollution levels across many scientific studies from the seafloor, water column, surface, beach and sea ice amounted to 3,127 macroplastic items/km^2 and 200,000 microplastic items/km^2, maximum levels are much higher. Not surprisingly, the mass of macro- and microplastic debris show a different pattern. For example, in the North Pacific Gyre, macroplastic (75%) dominated over microplastic in terms of mass, whereas microplastic items dominated in terms of numbers of items (94%). Coastlines have the highest numbers of macroplastic items while the deep seafloor has the highest numbers of microplastic particles – with concentrations even higher than those in the accumulation areas of the big ocean gyre systems. The size of plastic items does matter, as the spatial distribution of plastic pollution shows distinct differences for macro- and microplastics. Next to nothing is currently known about the distribution and concentrations of nanoplastics.

Future trajectories of oceanic microplastic concentrations could result in a 50-fold increase by 2100.

Projections for future plastic pollution

A few studies have predicted the future of plastic production and environmental emissions. All of their business-as-usual scenarios predict a substantial growth in plastic production and emission levels for the next decades. Business-as-usual means that annual emissions will at least triple by 2040–2060, but the predicted increases vary considerably between studies. The future investment plans of the chemical industry are also based on the assumption of further exponential growth. Such future trajectories could result in a four-fold increase of oceanic macroplastic concentrations by 2050 and a 50-fold increase of ocean microplastic concentrations by 2100. In contrast, the most optimistic scenarios, which rely on a massive source reduction, improved waste management, recycling and removal at a global scale, would reduce annual plastic emissions by 36–91%. However, even these optimistic scenarios would mean further increases in marine pollution, albeit at lower rates. To conclude, plastic pollution will inevitably continue to increase, but the magnitude of the increase is very much dependent on what governments, industry, wholesale and societies do.

Interactions of marine organisms with macroplastic items are diverse – like entanglement, ingestion or smothering.

Effects on marine species and ecosystems

Even though research on plastic pollution and its effects on aquatic and terrestrial species and ecosystems is still ongoing, the known impacts for certain species and ecosystems are already severe. The size, and to some extent also the shape and chemical makeup, of the zillions of plastic pieces now found in marine environments greatly determines how they interact with marine organisms and how much harm they do.

Macroplastic items primarily harm marine organisms through entanglement, ingestion (see Glossary), smothering and leakage of associated chemicals. They also provide a refuge to smaller animals and new substrates for settlement, mostly for sessile species, but may also allow species and pathogens to spread to new areas. While these interactions could lead to harm, in some cases even to death, to our knowledge they seldom drive critical decreases in population (see Glossary) at present. Other interactions are simple physical contact with no apparent harm.

Encounters with macroplastic could particularly affect large, charismatic animals.

Levels of plastic pollution and the effects on species vary greatly due to the geographic variation of plastic pollution but also due to different exposures related to the lifestyles of marine species. For example, filter-feeding species such as mussels or baleen whales could take up large amounts of plastic. Encounters with macroplastic could particularly affect large, charismatic animals, namely seabirds, turtles, marine mammals, corals, and sharks and rays. The number of individuals belonging to many of these groups are already declining as a result of other threats. Since the loss of the top predators and large herbivores (see "Megaherbivore" in the Glossary) has a great impact on ecosystem structure and function, the ramifications of losing further individuals, especially of already dwindling populations, will reverberate the impacts of plastic pollution throughout marine ecosystems.

Because of their size, microplastics and nanoplastics enter into the bodies of animals through ingestion and inhalation. Ingested microplastics can block the digestive tract, while both microplastics and nanoplastics can contribute to the chemical body burden and elicit toxicological effects. Numerous studies have conclusively established that microplastics and nanoplastics have entered the marine food chain, which thus introduces microplastic and nanoplastic pollution and its associated chemical pollution into higher trophic levels including

Loggerhead turtle trapped in an abandoned drifting net, Balearic Channel, Mediterranean sea.
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The harm caused by microplastics and nanoplastics is directly related to their concentration.

humans. Micro- and nanoplastics have been found in human stool, colons, saliva, hair, lungs, placentas and on the skin. However, the effects of microplastics and nanoplastic exposure differ widely. The many studies considered in this report demonstrate that the effects vary depending on (1) the size, type and concentration of microplastics and nanoplastics, (2) the length of exposure, and (3) the examined species or ecosystem. While some studies have demonstrated deleterious effects, including increased morbidity and mortality of individuals due to altered or decreased food uptake, growth, immune response, reproduction, altered cell functions, behaviours, and even negative effects on ecosystem functions, other studies reported few or no effects. As expected, harm is directly related to the concentration of microplastics or nanoplastics. Some experiments demonstrated harm at environmentally realistic concentrations whilst others did not. In addition, there is debate as to what are environmentally realistic concentrations, because most studies fail to detect the smallest microplastics, which account for the vast majority of particles, let alone nanoplastic. Therefore, reported environmental concentrations may often be considerable underestimates. As a result, risks could be underestimated.

Microplastics exist in various polymer types, shapes and sizes, and organisms can be exposed to them at different concentrations and for various time periods. If the possible experimental combinations are multiplied with the number of coral species, it soon becomes clear that a great number of laboratory experiments would have to be carried out to gain a full understanding of the risk. Furthermore, as almost all laboratory studies lasted a few days or weeks at most we know very little about the effects of long-term exposure. Our current knowledge therefore represents a very small glimpse of the full complexity and may also underestimate the severity of the problem. However, since there is enough evidence indicating adverse effects, the priority should be given to decreasing the emissions of plastics into the environment.

There are examples of coral reefs and mangrove forests that have been seriously damaged by plastic pollution.

Marine ecosystems that are already dealing with multiple stressors now face an additional stressor in macroplastic pollution. So far, research has documented serious damage to coral reefs and mangrove forests due to smothering and entanglement, which can lead to injury, disease and death of corals and mangrove trees. There are examples of coral reefs and mangrove forests, which have been seriously damaged by plastic pollution, since they experience several other threats at the same time, plastic pollution exerts further stress on these ecosystems that are vital to ocean health and human well-being. Other marine ecosystems, such as deep-sea canyons, are also increasingly polluted, but so far, we know little about possible impacts.

Plastic bag stuck on staghorn corals of a tropical reef near the Apo Island, Dauin, Negros, Philippines.
© Steve De Neef/National Geographic Creative

Negative effects of plastic interactions were reported for 88% of investigated species.

Given the global ubiquity of plastic pollution, it can by now be assumed, that almost every marine species has encountered plastic, although not all encounters with plastic lead to an adverse effect on the organism's health. The number of species to have interacted with plastics is steadily increasing, mostly due to the growing number of studies because almost every investigated species has had contact with plastics. A total of 1,253 scientific studies has documented 2,788 marine species that have encountered plastics, but even this number is a substantial underestimate because scientists cannot examine every species. Half of these studies only reported the interactions and did not investigate the effects of the encounters on 1,713 species. Effects of these interactions were reported for 43% (1,191) of the 2,788 species in field and experimental studies. In experimental studies, negative effects of plastic interactions were reported for 88% of 297 species.

In conclusion, many examples of harm caused by plastic pollution and affecting marine populations, species and ecosystems have been established, but many details and questions remain open. While macroplastic debris clearly causes harm to marine life, the consequences of microplastic pollution on marine biota are less well-known and the effects of nanoplastic pollution are largely unknown. However, this almost certainly does not mean no harm, in light of the evidence already available from laboratory studies of various effects of microplastics and nanoplastics on numerous marine species.

Wherever hotspots caused by other threats overlap with plastic pollution, negative effects of plastic pollution will be exacerbated.

Combination with other stressors

Plastic pollution cannot be considered in isolation. Rather, it adds another impact to the litany of existing pressures caused by humans, such as global warming and heat stress, ocean acidification, eutrophication (see Glossary), deoxygenation, overharvesting, bycatch, shipping and underwater noise, habitat destruction and fragmentation, and chemical pollution. These multiple stressors acting together may suffice over the longer term to push vulnerable marine species, populations, or ecosystems, in badly polluted areas, over the brink with probable detrimental effects for the functioning of the affected ecosystems and its services. Wherever hotspots caused by other threats overlap with hotspots caused by plastic pollution, the negative impacts of plastic pollution will be exacerbated, especially for vulnerable species or regional subpopulations. For example, the already threatened Mediterranean populations of monk seals or sperm whales will be further jeopardized by the effects of plastic pollution.

An increasing threat from plastic pollution, in combination with the other stressors, may be what leads to a further endangerment of one or several species. In many other cases, biodiverse, productive and resilient ecosystems will be replaced with simpler, unproductive and fragile ecosystems, especially when several stressors interact. Such ecosystems, in turn, provide fewer benefits and services, which then means fewer economic returns and less security and well-being for human societies. In conclusion, plastic pollution must now be considered a stressor of marine ecosystems, acting in combination with the many other severe stressors of marine ecosystems.

Effects of future plastic pollution

This report documents clear-cut cases of harm done to certain marine species, ecosystems and locations, where harm to date is mostly attributed to macroplastics. We should heed the examples given as ominous warning signs of much more common and widespread damage to come unless the future trajectory of plastic pollution is drastically changed.

The risk of high oceanic microplastic concentrations is predicted to spread considerably to other areas by the end of the 21st century.

Recently, studies have estimated the threshold level of risks to marine ecosystems caused by plastic pollution. One of these models suggested that oceanic microplastic concentrations, which can be considered ecologically dangerous currently only exist in a few regions, such as the Mediterranean, East China and Yellow Seas. However, projected increase of microplastic concentrations would spread this risk considerably to other areas by the end of the 21st century. Therefore, the precautionary approach should apply in order to avoid the risk of irreversible harm. With continued business-as-usual scenarios, the documented harmful effects of plastic pollution will increase, which could very well mean crossing critical thresholds for some species, populations or ecosystems. Currently, plastic pollution presents a legacy burden for future generations, who, on current trajectories, will have to endure oceans contaminated with plastics.

2. Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research

The Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) explores the Arctic, Antarctic, and the seas and coastal regions of the temperate latitudes, from the atmosphere to the deep sea. It has researched plastic pollution in the ocean for 15 years and developed state-of-the-art methodologies for the standardised detection of small microplastics in different environments. The work aims to unveil the distribution of plastic pollutants as well as its impacts on marine life and trends over time to provide scientific data that are needed to combat plastic pollution in the oceans. In addition, it synthesizes scientific data in the online marine litter portal LITTERBASE (Box 1).

The research vessel Polarstern, one of the important tools of German polar research and the flagship of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research. © Mario Hoppmann

Pollution from plastics — a threat to nature and society

© Justin Hofman/WWF-US

3. Introduction

The threat from plastic pollution has grown from a minor environmental nuisance and niche scientific issue to a major global environmental concern that is attracting considerable and sustained interest from researchers, the media, the public and decision-makers. In 2019, the United Nations referred to it as a 'planetary crisis' (MacLeod et al., 2021; Villarrubia-Gomez et al., 2018).

The Anthropocene (see Glossary) has also been named the 'Great Acceleration' because various socio-economic and Earth system related indicators experienced a continuous growth after World War II (McNeill and Engelke, 2016). One indicator of the Anthropocene is the emergence of plastic pollution, which was negligible before the war (Waters et al., 2016; Zalasiewicz et al., 2016). Already, the global mass of plastic produced during the Anthropocene exceeds the current total mass of all terrestrial and marine animals combined (Elhacham et al., 2020).

Plastic production has grown exponentially since World War II (Figure 1). In 1950, the annual plastic production was 1.5–2.0 million metric tons (MMT), 50 MMT in 1977, 100 MMT in 1989, 200 MMT in 2002 and 368 MMT in 2019 (Geyer et al., 2017; Lebreton and Andrady, 2019; PlasticsEurope, 2016, 2020). Half of all the plastic ever produced was made between 2003 and 2016.

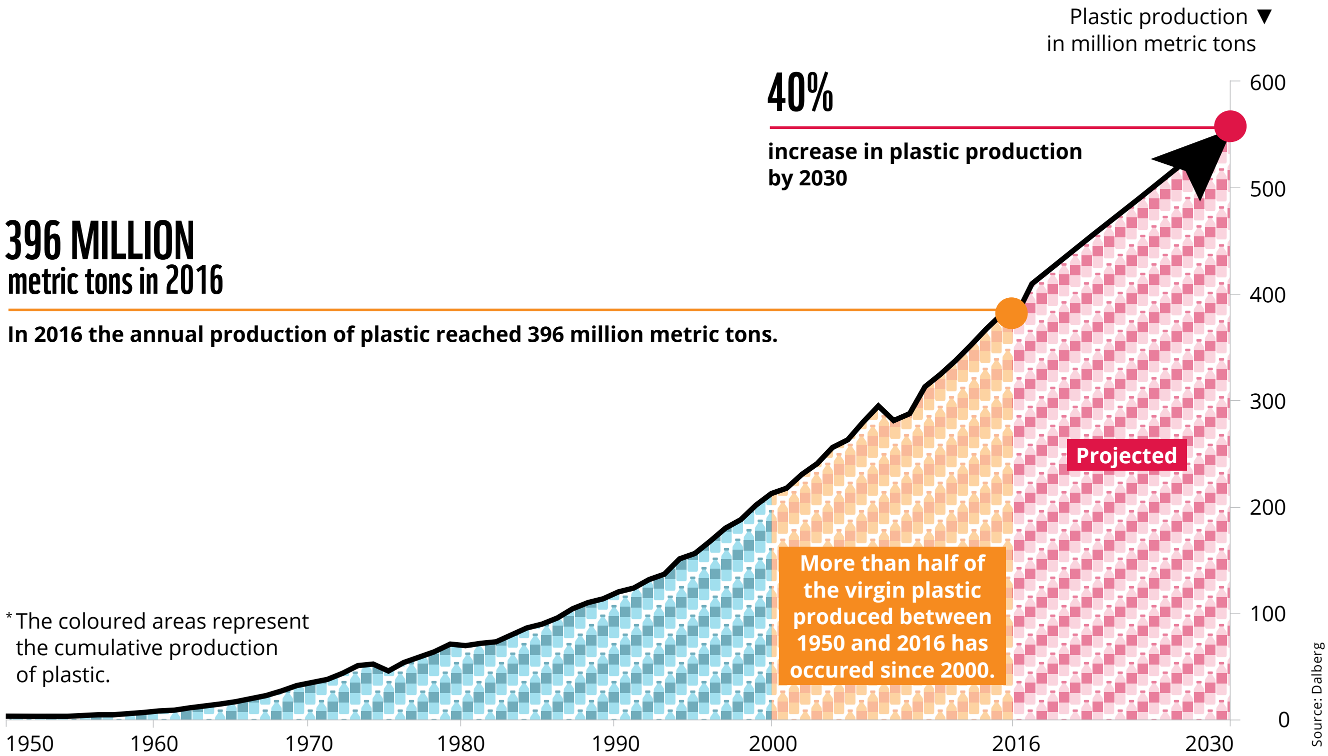


Figure 1: Global primary plastics production according to industrial use sector from 1950 to 2015. The figure was produced using the data from (Geyer et al., 2017). The coloured areas represent the cumulative production of plastic. MESAB, "The Circular Economy – a Powerful Force for Climate Mitigation"; CIEL, "Fueling Plastics: How Fracked Gas, Cheap Oil, and Unburnable Coal Are Driving the Plastics Boom."

Corporations have invested 180 billion US dollars into new plastic factories since 2010, which will lead to a 40% rise in plastic production within a decade (Taylor, 2017). Cheap fossil resources such as gas and oil have fuelled large new investments in plastics infrastructure around the world, with 164 billion US dollars planned for 264 new facilities or expansion projects in the USA alone (CIEL, 2017).

About 75% of all plastic ever produced had become waste.

By 2017, the total amount of all plastics ever made was 8,300 MMT, which comprised 6,800 MMT of plastic resins, 500 MMT of additives and 1,000 MMT of polyester, polyamide and acrylic fibres (PP&A). About 76% or 6,300 MMT had already become waste. Incinerated waste accounts for 12%. Another 9% had been recycled. Only 10% of this was recycled more than once. The remaining 79% ended up in landfills or in nature, which accounts for 60% of all plastics ever produced until 2017 (Geyer et al., 2017). In 2015, half of all plastic waste originated from plastic packaging alone (Geyer et al., 2017). Annual plastic production, excluding polyethylene terephthalate (PET), polyamide and polyacryl fibers had reached 368 MMT in 2019 (PlasticsEurope, 2020). Because of ineffective waste management, 4.8–12.7 MMT of macroplastics entered the oceans from land in 2010 (Jambeck et al., 2015), an estimate that rose to 19–23 MMT in 2016 (Borrelle et al., 2020).

Marine organisms are also exposed to chemicals entering the environment, some of which are related to plastic production.

Another important feature of plastic pollution is the variety of plastic types and additives involved, which are used to make millions of different products. The most important polymer types are: PP&A, low-density polyethylene (LDPE) and high-density polyethylene (HDPE), PET, polypropylene (PP), polystyrene (PS), polyurethane (PUR) and polyvinylchloride (PVC) (Geyer et al., 2017), although there are many more (Andrady and Rajapakse, 2016; Kutz, 2011; Wypych, 2016). Some of the most harmful chemicals, which enter the marine environment via plastics and that adsorb to plastics are endocrine disruptors (e.g. bisphenol A, phthalates, and alkylphenol additives), persistent organic pollutants (POPs) (e.g. flame retardants – see Glossary), and various toxic chemicals that are already in the environment. Some of these are related to plastic production, whereas others are legacy pollutants or pesticides, for example, polychlorinated biphenyl (PCBs) or dichlorodiphenyltrichloroethane (DDT) (Section 5.3). While a number of these polymers and additives are known to be harmful to marine organisms, many others could be harmful or not, but have not yet been studied. The chemicals enter the environment during production, transport, use and disposal of the product – in other words, throughout its life cycle. Marine organisms are exposed to them either directly via ingestion or indirectly via contact with water, air, sediment or food.

Scientific research on the scale and effects of plastic pollution has unveiled worrying results:

» ocean animals can suffer agonizing deaths, injuries and other health impairments due to interactions with plastic objects (Kühn et al., 2015).

» food chains are contaminated with micro- and nanoplastic (Box 2) and hazardous chemicals leached from plastic, with potentially serious consequences for growth, health and reproduction of animals, including humans (Box 3).

» functions of ocean ecosystems are negatively affected by structural, chemical and ecological changes (Lamb et al., 2018).

» invasive species, diseases and disease vectors spread as hitchhikers on plastic debris (García-Gómez et al., 2021).

» drainage, dams and wastewater systems become blocked, which can lead to floods and disease spread from stagnant waterways (Boelee et al., 2019).

» people get injured, sick or killed by coastal debris, germs on debris, or in shipping accidents and floods (Campbell et al., 2016).

» coastal and ocean-based recreation and tourism suffer from unsightly plastic pollution, which is costly and laborious to remove (Newman et al., 2015).

» industries such as shipping and yachting, fisheries, aquaculture, coastal agriculture or energy production infrastructures suffer from the costs due to obstructions in equipment caused by plastic debris and maritime accidents (Newman et al., 2015).

» financial and social costs of implementing mitigation technologies impact economies, social justice and human and environmental health (Borrelle et al., 2020).

Plastic production, use and disposal could account for 10–20% of the total greenhouse gas emissions budget.

Plastic pollution costs the global economy at least 13 billion US dollars each year (UNEP, 2018). In addition, plastic production, collection, disposal and the waste itself are significant sources of greenhouse gases (Ford et al., 2022; Royer et al., 2018; Zheng and Suh, 2019). In the 2000s, already 8% of the annual global fossil fuel production went towards plastic production (Hopewell et al., 2009). Future greenhouse gas emissions from plastic processing and incineration could therefore significantly impair the goal of keeping global warming below 2°C (Muffett and Feit, 2019). Plastic production, use and disposal could, within a few decades, account for 10–20% of the total emissions budget allowable to keep the global temperature increase below 1.5°C (Hamilton and Feit, 2019; PEW and SYSTEMIQ, 2020).

BOX 1: LITTERBASE

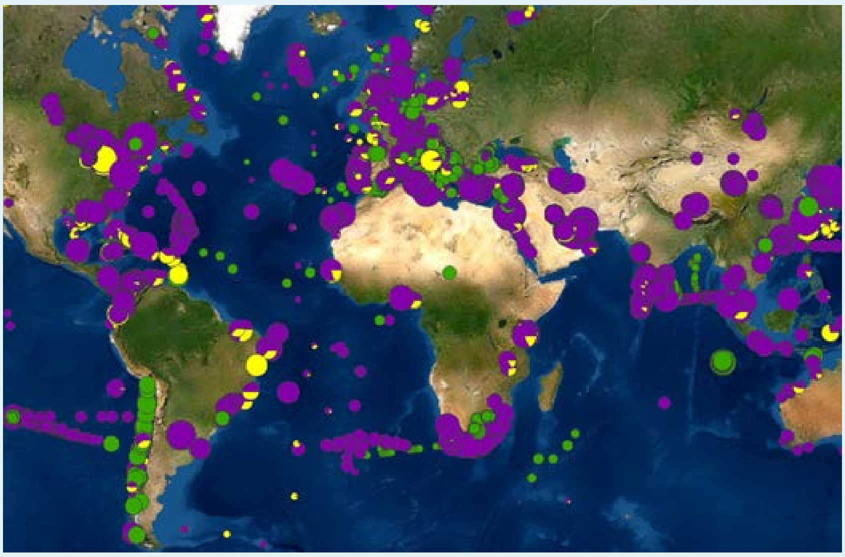
Over the last decade, the progress in marine litter research has increased exponentially (Figure 2) making it difficult to keep track of the progress. In response, the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research devised the online portal LITTERBASE (http://litterbase.org), which provides regularly updated information on the global distribution and composition of litter pollution and its impacts on biota.

The data presented in the portal are taken from peer-reviewed publications and reports and fed into a database using standardised protocols. Striving for a comprehensive picture, the scientific literature is continuously screened for new articles and bulk updates are performed periodically. As of November 2021, data from 2,881 studies had been entered into comprehensible global maps and infographics on the spatial and temporal distribution of litter pollution and its impacts on organisms, in order to communicate scientific knowledge to the general public.

The metadata for the distribution of man-made litter include bibliography, location, litter type, size category, amount unit (e.g. number or mass of items per kilometre, per square kilometre, per cubic metre) and biome (beach, sea surface, water column, seafloor). The units of measured litter concentrations were standardised when possible for comparability (e.g. m to km). Very large data sets had to be aggregated as they would have exceeded the capacity of manual data entry. As of January 2021, the compilation of litter distribution data with a publication date up to the end of 2018 had been completed, and the process of extracting data from more recent publications is in progress.

The following records of interactions between marine life and litter were entered: location and type of observed encounter (entanglement, ingestion, colonisation, other), species/taxon observed, effects (e.g. injury, mortality, growth, reproduction, behaviour), percentage of individuals affected, litter type, size, aquatic system and biome. So far, about 2,150 taxa have been recorded to have encountered marine litter in the wild. As of January 2021, the extraction of data from the studies, which had been published by the end of 2019 was completed, and the update for more recent literature is ongoing.

To draw a global picture, much of the information provided in this report relies on analyses of data from LITTERBASE unless other references are given. More details on methods and restrictions of the analyses are provided in Annex, Section 10.1 for plastic distribution and Annex, Section 10.2 for plastic impacts on marine life.



LITTERBASE is an interactive online portal, which provides access to our current state of understanding of marine litter to the general public and stakeholders. Published records of marine litter and microplastics and their impact on marine life are compiled in a database and are regularly updated: www.litterbase.org

Together with government institutions and the local community, WWF organises waste collection campaigns in Vietnam. © Melanie Gömmel/WWF

The last two decades have seen increasing grass roots actions, media campaigns, reports, and conferences organized by people and environmental NGOs (Dauvergne, 2018; Jorgensen et al., 2020; Nelms et al., 2017; Thiel et al., 2014; Walther et al., 2020; 2021). In turn, the interest of the media, public and decision-makers has grown tremendously, with plastic pollution now being one of the foremost reported global environmental issues in the press and internet (Prata et al., 2019; Völker et al., 2020; Walther et al., 2021). One likely reason is the fact that plastic pollution is much more visible and easier to grasp than the less tangible threats of climate change and loss of biodiversity (see Glossary).

As with any complex, global, environmental issue, there are many aspects to plastic pollution, such as understanding its scale and distribution, interactions with ecosystems, effects on human health and economies and mitigation policies. This report reviews the scientific literature to evaluate the impacts of plastic pollution on marine organisms, from the level of the individual (see Glossary) to the population and species level up to the level of entire ecosystems (see Glossary for definitions). Before assessing the details of the impacts on marine biota, details about the sources of plastic pollution and future predictions are covered (this chapter). Chapter 4 provides an overview of the spatial distribution of this pollutant. Chapter 5 reviews the interactions of plastic with species and the effects caused by the interactions, and in the same context Chapter 6 focuses on selected ecosystems. Chapter 7 evaluates the findings of this report.

Box 2: Tiny bits of plastics – micro- and nanoplastics

Plastics comprise a wide range of synthetic or semi-synthetic organic compounds that are malleable, so can be moulded into solid objects of almost any shape (Kutz, 2011; Wypych, 2016). Under the influence of sunlight, mechanic abrasion and temperature fluctuation, plastic items become brittle and break into smaller and smaller pieces in the environment. Their sizes often determine their biological impact. While different definitions circulate, usually the following size categories have been applied based on the longest linear dimension of the item: megaplastics (> 100 cm), macroplastics (100–2.5 cm), mesoplastics (25–5 mm), microplastics (5 mm–0.1 µm), and nanoplastics (< 0.1 µm). For ease of reading, we included mesoplastics into the category of macroplastics (see Glossary for more details on macro-, micro- and nanoplastics).

Microplastics are often further categorized into primary and secondary microplastics. Primary microplastics are pieces of plastic, which were produced in this size. Examples include microbeads or plastic scrubbers in cosmetic and hygienic products and pre-production pellets also called nurdles, which are then melted down to shape almost every product made of plastic. Secondary microplastics are fragments resulting from the breakdown of larger primary plastic items.

Microfibres from synthetic textiles have been identified as one of the main sources of microplastic pollution in the environment. Indeed, 0.6–1.5 million microplastic fibres are shed from synthetic textiles during a single wash of a normal 2.0–2.5 kg load of clothes (De Falco et al., 2019). When these microfibres reach wastewater treatment plants, a small but significant fraction is not retained; it ends up in waterways and eventually in the oceans. It should be noted that in the absence of treatment facilities, all of these particles inevitably reach the oceans.

While the vast majority of polymers (see Glossary) used today is made from petrochemicals, various new bioplastics have been developed, which are made from renewable materials such as polylactic acid from corn, ethanol from sugarcane, cellulose from cotton linters and even from chicken feathers, algae and prawn exoskeletons. However, depending on their chemical structure, many bioplastics are neither always recyclable or biodegradable (see Glossary). They could persist in the environment and often have the same effect as non-biodegradable plastics (Green, 2021; Napper and Thompson, 2019). The reason is that the polymer type and the environmental conditions determine the potential degradation pathways, products and speed (Bertling et al., 2018; Gewert et al., 2015; Peng et al., 2020).

Microplastics in sand.
© www.naturepl.com

Plastic and trash pollution in the eastern Caribbean between the islands of Roatan and Cayos Cochinos along the coast of Honduras. © Caroline Power

80% of ocean plastics are estimated to come from land-based sources.

Sources of plastic pollution

Depending on the product and location, the probability of plastic ending up in nature differs widely. Nevertheless, researchers have shown where most of the plastic pollution in the oceans comes from.

Plastic pollution can be distinguished between land-based sources and sea-based sources. It is often quoted that land-based plastics account for 80% of the marine plastic debris by number (LI et al., 2016). A global analysis of litter-type inventories resulted in a similar percentage (Morales-Caselles et al., 2021). Plastic makes up 80% of the litter items, and a set of plastic items from take-out food and beverages largely dominated global litter (50–88%). This category was followed by fishing-related litter (about 22%, but up to 61% in open waters). A continuous monitoring of beach litter provides data on the long-term balance between the inputs (land-based sources or stranding) and outputs (export, burial, degradation and clean-ups) (Galgani et al., 2015). The National Marine Debris Monitoring Program conducted between 2001 and 2006 in the US revealed that land and sea-based items contribute 49% and 18% of the collected debris, respectively. The origin of 33% of the items could not be attributed to any source category. The majority of the collected items was plastic (Sheavly, 2010). It should be noted that although densely populated and industrialised areas are the main sources for land-based plastic debris, it varies with region. The mass of sea-based plastic debris can exceed land-based sources. Plastics from fisheries constituted more than 80% of the overall weight of the litter collected from Arctic beaches (Bergmann et al., 2017). The mass of nets, lines and ropes from fishing and shipping accounted for 46% of the plastics floating in the North Pacific Gyre (Lebreton et al., 2018).

Box 3: Effects of plastic pollution on human health

While numerous reviews about the effects of plastic pollution on human health have been published (Azoulay et al., 2019; Barboza et al., 2018; Campanale et al., 2020; Fournier et al., 2021; Galloway, 2015; Halden, 2010; Prata et al., 2020; Rahman et al., 2020; Rist et al., 2018; Seltenreich, 2015; Sharma and Chatterjee, 2017; Smith et al., 2018; Thompson et al., 2009; Vethaak and Legler, 2021; Wright and Kelly, 2017) data from new studies are still sparse.

Large litter items can affect humans much in the same way as animals. For example, people can get injured when walking barefoot on a littered beach or become entrapped whilst swimming. Waste pickers can contract diseases when handling debris with germs (Kretchy et al., 2020). In the ocean, litter can cause maritime accidents, sometimes fatal, through collision and entanglement of propellers or of bottom fishing gear in large items on the seafloor (Lee, 2015).

Although there is a lack of conclusive research on the topic, potential risks to human health may also arise from microplastics or nanoplastics (Bouwmeester et al., 2015; Galloway, 2015; Kessler, 2011; Lehner et al., 2019; Mitrano et al., 2021; Peng et al., 2020; Revel et al., 2018; Schirinzi et al., 2017). Both size fractions may cause transfer of toxic compounds, and there is also the possibility of internal injury (Vethaak and Leslie, 2016).

Humans can be exposed to micro- and nanoplastic via three main routes: ingestion, inhalation, and through the skin (Hwang et al., 2020). Given that a wide range of food products (e.g. table salt, seafood, drinking water, tea bags, fruit, vegetable) and daily-care products contain microplastic (Carbery et al., 2018; Chen et al., 2020a; Conti et al., 2020; Cox et al., 2019; EFSA Panel on Contaminants in the Food Chain (CONTAM), 2016; Hantoro et al., 2019; Hernandez et al., 2019; Lee et al., 2019; Miller et al., 2016; Rochman et al., 2015; Senathirajah et al., 2020; Van Cauwenberghe and Janssen, 2014; WHO, 2019; Zhang et al., 2020), it does not come as a surprise that it has been detected in human stool, colon, saliva, hair and on the skin (Abbasi and Turner, 2021; Ibrahim et al., 2021; Schwabl et al., 2019).

Nurdles are the raw material of plastic packaging and biobeads are used in sewage treatment to break down human waste. 9 million of these microplastic pollutants have been collected by the Rame Peninsula Beach Care Group on a 100 m stretch of Tregantle Beach, Cornwall in just 7 visits. © Sam Hobson/ WWF-UK

An estimate for the consumption rate of US citizens was 1,419–2,321 microplastics per week (Cox et al., 2019). A global mass estimate was 0.1–5.0 g of microplastics per week (Senathirajah et al., 2020). However, a later study based on more comprehensive data claimed this to be a considerable overestimate and provided the following estimates: a median intake rate of 3,871 microplastic particles (1,288 ng) per week for children and 6,181 (4,081 ng) per week for adults (Mohamed Nor et al., 2021). By contrast, Zhang et al. (Zhang et al., 2021a) suggested that the uptake by infants is higher than by adults. Their results pointed out that infants ingest PET (polyethylene terephthalate) and PC (polycarbonate) particles with a daily concentration of 83,000 and 860 ng per kg body weight, whereas for adults, the concentration is 5,800 ng/kg for PET and 200 ng/kg for PC.

Synthetic fibres have been found in lung biopsies, confirming inhalation as a pathway into our bodies (Gasperi et al., 2018; Pauly et al., 1998; Suran, 2018). If not cleared by coughing, over time, microplastics could accumulate in our airways and promote conditions such as respiratory irritation, asthma, inflammation, or potentially carcinomas (Wright and Kelly, 2017). Interestingly, facemasks now worn commonly due to the COVID-19 pandemic can both reduce or enhance inhalation of microplastics depending on the type of mask, length of use and disinfection treatment (Li et al., 2021).

It remains unclear whether microplastics pass through the lungs or intestinal barriers into our bloodstream and other organs and if so, what effect this might have (Mitrano et al., 2021; Ramsperger et al., 2020). Small particles in the nano-size range are more likely to pass biological barriers and to be taken up by cells and could lead to inflammation and cationic toxicity (Mitrano et al., 2021). Recent evidence suggests that polystyrene nanoparticles can form a protein corona with biomolecules in human fluids, enabling them to pass the placenta barrier (Gruber et al., 2020).

Indeed, microplastics were recently found on both sides of human placentas suggesting that they can be passed from the mother to their fetus (Ragusa et al., 2021; Zhang et al., 2021a). In addition, cerebral and epithelial cells experienced oxidative stress when subjected to polyethylene and polystyrene microplastics (Schirinzi et al., 2017). Another study showed that human blood cells exposed to polystyrene nanoplastics experienced early-stage local inflammatory responses (Hwang et al., 2020). In-vitro cells exposed to nanoplastics and associated contaminants also showed clear metabolic alterations (Magrì et al., 2021). One reason could be the fact that nanoplastics can interact with proteins, which can lead to cellular damage (Hollóczki and Gehrke, 2019).

However, adverse effects may not only arise from the polymer itself but also from the associated chemicals such as plasticisers, pigments, or flame retardants that can leach from the particle into the body (Section 5.3). These chemicals can have a wide range of effects including breast cancer and heart disease and are also transferred through food packaging (Vandenberg et al., 2010). Therefore, experts from the field of ecotoxicology suggest incorporating chemical safety concerns into the design of sustainable packaging materials (Muncke et al., 2020). Serious concerns about the hormonal effects of plastic-derived endocrine disruptors (see Glossary), such as BPA and phthalates, need to be urgently researched and addressed as they may even threaten human reproduction itself (Section 5.3 and Albert and Jégou, 2014; Brockovich, 2021; Bryant, 2021; Levine et al., 2017; Swan and Colino, 2021).

Finally, plastic items can serve as disease vectors (see Glossary) (Vethaak and Leslie, 2016). For example, potentially pathogenic *Vibrio parahaemolyticus* was detected on microplastics sampled in the North and Baltic Sea (Kirstein et al., 2016), and *Escherichia coli* on plastic pellets sampled on beaches (Rodrigues et al., 2019). In addition, it could be a vector for the dispersal of multiple antibiotic resistant pathogens (Laganà et al., 2019).

Even though research on the adverse effects of plastic pollution on human health has not yet reached firm conclusions, potential risks suggest a need for a precautionary approach (Cox et al., 2019). Should the precautionary principle be followed, the most effective action would be to reduce the production and use of virgin plastic, especially considering the fact that microplastic pollution is accumulating and poorly reversible (MacLeod et al., 2021; Senathirajah et al., 2020).

Land-based sources of macroplastic inputs into aquatic ecosystems amounted to 19–23 MMT in 2016 (Borrelle et al., 2020). They originate from the land adjacent to the world's coastlines, but an additional 0.8–2.7 MMT per year are carried from further inland by 1,000 rivers, accounting for 80% of global riverine plastic emissions (Meijer et al., 2021). The contribution of macrolitter even from small rivers and streams was recently emphasized by the analysis of the first ever database of riverine floating litter across Europe, which estimated that 307–925 million items are released every year from Europe into the ocean, 82% of which are plastic (González-Fernández et al., 2021).

River deltas receive 52% of plastic pollution carried by fluvial systems.

River deltas comprise only 0.87% of the global coast but they receive 52% of the plastic pollution carried by fluvial systems, which remains close to the river mouth (Harris et al., 2021). Rainfall and floods flush the plastics load of rivers into the sea, yet the mechanisms of further dispersal are complex; plastic debris carried by rivers does not necessarily travel to the sea. An assessment in Cape Town, South Africa, showed that a large proportion of plastic carried by the investigated seasonal river was washed ashore after entering the sea (Ryan and Perold, 2021). The next biggest sink are tidal coasts, such as mangroves and salt marshes, which receive 30% of the rivers' plastic pollution (e.g. Lloret et al., 2021; Martin et al., 2019; 2020).

The amount of sea-based pollution emitted from commercial, fishing, military and recreational vessels, oil and gas platforms, and aquaculture is currently unknown. It is likely highly variable, depending on the type of vessel but also on the attitudes of its crews and passengers (Chen and Liu, 2013; Čulin and Bielić, 2016; Olsen et al., 2020; Pahl et al., 2020).

Recently, the long-range transport of air-borne particles has been identified as another source of plastics (Bergmann et al., 2019; Bianco and Passananti, 2020; Brahney et al., 2021; Dris et al., 2016; Zhang et al., 2020). Although the magnitude is currently unclear, it may be substantial (Liss, 2020) with particles carried as far as Arctic regions.

Projected future scenarios

The numbers presented in this section are global estimates of future plastic production and waste generation. It should be noted that the studies making these predictions had different aims: while some considered all plastics produced and discarded, others focused on plastic waste emitted into oceans.

An exponential increase in total plastic waste is predicted.

Jambeck et al. (2015) estimated that 4.8–12.7 MMT of plastic waste entered the oceans in 2010. They predicted at least a 10-fold increase in plastic waste entering the oceans from 2010 to 2025; predictions for 2025 range from just below 100 to 250 MMT. Geyer et al. (2017) projected an exponential increase in total plastic waste until 2050. They also predicted that more of this waste will be incinerated or recycled so that a smaller proportion of waste will be discarded. Nevertheless, the exponential increase in total plastic waste means an almost linear increase in discarded waste between now and 2050. In 2050, the total amount of discarded plastic is expected to be around 12,000 MMT, which

Group photo of the plastic-campaign, in front of the UNEA conferrence building in Kenya. © Markus Winkler/WWF

would presumably mostly end up in landfills or incinerated, but also in the natural environment. However, this study did not specify future emissions into the environment.

Even scenarios with improved waste management entail a further buildup of plastic waste.

Lebreton and Andrady (2019) estimated that 60–99 MMT of plastic waste entered all environments in 2015. They predicted that this amount could almost triple to 155–265 MMT by 2060 under a business-as-usual scenario (see Glossary). However, an improved-waste-management scenario could reduce the annual amount to about 50 MMT, and this coupled with a reduce-plastic-use scenario could further reduce the annual amount to 25 MMT. Nevertheless, even these scenarios entail a further build up of plastic waste, some of which would enter the oceans.

A business-as-usual scenario by Lau et al. (2020) projects that annual plastic pollution of aquatic and terrestrial environments (Box 4) will almost triple from about 30 MMT in 2016 to 80 MMT in 2040, of which 28 MMT will be emitted into aquatic environments. Four more ambitious scenarios, which involve improvements to collection, recycling and source reduction (see Glossary) would result in 20 to 45 MMT of annual plastic pollution in 2040. Of the 20 and 45 MMT, 5 and 18 MMT are estimated to enter aquatic environments, respectively. Again, even the most ambitious scenario entails further plastic pollution of the aquatic environment.

Borrelle et al. (2020) estimated that 19–23 MMT of plastic waste entered aquatic environments in 2016. A business-as-usual scenario projects that annual plastic pollution of the aquatic environment would reach 36–90 MMT in 2030. Two scenarios, which involve improvements in source reduction, collection and removal operations, predict either 3–12 MMT or 20–53 MMT in 2030. Again, even these ambitious scenarios would result in significant inputs of plastic pollution into the oceans.

Several studies predicted the increase in oceanic macroplastic concentrations based on future business-as-usual trajectories. A four-fold increase by 2050 and 2060 was predicted by Lebreton et al. (2019) and Isobe et al. (2019), respectively. Everaert et al. (2018) estimated a 50-fold increase of microplastic concentration by 2100.

To conclude, business-as-usual growth probably means a rapid and massive build-up of plastic pollution in the oceans. Even ambitious measures, which combine source reduction, better waste collection and recycling and environmental clean-ups still result in a continuous, albeit slower build up of plastic waste in aquatic environments.

In essence, plastic pollution resembles other global pollution crises, such as the pollution with greenhouse gases, heavy metals or POPs, because (1) business-as-usual growth means a continuous build-up of pollution, (2) the pollution affects the entire planet, and (3) solutions need to be of a radical, global and systemic nature to have any chance of success.

Box 4: Impacts of plastic pollution on terrestrial environments

Until recently, surprisingly little research had been undertaken into the impacts of plastic debris on life on land (Dioses-Salinas et al., 2020; Hurley and Nizzetto, 2018; Ng et al., 2018; Royal Society, 2019; Wang et al., 2019; Wong et al., 2020), even though this is the main human habitat (see Glossary) and where most of our food comes from. Plastic debris can affect terrestrial wildlife much in the same way as it affects marine wildlife, through entanglement, ingestion (Eriksen et al., 2021; Omidi et al., 2012; Weitzel et al., 2021) and potentially by inhalation of microplastics. It has been estimated that 32% of all the produced plastic may end up in soils (Kumar et al., 2020). Farmers in the USA currently use 57,000 tonnes of plastic mulch and 191,000 tonnes of plastic containers annually. Consequently, the microplastics content in agricultural soils is estimated to be between 63,000–430,000 and 44,000–300,000 tonnes in Europe and North America, respectively (Nizzetto et al., 2016).

The process of weathering and fragmentation of large plastic items is even faster on land than in water (Chamas et al., 2020) meaning that microplastics build up in the environment over time. Road traffic is another important source of terrestrial microplastics as vehicle tyres, road markings, and bitumen, a component of road surfaces, become abraded (Bertling et al., 2018). Because of their very small sizes, these particles can be transported quickly over long distances though the air. In addition, the remains of derelict mulching films pollute agricultural land along with polymer-based fertilizers and pesticides, plastic-coated seeds and sewage sludge. Sewage sludge contains the concentrated leftovers from wastewater treatment processes, which include microplastic particles and fibres at concentrations of thousands to tens of thousands of microplastics per kg, but could be much lower if effective treatments were used (Mahon et al., 2017; Zhang and Chen, 2020). Microfibres appear to remain unchanged for at least five years after the application of the sludge (Zubris and Richards, 2005). Terrestrial microplastic can infiltrate aquatic systems via groundwater and surface runoff (Bläsing and Amelung, 2018; Werbowski et al., 2021).

Deer with a plastic bag hooked on its antlers in Marbella, Andalusia, Spain. © iStock/Getty Images

But how does plastic pollution affect terrestrial ecosystems? Several studies have shown that microplastics change the physicochemical properties of soils such as density, water holding capacity and thermal properties (e.g. Carson et al., 2011; de Souza Machado et al., 2018; Khalid et al., 2020). Microplastics in soils also affect microbial composition and activity, which is one of the prime ecosystem services and of great importance for the global carbon cycle (de Souza Machado et al., 2018). Experiments showed that microplastics in soils can also increase the soil's carbon dioxide emissions and thereby increase global warming (Gao et al., 2020).

Nematodes, which have an important role in soil food webs, produce fewer offspring when exposed to microplastics (Schöpfer et al., 2020). This could affect important ecosystem functions and alter soil biogeochemical cycles (Schöpfer et al., 2020). Soil-dwelling organisms such as earthworms can transfer microplastics and their associated pollutants into deeper soil layers and even to the groundwater (Rillig et al., 2017; Weber and Opp, 2020; Yan et al., 2020; Yu et al., 2019). While the ingestion of microplastics is not necessarily lethal to the worms, it can alter their burrowing behaviour, immune system and cause stress (Prendergast-Miller et al., 2019; Rodriguez-Seijo et al., 2017).

A growing body of evidence suggests that microplastics could also affect plants including crops. It has been estimated that up to 0.13 trillion particles may accumulate on the surfaces of leaves in the 11 countries with the highest leaf area (Liu et al., 2020), but the impacts are still unknown. While nanoplastic in soils did not enter the root system of wheat in experimental conditions (Taylor et al., 2020), high levels of microplastics were found in market fruits and vegetables (Conti et al., 2020) and in the roots of beans (Jiang et al., 2019). This is important because it reveals that micro- and nanoplastics can infiltrate plants. Experiments with beans and rice showed increased stress as well as lower growth rates and biomass of plants after exposure to microplastics (Jiang et al., 2019; Meng et al., 2020; Wu et al., 2020). If this is true for other plants microplastic pollution of agricultural land could affect crop yields and forests but more research is needed to verify this.

A risk assessment concluded that environmentally relevant concentrations of microplastics reported in the literature could pose a considerable risk to soil biota, and that risks will increase with increasing plastic emissions (Jacques and Prosser, 2021).

Plastic pollution is considered a planetary boundary threat.

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4. The scale, extent and pathways of marine plastic pollution

As plastic pollution is considered a planetary boundary threat (MacLeod et al., 2021; Villarrubia-Gomez et al., 2018) the activities of scientists, NGOs, educational institutions, public authorities and citizens to combat it have increased. While the data gathered in numerous field campaigns still only allow us to draw a somewhat sketchy picture of the global extent of plastic pollution, scientific data are our only source of validated information. Since the 1980s, the number of peer-reviewed publications on plastic pollution, has increased exponentially (Figure 2). Consequently, we have to some extent acquired an understanding of the sources, transport processes and sinks of plastic debris in the world's oceans (Figure 3).

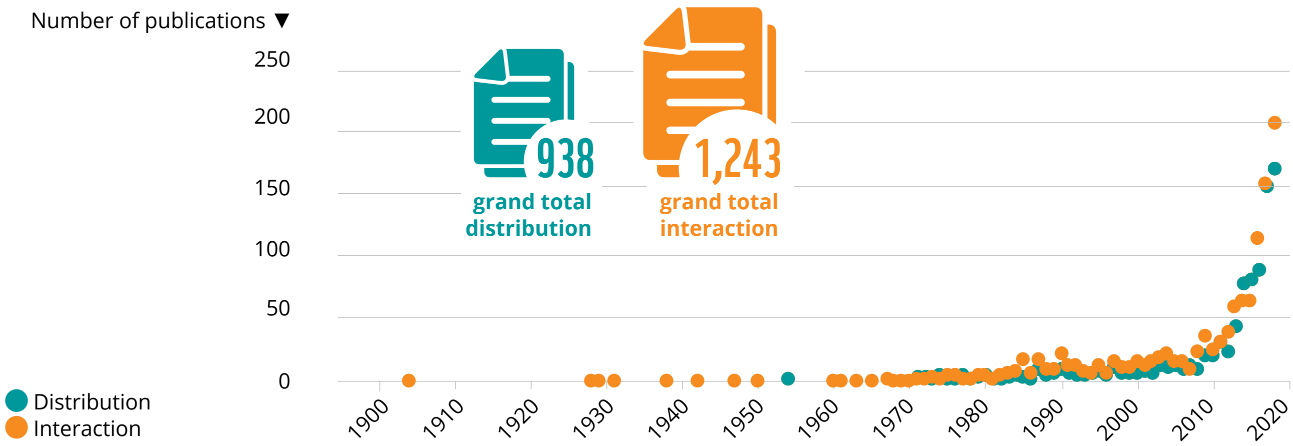


Figure 2: The number of scientific studies on the abundance of marine litter (green dots) and interactions between marine litter and marine life (orange dots) from different regions around the world published between 1900 and 2018 (LITTERBASE).

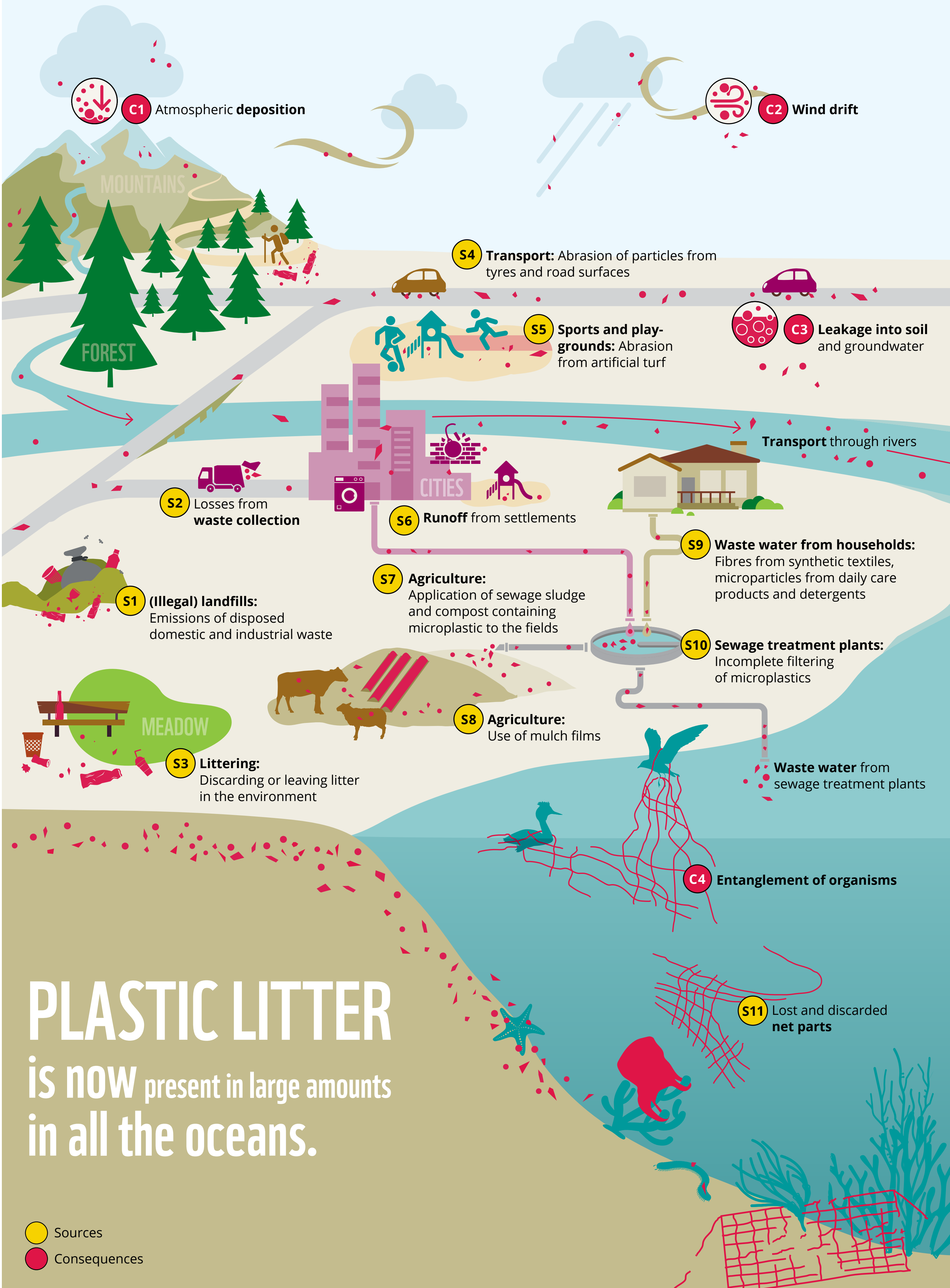
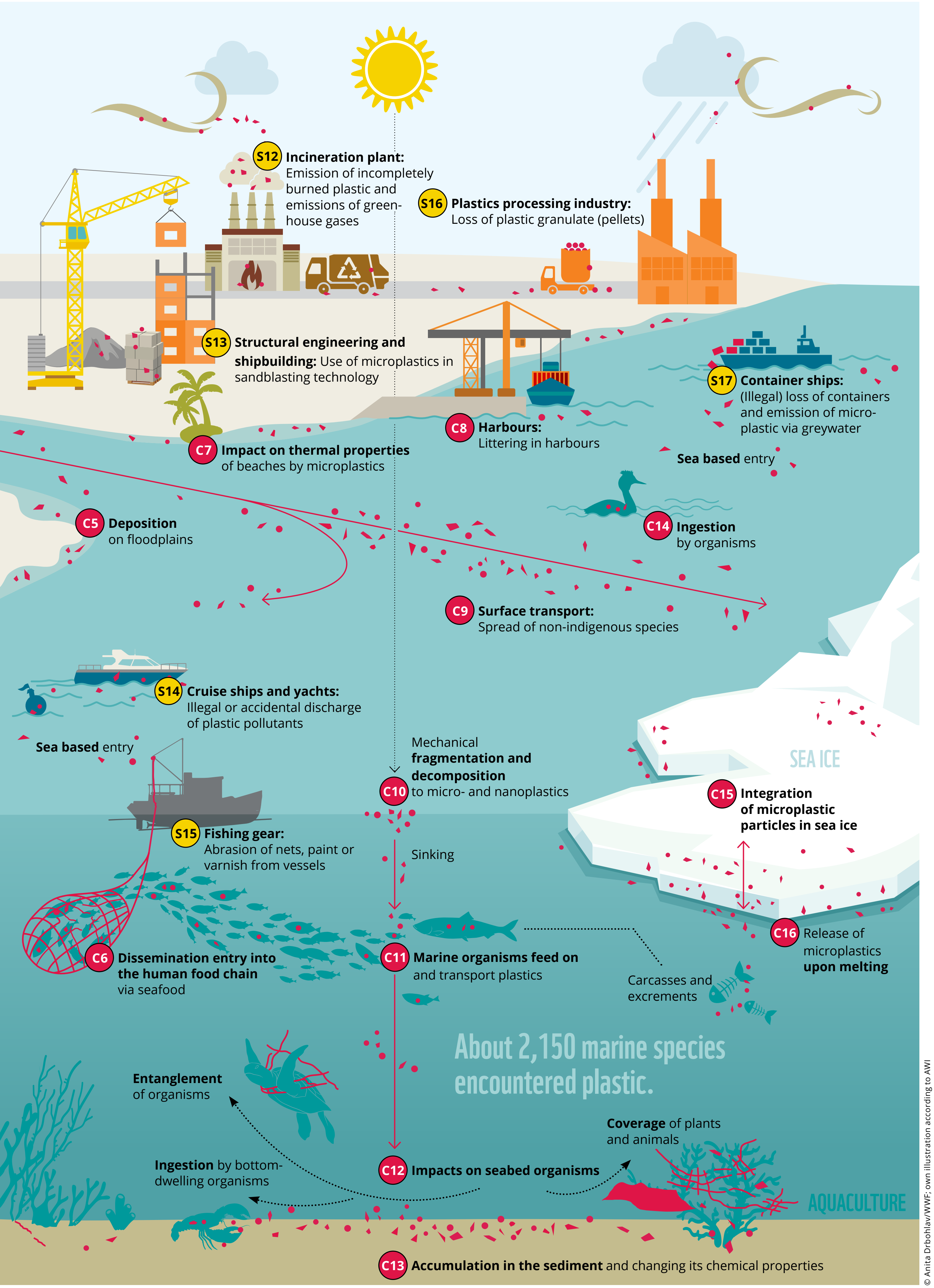


Figure 3: Pathways of plastics into the ocean



S12 Incineration plant: Emission of incompletely burned plastic and emissions of green-house gases
S16 Plastics processing industry: Loss of plastic granulate (pellets)
S13 Structural engineering and shipbuilding: Use of microplastics in sandblasting technology
S17 Container ships: (Illegal) loss of containers and emission of micro-plastic via greywater
C8 Harbours: Littering in harbours
C7 Impact on thermal properties of beaches by microplastics
Sea based entry
C5 Deposition on floodplains
C14 Ingestion by organisms
C9 Surface transport: Spread of non-indigenous species
S14 Cruise ships and yachts: Illegal or accidental discharge of plastic pollutants
Sea based entry
Mechanical fragmentation and decomposition
C10 to micro- and nanoplastics
SEA ICE
C15 Integration of microplastic particles in sea ice
S15 Fishing gear: Abrasion of nets, paint or varnish from vessels
Sinking
C16 Release of microplastics upon melting
C6 Dissemination entry into the human food chain via seafood
C11 Marine organisms feed on and transport plastics
Carcasses and excrements
About 2,150 marine species encountered plastic.
Entanglement of organisms
Coverage of plants and animals
Ingestion by bottom-dwelling organisms
C12 Impacts on seabed organisms
AQUACULTURE
C13 Accumulation in the sediment and changing its chemical properties
© Anita Drbohlav/WWF; own illustration according to AWI

The distribution of plastic pollution is ubiquitous, persistent and uneven. Plastic pollution has invaded almost every part of the oceans from urban beaches to the deepest ocean trenches and sea ice in polar regions (Peng et al., 2018, Peeken, 2018) (Figure 4). Influenced by geographic factors, ocean currents, plastic buoyancy (see Glossary) and marine organisms, plastic debris can accumulate in certain areas. For example, the five major ocean gyres (see Glossary) accumulate high concentrations of floating plastic debris due to ocean currents and wind patterns (Cózar et al., 2014; Eriksen et al., 2013, 2016; Lebreton et al., 2018; Moore et al., 2001; Pabortsava and Lampitt, 2020; Poulain et al., 2019; van Sebille et al., 2015). These gyres are also called oceanic 'garbage patches' (Lebreton et al., 2018; van Sebille et al., 2012) (see Glossary). Plastic pollutants also travel globally by air (Box 5), 'rain' on every part of the world's oceans and enter into global biogeochemical cycles (Brahney et al., 2021; Hoellein and Rochman, 2021; Zhu, 2021).

Top: Catching a barrel. © Roman Kroke 2019/UFZ; Left: A neuston catamaran sample. © Melanie Bergmann/AWI; Right: Plastic debris. © Roman Kroke 2019/UFZ; These three samples were collected for the BMBF-funded project MICRO-FATE during the research expedition SO268/3 of the German research vessel SONNE while crossing the North Pacific Ocean.

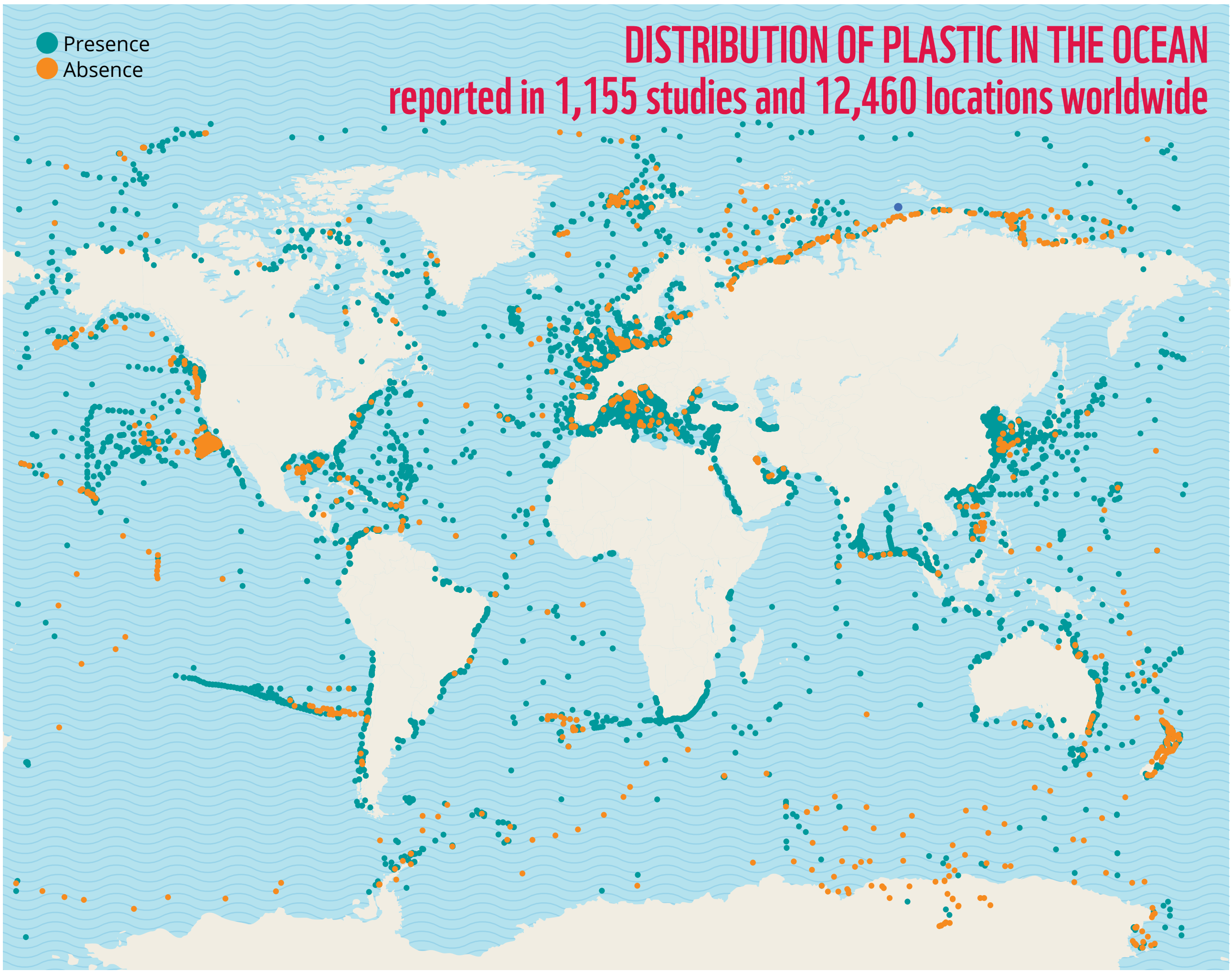


Figure 4: The global distribution of marine plastic debris recorded in scientific studies. The green dots show where plastic debris was observed (presence), and the orange dots where other types of litter were found (e.g. metal, glass) but not plastic (absence).

Seal caught in a fishing net. © Shutterstock/ Ian Dyball/WWF-Peru

Box 5: Transportation of microplastics and nanoplastics through the air

One time or another, we have probably all seen a plastic bag entangled in a tree or blown around by a gust of wind. Smaller items, especially microplastics and nanoplastics, are even more likely to be transported by wind currents. This is one reason why scientists have to be very careful to avoid contamination of their samples from the air in the laboratory. The first evidence of microplastics in the air was found in samples from two sites close to Paris in 2015 (Dris et al., 2016). Since then, microplastics have been recorded in rain, snow, glaciers, road dust and filtered air from the cities of Bremen (Bergmann et al., 2019), Dongguan (Cai et al., 2017), Hamburg (Klein and Fischer, 2019), Da Nang, Kathmandu, (Yukioka et al., 2020), London (Wright et al., 2020), Montreal (Wang et al., 2021), Shanghai (Liu et al., 2019) and Tehran (Dehghani et al., 2017). Airborne plastic particles also have been collected at remote uninhabited parts such as the Alps (Bergmann et al., 2019; Parolini et al., 2021), Andes (Cabrera et al., 2022; Cabrera et al., 2020), Pyrenees (Allen et al., 2019), Tibetan Plateau (Zhang et al., 2021) and even Mount Everest (Napper et al., 2020), from the North Atlantic atmosphere (Trainic et al., 2020) and the two polar regions (Bergmann et al., 2019; González-Pleiter et al., 2021). Microplastics and nanoplastics in the atmosphere may even enhance ice nucleation, cloud formation and precipitation events (Ganguly and Ariya, 2019). If emissions increase, they could even affect sun reflection (Revell et al., 2021).

Snow sampling for the assessment of atmospheric microplastic. The sampling took place on a sea ice floe in the Fram Strait during the research expedition PS107 of the German research icebreaker Polarstern (Bergmann et al., 2019). © Kajetan Deja

But where does this form of air pollution come from? The wear of tyres and brakes of cars are a major source of microplastic emissions, and it has been estimated that these are responsible for 140,000 metric tons per year entering the oceans (Evangeliou et al., 2020). If dark microplastics are deposited on ice surfaces (Bergmann et al., 2019), it could affect the reflectance of the sun (Albedo), potentially accelerating global heating. In addition, microfibers shed from our extensively used synthetic textiles and fabrics could add 7–34 metric tons per year to the ocean (Liu et al., 2020). Wind abrasion from plastic-coated surfaces of buildings, cars, ships and offshore platforms may be another important source along with particles that are released during waste processing. A recent study estimated that the total atmospheric burden of microplastics over the western US land regions amounts to currently 0.001 MMT, of which 84% stem from road dust, followed by sea spray (11%), agricultural dust (5%) and dust generated downwind of population sources (0.4%) (Brahney et al., 2021). This is important as this pathway has been paid little attention so far and opens a fast route to agricultural land as well as otherwise untouched remote areas. In addition, it highlights that microplastics – like other air pollutants – could be inhaled by humans (Cox et al., 2019; Pauly et al., 1998; Wright and Kelly, 2017) and air-breathing animals.

Deployment of McLane Large Volume Water Transfer System to filter seawater for plastics while crossing the North Pacific Ocean during the research expedition SO268/3 in 2019. © Roman Kroke 2019/UFZ

While we are gaining an increasingly accurate picture of the situation, we need to keep some caveats in mind. A global analysis of plastic pollution levels is challenging for at least three reasons. (1) Since a global assessment within a single sampling campaign is impossible, scientific studies only analyse the distribution of marine litter within a limited area. Therefore, estimates of the distribution and levels of global plastic pollution are necessarily based on the extrapolation of data from many different studies. (2) Since different studies rely on different sampling and analytical methods, any conclusions have to consider these differences (Edelson et al., 2021). (3) Sampling efforts also differ for different marine environments. For example, it is much more difficult to deploy sophisticated in-situ devices to a depth of thousands of metres than to collect plastic debris from beaches. Therefore, it is not surprising that we have more data on the pollution of coastal areas than of the seabed.

Beaches and the seafloor contain the largest microplastic concentrations.

Plastic pollution levels show distinct patterns in different marine ecosystem compartments (Figure 5). Beaches harbour the highest macroplastic concentrations. However, this result could be biased since more studies deal with beaches compared to other ecosystems (Figure 6), meaning that they could have caught more pollution hotspots. By contrast, the seabed harbours the highest microplastic levels. To illustrate the point: on a beach area the size of a football pitch, 3,500 (up to 12.5 million) macroplastic and 690,000 (up to 845 million) microplastic items can be found. The same area on the seabed harbours eight (up to 2.5 million) macroplastic and two million (up to 80 million) microplastic items (LITTERBASE). In general, microplastic concentrations are several orders of magnitudes higher than macroplastic concentrations (Table 1, Figure 5). This is not surprising given that plastic items break down into microplastics over time. Studies of the seafloor often rely on camera surveys, which overlook buried macroplastic items (Canals et al., 2021). Buried macroplastic may well be missed during beach surveys, yet these are mostly small items (Ryan, 2020).

A total of 1,115 scientific studies on the distribution of plastic debris were considered in this report (Figure 4), which showed that plastic debris was present at 12,460 locations. Despite thousands of sites surveyed, the expanse of the examined area is still very limited compared to the vastness of the oceans, and unknown pathways and sinks likely still exist. The common approach to quantify marine debris has been to either report abundances or weight per unit area, distance or volume. Since values given in different units cannot be compared, the studies reporting their results in the most commonly used units were included into the data analyses (Figure 5, Figure 6, Table 1).

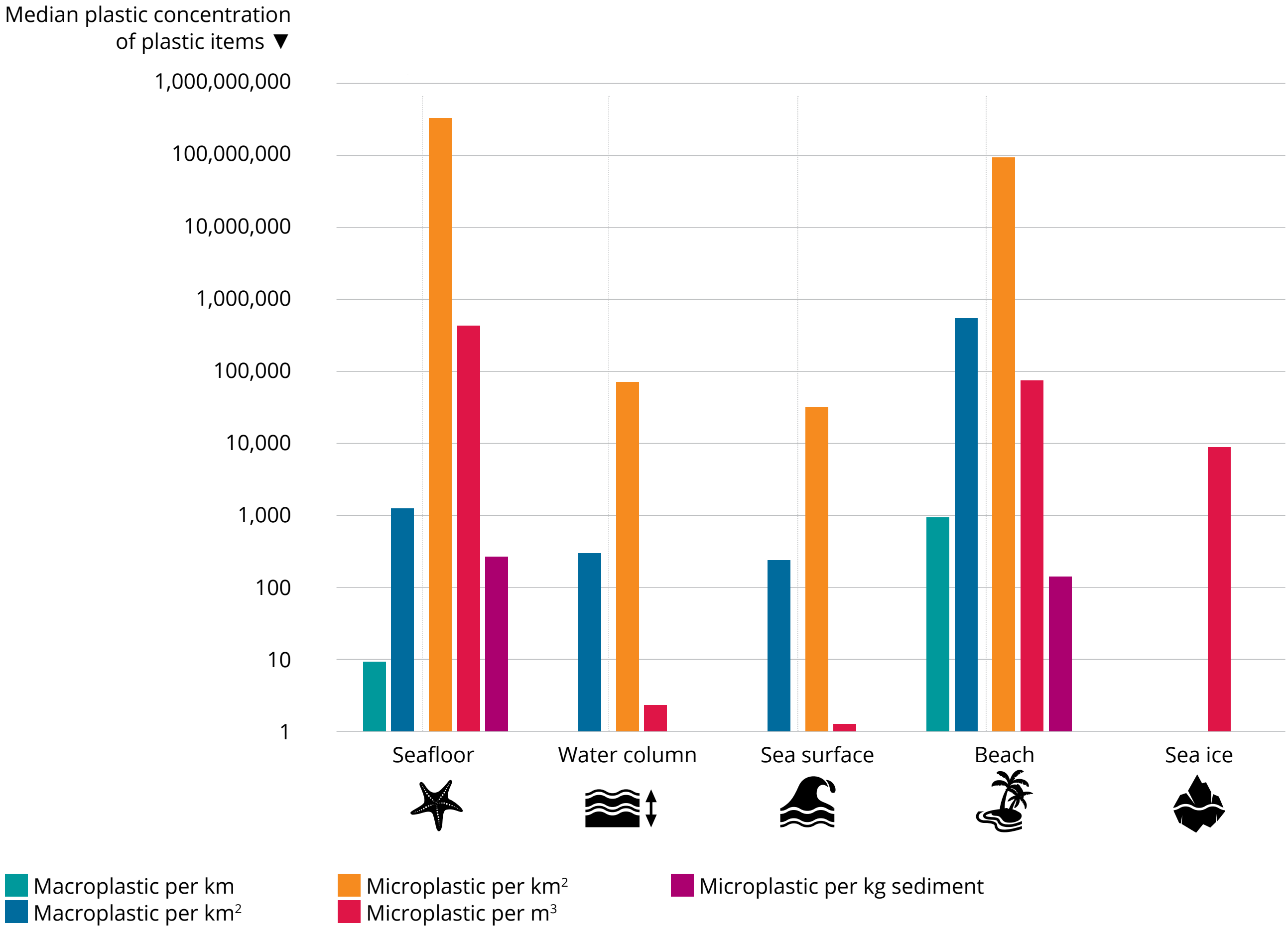


Figure 5: Median plastic debris quantities in different environmental compartments. Since amounts reported in different units are not comparable, a colour code was used to depict quantities per km, km², m³ and kg of sediment. Plastic concentrations are shown on a logarithmic scale. This analysis is based on 605 publications (LITTERBASE).

Table 1: Average global amount of plastic pollutants. The data are given in different units as provided in different studies. The analysis is based on 605 publications, reporting from 6,483 locations, which provided data in the most commonly used units. Because of the large range, median values are shown along with the 1st and 3rd quartiles, indicating variability of the values (LITTERBASE). Mesoplastic (5–25 mm) is grouped as a separate category because it leads to unrealistically high concentrations of macroplastics when included in macroplastics.

	Macroplastic	
	items/km²	items/km
Number of publications	192	96
Number of sampling locations	1,439	579
Median*	3,127	693
Minimum	0[1]	0[2]
Maximum	1,072,500,000[3]	1,476,000[4]
Q1**	97	100
Q3***	176,998	2,932

	Mesoplastic		
	items/km²	items/m³	items/kg
Number of publications	19	8	5
Number of sampling locations	182	31	25
Median*	3,150,000	0.12	13
Minimum	457[5]	0.01[6]	3[7]
Maximum	4,168,000,000[8]	1,200[9]	56[10]
Q1**	10,035	0.06	10
Q3***	20,750,000	0.30	26

	Microplastic		
	items/km²	items/m³	items/kg
Number of publications	113	170	102
Number of sampling locations	1,171	2,102	795
Median*	200,000	7	200
Minimum	0.01[11]	0[12]	0[13]
Maximum	118,469,000,000[14]	41,577,670[15]	630,005[16]
Q1**	21,489	0.16	72
Q3***	69,000,000	2,000	560

* Median: The value separating the higher half from the lower half of the dataset.
** 1st quartile: The middle number between the smallest number (minimum) and the median of the data set.
*** 3rd quartile: The middle value between the median and the highest value (maximum) of the dataset.

1 (Barnes and Milner, 2005; Campbell et al., 2017; D'Onghia et al., 2017; Galgani et al., 2000; Gutow et al., 2018; Havens et al., 2011; Hinojosa and Thiel, 2009; Katsanevakis and Katsarou, 2004; Moschino et al., 2019; Parga Martínez et al., 2020; Pogojeva et al., 2021; Rayon-Viña et al., 2018; Schmuck et al., 2017; Sen et al., 2019; Shimanaga and Yanagi, 2016; Stevens, 2000; Sullivan et al., 2019; Tekman et al., 2017; Wei et al., 2012)
2 (Jozwiak, 2005)
3 (Storrier et al., 2007)
4 (Debrot et al., 2013)
5 (de Scisciolo et al., 2016)
6 (Isobe et al., 2014)
7 (Blašković et al., 2017)
8 (Okuku et al., 2020)
9 (Kim et al., 2021)
10 (Blašković et al., 2017)
11 (Benson and Fred-Ahmadu, 2020)
12 (Chae et al., 2015; Jensen et al., 2019; Kuklinski et al., 2019; Lechthaler et al., 2020; Setälä, 2016)
13 (Talvitie et al., 2015)
14 (Kim et al., 2015)
15 (Brandon et al., 2020)
16 (Van Cauwenberghe et al., 2013)

Spatial distribution and transport pathways of oceanic plastic pollution

Beach litter pollution raises aesthetic concerns, which cause revenue from the tourism sector to fall, and undermine the beneficial effects of blue environments (Jang et al., 2014; Wyles et al., 2016). The ease of access and visibility of pollution at the shore has motivated beach clean-ups and citizen science activities worldwide, as marine plastic debris is relatively easy to identify, also for non-scientists. Therefore, it is not surprising that across marine compartments the studies on coastal plastic pollution have the highest share (44%) (Figure 6). Sampling campaigns by citizen scientists have contributed substantially to our knowledge of coastal litter pollution (Cigliano et al., 2015; Hidalgo-Ruz and Thiel, 2015; Rambonnet et al., 2019; Thiel et al., 2014). Since the density of the human population has been identified as a significant factor for plastic pollution (Pedrotti et al., 2016), the general perception is that local human activities are the main source of coastal plastic pollution. However, uninhabited remote beaches also suffer high levels of macroplastic pollution (Bergmann et al., 2017; Lavers and Bond, 2017; Ryan et al., 2019), which can come from both nearby and distant sources (Ryan, 2020; Ryan et al., 2021). Among other types of plastic debris, single-use plastics account for 60–95% of global marine plastic pollution (Schnurr et al., 2018).

Typical plastic pollution found on a German beach, dolly ropes on the left and pellets on the right (location: Norderney Island, date: 23.03.2021).
© Valeria Bers

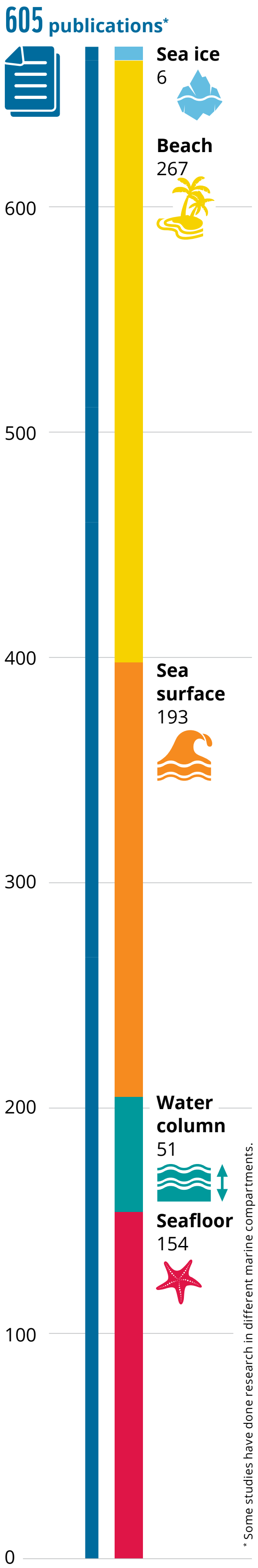


Figure 6: Proportion of publications on plastic pollution in different marine compartments. This analysis is based on 605 publications (LITTERBASE). Some studies focus on multiple marine compartments. Therefore the sum of publications reporting from individual compartments exceeds the total number of publications.

Floating microplastic (Figure 7) was estimated to account only for 1% of the mass of plastic released into the oceans (van Sebille et al., 2015). Another study (Koelmans et al., 2017) suggested a lower proportion: According to their model, 99.8% of 196 MMT of plastic that had entered the ocean since 1950 sunk below the surface waters by 2016. However, even the small proportion of 0.2% amounts to 15–51 trillion microplastics weighing between 0.09–0.3 MMT (Koelmans et al., 2017; van Sebille et al., 2015). Some studies suggest that the actual floating mass of microplastics and macroplastics has been grossly underestimated (Conkle et al., 2018; Lebreton et al., 2018; Lindeque et al., 2020; Pabortsava and Lampitt, 2020).

Figure 7: WWF global plastic navigator (https://plasticnavigator.wwf.de/) visualises the most recent and high-resolution data of current scientific publications on marine plastic pollution – from mismanaged waste on land, emission of rivers into the oceans and floating plastic concentration in the oceans.

It has been suggested, for example, that two-thirds of all the buoyant plastic (46.7–126.4 MMT of plastic), which were released into the marine environment since the 1950s are actually being stored by the world's shorelines as stranded, settled or buried debris (Lebreton et al., 2019). The remaining third had degraded into smaller microplastics and either remains floating in the ocean or has sunk to the ocean floor. More recent studies suggest even larger ranges of plastic debris trapped in coastal zones (Chenillat et al., 2021; Onink et al., 2021).

The most well-known floating polymer types are HDPE, LDPE, PP, linear low-density polyethylene (LLDPE) and expanded polystyrene, commonly referred to as Styrofoam (Reisser, 2015). More than half of the plastics ever produced is made of positively buoyant polymer types (Andrady, 2011; Geyer et al., 2017). Positively buoyant plastics float in water, at least initially. Therefore, it is not surprising to find high amounts of polyethylene (PE) and polypropylene (PP) in the North Pacific Subtropical Gyre (Lebreton et al., 2018). But even buoyant plastic can, over time, sink to the ocean floor. Plastics heavier than seawater likely sink to the seafloor immediately (Engler, 2012). However, depending on the location and environmental conditions, they do not necessarily remain settled. Baltic amber is repeatedly migrating between the beach and underwater slope under certain wind and current conditions (Chubarenko and Stepanova, 2017). Since many types of plastics have a density similar to amber, such migration of coastal plastic debris can be expected until they break down into smaller fragments and are mixed to deeper waters.

Plastic incorporation into sea ice could be an additional factor that amplifies global warming.

Some of the highest concentrations of microplastic measured to date were identified from sea ice, hence it is considered a temporal sink for microplastics (Peeken et al., 2018). Microplastic has been found in both the Arctic and Antarctic as well as in Baltic Sea ice (Geilfus et al., 2019; Hallanger and Gabrielsen, 2018; Kelly et al., 2020; Peeken et al., 2018). This could increase or decrease (Geilfus et al., 2019) the albedo effect depending on the colouration of particles, and affect heat adsorption and melting. Given the high concentrations found in Arctic sea ice and the projected increase (Chapter 3), plastic incorporation into sea ice could be an additional factor that amplifies global warming and elicits further pressure on ice-associated organisms.

The German polar research base Neumayer station III in Antarctica.
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Several mechanisms enable the transport of floating debris to the ocean floor: (1) Degradation, dissolution and leaching of additives can alter plastic composition and thus density (Booth and Sørensen, 2020; Suhrhoff and Scholz-Böttcher, 2016; Zhu et al., 2020). (2) Bio-fouling (see Glossary) can decrease the buoyancy of plastic (Booth and Sørensen, 2020; Fazey and Ryan, 2016; Kaiser et al., 2017; Wang et al., 2018). Any object floating in aquatic environments is subject to colonisation by organisms. Once fouling is extensive enough to overcome the positive buoyancy, plastic debris starts to sink. However, fouling does not guarantee an ultimate sinking path as submerged items could undergo de-fouling, become positively buoyant again and resurface (Ye and Andrady, 1991). (3) Turbulence of ocean waters can force smaller microplastics downwards (Poulain et al., 2019). (4) Incorporation in marine snow (see Glossary) and algal clumps (Kvale et al., 2020; Long et al., 2015; Porter et al., 2018); and (5) ingestion and transport by animals (Choy et al., 2019; Cole et al., 2016; Courtene-Jones et al., 2017; Coyle et al., 2020; Katija et al., 2017; Savoca et al., 2021; Vroom et al., 2017).

The seafloor is considered an accumulation area for microplastics.

Although the water column is the largest biome on Earth, it is "out of sight" and therefore has not received much attention in terms of plastic pollution research. However, after the seafloor was identified as a major sink for microplastics, scientific curiosity has been directed to sinking mechanisms of these particles. Biological processes in this biome directly affect the food supply to the seafloor (Iversen and Ploug, 2010). This raises the question of how this pollution will affect pelagic (see Glossary) ecosystems and the biological pump (see Glossary).

Recent studies have confirmed the existence of microplastic in the water column and incorporation of these particles into sinking aggregates (Long et al., 2015; Tekman et al., 2020; Zhao et al., 2018). Sinking particles are consumed by pelagic species (partly or completely), including plankton, which form the base of marine food webs (Brandon et al., 2020; Cole et al., 2013; Davison and Asch, 2011; Katija et al., 2017). Any disruption in the efficiency of these processes could affect the amount of food reaching the seafloor (Wieczorek et al., 2019), which may cause changes in food-limited benthic (see Glossary) ecosystems.

Recent research also highlighted the importance of sideward transportation of particles through the water column due to water currents (Li et al., 2020; Tekman et al., 2020) and trapping in turbidity layers (Zhou et al., 2021). All these results indicate a much more complex sinking process of plastic debris than anticipated. Basically, plastic particles are travelling in the water column, and once they start to sink, it is very hard to estimate where and when they will end up and how they affect the food web.

Once plastic debris reaches the deep seafloor, further long-range dispersal is unlikely because of the relatively stable conditions. Still, bottom currents can carry microplastic particles to accumulation hotspots on the deep seafloor (Kane et al., 2020). The seafloor is thus considered an accumulation area for microplastics (Woodall et al., 2014). Indeed, our analysis of data from 67 studies (LITTERBASE) showed that the seafloor harbours the highest median microplastic concentration among all marine compartments (Figure 5).

Temporal distribution of oceanic plastic pollution

Table 1 shows that the amounts of plastic pollutants reported from different studies vary considerably. Such wide variation would likely lead to biased results, if temporal trends were deduced only by aggregating data from different studies. Therefore, consistent time-series data are very valuable for identifying temporal trends of plastic pollution and accumulation, yet they are scarce and report observations from a limited area (Galgani et al., 2021; Gerigny et al., 2019; Maes et al., 2018; Parga Martínez et al., 2020; Ribic et al., 2010; Unger et al., 2021). While the abundance of industrial plastic in both stomachs of North Sea fulmars and water samples from the North Atlantic subtropical gyre decreased between the 1970's and 2012, there was no consistent trend in the abundance of user plastics (van Franeker and Law, 2015). Similarly, plastic levels remained relatively constant both in Baltic Sea water samples and herring and sprat between 1987 and 2015 (Beer et al., 2018). Likewise, no clear trend could be deduced from 25 years of beach litter surveys from the southeastern North Sea (Schulz et al., 2015). However, continuous Plankton Recorder surveys in the North Atlantic and adjacent seas revealed an exponential increase in plastic pollution from 1957 to 2016 although levels decreased slightly over the last decade (Ostle et al., 2019). Microplastic pollution in the North Pacific Subtropical Gyre increased by two orders of magnitude between 1972 and 2010 (Goldstein et al., 2012). In the Arctic deep sea, marine litter pollution, most frequently plastics, had increased between 2002 and 2017 (Parga Martínez et al., 2020). A continuous growth was reported in the number of small plastics after 2014, implying that even if we stop emissions into the oceans, legacy plastic will continue to fragment, leading to an increase of micro- and nanoplastics pollution.

The increase in the abundance of microplastic rises in line with global plastic production rates.

An alternative approach of analysing naturally-accumulating archives has proven to be very reliable (Bancone et al., 2020). Since the seafloor is an area of continual particle deposition, the analysis of microplastic particles in sediment layers has revealed temporal trends of plastic pollution (Brandon et al., 2019; Chen et al., 2020; Courtene-Jones et al., 2020; Fan et al., 2019; Martin et al., 2020). Using these stratigraphic methods, 40 years' of increase in the abundance of microplastics were shown for the South China Sea (Chen et al., 2020). Mangrove sediments across the Red Sea and the Arabian Gulf showed an exponential rate of microplastic burial, corresponding to plastic production rates (Martin et al., 2020). Similarly, the increase in microplastic deposition rates of coastal sediments from the Santa Barbara Basin, California, was linked to global plastic production (Brandon et al., 2019) (Figure 8).

These conflicting temporal trends indicate that plastic pollution is localized, and long-term observations from a region do not reveal much about the global trends. Also, stable sink-environments such as the seafloor could be more appropriate for long-term monitoring. An assessment of temporal trends would require a closed mass balance of all plastics in all seas (Galgani et al., 2021). Currently, such an assessment would be very challenging, as we only have recently started to understand the mechanisms of transport, degradation and accumulation within and between marine compartments.

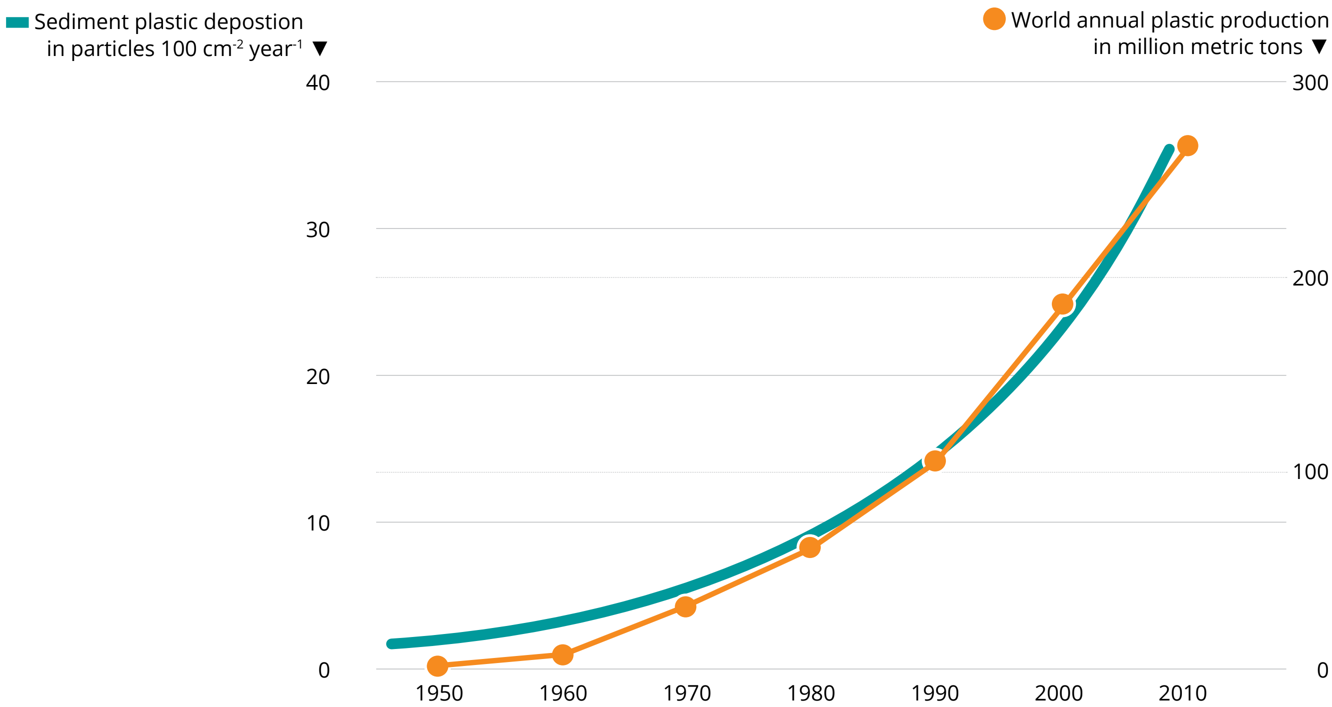
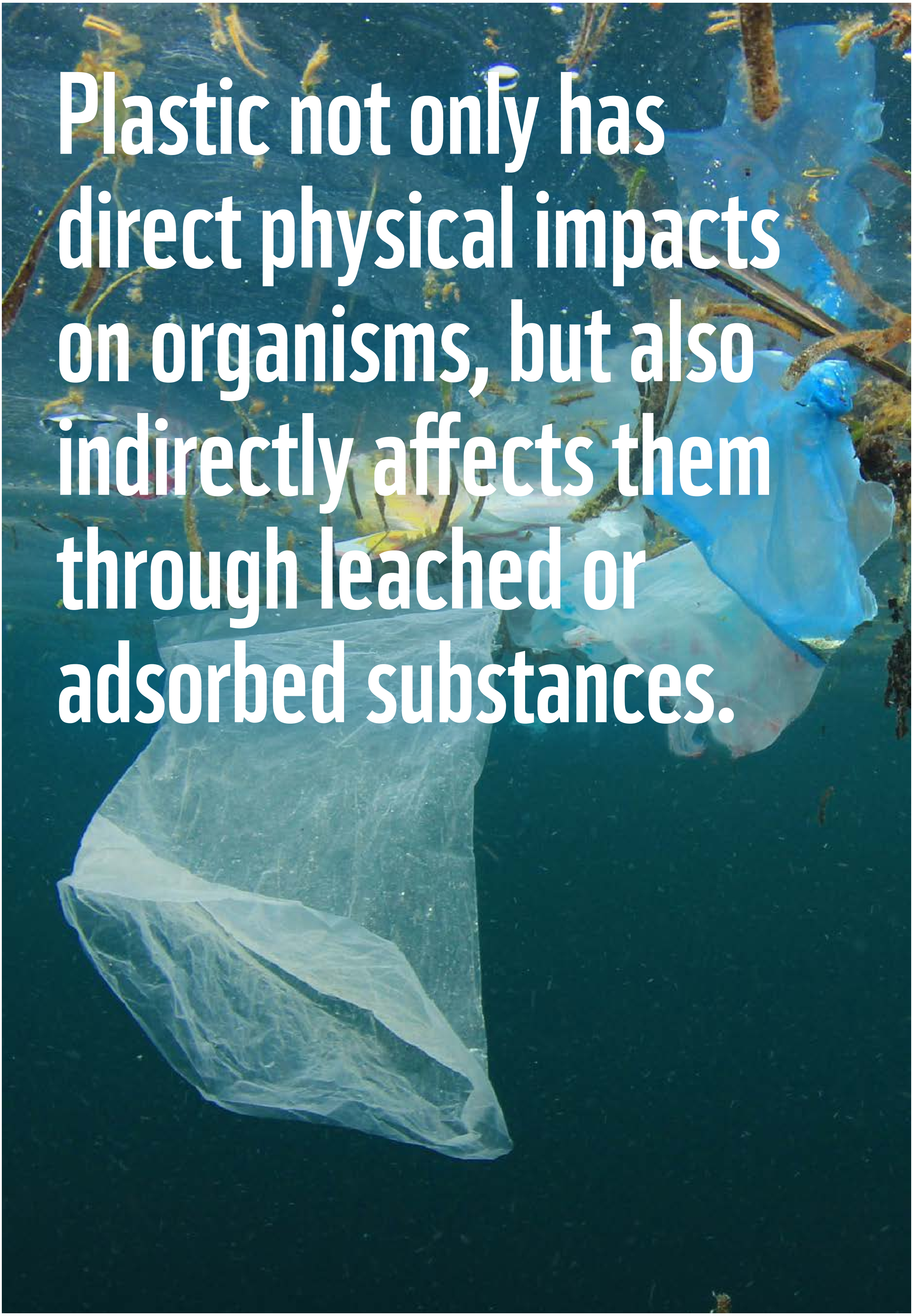


Figure 8: Plastic deposition into sediments and global plastic production rates (reproduced from Brandon et al., 2019).

Plastic not only has direct physical impacts on organisms, but also indirectly affects them through leached or adsorbed substances.



5. Effects of plastic debris and hazardous substances on marine species

5.1 Introduction

Plastic pollution of the oceans has recently reached the consciousness of the public (Prata et al., 2019; Völker et al., 2020; Walther et al., 2020; 2021b), especially through images of interactions between charismatic animals and marine debris (NOAA-MDP, 2014; Warner et al., 2020, Parton, 2019), even from places as secluded as the Arctic (Bergmann et al., 2017a; Collard and Ask, 2021). Physical interactions are not limited to charismatic species as shown by a growing body of evidence of the impacts of plastic pollution on marine species (Figure 9, 10) in terms of the physical and chemical effects of plastic debris. Plastic products are made up of hundreds of polymers and additives (Andrady and Rajapakse, 2016; Kutz, 2011; Wypych, 2016), some of which can be a threat to marine life. Therefore, plastic items not only have a direct harmful physical impact on organisms, but also indirectly affect them though leached or adsorbed substances (Silva et al., 2021).

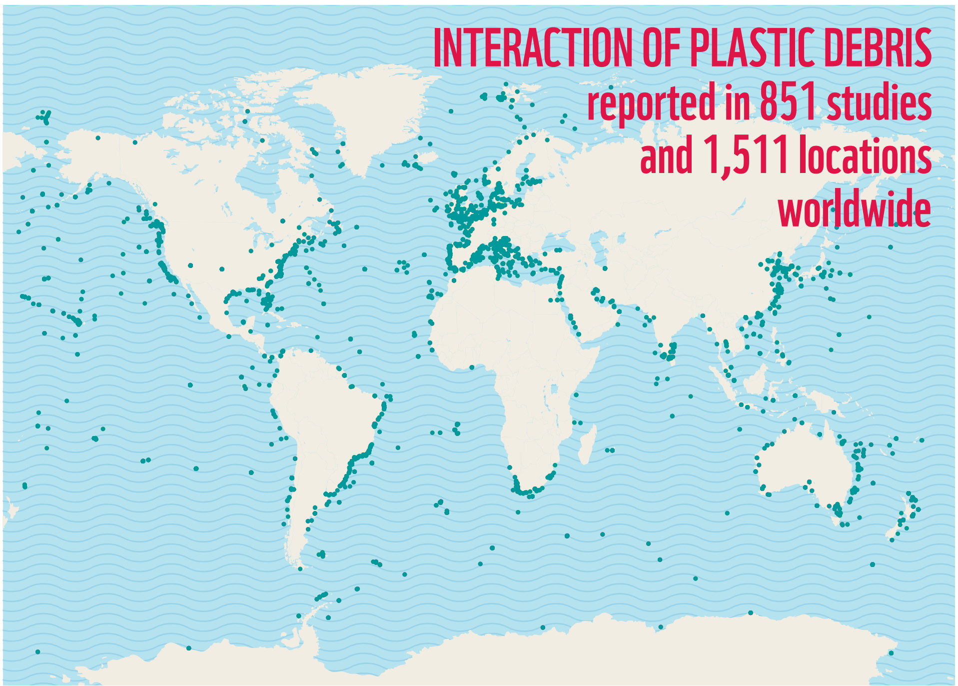


Figure 9: Map of encounters between plastic pollutants and marine life. The dots on the global map refer to 1,511 locations reported in 851 studies (LITTERBASE).

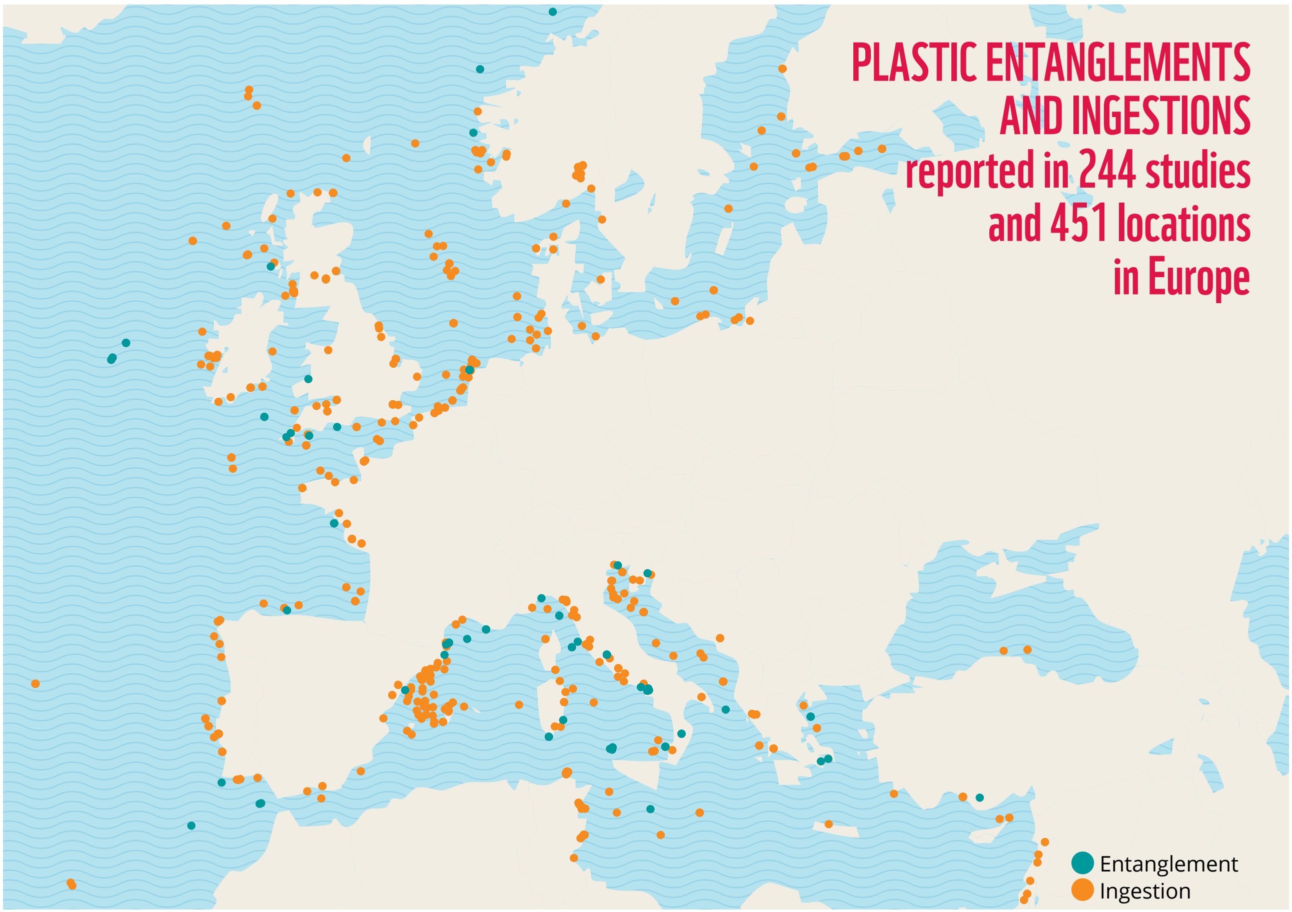


Figure 10: Plastic entanglements and ingestions reported in 244 studies and 451 locations in Europe (LITTERBASE).

The nature of the impact of plastic debris and chemicals depends on the shape, body size, movement, feeding mode and habitat of the species as well as on the type, shape, size and density of the plastic items and fragments (Bucci et al., 2020; Rochman, 2019). For example, the size of a petrel's head scales with the size of ingested and retained plastic debris (Roman et al., 2019b). Plastic debris as big as a part of a car was found in stranded sperm whales (*Physeter macrocephalus*) (Unger et al., 2016).

Occurence and severity of impacts depend on exposure levels.

In this chapter, we review the scientific literature on the physical and chemical impacts of plastic pollution on species and populations. Both the occurrence and the severity of impacts depend on exposure levels (Besseling et al., 2019). Experimental studies on microplastic ingestion have often been criticised for using unrealistically high concentrations of particles (Section 5.2.2) and therefore, it is critical to determine the threshold levels, at which the effects occur so that studies can realistically address the impacts. Recently, models have been developed to assess the ecological risks of plastic pollution and establish threshold levels (Chapter 7) (Besseling et al., 2019; Burns and Boxall, 2018; Compa et al., 2019; Everaert et al., 2018; 2020; Gouin et al., 2019; Jung et al., 2021). However, if such risk assessments underestimate microplastic concentrations, they are more likely to conclude low harm at current pollution levels (e.g. Everaert et al., 2018; 2020).

The physical impact of plastic pollution on biota can be understood by looking at two levels of information: Interactions and their effects (Figure 11). In this report, 'interaction' refers to encounters between organisms and plastic such as (1) entanglement, (2) plastic ingestion, (3) colonisation of plastic items by marine life and (4) contact or coverage (e.g. smothering) of organisms with plastics and are reviewed in the "Physical Interaction" Section (5.2). The impacts of harmful substances are addressed in the "Chemical Interactions" Section (5.3).

Whether these interactions actually have an effect on the well-being of the organisms is a more difficult question to resolve and is categorised as 'effects' in this report (Figure 11). The most frequently observed effects of interactions are restrained movement, injury, mortality and dispersal of organisms by rafting. A complete list of effects and the approach for their evaluation is given in Annex (Section 10.2). Some effects cannot be easily assessed through field sampling (e.g. changes in reproduction or growth) and are thus usually studied in laboratory experiments.

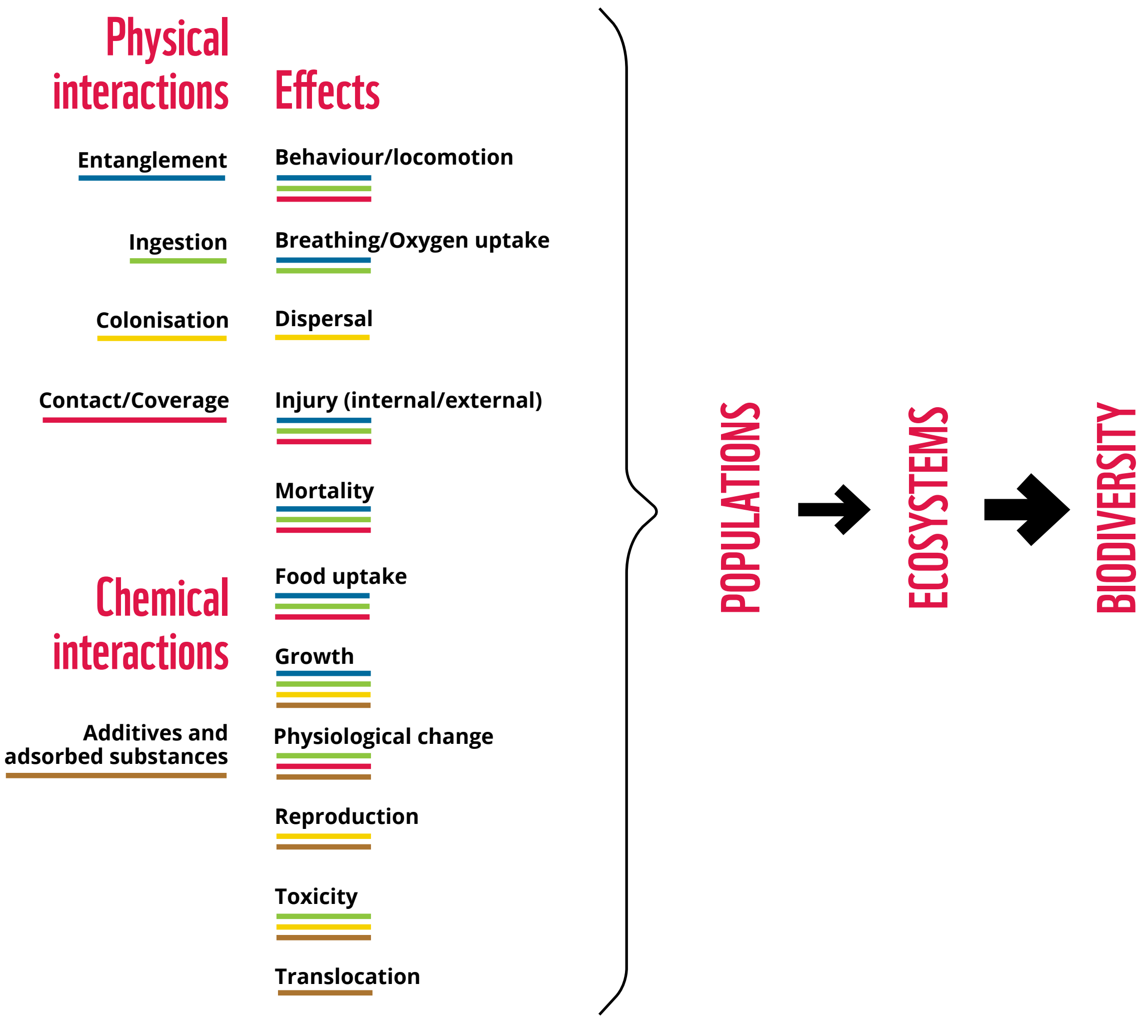


Figure 11: Diagram of the most frequently reported interactions and their effects on organisms (LITTERBASE). The colours represent the respective interactions.

To assess the impacts of plastic pollution on marine species, we analysed data from 1,253 scientific studies (LITTERBASE). For our analyses, those studies that did not explicitly name plastic as a distinct type of marine litter were not included in the dataset. For example, unless specified as plastic, fisheries' debris or ropes were not included in the analysis. Therefore, the figures in this report are conservative (Annex). Our analysis shows that overall 2,788 species interact with plastic debris (Figure 12). A total of 63 studies performed field experiments. On top of these, 30 conducted both experiments and field sampling. A total of 309 studies examined the interactions of plastic with 367 species in the laboratory. The remaining 851 publications reported encounters between 2,144 marine organisms and plastics in the wild (LITTERBASE).

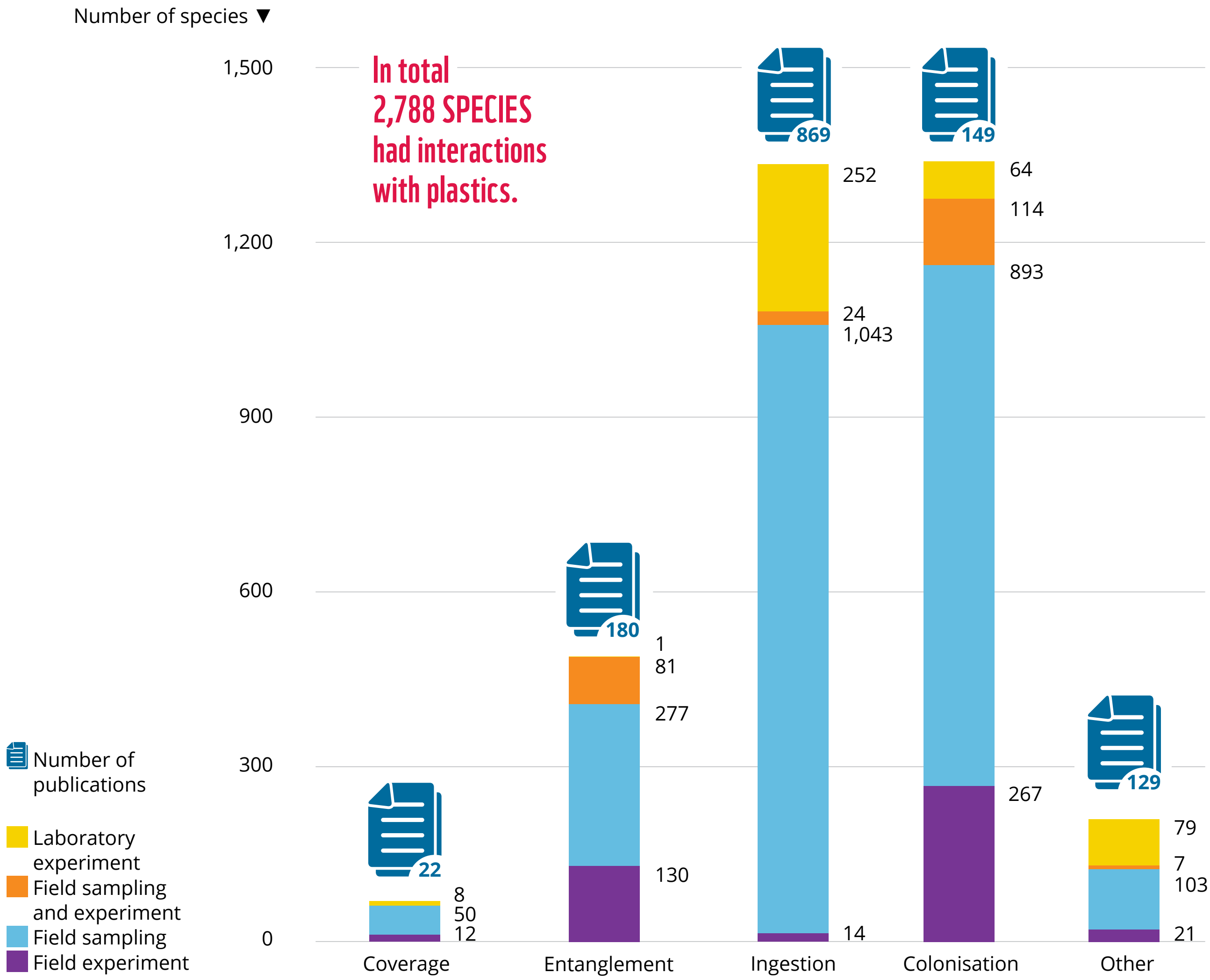


Figure 12: Types of interactions with plastic debris observed in field sampling and reported in field and laboratory experiments. These interactions were reported for 2,788 species in 1,253 studies (LITTERBASE). Multiple interactions were recorded for some species. Similarly, some species were subject to different types of interactions in experiments. Therefore, the number of species next to the bars amounts to a higher value than the total number of species. The blue thumbnails above the bars represent the total number of publications for each type of interaction. As with the species, some studies investigated multiple effects.

Colonisation on floating plastic debris can promote the dispersal of invasive species.

This report pays special attention to the "colonisation" type of interaction whose main effect is the dispersal of associated organisms on floating debris (García-Gómez et al., 2021). Although, colonisation has little direct effect on the organism itself, it can promote the dispersal of invasive species or pathogens. 745 species were recorded from floating or beached plastic debris, including exotic species (see Glossary) and pathogens. Of the remaining interactions, significant effects were reported for 467 species. This comprised field observations, such as injuries due to entanglement and laboratory studies. A total of 255 laboratory studies evaluated the effects of interactions with plastic debris on 175 species. These interactions were found to have a significant effect on 68% of the examined species in 66% of the studies.

In the beginning of this chapter, different types of physical interactions and harmful substances associated with plastics will be introduced, followed by the impacts of these interactions on marine populations. In the second part, the scientific literature on encounters between plastic pollutants and seabirds, sea turtles, marine mammals and fishes will be analysed. Interactions with fish species will be discussed in two groups: "Sharks and rays" and "other fishes". Moreover, the interactions and effects of plastic pollution on some species from each taxon, that are well-known by the public or have an ecological importance, will be evaluated.

Rice sack litter above Tubbataha reef, Sulu seas, Palawan, Philippines. Date: 11.04.2009. © Jürgen Freund/WWF

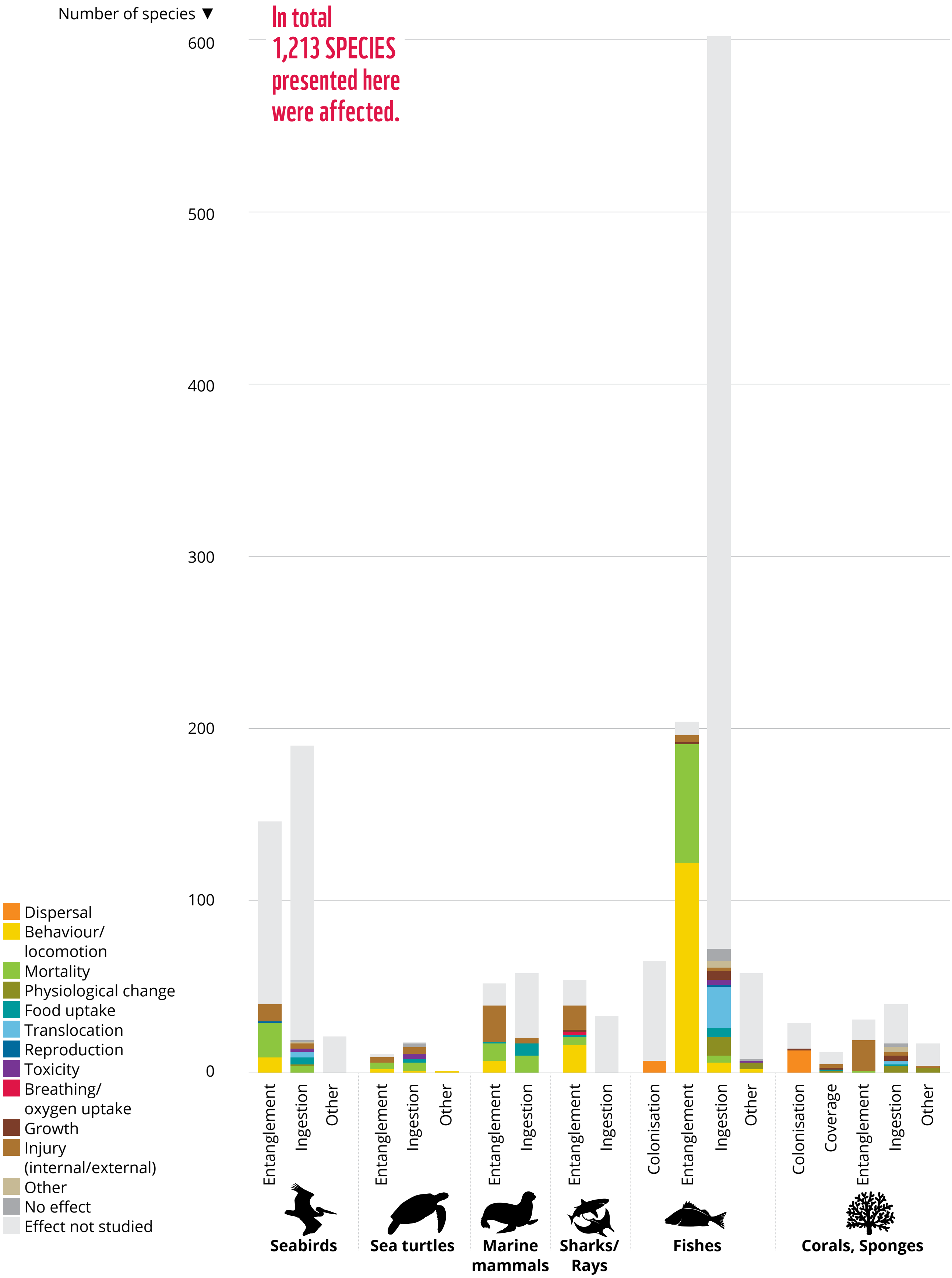


Figure 13: The effects of interactions with plastic on seabirds, corals, sponges, sea turtles, sharks, rays and fishes. The height of the bars refers to the number of species. The data are from 778 publications based on field and experimental studies (LITTERBASE).

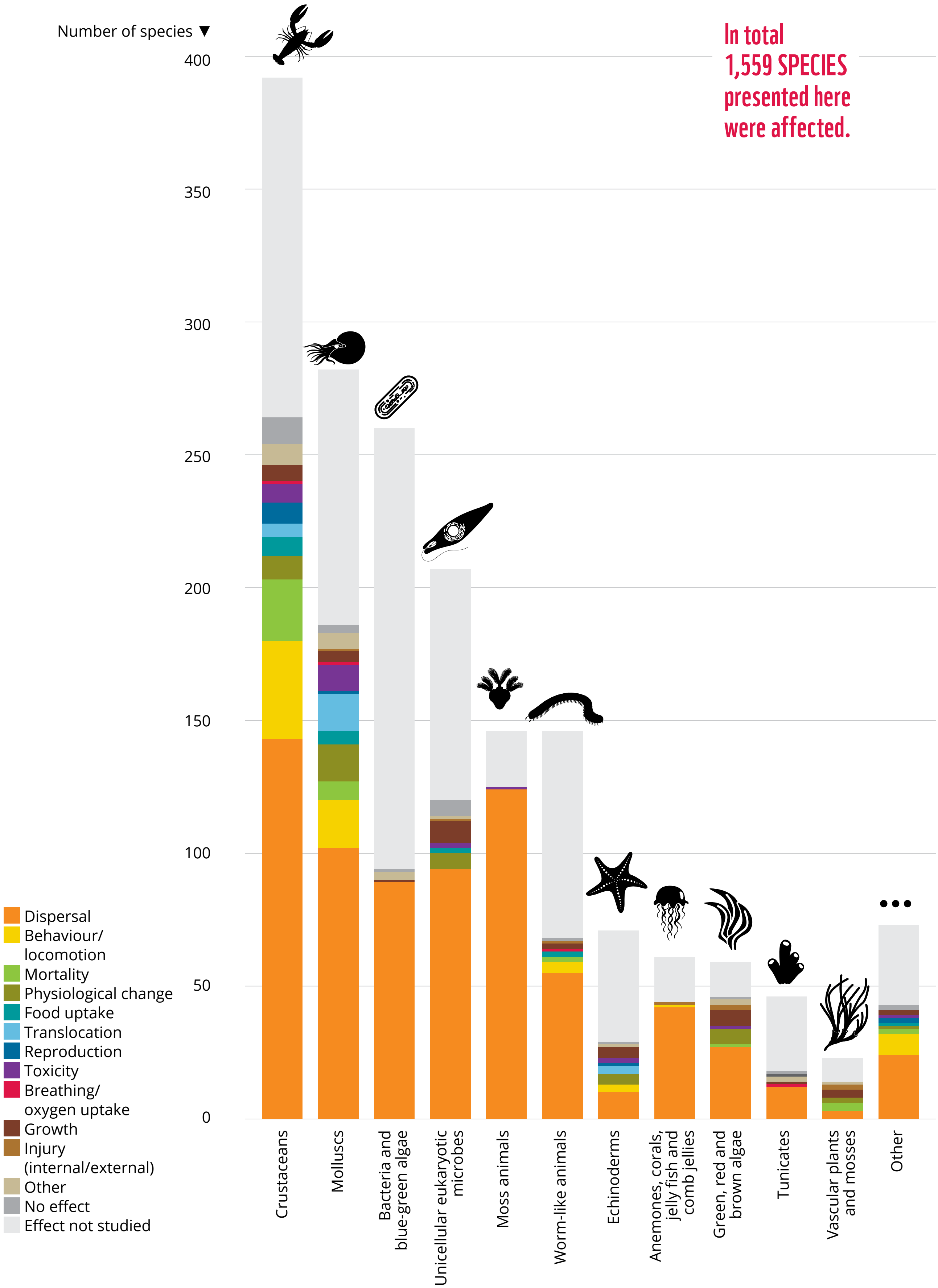
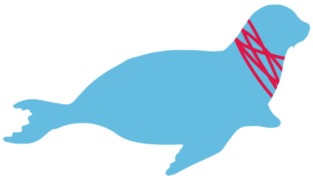


Figure 14: The effects of interactions with plastic on the species, which do not belong to seabirds, corals and sponges, sea turtles and fishes. The "Other" group refers to the species of Chaetognatha, Chelicerata, Fungi, Ochrophyta and Rotifera. The height of the bars refers to the number of species. The data are from 557 publications based on field and experimental studies (LITTERBASE).

5.2 Physical interactions



5.2.1 Entanglement with plastic debris

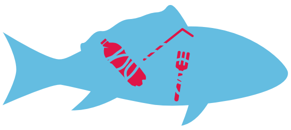
Entanglement happens if a plastic item in the shape of a rope or loop wraps itself around the body. Abandoned ghost nets (see Glossary) catching marine mammals is a typical example, but monofilament lines, plastic sheets or rings can wrap themselves around marine animals and plants, too (Macfadyen et al., 2009; NOAA-MDP, 2014; Richardson et al., 2019; Warner et al., 2020; World Animal Protection International, 2014; WWF, 2020; Parga Martínez et al., 2020). Fishing related debris, balloons and plastic bags pose the greatest risks of entanglement (Wilcox et al., 2016).

An edible crab (Cancer pagurus), hydrozoans and seaweed entangled in a lost fishing net that happens to be colonised by barnacles (location: Norderney Island, Germany, date: 10.01.2021). © Valeria Bers

At least 451 species have been reported to have suffered from being entangled (LITTERBASE). Effects of entanglements were reported for 276 species in 161 studies and are either restrained (200 species), injured (71 species) or killed (125 species). However, the cause of death or injuries can only be attributed to entanglement if the carcass has severe recent injuries. For example, in northern Patagonia, 27 kelp gulls (*Larus dominicanus*) were found with fishing lines wrapped around their bodies. 81% had recently died, and some of the survivors were seriously injured (Yorio et al., 2014). In this case, the cause of injuries and deaths could be attributed to entanglement.

If entangled underwater, air-breathing animals cannot return to the sea surface to breathe and die of suffocation. But even gill-breathing animals are affected: if fish or invertebrates remain entangled for too long, they starve or are eaten. The odour of carcasses attracts further animals, which may also become entangled, especially in items such as lost fishing gear (see Glossary) (Erzini et al., 2008). This vicious cycle is called 'ghost fishing' and can go on for quite some time. Therefore, most entangled animals will never be recorded as they die out of sight and the numbers presented above likely represent the "tip of the iceberg".

The majority of entangled species are seabirds, fishes, sharks and rays, mammals, and corals (138, 132, 40, 38, and 30 species, respectively) (Figure 13). Given our observation bias (see Glossary), and the ubiquity of plastic debris, many more species in each group are probably affected.



5.2.2 Ingestion of plastic debris

Ingestion of plastic debris is the most frequently studied type of interaction (LITTERBASE). A wide range of animals consume plastics, from charismatic species such as whales, turtles, and seabirds, to fishes, crustaceans, molluscs, worms and plankton.

Plastic debris (more than 181 items, weighing 75 g) found inside a loggerhead sea turtle (location: La Réunion, western Indian Ocean, 2015). © Stéphane Ciccione

Uptake of macroplastic can cause blockage or injury to the intestines and lead to a reduced food uptake.

The uptake of macroplastic can cause a blockage of or injury to the intestines and lead to a reduced food uptake or death (Byrd et al., 2014; de Stephanis et al., 2013; Dickerman and Goelet, 1987; Macedo et al., 2011). In addition, items that cannot be egested (see “Egestion” in the Glossary) can lead to a false sense of satiation causing the animal to eat too little up to the point that fitness, growth and reproduction could be affected (Baak et al., 2020; Santos, 2020). In the Mediterranean, 6% of commercially important narwal shrimps (*Plesionika narval*) had ingested plastics. Some had empty stomachs, especially those with balls of tangled plastic fibres, which indicates a blockage of their digestive systems (Bordbar et al., 2018). Plastic bags and utensils pose the greatest ingestion risks, although many other plastic items are eaten (Wilcox et al., 2016).

Studies have reported that microplastic ingestion can also cause reduced feeding, growth and reproduction, changes in physiology, oxidative damage, alter the antioxidative system and metabolism, and have toxic effects on the nervous system (Prokić et al., 2019; Prinz, 2020). The effects depend on the size and dose of microplastics and their interaction with other xenobiotics (see Glossary). Microplastics were found in the stomachs of all fish sampled at the Bahía Blanca Estuary in Argentina (Arias et al., 2019). The number of plastic items per fish was positively correlated with the hepatosomatic index (see Glossary), indicating lower energy reserves caused by plastic ingestion. In experiments, young glassfish (*Ambassis dussumieri*) whose food contained microplastics (0.25–1 mm) grew less than fish offered natural food (Naidoo and Glassom, 2019). In a similar experiment, small microplastics (1–5 µm) passed into the muscle of European sea bass (*Dicentrarchus labrax*) (Zeytin et al., 2020), which is consumed by humans.

A copepod crustacean (Pseudodiaptomus annandalei) that ingested polystyrene beads in a laboratory study.
© Ariana Chih-Hsien Liu

The size of microplastics determines the uptake and their impact. In an experiment, two Caribbean corals actively fed on large microplastics but not on sizes below 250 µm (Hankins et al., 2018). Clams (*Pecten maximum*) took up greater amounts of 24-nm sized nanoplastics than of 250 nm sized nanoplastics (Al-Sid-Cheikh et al., 2018). In another experiment, high amounts of nanoplastics of 0.07-µm size decreased the growth, survival and reproduction of rotifers (zooplankton), whereas larger particles elicited no effects (Sun et al., 2019). The uptake of small, but not of large, microplastic particles decreased the growth and body condition of the spiny chromis fish (*Acanthochromis polyacanthus*) (Critchell and Hoogenboom, 2018).

Microplastics can be taken up by a much wider range of species.

Generally speaking, microplastics can be taken up by a much wider range of species than large plastics, so their potential to enter marine food webs and move up trophic levels through predation is higher (Carbery et al., 2018; Nelms et al., 2018; Hipfner, 2018). Especially filter-feeding animals from small mussels to large whale sharks (*Rhincodon typus*) can take up considerable amounts of microplastics (Germanov et al., 2019).

While a wide variety of effects of microplastic ingestion on marine organisms have been shown in experiments, the findings are debated because they often use unrealistically high concentrations to explore the path of plastic in animals (Phuong et al., 2016) and therefore seem not to reflect real-life conditions (Backhaus and Wagner, 2020; Cunningham et al., 2020; Völker et al., 2020). It should be noted, however, that few field studies measure concentrations of particles smaller than 0.1 mm (Bergmann et al., 2017b; 2019; Haave et al., 2019; Lorenz et al., 2019; Tekman et al., 2020). Those studies that did, showed that more than 80% of microplastic items were smaller than 0.1 mm, which means that most field studies currently underestimate pollution levels (Conkle et al., 2018; Lindeque et al., 2020).

To summarize, studies have reported that hundreds of species have ingested plastics of various sizes in the wild, from large fishing nets to microplastics. Apart from field observations and sampling, plastic ingestion was examined in experiments: 869 field and experimental studies reported macro- and microplastic ingestion by 1,254 species. 80% of these species were sampled in the field and 20% studied in the laboratory. The effects of plastic ingestion were evaluated for 190 species and harmful effects were found in 83% of them. A total of 119 species (62%) were investigated in laboratory experiments for the effects of plastic ingestion and significant effects were found for 73% of these species. The most often reported effects in the field and in experiments include mortality (42 species), changes in food uptake (36), physiology (44), growth (26) or behaviour/locomotion (22), passage from the intestinal tract to blood or organs (translocation, 49), toxicity (25) and injury (16) (LITTERBASE). While the effects can be severe for some individuals, the impacts are probably minor to negligible for most others, toxicological impacts notwithstanding. However, given the current trajectory in plastic production and pollution, adverse effects will likely increase in the future (Everaert et al., 2018; 2020).

5.2.3 Colonisation of plastic debris

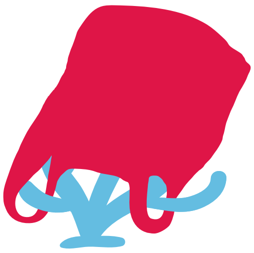
Any material adrift in the ocean becomes colonised by microbes, algae and animals. It is therefore not surprising that colonisation is the type of interaction that was reported for the highest number of species (1,187 species in 149 studies, LITTERBASE). 62% of these species rafted on floating plastics and ended up somewhere else ('dispersal'). Colonisation of plastic debris can be a threat to functioning marine ecosystems because it promotes the dispersal of species beyond their normal geographic range where they can become disruptive and invasive (see Glossary) (Barnes, 2002; García-Gómez et al., 2021). Plastic debris comes in addition to natural rafts such as plant debris and pumice and adds to the opportunities of alien invasion through aquaculture and discharge of ballast water by ships.

Plastic debris collected while crossing the North Pacific Ocean during the research expedition SO268/3 of research vessel SONNE in 2019. Left: © Melanie Bergmann/AWI; Right: © Gritta Veit-Köhler/Senckenberg am Meer

A showcase for this type of dispersal is the Japanese tsunami in 2011. In the following five years, more than 289 coastal invertebrate and fish species from Japan reached the shores of North America and Hawai'i by transoceanic rafting (Carlton et al., 2017). The Japanese seaweed *Pyropia* became established in British Columbia (Lindstrom, 2018). The highly invasive *Tubastraea* corals (Mantelatto et al., 2020) are another example of range extension through marine litter. First introduced to Brazil's rocky reefs by oil platforms these corals were recently observed on floating marine debris, including plastics suggesting that plastic is a secondary dispersal vector for these corals along the Brazilian coast.

Various Red Sea coral species that colonised a discarded tyre (location: Eilat, Israel, Red Sea, date: 10.07.2020; water depth: 8 m) © Marcos Schönholz/ WeSea

Plastics provide a hard substratum for organisms to settle on. This can happen in seawater but also in muddy or sandy ecosystems, where few hard substrata exist naturally. Vast expanses of the deep ocean consist of uniform muddy environments (Meyer-Kaiser et al., 2019) and marine debris introduces new structures on which species can settle. For example, Arctic deep-sea anemones have settled on plastic more often than on other types of litter (Tekman et al., 2017). The appearance of these species alters the community structure of the native ecosystems (Katsanevakis et al., 2007; Song et al., 2021), e.g. by limiting the resources for other species, with unknown repercussions for ecosystem functioning.



On the coastline of central Java, plastic debris covered up to half of the mangrove forest floor at several locations.

5.2.4 Contact or coverage with plastic debris

The contact or coverage with plastic, also called smothering, is another type of interaction. To understand the ecological impacts of coverage, experimental studies have assessed the impacts of plastic items on the organisms underneath. For example, a field experiment on an Irish intertidal shore showed that, after coverage with a plastic bag for nine weeks, the sediment below the bag suffered from oxygen-deficiency, and the number of sand-dwelling organisms decreased (Green et al., 2015). On the coastline of central Java, South East Asia, plastic debris covered up to half of the mangrove forest floor at several locations (van Bijsterveldt et al., 2021). In experiments, plastic coverage led to suffocation and leaf loss, and a complete coverage of the roots caused death of the trees (van Bijsterveldt et al., 2021). In the Philippines, coverage of the foraging area with plastic litter negatively affected the feeding behaviour of the intertidal snail *Nassarius pullus* (Aloy et al., 2011). A total of 68 species were reported to be covered by or in contact with plastic in 22 studies (LITTERBASE). These numbers are most likely an underestimation limited by our capacity for ocean floor observation. Since this interaction is insufficiently studied, the effects of plastic coverage on marine biota should receive far more attention given plastic's ubiquitous spread on the seafloor (Canals et al., 2021), where it is in contact with or covers sediment and sessile (see Glossary) organisms such as corals or sponges (Angiolillo et al., 2015; Oliveira et al., 2015; Parga Martínez, 2020).

5.2.5 Other types of physical interactions

Several types of physical interactions have been reported, which do not fall into any of the four main interaction categories. For example, birds use plastic debris for nests (Section 5.4.1). Similarly, pollution on beaches can affect the nesting of adult sea turtles and survival of their offspring (Section 5.4.2).

Hermit crab sheltering in a piece of transparent plastic on a beach. *© iStock/Getty Images*

Thousands of strawberry hermit crabs are trapped in containers and die each year on Henderson Island.

Plastic containers on beaches can entrap organisms. Thousands of strawberry hermit crabs (*Coenobita perlatus*) are trapped in containers and die each year on Henderson Island (Lavers et al., 2020). 1,403 animals including insects, beetles and gastropods were found to be trapped in bottles discarded in Italian dunes (Poeta et al., 2015). The 'trap effect' does not only apply to the organism but also to the debris itself. The burrows of the crab *Chasmagnathus granulata*, which cover vast areas of southwest Atlantic estuaries act as passive traps and sinks for debris (Iribarne et al., 2000). Similarly, bottom-dwelling animals work plastic particles deeper into the sediment as they burrow in it (Näkki et al., 2017). Burrows of the ghost crab *Ocypode quadrata* that contain plastic items are inhabited at a higher density (~68%) compared to those without marine debris (~28%), indicating that crabs use plastic debris to mark their burrows (Costa et al., 2018).

Macroplastic debris on the seafloor can be broken down into microplastic by the resident fauna.

Another type of interaction is the breakdown of plastic debris by organisms. A large number of expanded polystyrene (EPS) particles were found in the digestive tracts of burrowing polychaetes (*Marphysa sanguinea*) living on expanded EPS buoys. Further experiments on the individuals sampled in the field showed that a single polychaete can produce hundreds of thousands of microplastics per year, suggesting that macroplastic debris on the seafloor can be broken down into microplastics by the resident fauna (Jang et al., 2018). Langoustines also promote fragmentation into smaller plastic particles (Cau et al., 2020) as do boring isopods, which release thousands of microplastic particles as they damage aquaculture floats in Asia, Australia, Panama and the USA (Davidson, 2012). In the laboratory, the amphipod *Orchestia gammarellus* shredded plastic bags into microplastics of 489 µm (Hodgson et al., 2018), which raises the question: Up to what size of plastic can be broken down by animals? In an experiment, Antarctic krill (*Euphausia superba*) shredded microplastics from 32 µm to less than 1 µm (Dawson et al., 2018).

Biodegradation (see Glossary) of plastic by bacteria has been studied with a view to mitigating legacy pollution in landfills (Helinski et al., 2021; Schmaltz et al., 2020). In trials, three out of 60 marine bacteria were able to grow on polyethylene as the sole carbon source, with a polyethylene weight loss of 1.5% in 30 days (Harshvardhan and Jha, 2013). *Rhodococcus ruber* formed a biofilm on polyethylene, reducing the mass by up to 8% in 30 days (Orr et al., 2004). Similarly, the activity of *Bacillus cereus* and *B. gottheilii* caused a weight loss of 1.6–7.4% over 40-day experiments using different types of plastics (Auta et al., 2017; 2018). While these studies demonstrate the general potential to use bacteria to combat marine plastic pollution, the low biodegradation rates raise questions about upscaling. Therefore, the importance of the prevention of plastics entering into the oceans must be emphasized.

Passive removal of microplastics from the seawater through adhesion to organisms has been reported for some species and ecosystems. In the laboratory, plastics stuck to the shells of Red Sea giant clams (*Tridacna maxima*), which removed 66% of the microplastics from the water (Arossa et al., 2019). Similarly, scleractinian corals removed microplastics from seawater (Martin et al., 2019) (Chapter 6). The blades of the seaweed *Fucus vesiculosus* also trap microplastic, which is grazed and ingested by the snail *Littorina littorea*, highlighting an entry point into the food web (Gutow et al., 2016). Snails also produce trails of mucus that retain microplastics, which are then ingested by other organisms (Gutow et al., 2019).

Interactions were reported for 205 species in 129 studies (LITTERBASE).
The types of interactions of plastics with various species are not limited to the ones summarised above and they merit further study to gain an accurate understanding of the extent of the impacts on species, populations, ecosystems and biodiversity.

5.3 Chemical interactions

Plastic items are made up of hundreds of polymers and additives (Andrady and Rajapakse, 2016; Kutz, 2011; Wypych, 2016), of which substantial numbers leak into marine environments. For example, the mass of 20 chemical additives, which entered the oceans in 2015 via seven items of common plastic debris was estimated to be 190 metric tons (De Frond et al., 2019).

Below, we summarize the effects of harmful chemical substances linked to plastic production. These are defined as chemical interactions in contrast to the physical interactions described above. Exposure results from direct uptake by ingestion or contact with contaminated water, air, sediment or food. The health risk of exposure should always be considered in the context of the overall exposure to chemical pollution and other stressors (Box 6).

Box 6: Plastic pollution as one of many stressors of biodiversity and ecosystems

Plastic pollution, including the chemical pollution due to plastics, should always be considered in the context of the overall pollution of the biosphere and the many other stressors (see Glossary), which affect biodiversity and ecosystems (Ibanez et al., 2007; Nash et al., 2017; Persson et al., 2013; Steffen et al., 2015). While the impact of a single chemical can be small, it is only one of a mix of chemical pollutants, which marine plants, animals and humans experience (Landos et al., 2021).

Marine ecosystems are also subject to heat stress, acidification, decreased oxygen content, overharvesting, maritime traffic, noise, invasive species and habitat degradation. While very little is known about the additive, combinatory or synergistic effects (see Glossary) of these stressors (Coe et al., 2013; Gunderson et al., 2016; Kroeker et al., 2017; Landos et al., 2021; McComb and Cushman, 2020; Orr et al., 2020) experts agree that we are already at the beginning of a mass extinction (Barnosky et al., 2012; Ceballos et al., 2015; Jackson, 2008; Pereira et al., 2010). One stressor alone, such as the chemical pollution from plastics, may in itself not be so harmful, especially in a laboratory setting where all other stressors are absent. However, combined with several others, it may just push an individual, population or ecosystem into decline and possibly over a critical threshold.

Harm can only occur in certain individuals, populations, species, ecosystems, or under certain circumstances. Therefore, in a scientific context, the use of modal verbs means that there is a certain probability harm will occur, which is not the same as zero effect. Accordingly, several of the potentially harmful effects, which we described are still being investigated. Plastic pollution is accumulating and poorly reversible on remote ocean surfaces and coastlines, in the water column, deep sea, soils, organisms and considered a planetary boundary threat (MacLeod et al., 2021). As with any potential environmental or health problem (e.g. air pollution and smoking cause health problems), we should not wait for absolute certainty to act.

Climate change is destroying the reef's unique habitat in Belize. © Richard Aronson

5.3.1 Harmful substances associated with plastics

Bisphenol A (BPA)
BPA is a precursor to an important group of plastics, primarily certain polycarbonates and epoxy resins that are used for various common consumer goods (see Glossary). It belongs to the so-called endocrine disruptors, which interfere with the hormonal functions of animals. This chemical enters the environment during production, transport and use of the product (Flint et al., 2012; Hong et al., 2013; Rochman, 2013). During production, BPA is discharged from manufacturing plants, which amounted to 2 MMT per year in Europe and the USA in the 2000s (Corrales et al., 2015).

There are many pathways by which animals and humans are exposed to BPA.

BPA also leaches from the plastic lacquer lining of tin cans into foods, from dental sealants into saliva, from polycarbonate bottles into their contents (Rubin et al., 2001) among other sources (Corrales et al., 2015). It also seeps from microplastics into seawater (Chen et al., 2019). BPA is found at low levels in the water, sediment, soil and animals in most parts of the world. Consequently, there are many pathways by which animals and humans are exposed to BPA either chronically or during sensitive life stages (Flint et al., 2012).

BPA could amplify or lower hormonal responses (Diamanti-Kandarakis et al., 2009; Flint et al., 2012; Gore et al., 2015). Excessive oestrogenic activity (see Glossary) can cause many adverse health effects in fetal and juvenile mammals, even at very low doses, because it interferes with the animals' hormone regulation and hence with normal development (Talsness et al., 2009; Vandenberg et al., 2012). It can also affect thyroid function and increase the risk of polycystic ovary syndrome (see Glossary) and miscarriages, perhaps because of mutagenic effects (see Glossary) on the embryo's karyotype (see Glossary) (Meeker et al., 2009). Epoxy resins of BPA are toxic to cells and may increase cell division rates (Lau and Wong, 2000). Exposure of humans to BPA is widespread (Vandenberg et al., 2010) and thought to increase the risk of heart disease (Melzer et al., 2012) and breast cancer, the second most fatal cancer in women (Shafei et al., 2018). BPA is also mutagenic (Jalal et al., 2018) and pro-inflammatory and thus causes inflammatory and autoimmune diseases (Bergman et al., 2013).

It should be noted that the effects are usually but not always detected in laboratory studies without the additive, combinatory or synergistic impacts of other stressors, and that effects may be very different for different individuals, populations and species facing various additional stressors (Beaman et al., 2016; Braun, 2017; Diamanti-Kandarakis et al., 2009; Flint et al., 2012; Gore et al., 2015; Landos et al., 2021; Oehlmann et al., 2009) (Box 6). For example, although BPA is nearly ubiquitous in aquatic environments globally, exposure levels differ greatly (Flint et al., 2012). BPA concentrations in wildlife, mostly fish, ranged from 0.2 to 13,000 ng/g, which spans more than four orders of magnitude (Corrales et al., 2015).

BPA and another widely used group of additives called phthalates (Section 5.3.1) affect the movement, behaviour, sexual development, growth including abnormalities, survival and reproduction of aquatic species and can bioaccumulate (see Glossary) in organisms such as fish and tadpoles (Oehlmann et al., 2009). Early life stages, amphibians, fishes and invertebrates are particularly sensitive (Chapin et al., 2008; Flint et al., 2012; Oehlmann et al., 2009; Wu and Seebacher, 2020). While some of these effects were only found at high concentrations, which were so far only recorded from very polluted sites, others occurred already at realistic concentrations (Oehlmann et al., 2009).

Often, political action has not followed scientific advice to address these chemicals. While the European Food Safety Authority and the US Environmental Protection Agency stated that BPA poses no health risk at current levels, the European Chemicals Agency listed BPA as a substance of very high concern in 2017 (Lehmler et al., 2018). Already in 2012, the US Food and Drug Administration had banned the use of BPA in baby bottles, and it is now also banned in baby and children's utensils in Brazil, Canada and the EU (Jalal et al., 2018). In 2019, the EU listed BPA as a substance of very high concern because of its likely effect on human reproduction. Because of concerns and bans, substitutes of chemicals have been used in so-called 'BPA-free' products. However, some of these are also bisphenols, such as bisphenol S and F and cause effects similar to those of BPA (Rochester and Bolden, 2015). In experiments, Bisphenol S and F had negative effects on round worms (Ficociello et al., 2021).

All phthalates are of concern, because they are easily released from plastics into the environment.

Phthalates

Some 20 phthalates are added as plasticisers (see Glossary) to make plastics more pliable (Beaman et al., 2016). With an annual production of 2 MMT and a wide usage in medical devices, one of the principal phthalates is di-2-ethylhexyl phthalate (DEHP) (Halden, 2010). In the late 1960s, it was shown that DEHP leaches from medical plastics into the body fluids and translocates into tissues (Halden, 2010). But all phthalates are of concern, because they are easily released from plastics into the environment and also act as endocrine disruptors (Diamanti-Kandarakis et al., 2009; Gore et al., 2015; Hauser and Calafat, 2005; Katsikantami et al., 2016).

Humans ingest phthalates through fat-containing foods such as butter, meat, and milk. Small children are particularly susceptible to phthalate exposure, suffering from food allergies and neurobehavioral disorders due to early life exposure (FAO and UNEP, 2021). Concerns are mounting that phthalates can be linked to diabetes, breast cancer, obesity, immune function and harm the normal development of the male reproductive system, decreasing testosterone production and male fertility (Meeker et al., 2009; Talsness et al., 2009; Teuten et al., 2009). However, no firm conclusions could be drawn on the effects of phthalates, on the anti-androgenic (see Glossary) consequences, because of the difficulties of studying humans over long time periods and other unresolved methodological problems (Albert and Jégou, 2014). Various impacts on the movement, feeding behaviour, sexual development, growth and reproduction of aquatic animals have also been documented (Bergman et al., 2013;

Oehlmann et al., 2009). Diethyl phthalate has moderately harmful effects on the development, liver and sperm of various mammal species (Weaver et al., 2020). Only few studies have considered the effects of phthalates on populations, but one found that the community structure of bottom-dwelling animals was altered after 2 months such that the density of all groups was reduced by 15% and 32% at the lowest (10 µg/g) and highest concentrations (1,000 µg/g) of dibutyl phthalate in sand (Tagatz et al., 1986).

Flame retardants

Flame retardants are commonly added to long-lifespan plastic items to decrease their flammability (Samani and van der Meer, 2020). Tetrabromobisphenol A (TBBPA) is a classical brominated flame retardant (see Glossary) and can disrupt thyroid function or hormone levels in animals and humans, which, in turn, may hinder the development of the nervous system, especially in children (Talsness et al., 2009; Zhou et al., 2020). TBBPA also promotes oestrogenic activity, growth of the brain's pituitary gland and growth hormone production (Talsness et al., 2009). Polybrominated diphenyl ethers (PBDEs) are another group of widely used flame retardants and classified as persistent organic pollutants (Bergman et al., 2013). Chronic exposure may decrease intelligence (Vuong et al., 2020). Toxicological studies with animals and humans have demonstrated that PBDEs are potential carcinogens, endocrine disruptors, and have toxic effects on the liver, nervous system, neurobehaviour, and reproduction (Akortia et al., 2016; Talsness et al., 2009). Flame retardants can also act as anti-androgenics (see Glossary) and cause cryptorchidism (see Glossary), testicular cancer and lower birth weight (Gore et al., 2015; Meeker et al., 2009; Talsness et al., 2009). Several studies found sound evidence of the relationship between prenatal exposure to PBDEs and impaired motor, cognitive and behavioural abilities in small children, who showed a lower intelligence quotient or aggressive behaviour (FAO and UNEP, 2021).

Flame retardants are found in plastic debris and marine animals.

Flame retardants are found in plastic debris and marine animals, including benthic invertebrates, shellfish, sea turtles, sharks, dolphins, polar bears, seals, whales and birds (Law et al., 2014). Brominated flame retardants were found in the tissue of blue sharks (*Prionace glauca*), often at levels unsafe for human consumption (Alves et al., 2016).

Flame retardants are most likely responsible for high concentrations of bromine and chlorine in beached microplastic debris (Turner, 2016). Hexabromocyclododecane (HBCD) is used to make Styrofoam buoys used in oyster farms in South Korea (Hong et al., 2013). Although the use of HBCD is banned under the Stockholm Convention (see Glossary), an exemption is made for Styrofoam products. Because of leaching, high HBCD concentrations were found in the farmed oysters, water column and sediments near the farms. PBDEs, PCBs, and organochlorine pesticides were also detected in Black-browed albatrosses (*Thalassarche melanophris*) and Cape petrels (*Daption capense*) from Argentinian marine waters (Adrogué et al., 2019). However, PBDE concentrations are lower in seabirds than in freshwater or terrestrial birds (Law et al., 2014). The US Environmental Protection Agency phased out production of pentabromodiphenyl-, octabromodiphenyl – and decabromodiphenyl ethers, and set a safe daily exposure level for the four most common PBDE congeners (see Glossary) (Beaman et al., 2016). The EU banned the use of two classes of flame retardants, namely PBDEs and polybrominated biphenyls in electric and electronic devices. In 2009, the parties of the Stockholm Convention declared pentaBDE and octaBDE to be persistent organic pollutants. However, despite the phase out, PBDEs persist in the environment as they have been used since the 1970s (Gorini et al., 2018).

Metals

Metals are added to plastic during manufacture, e.g. as biocides, catalysts, fillers, pigments, plasticisers, heat stabilisers or slip agents (Hahladakis et al., 2018; Nakashima et al., 2012; Turner, 2016). They can leach from plastics, but can also adsorb onto plastic debris from the marine environment (Ashton et al., 2010; Rochman et al., 2014a).

Many metals such as antimony, cadmium, lead and tin (as organotin), have been commonly used as plastic additives (Hahladakis et al., 2018). The harmful effects of elevated exposure to metals, especially heavy metals, have been reported for decades (Castillo, 2016; Lavers et al., 2014, Rai, 2019; Vardhan et al., 2019). Various metals were detected in and on beached microplastic debris (Ashton et al., 2010; Holmes et al., 2012; Nakashima et al., 2012; Turner, 2016). Consequently, for many of the hazardous compounds, maximum concentrations in different products were set within the EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

Petroleum hydrocarbons

Petroleum hydrocarbons comprise several hundred chemical compounds that include crude oil and products refined from crude oil, such as diesel and gasoline. They also absorb to plastic items, which are ingested, among others, by fishes and seabirds (Teuten et al., 2009). For example, polyhalogenated aromatic hydrocarbons (PHAHs) accumulate in swordfish (*Xiphias gladius*), an important top predator that is fished recreationally. PHAHs can act as endocrine disruptors, which affect the swordfish's reproductive functions (Fossi et al., 2001).

Still PCBs persist in the global environment and on marine plastic debris.

Polychlorinated biphenyls (PCBs) and organochlorine pesticides

PCBs were once widely used as dielectric, heat transfer and coolant fluids in electrical appliances and carbonless paper. Harmful biological effects such as endocrine disruption, neurotoxicity and carcinogenic effects have been linked to PCBs (Gore et al., 2015; Neal, 1985). The human consumption of fish contaminated with PCBs appears to cause excess cardiovascular mortality, counteracting the health benefits of eating fish (Donat-Vargas et al., 2020). Because of their toxicity, PCBs are classified as persistent organic pollutants (Bergman et al., 2013) and production is banned under the Stockholm Convention. Still, PCBs persist in the global environment and on marine plastic debris because they adsorb so well to plastics (Antunes et al., 2013; Hirai et al., 2011; Karapanagioti et al., 2011; Mizukawa et al., 2013), which are ingested, among others, by fish and seabirds (Engler, 2012; Teuten et al., 2009). Pesticides such as DDT (dichlorodiphenyltrichloroethane), its metabolites (DDE, DDD) or hexachlorinated hexanes (HCHs) can also adsorb to plastic items and be ingested by marine animals (Beaman et al., 2016; Teuten et al., 2009). DDT and HCHs have been associated with cancer in humans and their production is banned (with an exemption of DDT production for disease vector control – see Glossary), yet as persistent organic pollutants they are still present in the environment (Man et al., 2011).

The global persistence of PCB in the marine food web is a clear warning that the continuous use of persistant organic pollutants endangers marine life.

PCBs accumulate in species at the top of food webs, particularly those found in high-latitude northern regions, and interfere with reproduction (Godfray et al., 2019). The mass of plastic ingested by adult great shearwaters (*Ardenna gravis*) was correlated with PCB levels in fat tissues (Ryan et al., 1988). Similarly, the mass of plastic ingested by short-tailed shearwaters (*Ardenna tenuirostris*) was correlated with the level of PCB congeners (Yamashita et al., 2011). In a global study, several persistent organic pollutants including PCBs were detected in 24 species of seabird (Yamashita et al., 2018). In a global analysis of contamination of rays and sharks with PCBs, DDTs, and heavy metals, the highest concentrations were found in sharks at the top of the food chain (Tiktak et al., 2020). Furthermore, European bottlenose dolphins (*Tursiops truncatus*), killer whales (*Orcinus orca*), and striped dolphins (*Stenella coeruleoalba*) had PCB levels markedly above all known marine mammal PCB toxicity thresholds, and thus likely cause population declines and suppress population recovery (Jepson et al., 2016). Killer whales are so contaminated with PCBs that more than half of all populations could go extinct due to impaired immune systems and reproduction (Desforges et al., 2018). Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) from the Barents Sea were also contaminated with PCBs (Boitsov et al., 2019). Likewise, fishmeal sourced from around the world and fed to farm animals is contaminated with PCBs, with 4.5% of all samples considered unsafe by EU standards (Li et al., 2019). Regular consumption of whale meat, fish and livestock could harm human health (Li et al., 2019). The global persistence of PCB in the marine food web is a clear warning that the continuous use of persistent organic pollutants endangers marine life.

Polycyclic aromatic hydrocarbons (PAHs)

PAHs are ubiquitous and persistent chemicals that are generated during the incomplete combustion of organic materials (e.g. coal-fired power plants, residential heating, smoking), which can adsorb to plastic items. They have adverse effects on aquatic organisms and ecosystems due to their toxicity, persistence and bioaccumulation characteristics (Recabarren-Villalón et al., 2019). For example, PAH exposure in fish can induce liver damage and biochemical or physiological disorders. Several PAHs are endocrine disruptors (Bergman et al., 2013) and also cause cancer and cardiovascular diseases. PAHs were found on plastic pellets, which are ingested, among others, by fishes and seabirds (Fisner et al., 2013; Rochman et al., 2013b; Teuten et al., 2009).

Other chemicals

This is by no means an exhaustive list of chemicals used in or adsorbed to plastics, which are of concern to marine organisms (Bergman et al., 2013; Crawford and Quinn, 2017; De Frond et al., 2019; Diamanti-Kandarakis et al., 2009;

Gallo et al., 2018; Gore et al., 2015; Hahladakis et al., 2018; Hermabessiere et al., 2017; Landos et al., 2021; Li, 2018; Lithner et al., 2011; Muncke et al., 2020; Ramanayaka et al., 2020; Rochman, 2015; Takada and Karapanagioti, 2016; Teuten et al., 2009; Wang et al., 2018a; Wang et al., 2018b; Ziccardi et al., 2016 for further substances of concern). A recent study on zooplankton crustaceans highlighted that insecticide-loaded microplastics elicit a higher toxicity than insecticide alone (Bellas and Gil, 2020) corroborating the role of microplastics as vectors of pollutants to marine animals thus increasing the overall toxicity of the insecticide. In addition, many polymers are composed of hazardous monomers combined with hazardous additives (see above). In fact, more than half of all polymers produced worldwide are made from monomers that are considered hazardous (Lithner et al., 2011; Rochman, 2013). Various chemicals leached from plastics have already been shown to be toxic to aquatic animals (Hermabessiere et al., 2017). For example, 13 out of 16 leachates derived from 16 different types of plastic packaging caused reduced and abnormal growth in sea urchins (Piccardo et al., 2021). Plastic leachates also impaired the growth and oxygen production of *Prochlorococcus*, the ocean's most abundant photosynthetic bacteria (Tetu et al., 2019).

Various chemicals leached from plastic have already been shown to be toxic to aquatic animals.

5.3.2 Spatial variation

Concentration levels of harmful substances vary geographically and across individuals and species (Corrales et al., 2015; Teuten et al., 2009). For example, alkylphenols, PAHs, PBDEs and PCBs were detected at levels ranging from 1 to 10,000 ng/g in samples collected on beaches and in the open ocean (Hirai et al., 2011). Levels in seawater and sediments also varied by several orders of magnitude (Hermabessiere et al., 2017). The levels of PAHs and PCBs were higher for plastic debris collected from urban beaches compared to debris from remote beaches or the open ocean (Hirai et al., 2011). The International Pellet Watch, a global volunteer-based initiative gathering information on marine pollution, also found that contamination levels varied substantially across the globe (Beaman et al., 2016).

HCH preen oil is excreted from a gland above the tail of seabirds and used as an indicator of pollution in fat tissues. POP levels were lower in the preen gland oil of seabirds from polar regions compared to other regions (Yamashita et al., 2021). Spatial variation in POP contamination was also evident in baleen whales, whereby Pacific whales had a much higher burden than Atlantic whales (Winfield et al., 2020). Spatial variations of PBDEs and HBCDs were documented for various marine species (Law et al., 2014) and also for POPs across animals from the Canadian Arctic (Braune et al., 2005). An example of spatial variation of heavy metal pollution at the regional level was recently described for China. Among the examined metals, zinc showed the highest concentrations in seawater, sediment and marine organisms, whereas the concentration of mercury was the lowest. However, differences were observed between coastal regions, marine compartments and species. Higher concentrations were found in crabs than in fishes, which was explained by higher sediment background values (Hao et al., 2019).

5.3.3 Sorption and desorption of chemical pollutants

Adsorbed pollutants have been found on plastic debris all around the world.

Plastic items can also fetch additional pollutants from contaminated water or sediments (GESAMP, 2015, 2016; Ramanayaka et al., 2020; Takada and Karapanagioti, 2016; Wang et al., 2018a; Wang et al., 2018b). Over time, metal and organochlorine pollutants accumulate on the items' surface (Ashton et al., 2010; Holmes et al., 2012; Lee et al., 2014; Mato et al., 2001; Rochman et al., 2014a). Adsorbed pollutants have been found on plastic debris all around the world and include dioxins, DDT, PAHs, PCBs, POPs, metals and pesticides (Engler, 2012; Holmes et al., 2012; Rios et al., 2007; Rochman et al., 2013b; Takada, 2013; Teuten et al., 2009). Their concentrations on microplastics are often orders of magnitude higher than in ambient seawater (Ogata et al., 2009). Depending on environmental factors and concentration gradients, both the added and adsorbed pollutants can be released back into the environment or marine organisms, making plastic debris both a sink and a source of toxic chemicals (Engler, 2012; Wang et al., 2018a; Wang et al., 2018b).

In the laboratory, PAH adsorbed to microplastics, accumulated in several organs of mussels and caused toxic effects on molecular and cellular pathways (Avio et al., 2015). Similarly, Japanese rice fish fed on plastic pellets with chemical pollutants accumulated pollutants in their tissues causing liver toxicity and pathology (Rochman et al., 2013a). It was argued that microplastics combined with adsorbed pollutants constitute a novel threat unlike the same pollutants adsorbed to sediment particles, which are also eaten by organisms (Rochman). Therefore, microplastic particles are hazardous by themselves, and in addition they transport and transfer hazardous pollutants.

Plastic waste contaminated with oil accumulated in a nature reserve on an island in the Can Dao archipelago (Vietnam). © Bernhard Bauske/WWF

5.3.4 Pathways of exposure

Contaminants can be taken up from ingested plastic, but microplastic can also take up contaminants from the body.

There are different mechanisms that enable the transfer of chemicals from plastics to organisms (Koelmans et al., 2016). They can leach directly from the ingested plastics into the body or into the environment from which they are taken up through the skin or gills or via consumption of contaminated prey. However, depending on microplastic properties and gradients of chemical concentrations, chemicals from the body can also adsorb to microplastics and then be excreted, which reduces the burden on the body. Similarly, plastics in the water can accumulate chemicals, leading to a lower concentration of chemicals in the water. Other publications also describe exposure pathways in detail (GESAMP, 2015, 2016; Koelmans, 2015; Ziccardi et al., 2016).

5.3.5 Contribution of plastic pollution to overall chemical pollution

While exposure pathways of harmful substances are well established, it is less well-known how much the chemical pollution from plastics contributes to the overall chemical pollution that marine life experiences. A number of studies have suggested that the contribution of ingested plastics to the body burden of chemical pollutants is likely to be small in relation to direct uptake via sediment, water or contaminated prey (Bakir et al., 2016; Beckingham and Ghosh, 2017; Besseling et al., 2017; Devriese et al., 2017; Gouin et al., 2011; Herzke et al., 2016; Holmes et al., 2012; Koelmans et al., 2016; Koelmans et al., 2014; Paul-Pont et al., 2016; Ziccardi et al., 2016).

Relative contributions of the various pathways of contaminants can differ widely for different individuals.

The relative contributions of the various pathways, however, differ widely for different individuals, populations and species. While the contribution of ingested microplastics to the overall chemical burden of the lugworm *Arenicola marina* seemed negligible (Section 5.4.7), it can be substantial for other species such as great shearwaters, whose PCBs levels were related to the mass of ingested plastic (Ryan et al., 1988). The presence of ingested plastics was also linked to nonylphenol and PBDE burdens in fish (Gassel et al., 2013; Rochman et al., 2014b) and PBDE/PCB congeners and toxic metals in seabirds (Lavers et al., 2014; Tanaka et al., 2013; Yamashita et al., 2011).

In another study, ingested plastics accounted for 6% and 30% of the northern fulmar's (*Fulmarus glacialis*) exposure to and accumulation of lead and brominated compounds, respectively (Turner, 2018). This shows that, even for the northern fulmar, most chemical pollution comes through other pathways. This proportion is probably much lower in other species, including humans (Koelmans et al., 2016). Still, certain results from natural populations as well as experimental studies (Beaman et al., 2016; Besseling et al., 2013; Browne et al., 2013; Tanaka et al., 2015) imply some contribution of microplastics to the contamination of marine life. Plastic-mediated exposure could be minor where background pollution is high, e.g. in industrial areas, but be important in remote areas with low background pollution (Tanaka et al., 2016).

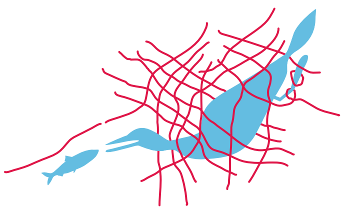
5.3.6 Application of the precautionary principle

The science of understanding the impact and severity of an emerging environmental threat is usually lagging behind the reality of the situation because we still adhere to a linear material's economy, which releases all kinds of waste into the environment and only considers the consequences once substantial pollution levels have built up, whether this is greenhouse gases, persistent organic pollutants or plastics.

One editorial warned that "it should be clear that the current policy of releasing chemicals into the environment and then waiting for the consequences is irresponsible at best and criminal at worst" (Walther, 2009). In the long term, it seems futile to try to manage the risk of chemical pollutants by determining maximum levels of pollutants and risks to human health. The task is simply too big: "For some of the most controversial chemicals like BPA and phthalates, evidence continues to accumulate while thousands of other [chemicals] that migrate into food lack hazard and exposure information" (Muncke et al., 2020).

Many scientists endorse the precautionary approach and have called for urgent preventive measures.

Therefore, many scientists endorse the precautionary approach and have called for urgent preventive measures (Gallo et al., 2018; MacLeod et al., 2021; Kessler, 2011; Leslie and Depledge, 2020) to avoid chemical and plastic pollution reaching dangerous levels. Over evolutionary time scales, animals have adapted to toxins, which are present in nature, but they cannot be expected to adapt to a multitude of new toxins in such short time frames.



5.4 Impacts of plastic pollution on species

5.4.1 Impacts on seabirds

Plastic ingestion is predicted to affect almost all seabird species in a few decades.

Seabirds are a diverse group of birds that make a living from the ocean. They include albatrosses, auks, boobies, cormorants, fulmars, gannets, gulls, penguins, pelicans, petrels, sea ducks, shearwaters and terns. Because of their diverse habitats and behaviours, they face varied threats. Monitored seabird species declined by 70% globally between 1950 and 2010 (Paleczny et al., 2015). Recent global assessments of threats to seabirds concluded that the top three threats are bycatch, climate change, and invasive species like cats and rodents. Other important threats include egg theft, disturbance at or destruction of breeding colonies and overfishing (Croxall et al., 2012; Dias et al., 2019; Rodríguez et al., 2019).

So far, plastic pollution has only been associated with seabird population declines for the flesh-footed shearwater (*Ardenna carneipes*). Entanglement affected both diving and surface-feeding birds (Donnelly-Greenan et al., 2019). Plastic ingestion is predicted to affect almost all seabird species in a few decades (Wilcox et al., 2015). However, despite a large body of literature on plastic ingestion in seabirds global and long-term analyses are still hampered by the use of non-standardised methods (Provencher et al., 2017).

In the northeast Atlantic, 74% of the examined seabird species had ingested plastic (O'Hanlon et al., 2017) and 69% in Hawai'i (Rapp et al., 2017). Northern fulmars, sooty shearwaters and great shearwaters from Sable Island, Canada, ingested plastic at a high rate (>72%) with the highest amounts found in northern fulmars (93%) (Bond et al., 2014). While a temporal increase in the ingestion rates was reported (Wilcox et al., 2015), recent studies found a slight decrease of ingestion rates in flesh-footed shearwater fledglings in the Lord Howe Island, New South Wales and in northern fulmars in the North Sea between 2005 and 2019 (Lavers et al., 2021; van Franeker et al., 2021).

Once eaten, plastic-related chemicals can leach from ingested plastics to the tissues of seabirds (Tanaka et al., 2013; 2015). Japanese quail (*Coturnix japonica*) was used to assess the impact of plastic ingestion on seabirds (Roman et al., 2019a). Although no lasting toxic effects were found, cysts in the male reproductive system, minor delays in growth and sexual maturity could be expected. However, as these endocrine effects did not affect the species' survival, population-level effects seem unlikely.

Left: Lost gill net with cormorant. © Wolf Wichmann; Right: Young pink pelican with a piece of plastic in its beak. © iStock/Getty Images

The incidence of plastic particles in Northern fulmar stomachs is used to monitor plastic pollution in the North Sea as they feed exclusively at the sea surface. The OSPAR Convention has defined an Ecological Quality Objective that aims to reduce plastic pollution so that fewer than 10% of northern fulmars have more than 0.1 g of plastic in their stomach. Currently, more than half of the birds exceed this threshold (van Franeker et al., 2021).


Left: copious amounts of plastic debris incorporated into the nests of northern gannets on Helgoland, Germany with one strangulated bird (date: 24.06.2017). © Doruk Dündar; Right: A common murre (Uria aalge) entangled in a string attached to a plastic balloon (location: Texel, The Netherlands, date: 18.02.2012). © Jan van Franeker/ Wageningen Marine Research

A study in the Canadian high Arctic, highlighted that different feeding modes affect the uptake of plastic with surface-feeding birds (northern fulmar, black-legged kittiwake) ingesting more plastics than pursuit-diving birds (thick-billed murre, black guillemot) (Poon et al., 2017). However, plastic debris can also be passed on to predatory birds such as great skuas (*Stercorarius skua*) if they feed on surface-feeding northern fulmars, for example, that had previously ingested plastic, as observed off the Faroe Islands (Hammer et al., 2016). Once in the gastrointestinal tract, plastic can be broken down, in the grinding section of bird stomachs, until small enough to pass into the intestines and be egested (Nania and Shugart, 2021). The type, colour, density and shape of plastic particles may also influence whether they are eaten or incorporated into nests (Hidalgo-Ruz et al., 2021). Light objects are more easily noticed from above and could be picked up more frequently by seabirds (Santos et al., 2016) as observed for black-footed albatrosses (*Phoebastria nigripes*) (Nishizawa et al., 2021).

The incorporation of plastic debris into seabird nests has been reported as another type of interaction (Figure 13, it is one of the “Other” type of interactions). Twenty-nine colonies of northern gannets (*Morus bassanus*) were examined to assess the rate of the incorporation of marine debris into the nests across the species’ range (O’Hanlon et al., 2019). With a preference for threadlike plastics, debris was present in 46% of 7,280 examined nests. In one of these colonies on Helgoland, Germany, debris was embedded in 92% of the nests (O’Hanlon et al., 2019). On two Brazilian coastal islands, 61% of brown booby (*Sula leucogaster*) nests contained plastic debris (Tavares et al., 2016).

However, the occurrence of plastic debris in seabird nests does not always indicate that it was used for construction. Regurgitations can be another source of plastic as it was observed in the Kelp gull (*Larus dominicanus*) nests in the Western Cape, South Africa (Witteveen et al., 2017). A higher plastic abundance in these nests was observed at colonies close to urban landfill sites. Another example for diet-related origin was reported from the island of Ohinau, New Zealand, where flesh-footed shearwaters nest in colonies of burrows (Buxton et al., 2013).

In a Kittiwake (*Rissa tridactyla*) colony in Northwest Denmark, the number of plastic incorporating nests accounted for 39% in 1992, whereas a later evaluation in 2005 showed an 18% increase (Hartwig et al., 2007). The type of debris in the nests corresponded to the plastic distribution on the nearby beach (Hartwig et al., 2007). For a colony in Helgoland, Germany, 11% of the nests contained plastic debris, even though sufficient natural material was observed in the surroundings (Hartwig et al., 2007). Contrary to this, plastic abundance in the nests of Kelp gulls in Western Cape corresponded with the limited vegetation in the surroundings (Witteveen et al., 2017). For a study of the endangered Black-faced spoonbill (*Platalea minor*) in South Korea, natural materials (tree branches and rice straws) were placed in the nesting area at the beginning of the breeding seasons in 2011 and 2012, in order to monitor the changes in plastic abundances in the nests (Lee et al., 2015). Not only did the number of nests containing plastic decrease (2010: 71%, 2011: 37% and 2012: 33%), but the total number of nests also increased (2010: 28, 2011: 38 and 2012: 43).

Entanglement with the plastic incorporated into their nests can cause mortality to adults and juveniles.

On one island associated with a higher fishing activity, more fishing related debris was incorporated into the nests, while on another island with more beaches, more hard plastic fragments were prevalent within the nests (Tavares et al., 2016). The high amount of fishing gear in the nests of northern gannets in Newfoundland was associated with the gillnet fishing effort in the area (Bond et al., 2012). Environmental consequences of human activities are thus reflected in the nests of seabirds. Entanglement with the plastics incorporated into their nests can cause mortality to adults and juveniles, yet further investigation is required to assess this impact on a population level.

According to 214 studies in LITTERBASE, a total of 272 (of 346) seabird species had encountered plastic debris by ingestion (68%), entanglement (50%) and other interactions (8%) including its use for nests. Quite a few species experienced several of these interactions. Harmful effects of interactions were reported for 40 species and comprised mortality (23 species), injury (13), changes in locomotion/behaviour (9), hampered food uptake (4), translocation of ingested plastic particles to organs (3) and physiology (1) (Figure 13).

The northern fulmar

Species: The northern fulmar *Fulmarus glacialis* is a fulmarine petrel with distinctive tube-shaped nostrils.

Distribution: Northern parts of Atlantic and Pacific Oceans, breeding in large colonies on narrow ledges of precipitous sea cliffs or crags located on shorelines and islands.

Food: Mainly crustaceans, cephalopods, fish, fish offal and carrion, mostly by seizing food from the sea surface, more rarely by diving.

Conservation status: Least concern.

Interaction with plastic pollution

Because of its feeding mode, surface-seizing and shallow-diving, northern fulmars may mistake plastic debris for food or ingest plastic items in combination with their regular food. As early as the 1970s–1980s, researchers documented plastic items in the digestive tracts of the northern fulmar (Baltz and Morejohn, 1976; Provencher et al., 2017; van Franeker, 1985). Since then, dozens of studies from all parts of its distribution range have documented plastic debris in northern fulmars. As a widespread and abundant seabird it was chosen as an indicator for plastic pollution in the North Sea (van Franeker et al. 2011, 2021).

Plastic ingestion by the northern fulmars was reported around the globe. 95% of 1,295 individuals in the North Sea (van Franeker et al., 2011), 93% of 176 in Nova Scotia, Canada (Bond et al., 2014), 79% of 70 in the west Atlantic (Avery-Gomm et al., 2018) and 93% of 67 from beaches in the eastern North Pacific (Avery-Gomm et al., 2012) had ingested plastic. Of these, 58%, 66%, 34% and 54% had ingested more than 0.1 g of plastic, respectively and thus exceeded the Ecological Quality Objective.

In some regions plastic ingestion increased from the 1970s to 2010 (Avery-Gomm et al., 2012). A long-term study in the Netherlands showed a slightly decreasing trend from the 1970s to the 2010s but with more than 50% of the fulmars exceeding the Ecological Quality Objective, and no regional population remaining within it (Van Franeker et al., 2021). The average frequency of occurrence of plastic ingestion by the northern fulmars across 26 studies was 82% (Kühn and Van Franeker, 2020). Around a fulmar colony in Baffin Island, Canada, microplastic pollution could be traced to several pathways, which included fulmar guano, atmospheric

A northern fulmar flying over the water in Svalbard, Norway. © Canon/Brutus Östling/WWF-Sweden deposition, surface sediment and surface water (Hamilton et al., 2021). By depositing guano, fulmars also introduce millions of plastic particles into their own colonies (Bourdages et al., 2021). Ingested microplastics can also introduce hazardous chemicals into the fulmars' bodies (Kühn et al., 2020a; Tanaka et al., 2019). For example, PBDEs may pass to fulmar livers, leading to poor body condition (Neumann et al., 2021). However, the transfer of POPs from ingested microplastics could be considered negligible compared to the transfer of POPs from ingested prey (Herzke et al., 2016).

Four studies recorded entanglement of fulmars (Camphuysen, 1990; Degange and Newby, 1980; Moore et al., 2009; Ryan, 2018), and 35 studies reported plastic ingestion (Battisti et al., 2019; Kühn and Van Franeker, 2020).

Researcher Dr. van Franeker demonstrating how much plastic a human would have to ingest to consume a comparable amount to that which a northern fulmar typically ingests (scaled by body mass).
© Jan van Franeker/Wageningen Marine Research

The northern gannet

Species: The northern gannet (*Morus bassanus*) is the largest species of the bird family of boobies and gannets (Sulidae) known for their stream-lined bodies, which they use to plunge dive at high speed to catch fish below the sea surface.

Distribution: Northern parts of the Atlantic Ocean, breeding in colonies on isolated stacks or small uninhabited islands, or inaccessible cliffs on the mainland or large islands.

Food: Mainly fish caught during dives. The gannet is a top predator.

Conservation status: Least concern.

Interaction with plastic pollution

Some of the earliest records of detrimental interactions with plastic waste refer to this species: As early as the 1970s, gannets used plastic debris to build their nests (Bourne, 1976), 12 gannets were found entangled in net fragments (Lucas, 1992; Schrey and Vauk, 1987), and one gannet died of starvation because Styrofoam from a lobster-pot buoy blocked its stomach (Dickerman and Goelet, 1987; Pierce et al., 2004).

Gannets could become entangled when they plunge-dive into the water to catch fish, but also because of net fragments in their nests. Even in the remote Russian Arctic, most of the nests from two colonies contained plastics (CAFF, 2019). Similarly, in Newfoundland, 97% of all examined nests contained plastic (Montevecchi, 1991) and the proportion of nests with plastic debris decreased after the closure of a nearby fishery in 1992 (Bond et al., 2012). In a colony of 40,000 gannets in Wales, nests contained on average 470 g of plastic, which scales to 18.5 tonnes of plastic waste for the entire colony (Votier et al., 2011). Several hundred gannets died because of entanglement over an eight-year period, but these mortalities had no adverse impact on population dynamics. However, on Helgoland, Germany, 99% of the nests contained plastic litter, and 26 gannets died due to entanglement in 2015, sometimes over a period of weeks (Werner et al., 2016). As a result, annual adult mortality increased from 0.5% to 4–8%, which is in contrast to the results from Wales (Votier et al., 2011). In a study of 29 colonies on both sides of the Atlantic, plastic had been incorporated into 46% of all nests (O'Hanlon et al., 2019). Highest rates of entanglement were reported from wintering grounds in Spain, where 1% of the gannets were entangled with plastic items (Rodríguez et al., 2013). But there was large variation: while two sites had no entangled birds another had 20% entanglement, which likely reflects variable pollution levels. Gannets also ingest plastics, albeit at lower rates than other seabirds (Basto et al., 2019). As they follow their prey rather than plucking it from the water, they are less likely to swallow plastic items by mistake than other seabirds. In total, four studies recorded entanglements with plastic debris, and six studies reported plastic ingestion (LITTERBASE).

A northern gannet with plastic nets entangled in its beak (location: Texel, The Netherlands, date: 06.09.2009). © Jan van Franeker/Wageningen Marine Research

The Laysan albatross

Species: The Laysan albatross (*Phoebastria immutabilis*) is a large seabird, which flies long distances over the ocean in search of food.

Distribution: Northern and central parts of the Pacific Ocean, breeding almost exclusively in colonies on the northwest Hawai‘ian Islands.

Food: Mainly cephalopods, but also fish (eggs), crustaceans and other invertebrates from the sea surface.

Conservation status: Near threatened.

Interaction with plastic pollution

Reports of interactions between plastic pollution and Laysan albatrosses go back as long as 1966, when 74 out of 100 deceased albatrosses found in Hawai‘i already had plastic in their digestive systems (Kenyon and Kridler, 1969). Later, a dead young chick from Midway Islands had died because of intestinal obstruction by plastics (Pettit et al., 1981), which it had probably been fed by its parents. Later studies found that 83–94% of adult birds contained plastics (Gould et al., 1997; Gray et al., 2012; Robards et al., 1997), and that 67–100% of examined chicks had plastics in their digestive tracts, including intact bags, caps, toys, lighters and a toothbrush (Cooper et al., 2004; Fry et al., 1987; Kinan and Cousins, 2000; Lavers and Bond, 2016a; Sileo et al., 1990; Sileo, 1990). Chicks with larger volumes of ingested plastics had lower fledging weights, but plastics were very rarely the direct cause of death (Sievert and Sileo, 1993). However, a decreased body condition appears to indirectly increase the risk of death from natural causes (Auman et al., 1998). Adults that feed in more contaminated ocean patches feed more plastic to their chicks; indeed, chicks from one colony were fed almost ten times more plastic than chicks from another colony (Young et al., 2009). In addition, chicks with more plastic inside had increased concentrations of trace metals in their feathers, and both plastic and trace metal concentrations have increased from the 1960s–2010s (Lavers and Bond, 2016a). A recent study showed that ingested microplastics introduce hazardous chemicals into the albatrosses’ bodies (Tanaka et al., 2019). In total, 17 studies recorded ingestion of plastic items (LITTERBASE). Laysan albatrosses also suffered entanglement (Degange and Newby, 1980).

Corpse of a young Laysan albatross with plastic items in its stomach (location: Midway Atoll, date: June 2011).
© Shigeru Fujieda

The flesh-footed shearwater

Species: The flesh-footed shearwater (*Ardenna carneipes)* is from the same family (*Procellariidae*) as northern fulmars.

Distribution: Large parts of the Indian Ocean, western parts of the Pacific Ocean, some eastern parts south of Alaska. It breeds in colonies in two distinct areas, one in the southwest Pacific and one on islands along Western Australia and extending to Saint Paul Island in the southern Indian Ocean.

Food: Fish and squid, but not well-studied; mostly at the sea surface or during short dives.

Conservation status: Near threatened.

Interaction with plastic pollution

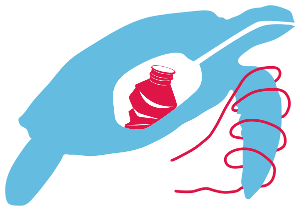
A comprehensive study found 95% of flesh-footed shearwaters in the Central North Pacific had ingested plastics (Robards et al., 1997). Thirteen out of 30 shearwaters had ingested plastics near New Zealand in the early 2000s (Robertson et al., 2004).

In addition to long-line fishing and loss of nesting habitat, plastic pollution could have contributed to the decade-long decrease of the population on Lord Howe Island (Hutton et al., 2008). 79% of fledglings had ingested plastics.

This likely contributes to contamination with toxic metals and metalloids (see Glossary), reducing the fledglings' body condition and thus decreasing breeding success (Bond and Lavers, 2011; Lavers et al., 2014; Lavers et al., 2019a). However, a recent study found no relationship between the levels of ingested microplastics and pollutants in fledglings (Szabo et al., 2021). Usually, they contain more plastic items than adults (Lavers and Bond, 2016b), including ultrafine plastic particles (1 µm–1 mm) (Lavers et al. 2019b, c). Plastic fragments were common in a large flesh-footed shearwater colony on Ohinau, New Zealand, but absent at a nearby colony on Mauitaha (Buxton et al., 2013). It has been estimated that the density of plastic fragments introduced by shearwaters into their colony on Lord Howe Island was 218 items/100 m^2, scaling up to almost 690,000 fragments deposited each year (Grant et al., 2021). 10 studies recorded ingestion of plastic items (LITTERBASE). Flesh-footed shearwaters also become entangled in plastics (Taylor, 2004)

Flesh-footed shearwater on the water, Oman.
© IMAGO/Nature Picture Library

5.4.2 Impacts on sea turtles



Sea turtles (also called marine turtles) comprise only seven species (IUCN red list status in brackets): hawksbill sea turtle (critically endangered), Kemp's ridley sea turtle (critically endangered), green sea turtle (endangered), leatherback sea turtle (vulnerable), loggerhead sea turtle (vulnerable), olive ridley sea turtle (vulnerable), flatback sea turtle (data deficient).

The threats that make sea turtles one of the most endangered groups of marine species include overharvesting of eggs and adults for food, shells, traditional medicines, or as bycatch; alteration of nesting beaches, introduced (egg) predators; climate change; boat strikes; and oil and plastic pollution. Several global analyses have demonstrated significant harm to sea turtles from plastic ingestion and entanglement (Duncan et al., 2017; 2019; Nelms et al., 2016; Schuyler et al., 2014a; 2016).

Entanglements causing the amputation of limbs have been reported for all species of sea turtle (Kühn et al., 2015). In Rapa Nui for example, when a loggerhead turtle was entangled in a fishing line, causing the amputation of its flippers and a few hours later its death (Thiel, 2018).

A loggerhead sea turtle (Caretta caretta) got caught in plastics and nets. © Alexis Rivera/WWF

An assessment of stomach contents of sea turtles from southern Brazil showed that all five species and 49 out of 86 individuals had ingested plastics (Rizzi et al., 2019). The two omnivorous species (green, hawksbill) ingested more plastic (80%) compared to carnivores (25% for leatherback, loggerhead, olive ridley). The encounter-ingestion ratio of artificial debris in green turtles (62%) was much higher than that in loggerhead turtles (17%) on the Sanriku Coast in the Japanese archipelago. A carnivorous diet poses a lower risk for plastic ingestion than gelatinovorous, herbivorous, or omnivorous feeding habits probably because the carnivorous species are more selective with their diet.

A typical example of a sea turtle (green turtle) entangled by plastic debris (location: La Réunion, western Indian Ocean, date: 13.02.2012). © Jérome Bourjea IFREMER

Oceanic juvenile life stages are more prone to plastic ingestion, probably because they feed mostly in the water column close to the sea surface or coastal areas, where plastic accumulates (Rizzi et al., 2019; Schuyler et al., 2014a; 2016). While 23% of the juveniles and 54% of post-hatchlings from east Australia contained plastic, only 16% of the adults had ingested plastic (Wilcox et al., 2018).

A study on microplastic ingestion by sea turtles found microplastics in all of the 102 individuals from all seven sea turtle species sampled in the Atlantic, Mediterranean and Pacific (Duncan et al., 2019). It suggested that polluted seawater, sediments and prey all contribute as pathway of microplastic ingestion. Since there are no studies on the effects of microplastic ingestion on sea turtles, this issue requires further investigation. A recent study showed that sea turtles are attracted to the odour emanating from bio-fouled plastics, which could act as olfactory traps, promoting both entanglement and plastic ingestion, especially in very polluted regions (Pfaller et al., 2020).

On beaches, plastic debris can slow down or obstruct the passage of sea turtle hatchlings to the open water.

On beaches, plastic debris can slow down or completely obstruct the treacherous passage of sea turtle hatchlings to the open water after crawling out of their nests. This prolongs their crawling time significantly (Aguilera et al., 2018) and gives predators more time to catch hatchlings (Özdilek et al., 2006). During nesting, marine debris can entangle and entrap both mothers and hatchlings, which can limit the number of offspring (Gündoğdu et al., 2019).

Interactions between sea turtles and plastic were investigated in 81 studies and all species ingest plastic debris or get entangled in it (LITTERBASE). Plastic pollution poses a serious threat to sea turtles (Nelms et al., 2016).

The hawksbill sea turtle

Species: The hawksbill sea turtle (*Eretmochelys imbricata*) belongs to the Cheloniidae family and can be distinguished from other sea turtles by its sharp, curving beak (hence the name).

Distribution: Worldwide in all major oceans on both sides of the equator, mainly tropical and subtropical but also in temperate waters. Adults accomplish extensive migrations.

Food: Omnivorous, although 70–95% of its diet consists of sponges; they also feed on algae, corals, jellyfish and sea anemones.

Conservation status: Critically endangered.

Interaction with plastic pollution

Four out of 20 examined hawksbills had ingested plastics in Costa Rica in the early 1970s, and other early records from the 1970s and 1980s were from Ascension Island, the eastern Atlantic, Florida and Hawai'i (Balazs, 1985) and Madeira (Den Hartog, 1979). Some of the earliest entanglement records also date back to the 1970s and 1980s when 14% of the stranded individuals in the US were entangled (Balazs, 1985; Laist, 1997).

Six dead entangled individuals were reported from islands off Texas, and seven out of eight examined individuals had ingested plastic (Plotkin and Amos, 1990). Entanglement was later reported from Australia (Duncan et al., 2017; Wilcox et al., 2014), Florida, USA (Adimey et al., 2014), Kaeyama Island, Japan (Duncan et al., 2017), and the Maldives (Duncan et al., 2017). Plastic ingestion was recorded for turtles from Brazil (Macedo et al., 2011; Poli et al., 2015), Easter Islands, Chile (Thiel, 2018) and Queensland, Australia (Duncan et al., 2019; Schuyler et al., 2012; 2014b).

In total, three studies recorded entanglement, and seven studies recorded ingestion of plastic items (LITTERBASE, Kühn et al., 2020a). One problem with this species is that sample sizes are very low because it is critically endangered and therefore very rare. Hence, studies on many individuals, which would allow us to estimate the overall impact of plastic pollution, are almost impossible.

Newly hatched hawksbill turtles trapped in plastic washed-up on the beach. Manatee Lagoon Beach, Belize. © Anthony B. Rath/WWF

The leatherback sea turtle

Species: The leatherback sea turtle (*Dermochelys coriacea*) is the only species in the Dermochelyidae family, the largest of all living turtles.

Distribution: Worldwide in all oceans on both sides of the equator in tropical, subtropical and temperate waters. Adults accomplish extensive migrations.

Food: Mainly jellyfish whose populations they control; in addition, they feed on other soft-bodied animals, such as cephalopods and tunicates.

Conservation status: Vulnerable.

Interaction with plastic pollution

Since the leatherback's main diet consists of jellyfish, they ingest many floating plastic bags, which resemble jellyfish (Mrosovsky et al., 2009). Already in the 1960s to 1980s, more than half of 24 examined turtles (Mrosovsky, 1981) and 27% of 221 examined turtles (Balazs, 1985) had plastic bags, sheets and other plastic items in their stomachs (Brongersma, 1972; den Hartog and van Nierop, 1984). However, the cause of death of some of them was entanglement in discarded nets. Some of the earliest entanglement records are from the Atlantic, Pacific and Mediterranean from the 1960s–1980s affecting 7% of stranded individuals (Balazs, 1985; Laist, 1997). Later records of entanglement were from the Bay of Biscay, France (Duguy et al., 1998), Scotland (Gill et al., 2000) and the USA (Adimey et al., 2014; Moore et al., 2009; Plotkin and Amos, 1990).

Plastic ingestion was reported for many locations including the Adriatic (Poppi et al., 2012), southeast Canada (Lucas, 1992), North Carolina (Duncan et al., 2019), Bay of Biscay, France (Duguy et al., 1998), Scotland (Gill et al., 2000), Azores (Barreiros and Barcelos, 2001), Brazil (Bugoni et al., 2001; Lima et al., 2018), French Guiana (Plot and Georges, 2010) and Pacific (Cawthorn, 1985; Clukey et al., 2017; Davenport et al., 1993; Thiel, 2018; Wedemeyer-Strombel et al., 2015).

Four studies refer to entanglement and 10 studies to the ingestion of plastic items (LITTERBASE, see also Kühn et al., 2020a). Deadly or harmful interactions between leatherback turtles and plastic pollution occur worldwide, which is concerning because this species is considered vulnerable.

Leatherback turtle caught in a net in late 1999. Principe, Sao Tome and Principe.
© Michel Gunther/WWF

The loggerhead sea turtle

Species: The loggerhead sea turtle (*Caretta caretta*) belongs to the Cheloniidae family and is distinguished by its relatively large head and yellow to reddish-brown colouration.

Distribution: Worldwide in all major oceans on both sides of the equator mainly in tropical, subtropical and temperate but also in subarctic waters, e.g. Alaska. Adults accomplish extensive migrations.

Food: Omnivorous, feeding on algae, corals, invertebrates (including jellyfish), fish, plants and turtle hatchlings (including those of its own species). Their powerful jaws enable them to feed on hard-shelled prey, such as conchs and whelks.

Conservation status: Vulnerable.

Interaction with plastic pollution

In a study of loggerheads in the Mediterranean, the turtles only ingested transparent or white plastic particles; the authors therefore concluded that these materials were mistaken for jellyfish (Gramentz, 1988). In contrast to this, a preference for white and blue items by the hatchlings was reported from southern Cape beaches, where translucent items were more abundant (Ryan et al., 2016). Other scientists believe that loggerheads are indiscriminate feeders because other types of plastics were also ingested (Carr, 1987; van Nierop and den Hartog, 1984) or that it is the odour of bio-fouled plastic items that attracts loggerheads (Pfaller et al., 2020; Ryan et al., 2016). Some of the earliest records of ingested plastics are from loggerheads collected in the Azores, Madeira, and North Atlantic from the 1960s to the 1980s (Brongersma, 1968, 1972; Sadove and Morreale, 1990; van Nierop and den Hartog, 1984) but also from the Mediterranean, Australia, Japan, South Africa and the USA (24–52% with ingested plastics) (Balazs, 1985; Plotkin and Amos, 1990). Plastic ingestion was later reported from the Azores (83% with ingested plastics) (Frick et al., 2009; Pham et al., 2017), the Bay of Biscay (Duguy et al., 1998), Portugal (59%) (Nicolau et al., 2016), Brazil (Bugoni et al., 2001; de Carvalho et al., 2015; Rizzi

Loggerhead sea turtle trapped in a loose free floating ghost net, Azores. © IMAGO/blickwinkel et al., 2019), Florida (Bjorndal et al., 1994; Carr, 1987; Lutz, 1990), Hawai'i (Wedemeyer-Strombel et al., 2015), the Mediterranean (14–85%) (Camedda et al., 2014; Campani et al., 2013; Casale et al., 2008; Domènech et al., 2019; Matiddi et al., 2017; Tomás et al., 2002), Adriatic Sea (35%) (Lazar and Gračan, 2011), South Africa (60%) (Ryan et al., 2016), Australia (Boyle and Limpus, 2008), the Indian Ocean (51%) (Hoarau et al., 2014) and the Pacific Ocean (35–80%) (Clukey et al., 2017; Parker et al., 2005). Loggerheads foraging in open waters had much higher plastic ingestion rates (80%) than those feeding on bottom-dwelling prey (13%) (Casale et al., 2016).

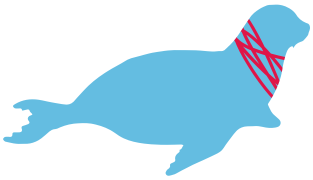
Some of the earliest records of entanglement are from the Lesser Antilles and the USA in the 1970s and 1980s (1% of stranded individuals entangled) (Balazs, 1985; Laist, 1997; Plotkin and Amos, 1990; Sadove and Morreale, 1990). More recent records come from the Azores (Barreiros and Raykov, 2014), Canary Islands (Orós et al., 2005), Cape Verde Islands (López-Jurado et al., 2003), the Mediterranean (Casale et al., 2010), Florida (Adimey et al., 2014), Chesapeake Bay (Barco et al., 2016), northern Australia (Wilcox et al., 2014) and South Pacific (Thiel, 2018).

Young loggerheads are especially affected by plastic pollution. Hatchlings are impeded by plastic debris lying on the beach, which can block their passage to the water or even entangle and entrap them (Aguilera et al., 2018; Triessnig et al., 2012). When they begin feeding in the water, plastic ingestion causes young loggerheads to suffer from a lower intake of energy and nitrogen. Such effects lower growth rates and prolong developmental periods, which could reduce survival and reproduction (McCauley and Bjorndal, 1999).

In total, 7 studies recorded entanglement and 36 studies recorded ingestion of plastic items (LITTERBASE). Because the loggerhead turtle is still a relatively widespread and abundant species, the EU Marine Strategy Framework Directive (see Glossary) selected this species as an indicator for monitoring the amount and impact of marine litter (Domènech et al., 2019; Matiddi et al., 2017).

Post-hatchling loggerhead turtle that died in a rehabilitation centre after stranding on the South African south coast in 2015. The plastic debris pictured was found at post mortem examination obstructing the distal gastro-intestinal tract, cloaca and bladder. Date: 08/05/2015. © Georgina Cole

5.4.3 Impacts on marine mammals



The threats identified for 98% of the 123 marine mammals include the following: incidental catch (112 species), pollution (99 species), direct harvesting (89 species) and traffic (86 species). 33 species were classified as globally endangered or threatened (Avila et al., 2018).

Plastic debris including nets, ropes, plastic bags, foils, packaging material, caps, strapping tapes, duct tape and a part of a car were found in the gastro-intestinal tracts of 22 out of 30 sperm whales (*Physeter macrocephalus*) stranded along the North Sea coast in 2016 (Unger et al., 2016). The amount of ingested debris varied largely with up to 25 kg of debris in one whale. Ingestion or entanglement have been reported from necropsies of stranded sperm whales from all around the world: The Mediterranean (Alexiadou et al., 2019; de Stephanis et al., 2013; Mazzariol et al., 2011; Roberts, 2003), North Sea (Unger et al., 2016), Ireland (Lusher et al., 2018), Iceland (Lambertsen and Kohn, 1987; Martin and Clarke, 1986), Canary Islands (Arbelo et al., 2013; Puig-Lozano et al., 2018), the USA (Byrd et al., 2014; Jacobsen et al., 2010), Peru (Ignacio et al., 2013) and south Australia (Evans and Hindell, 2004).

An Atlantic grey seal entangled in a piece of fishing net. © Kev Gregory/Shutterstock

Studies investigating a wider area, or a longer period can elucidate how marine mammals in general have been impacted by plastic pollution. For example, a study on stranded cetaceans around the Canary Islands over 16 years reported litter in 8% of 465 necropsied dolphins and whales (Puig-Lozano et al., 2018). Plastic bags, caps, nylon wires and cylindrical plastic items accounted for 80% of ingested items. More debris was found in deep-diving species than in those of shallow divers suggesting that deep-diving behaviour increases the risk of plastic ingestion (Puig-Lozano et al., 2018).

Entanglement of seals in marine debris has been observed since the early 1970s (Butterworth and Sayer, 2017; Shaughnessy, 1980). Entanglements limit the movements of pinnipeds and cause them to use up more energy (Feldkamp et al., 1989). Marine debris interactions have been reported for 22 out of the 33 species of pinnipeds (Jepsen and de Bruyn, 2019). Younger animals are more prone to entanglement (Lawson et al., 2015). The feeding mode appears to be one of the most important factors influencing plastic debris interactions. Many reports for seals refer to plastic rings around their necks (Jepsen and de Bruyn, 2019), which injure and strangle them as they grow (Butterworth, 2016; Derraik, 2002). Entangled northern fur seal females have been observed to spend more time at sea, which decreased their pups'weight gain and chances of survival (DeLong et al., 1985).

11% of 6,561 examined manatees had ingested marine debris.

Plastic entanglement and ingestion have also been reported for sirenians (dugongs and manatees) (Adimey et al., 2014; Attademo et al., 2015; Barros et al., 1990; Beck and Barros, 1991; Owen et al., 2017). For example, 14% of 439 rescued Florida manatees (*Trichechus manatus latirostris*) had ingested marine debris, 1% died as a direct result and 3% by entanglements in lines and nets (Beck and Barros, 1991). A 20-year-study showed that 11% of 6,561 examined manatees had ingested marine debris or become entangled, and 50 individuals died as a direct result (Reinert et al., 2017). Plastic is also consumed by Amazonian manatees (*Trichechus inunguis*), which caused the death of one (Guterres-Pazin et al., 2012). An interesting case was presented for 40 rescued Antillean manatees (*Trichechus manatus manatus*) of which four had ingested plastic debris (Attademo et al., 2015). After treatment, they were released into the wild, but two died subsequently, and the two others had to be rescued again because they were debilitated and unable to survive in the wild.

The studies on interactions of plastic debris with marine mammals mostly rely on the examination of stranded animals, but this method overlooks animals dying out a sea, which introduces bias. In addition, some of the stranded animals are in such a bad state that a determination of their cause of death is impossible. Therefore, until more systematic surveys are done, the rate of entanglement and other causes of death will be underestimated when only beached animals are used (Williams et al., 2011).

Sperm whale interacting with plastic bag; status: vulnerable (IUCN), Pico Island, Azores, Portugal, Atlantic Ocean.
© naturepl.com/Franco Banfi/WWF

According to 156 studies, 71 of the 123 species of marine mammals have endured interactions with plastic (LITTERBASE). Adverse effects caused by entanglement with and ingestion of plastic debris have been reported for 35 species including dolphins, whales, seals, sea lions, sea otters, polar bears and manatees. Restrained movement (7 species), reduced feeding (7), injury (23) and mortality (19) are amongst the adverse effects recorded (Figure 13).

The harbour porpoise

Species: The harbour porpoise (*Phocoena phocoena*) is one of the smallest members of the Phocoenidae family. It resembles a dolphin, but is actually more closely related to belugas and narwhales.

Distribution: Temperate and colder waters of the equator and far into Arctic waters. They regularly visit bays, estuaries and harbours, hence the name. Interestingly, there is a geographically isolated population in the Black Sea, which extends into the Marmara and northern Aegean Seas.

Food: Mainly small pelagic shoaling fish, particularly herring, capelin and sprat, crustaceans, squid; usually hunting alone, but sometimes in groups.

Conservation status: Least concern.

Interaction with plastic pollution

The earliest record of an interaction with plastic debris dates back to 1975 when a harbour porpoise from North Carolina was found with a piece of cloth and plastic in its stomach (Walker and Coe, 1990). In 1991, an emaciated female found on the Dutch coast contained a large plastic bag and a fishing line (Kasteleine and Lavaleye, 1992), and several other unpublished records of plastic ingestion were reported from the Netherlands in the 1990s (Baird and Hooker, 2000). An emaciated male from Nova Scotia had a balled-up piece of plastic blocking the oesophagus (see Glossary) (Baird and Hooker, 2000). Five out of 42 porpoises caught in fishing nets in 2002–2003 had plastics in their stomachs (Tonay et al., 2007). In a study from Irish waters, six and five individuals out of 125 had ingested macrodebris and microplastics, respectively (Lusher et al., 2018). 2% of 456 individuals stranded in the UK had ingested debris (Baulch and Perry, 2014). Among 654 individuals from the Netherlands, 7% had ingested plastics from 2003–2013 (van Franeker et al., 2018). In the eastern Mediterranean, one out of five individuals collected between 2000 and 2013 had a plastic sheet in its stomach (Alexiadou et al., 2019). On average 5 microplastic particles were detected in the digestive tracts of 21 dead individuals recovered in southwest England, all of which contained microplastics (Nelms et al., 2019).

63% out of 40 porpoises stranded on the eastern US coast in the 1990s had been entangled; however, these numbers are dwarfed by the thousands of porpoises killed annually as bycatch in Canadian and US fisheries (Cox et al., 1998). In total, eight studies recorded ingestion of plastic items (LITTERBASE).

A harbour porpoise killed by discarded fishing nets in north Wales, United Kingdom. © Paul Kay/Photodisc/ Getty Images

The common bottlenose dolphin

Species: The common or Atlantic bottlenose dolphin (*Tursiops truncatus*) is a member of the family of true dolphins (*Delphinidae*).
Distribution: Worldwide in all oceans on both sides of the equator, tropical and subtropical but also in temperate waters.
Food: Mainly eels, shrimp, squid and various species of fish, often hunting in groups and locating prey primarily with echolocation.
Conservation status: Least concern.

Interaction with plastic pollution

Ingestion of plastic was already noticed among six wild dolphins from California in the 1970s and 1980s (Schwartz et al., 1992; Walker and Coe, 1990). The death of an emaciated dolphin in Florida was also attributed to plastic ingestion (Barros et al., 1990). Eleven dolphins died because of marine litter in Croatia (Baulch and Perry, 2014). In Israel, a female died after ingesting a large net in 2007 (Levy et al., 2009). An emaciated male died in Virginia in 2009 because of entanglement with fishing twine marketed as extra strong (Barco et al., 2010). Researchers observed a mother when her calf became entangled in a monofilament line in western Australia in 1990 (Mann et al., 1995). Eighteen fatal cases of ingestion were reported for bottlenoses interacting with discarded hook and line fishing gear in Florida over a 13-year period (Stolen et al., 2013). Macroplastic and microplastic ingestion was also documented for dolphins in Ireland (Lusher et al., 2018) and Wales in 2016 (Nelms et al., 2019). In total, nine studies recorded plastic ingestion and five studies recorded entanglement of bottlenose dolphins (LITTERBASE).

Sociable wild bottlenose dolphin Belize. © naturepl.com/Doug Perrine/WWF

The fin whale

Species: The fin whale (*Balaenoptera physalus*) is a filter-feeding baleen whale and the second largest animal species after the blue whale.
Distribution: Worldwide in all oceans on both sides of the equator.
Food: Mainly small swarming crustaceans like copepods (see Glossary) and krill (Euphausiacea), fish, squid.
Conservation status: Vulnerable.

Interaction with plastic pollution

Some of the earliest records of interaction of fin whales and plastic go back to 1985 where 7% of 82 whales had ingested plastics and 5% of 95 whales showed signs of entanglement (Sadove and Morreale, 1990). Both entanglement and plastic ingestion had been reported for fin whales by 2008 (Williams et al., 2011), and one fin whale died in the Canary Islands because of marine debris (Baulch and Perry, 2014). A fin whale stranded in Ireland in 2000 had a nylon rope tucked in its baleen plates and swallowed part of it (Lusher et al., 2018; Smiddy et al., 2002).

In the western Mediterranean, researchers found high concentrations of phthalates in samples of neustonic plankton and also in fin whales feeding on it, suggesting an emerging threat of plastic additive contamination to these whales (Fossi et al., 2012, 2014). Additionally, several persistent organic pollutants were found in fin whale tissues (Fossi et al., 2016). Since some Mediterranean populations feed in areas of high plastic concentrations (Fossi et al., 2017a), which may contribute to high body burdens of persistent organic pollutants (Fossi et al., 2016), fin whales were proposed as an indicator for monitoring marine litter under the EU Marine Strategy Framework Directive (see Glossary) (Fossi et al., 2014). Four studies recorded entanglement and four studies recorded ingestion of plastic items by fin whales (LITTERBASE).

Fin whale near sea surface. Pico Island, Azores, Portugal. © naturepl.com/Luis Quinta/WWF

The grey seal

Species: The grey seal (*Halichoerus grypus*) is a large seal from the Phocidae family.
Distribution: Two separate subspecies, one in the Baltic Sea, the other one in the North Atlantic found along Europe's coastline from Russia to France, around Iceland and from Newfoundland to Massachusetts.
Food: Mainly various fishes, but also lobsters, octopuses and occasionally much larger prey such as harbour porpoises and harbour seals.
Conservation status: Least concern.

Interaction with plastic pollution

Already in the 1980s, dozens of entangled grey seals were observed in Nova Scotia, Canada, mostly in trawl nets, e.g. 3% of 241 pups were entangled (Lucas, 1992). Eleven seals were found entangled in Massachusetts in the 2000s (Bogomolni et al., 2010). At a resting site in southwest England, 4–5% of all seals were entangled, mostly by fishery-related material, and entangled seals often had serious injuries and lower survival rates (Allen et al., 2012).

Microplastic was found in the faeces of captive grey seals (Nelms et al., 2018). Another study in southeast Massachusetts, USA, detected microplastics in 1% of the faeces (Hudak and Sette, 2019). Three seals washed ashore in southwest England contained 4–8 microplastics per seal (Nelms et al., 2019). Thirteen bycaught seals from Irish waters all contained microplastics (mean 28 particles/seal) but no macrodebris (Hernandez-Milian et al., 2019). Five seals from northern Germany all contained microplastics (mean 18 particles) (Philipp et al., 2020). In total, four studies recorded entanglement, and four studies recorded ingestion of plastic items by grey seals (LITTERBASE).

Seal entangled with plastic band around its neck, which has cut through the seal's blubber to the flesh. Horsey, Norfolk. © Sam Hobson/WWF-UK

The harbour seal

Species: The harbour seal or common seal (*Phoca vitulina*) is a medium-sized seal from the Phocidae family.

Distribution: Along most temperate to Arctic coastlines, can swim almost 200 km up-stream in large rivers to hunt fish.

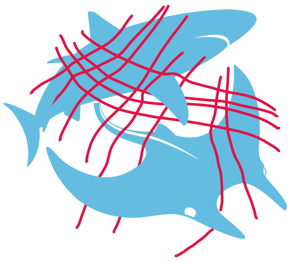
Food: Mainly fishes, but occasionally also ducks, crabs, molluscs, shrimp, squid. Although primarily coastal, dives down to over 500 m have been recorded.

Conservation status: Least concern.

Interaction with plastic pollution

In the 1980s, dozens of entangled seals were observed in Nova Scotia, Canada, mostly in trawl nets (Lucas, 1992). Only three (0.09%) out of 3,394 seals sampled on two Californian islands in 1985–1986 were entangled but these surveys likely underestimate entanglement rates since entangled seals often die out at sea (Stewart and Yochem, 1987). Three seals were found entangled during a 23-year study on a Californian island (Hanni and Pyle, 2000). Three out of 1,072 seals (0.28%), which were found stranded on the Californian coast during a 13-year study had been entangled by plastic debris (Goldstein et al., 1999). Eleven harbour seals were found entangled during a five-year study in California with a 0.04% entanglement rate (Moore et al., 2009). Several seals were also found entangled in Massachusetts in the 2000s (Bogomolni et al., 2010) and British Columbia (Laist, 1997; Williams et al., 2011). 11% of 107 examined stomachs of Dutch seals contained plastic debris (Bravo Rebolledo et al., 2013). Six percent of harbour seal faeces from southeastern Massachusetts contained microplastics (Hudak and Sette, 2019). All four dead seals from southwest England had microplastics in the digestive tract with a mean of 4 microplastics per seal (Nelms et al., 2019). Five dead seals from northern Germany all contained microplastics (mean 33/seal) (Philipp et al., 2020). In total, ten studies recorded entanglement and three studies recorded ingestion of plastic items by harbour seals (LITTERBASE).

Harbour seal entangled in rope cutting through the skin causing severe wounding. Location: Svalbard, Arctic.
© Eigil Molvik/The Governor of Svalbard



5.4.4 Impacts on sharks and rays

In a global review, the main threat to chondrichthyan fishes, which include sharks, rays, and chimaeras, was overfishing (targeted harvesting and bycatch), followed by habitat degradation, persecution and climate change (Dulvy et al., 2014). Globally, shark and ray populations have declined by 71% since 1970 due to an 18-fold increase in fishing pressure (Pacoureau et al., 2021). In comparison, plastic pollution is currently, probably a minor threat to sharks and rays.

Baby blue shark with a plastic ring around its mouth, leaving behind an incision. *© Domenico Ottaviano*

The impacts of plastic pollution on sharks and rays are poorly studied compared to other marine vertebrates. Nevertheless, sharks and rays are also affected by plastic pollution. A review reported entanglements for 34 species of sharks, rays and chimaeras (Parton et al., 2019). Lost fishing gear accounted for 74% of the cases, and strapping bands for another 11%. 26 species of sharks were entangled, with reports partly gleaned from Twitter, and fishing gear caused 95% of all entanglements. Only a few blue sharks and no mako sharks were observed with plastic straps around their gills in a survey between 2004 and 2018 in the South Pacific and North Atlantic (Mucientes and Queiroz, 2019). In the southwest Atlantic, plastic rings around the gills or mouth regions caused severe abrasions on Brazilian sharpnose sharks (*Rhizoprionodon lalandii*) (Sazima et al., 2002) and as the animals grew, these rings likely hampered their feeding and breathing.

Similarly, strapping bands were found around the gills and heads of 0.19% of 28,687 sharks (spinner, copper, bull, blacktip, dusky, sandbar, great white and tiger sharks), which were caught in the nets that protect beach users from shark attacks in KwaZulu-Natal, South Africa (Cliff et al., 2002). 0.02% of these had plastic in their stomachs. While plastic ingestion by sharks was presumed to occur rarely (Thiel, 2018), recent studies on blue sharks confirmed plastic ingestion for several localities (Barreto et al., 2019; Bernardini et al., 2018; Colmenero et al., 2017; Fernández and Anastasopoulou, 2019; Mucientes and Queiroz, 2019). 25% of 139 critically endangered blue sharks from the Mediterranean had ingested macro- and microplastics (Bernardini et al., 2018), likely originating from packaging material.

Since whale sharks, manta rays and basking sharks filter zooplankton from water, they are good indicators of microplastic pollution (Fossi et al., 2014). Indeed, examination of faeces from three Indonesian locations suggest an uptake of up to 63 and 137 microplastics per hour for manta rays (*Mobula alfredi*) and whale sharks (*Rhincodon typus*), respectively (Germanov et al., 2019). A much lower ingestion rate of 7 microplastics per hour was reported for whale sharks from Baja California (Fossi et al., 2017a). The ingestion rates of microplastic by basking sharks from the Mediterranean was estimated at 540 microplastics per hour (Fossi et al., 2014). However, the effect of microplastic ingestion is currently unknown.

According to 46 studies in LITTERBASE, 56 species encountered plastic via entanglement (40 species) or ingestion (33) or both. Effects of entanglements were reported for 25 species (Figure 13) causing restrained movements (16 species) and injuries (14). Very few reports on the effects of ingestion are available other than the fatal case of a drinking straw in a whale shark.

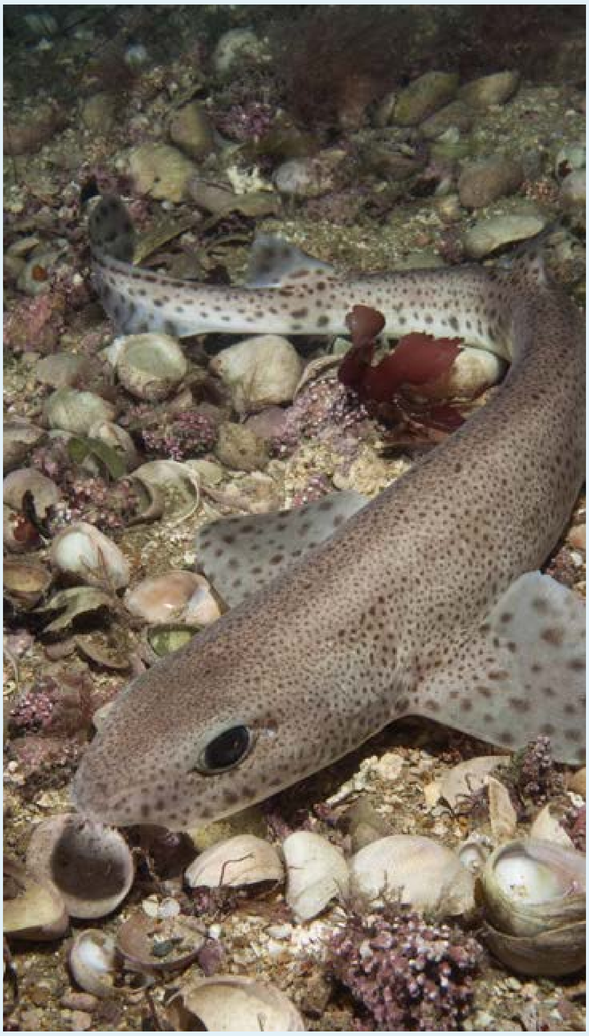
This manta ray (Manta birostris) is entangled in a fishermans net, Yap, Micronesia. © IMAGO/VWPics

The lesser spotted dogfish

Species: The lesser spotted dogfish or small spotted catshark (*Scyliorhinus canicula*) belongs to the catshark family (*Scyliorhinidae*).
Distribution: From the North Sea to Senegal, and throughout the Mediterranean.
Food: Feeds opportunistically on small prey animals in coastal waters, mainly crustaceans, small fishes, molluscs, octopuses, squids, snails, but also echinoderms, bristle worms, sipunculids, tunicates.
Conservation status: Least concern.

Interaction with plastic pollution

Both a gill and a trammel net experimentally manipulated to simulate 'ghost nets' entangled 79 dogfish each over several months (Kaiser et al., 1996). In a similar experiment, two dogfish were caught in the Cantabrian Sea (Sancho et al., 2003), and one off Wales (Bullimore et al., 2001). Five cases of dogfish entanglement were also reported from UK and French waters (Parton et al., 2019).



Dogfish also ingest plastics: Out of 20 individuals caught in the North Sea, 15% contained (micro-) plastic (Smith, 2018) as did 25% of eight dogfish from UK waters with a mean of 1.5 microplastic items per fish (McGoran et al., 2018). A quarter of 20 dogfish from Portuguese waters contained 0.12–0.67 microplastics per fish (Neves et al., 2015). 15% of 72 dogfish caught off Spain had ingested on average one microplastic per fish (Bellas et al., 2016). Only 0.07% of 9,981 individuals caught in the Spanish Bay of Biscay contained macroplastic items (López-López et al., 2018). 67% of 12 individuals caught in the northeast Atlantic contained microplastics, mostly fibres, ranging from 0–6 items per fish (Parton et al., 2020). 75 microplastic particles were found in 30 dogfish caught in the western Mediterranean (Valente et al., 2019). Current evidence suggests a relatively low burden of plastic in lesser spotted dogfish overall. Three studies recorded entanglement and nine studies recorded ingestion of plastic items (LITTERBASE).

Lesser spotted dogfish on the seafloor, Jersey, British Channel Islands. © IMAGO/Nature Picture Library

The whale shark

Species: The whale shark (*Rhincodon typus*) is one of three filter-feeding sharks, the only member of its family (*Rhincodontidae*), and the largest fish species.

Distribution: Worldwide in all oceans on both sides of the equator, mainly tropical and subtropical but also in temperate waters.

Food: Mainly planktonic and nektonic prey including small fishes, copepods, krill, jellyfish, squid, eggs and larvae.

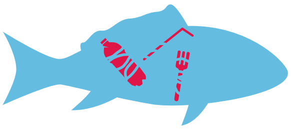
Conservation status: Endangered.

Interaction with plastic pollution

A stiff plastic drinking straw was found in the gastric lumen of a whale shark caught in Thailand in 2005, which caused wounds and infection, and probably its death (Haetrakul et al., 2009). A juvenile whale shark stranded in Bahia, Brazil, in 2013 had ingested a plastic cotton swab, rings, and packaging material (Sampaio et al., 2018). Marine litter was also found lodged in the gills of a whale shark stranded in the Philippines in 2018 along with 38 plastic items in its stomach (Abreo et al., 2019). Mexican whale sharks could consume about 171 microplastics per day (Fossi et al., 2017a) while Indonesian whale sharks ingest around 3,300 microplastics per day (Germanov et al., 2019). One study also reported numerous cases of whale shark entanglement gleaned from social media (Parton et al., 2019). Globally, the whale shark distribution overlaps with several hotspots of microplastic pollution, which could put this species at risk given its filter feeding turnover (Germanov et al., 2018). Several harmful plastic additives were found in skin biopsies of whale sharks (Fossi et al., 2017a). One study recorded entanglement and two studies recorded the ingestion of plastic items by whale sharks (LITTERBASE).

A whale shark swims near a floating plastic bag in Oslob, Cebu, Philippines. © Steve De Neef/National Geographic Creative

5.4.5 Impacts on other fish species



A global review of marine fish species found that 70% had ingested plastic.

Other fishes that have been investigated for interactions with plastic debris were subject to a large diversity of studies with regard to their body types, feeding habits, and habitats.

There is ample scientific evidence to confirm plastic ingestion by fishes; from top predators to plankton eating fishes, plastic debris has been identified in their stomachs. A recent global review of 555 marine fish species found that 386 species (70%) had ingested plastics whereby the abundance of plastic in surface waters was positively correlated to plastic ingestion (Savoca et al., 2021).

The impacts of microplastic ingestion on fishes were identified as mortality, changes in physiology, growth, locomotion and food uptake, and the translocation of microplastics into organs or the blood stream (LITTERBASE). However, the seriousness of these effects is being debated, especially given that some laboratory studies have used higher concentrations than usually found in the wild. For example, the ingestion of polyethylene microbeads in an experimental setup with European sea bass larvae resulted in limited impacts, most likely due to the short retention time and quick egestion of the microbeads (Mazurais et al., 2015). The mortality rate increased significantly with the amount of microbeads found inside the larvae, but only the highest dose slightly impacted mortality rates. On the other hand, marine jacopever (*Sebastes schlegelii*) responded to plastic exposure with reduced feeding activity, swimming and exploration ability, growth, energy reserves, but with enhanced shoaling behaviour (Yin et al., 2018).

When fish are consumed, whether by predators or humans, chemical additives and persistent organic pollutants on plastic particles (Section 5.3) could elicit ecotoxicological effects. Therefore, microplastic pollution has been getting a lot of attention from the public and media because it is bioavailable, ubiquitous and abundant in the oceans.

The observations of entanglement in plastic debris of fishes are scarce, except for studies on derelict fishing gear, where fishing nets were intentionally deployed to certain areas to assess their effects on fish survival (Ayaz et al., 2006; Baeta et al., 2009; Campbell and Sumpton, 2009; Erzini et al., 2008; Nakashima and Matsuoka, 2004). Almost all of these studies reported hundreds of fish entanglements initially followed by an exponential decrease during the following 5 to 8 months, due to the changing state of the nets. The number of entangled fishes by lost or discarded fishing gear can well be an underestimation because of the high rates of predation and scavenging by octopuses, cuttlefish, eels and other fish (Erzini et al., 2008).

A recent study reported entanglement in plastic rings of tropical silver mojarra (*Eucinostomus argenteus*), Atlantic thread herring (*Ophistonema oglinum*), tomtate grunt (*Haemulon aurolineatum*) and gray parrotfish (*Sparisoma axillare*) (Nunes et al., 2018), which reduced swimming performance, feeding and

Above: Stomach contents of a yellowfin tuna with a 1.5 cm black plastic pipe and a 60 cm plastic rope. Location: central North Pacific, date: 29.08.2012 (Fujieda et al., 2014). © Shigeru Fujieda; Below: Eel entangled by plastic string commonly used in oyster farms. Location: Xia Zhuang Harbor in Chiayi County, Taiwan, date: 16.07.2017). Fishermen informed the photographer that entanglements by oyster strings are very common in the local harbor. © Po-Hsiu Kuo

antipredator behaviour. These effects have been reported for numerous other species, which emphasizes the need to tackle the threat caused by plastic rings.

An interesting interaction type for fish is the ‘colonisation’ of floating plastic debris, which is more of an association. Small fishes and juveniles aggregate with floating plastics, feed on the biota on rafts, some prey on small fishes seeking shelter below rafts or use rafts as a spawning ground (Thiel and Gutow, 2005). Furthermore, fishes from two taxa associated to the floating tsunami debris rafted from the coasts of Japan all the way to the shores of the U.S. Pacific Northwest (Carlton et al., 2017).

According to 270 studies in LITTERBASE, 718 fish species interacted with plastic debris (Figure 13). Plastic ingestion accounted for 80% (577 species) and entanglement in plastic debris for 18% (132 species) of all affected species. A total of 559 fish species ingested plastic and 14 species became entangled with plastic debris in the wild. The rest of the interactions included ‘colonisation’ on debris and other interactions. Effects of these interactions were reported for 167 species in 137 studies. 58 studies investigated the impacts of plastic ingestion in experiments and found adverse effects for 112 species.

The Atlantic cod

Species: The Atlantic cod (*Gadus morhua*) is a very important commercial fish widely consumed by people (e.g. in 'fish and chips').
Distribution: Subtropical to Arctic waters in both sides of the North Atlantic.
Food: Top predator, which feeds on smaller fishes, crustaceans, molluscs and worms.
Conservation status: Vulnerable.

Interaction with plastic pollution

In an experimentally set gill net, the predominant species caught was Atlantic cod (Carr et al., 1985). Cod were also caught by a ghost gill net drifting near Greenland (Bech, 1995). It was one of the two main species caught by an experimentally set bottom gill net (Tschernij and Larsson, 2003).

Five out of 205 cod caught for human consumption in the Atlantic contained microplastics (1–5 mm), with seven particles found in total (Liboiron et al., 2016). 13% of 80 sampled North Sea cod contained microplastics, with all particles < 3 mm (Foekema et al., 2013). 30% of 201 cod caught in the Baltic and North Seas had microplastics in their stomachs, with more offshore cod containing microplastics compared to coastal fish (Lenz et al., 2016). 3% of 302 individuals caught in Norwegian waters had plastic particles in their stomachs (Bråte et al., 2016). 1% of 81 cod caught in the Baltic and North Seas had ingested plastics (Rummel et al., 2016). 2% of 1,010 fish caught in Newfoundland had ingested plastic (Liboiron et al., 2019). Among 114 cod, 12% ingested microplastics with a mean of 0.13 particles per fish, a pollution burden, which was higher than in other North Sea fishes (Kühn et al., 2020b). A biodynamic model suggests that leaching of BPA and nonylphenol from ingested microplastics constitutes a small proportion of the cod's total exposure to these pollutants via other pathways, such as uptake of prey and water (Koelmans et al., 2014). Three studies recorded entanglement, and 11 studies recorded ingestion of plastic items (LITTERBASE).

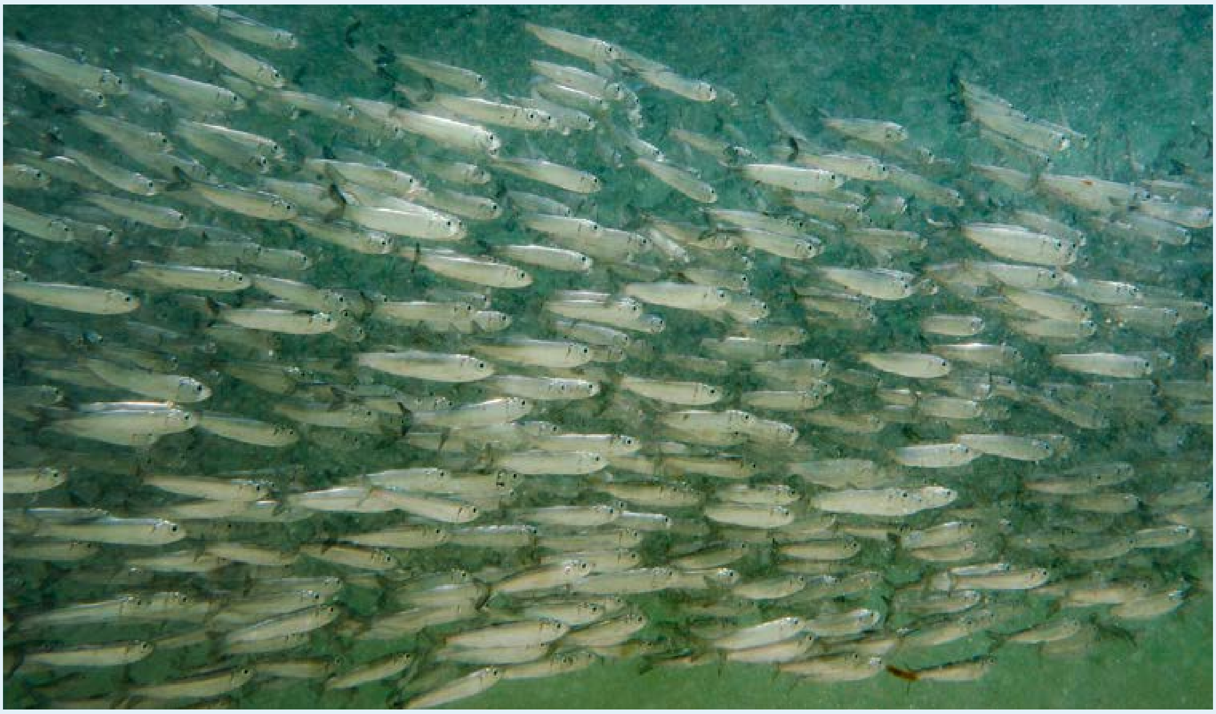
Dead cod entangled in a net lost on a wreck off the island of Ruegen, Baltic Sea. Date: 08.03.2014.
© Wolf Wichmann

The Atlantic herring

Species: The Atlantic herring (*Clupea harengus*) is a member of the Clupeidae family, one of the world's most abundant fish species and of high commercial importance.
Distribution: Subtropical to Arctic waters at both sides of the North Atlantic.
Food: Zooplankton, mainly copepods, other crustaceans and smaller fish species, but also arrow worms, diatoms, and eggs and larvae of various species.
Conservation status: Least concern.

Interaction with plastic pollution

Herring entangled in a ghost net that was at least seven years old was reported for British Columbia (Breen, 1990). Polystyrene spherules were already reported from Atlantic herring in the eastern North Atlantic (Day et al., 1988). Plastic ingestion by herring has been reported in the Baltic and North Sea (Collard et al., 2015). While one study found microplastic in 17% of 205 herring from the Baltic and North Seas (Lenz et al., 2016) another found none in 33 herrings from this area (Rummel et al., 2016) or even in 52% of 130 herrings from the Baltic Sea with 88% fibres and 12% fragments (Ogonowski et al., 2017). Among 1 % of 1,143 herring sampled between 2010 and 2018 in different regions of the North Sea, the mean number of microplastic items per fish was 0.019 (Kühn et al., 2020b). Other studies reported microplastics in 2% of 164 Baltic Sea herrings (Budimir et al., 2018). Microplastics were also detected in the livers of two herrings caught in the North Sea indicating that they pass from the gastrointestinal tract to organs (Collard et al., 2017a). In total, nine studies recorded ingestion of plastic items (LITTERBASE). While the incidence varies, overall the pollution burden seems low given the filter-feeding mode of this species.



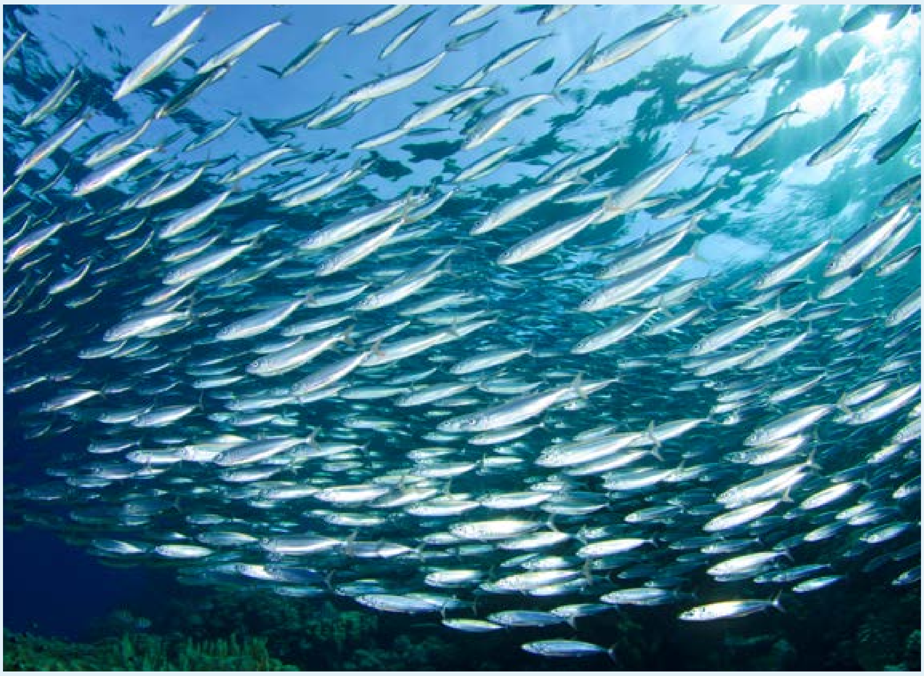
Swarm of herrings. © Philipp Kanstinger/WWF

The sardine

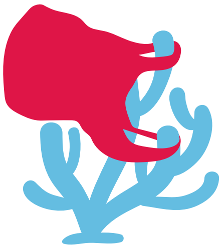
Species:	The sardine or European pilchard (*Sardina pilchardus*) is another member of the Clupeidae family and also of commercial importance.
Distribution:	Northeast Atlantic Ocean, Mediterranean and Black Sea.
Food:	European pilchards are an important converter of phytoplankton and zooplankton (mainly copepods and their larvae).
Conservation status:	Least concern.

Interaction with plastic pollution

Of three planktivorous fish (herrings, anchovies, sardines), sardines likely ingest more microplastics because their feeding apparatus has the highest filtration area and the closest gill rakers (Collard et al., 2017b). Microplastics were also detected in the livers of two sardines caught in the English Channel, with a mean of < 0.5 microplastic particles per individual indicating passage to organs (Collard et al., 2017a). While 15% of 105 sardines from the Spanish Mediterranean contained microplastics (Compa et al., 2018), 47% of 36 sardines caught in Greek waters contained on average 0.8 microplastics per fish (Digka et al., 2018). 19% of 139 sardines caught in the Adriatic and Ionian Sea contained plastic particles (Anastasopoulou et al., 2018) as did 20% of 20 sardines from the Spanish Mediterranean (Rios-Fuster et al., 2019). 12% of 85 individuals caught in the northwestern Mediterranean contained on average 0.2 microplastics per fish (Lefebvre et al., 2019). In the Adriatic Sea, even 96% of 80 sardines contained on average 4.6 microplastics per fish (Renzi et al., 2019) and along the Atlantic coast of Spain, 87% of 15 sardines contained on average 1.53 microplastics per fish (Filgueiras et al., 2020). 58% of 104 sardines from the northwest Mediterranean contained on average 1.5 microplastics per fish (Pennino et al., 2020). Four out of 20 brands of canned sardines and sprats contained microplastic highlighting the link to human health (Karami et al., 2018). In total, two studies recorded entanglement and 20 recorded plastic ingestion by sardines (LITTERBASE). While sardines appear to be susceptible to plastic ingestion, we do not know the consequences of this on fish health.



Large swarm of sardines swims over a coral reef. © richcarey/iStock/Getty Images



5.4.6 Impacts on corals and sponges

Corals and sponges are emblematic habitat engineers, which support very diverse bottom and fish communities. They are sessile animals that often have a rugose spikey surface. This renders them particularly vulnerable to entanglement and coverage, which are the most frequently observed types of interaction along with colonisation of plastic debris.

Even in the remote Arctic deep sea, up to 20% of the sponge colonies had entangled plastic (Parga Martínez et al., 2020). In the Mediterranean, red corals (*Corallium rubrum*), black corals (*Antipathella subpinnata*), orange tree coral (*Dendrophyllia ramea*), violescent sea-whip corals (*Paramuricea clavata*), hairy sea fan coral (*Acanthogorgia hirsuta*) and yellow gorgonians corals *(Eunicella cavolini*) were entangled in fishing gear. The effects are broken or dead branches of corals and detachment from the hard substrate (Consoli et al., 2019). Coral cover decreased significantly as the amount of litter increased in the lagoons of the Marshall Islands (Richards and Beger, 2011). Likewise, in Oahu, Hawai'i, 65% of coral colonies had fishing lines and 80% of colonies were at least partially dead, which was positively correlated with the abundance of fishing lines (Yoshikawa and Asoh, 2004). Damage or breakage causes tissue abrasion and partial or colony mortality in sponges, as observed in Florida (Chiappone et al., 2005). Injury renders organisms more susceptible to predation, disease and competitive overgrowth.

Plastic foil covering corals. Marsa Alam, Egypt. © Philipp Kanstinger/WWF

Plastic debris deprives corals of light and oxygen exchange, leaches chemicals and gives pathogens a foothold.

Plastic debris deprives corals of light and oxygen exchange, leaches chemicals and gives pathogens a foothold for invasion, such that the likelihood of disease increased 20-fold when corals were covered with plastic in the Asia-Pacific region (Lamb et al., 2018). Coverage of sponge or coral structures can impair prey capture and growth rates as observed for *Lophelia* (Mouchi et al., 2019). On the other hand, corals often colonise debris. For example, stranded buoys from lost fishing gear near Sicily were colonised by endangered deep-sea corals (*Lophelia pertusa, Madrepora oculata*) as were fishing lines in French Mediterranean canyons (Fabri et al., 2014).

Many corals feed on particles, which they filter from the seawater. In laboratory experiments, various species interacted with microplastics. Effects included adhesion of microplastic particles to polyps, ingestion, decreased photosynthetic rate, bleaching and tissue necrosis (Figure 15) (Martin et al., 2019; Reichert et al., 2018; 2019). Another effect was mucus production and overgrowth, which are responses to natural particles and enable self-cleaning to prevent smothering of their tissues (Duckworth et al., 2017). However, these responses come at energetic cost and could lower the energy reserves of corals (Reichert et al., 2018). In another study, 10–20% of the microplastic ingested by stony corals were egested only after 6–24 hours and 6% retained (Allen et al., 2017). Prolonged retention of particles may affect coral health.

According to LITTERBASE, a total of 93 species of corals and sponges interact with plastics (Figure 13). This is most probably a gross underestimation due to insufficient sampling because the pollution rates documented (Section 6.2) suggest that most species of tropical coral reefs have at least encountered if not been damaged or killed by plastic pollution.

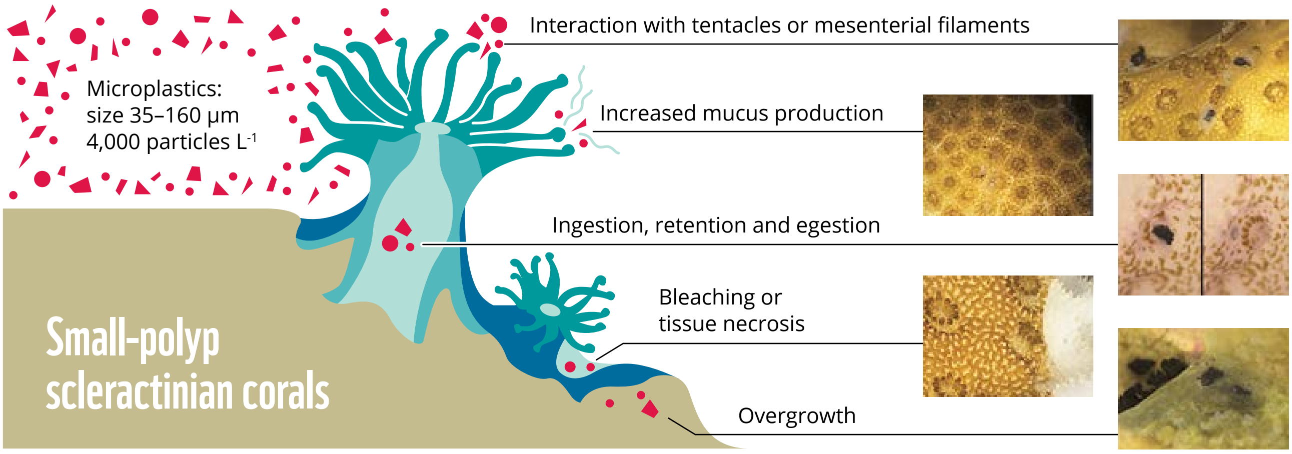


Figure 15: The impacts of microplastic ingestion on reef-building corals (recreated from Reichert et al., 2018).

Lophelia pertusa

Species: *Lophelia pertusa*, a cold-water coral.

Distribution: Cosmopolitan, mostly found in the deep waters of the Atlantic Ocean and Mediterranean Sea but so far discovered only rarely in the Southern, Indian and Pacific Oceans. *Lophelia* is slow-growing and important species of cold-water reefs, which host diverse bottom communities.

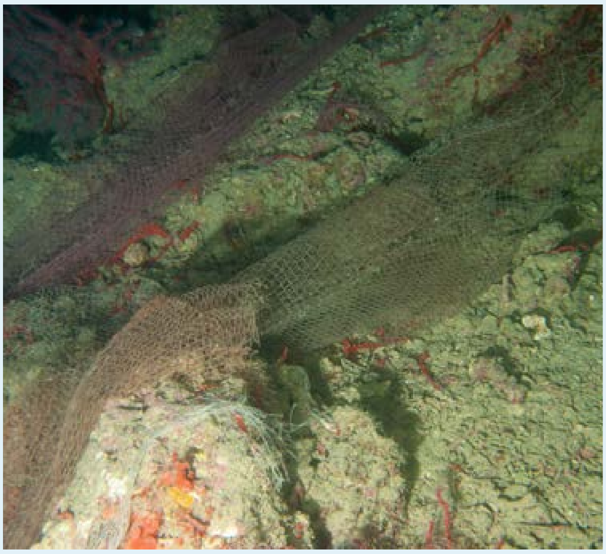
Food: The coral polyps catch live prey (zooplankton and carrion) from the water with its stinging tentacles; it is a generalist feeder and prefers fast currents, which increase prey capture.

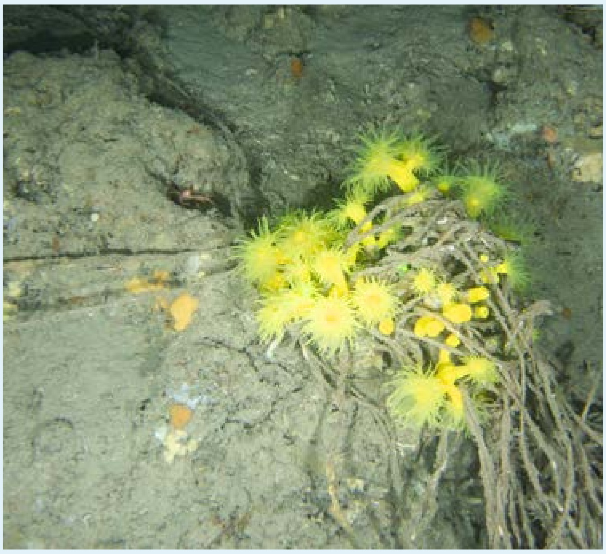
Conservation status: Least concern.

Interaction with plastic pollution

Lophelia reefs take thousands of years to grow (Hall-Spencer et al., 2002) and support diverse ecosystems including commercially important fish. Therefore, they are damaged by bottom fishing activities worldwide. In Norwegian waters, for example, 30–50% of *Lophelia* reefs were damaged by fishing, which also resulted in the loss of numerous nets, long-lines and other fishing-related debris entangled in corals (Fosså et al., 2002). Similar observations were made off Ireland, Atlantic Canada, the northwest Mediteranean and Florida (Buhl-Mortensen, 2017; Dominguez-Carrió et al., 2020; Ross et al., 2017; Söffker et al., 2011). Likewise, most of 17 deep-water canyons in the French Mediterranean harboured lost fishing gear, including nets hooked to corals, which were colonized by various species, including corals (Fabri et al., 2014). The same was observed in the Ionian Sea and submarine canyons of the Bay of Biscay (Taviani et al., 2005; van den Beld et al., 2017).

In experiments, plastic coverage of *Lophelia* acted as a barrier for food supply, which led to higher polyp activity but lower prey capture rates likely affecting energy acquisition and therefore skeletal growth (Chapron et al., 2018; Mouchi et al., 2019). In total, seven studies recorded entanglement, one study colonization, two studies coverage and two studies ingestion of microplastic (LITTERBASE).





Left: Plastic nets covering and abrading the red coral (Corallium rubrum) (Gulf of Naples, Thyrrenian Sea, 80 m water depth, 2012); Right: Plastic lines entangled in scleractinian cold-water coral Dendrophyllia cornigera (Ligurian Sea, 110 m water depth, 2015). © both by Michela Angiolillo/ISPRA

5.4.7 Impacts on other marine species

The analysis of 238 studies revealed that another 1,089 marine species including microbes and plants interact with plastics in the wild, in addition to the groups outlined above (Figure 14). In addition, another 319 studies investigated the impacts of plastic pollution experimentally on 625 species. Because of their size, habitat or ecological role, most of them do not capture the public's attention despite their ecological importance. In this section, we give a brief overview of how plastic pollution interacts with these 'invisible' animals from the sea surface throughout the water column to the seabed. The impacts of plastic pollution on seagrass and mangrove ecosystems are described in detail in Chapter 6.

More than half of the studies (57% of 557) concerning other marine species, which we describe in this chapter, investigated the ingestion of plastics by 365 species (LITTERBASE). Microplastics in the digestive system may cause false satiation, which can lead to reduced food uptake, and in turn to reduced fertility and even mortality (Besseling et al., 2014; Besseling et al., 2013; Horn et al., 2020; Watts et al., 2015; Welden and Cowie, 2016b).

Since experimental studies may have used unrealistically high exposure levels (Section 5.2.2) it is important to consider the distribution of field and experimental studies here. For some species, both approaches were used. The studies reporting their results based exclusively on field observations account for 36%. The remainder conducted field and laboratory experiments. Plastic ingestion was reported mostly for crustaceans (119 species) and molluscs (95 species). The proportion of experimentally studied crustacean species is 51%, and 9% of the species were investigated both experimentally and by field observations.

Sea urchin, covered with plastic.
© Gauthier Saillard/WWF

Underwater litter from a populated area topside. Banda Neira, Moluccas, Indonesia. © Jürgen Freund/WWF

For molluscs, the distribution of the methods is quite different: 61% of the species were studied using field sampling and 19% experimentally with an additional 20% using both approaches. Plastic ingestion by worm-like animals (41 species) and echinoderms (34 species) were confirmed mostly in experimentals (63% and 59% of the species, respectively), whereas plastic ingestion by tunicates (23 species) was mostly reported from the field (57% of the species). Plastic ingestion was reported for another 53 species of anemones, jelly fish, comb jellies, unicellular eukaryotic organisms, bacteria and blue-green, green, red and brown algae (Figure 14).

Any impact of plastic pollution on zooplankton may reverberate throughout the entire ecosystem.

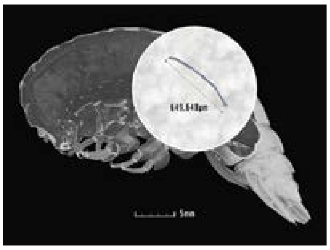
As the primary consumer in most marine food webs, any impact of plastic pollution on zooplankton may reverberate throughout the entire ecosystem. Already in 1973, a first account described size-selective predation in copepods (*Acartia tonsa*) using small plastic beads (7–70 µm) (Wilson, 1973). Since then, ingestion of microplastics soon became the primary research subject in many zooplankton studies. For example, one study showed that 13 of 15 zooplankton groups from the Northeast Atlantic ingest polystyrene particles (7.3–30.6 µm) (Cole et al., 2013), that particles stuck to their body and that certain particle sizes decreased feeding rates. Although the animals egested the microplastics, other possible consequences of microplastic exposure were highlighted. The copepod *Centropages typicus* appeared not to be able to differentiate between the algae and small beads, leading to decreased algal feeding (Cole et al., 2013). Small particles became trapped between the appendages, which could lower copepod survival rates, as the appendages have important roles in locomotion, ingestion, mating and mechanoreception.

Colonisation on plastic items by organisms belonging to the other marine species was addressed in 146 studies, having an impact on 1,093 species. 718 of the colonising species including invasive species and pathogens were identified on floating debris, which means they can raft across entire oceans (LITTERBASE). This effect is referred to as 'dispersal' in this report (Figure 14), meaning that species can spread to new locations. Within a few weeks after plastic enters the ocean, microbial communities start forming slimy biofilms on the plastic surfaces, the 'plastisphere' (Ye and Andrady, 1991; Zettler et al., 2013). Fouling communities on marine plastic debris are diverse and were found to differ from the communities in the surrounding open ocean waters (Zettler et al., 2013). A plastic fragment of 1 g, whose microbial biomass accounts for 6% of its total weight, harbours more microbes than are found in 1,000 litres of the surrounding seawater (Mincer et al., 2016). Biofilms facilitate the colonisation by other sessile organisms such as hydroids, tunicates, echinoderms, polychaetes, crustaceans, molluscs, corals, sponges and macroalgae. The process of colonisation on substrates in aquatic environments is called biofouling and such rafts also attract fish (Carlton et al., 2017; Goldstein et al., 2014). The effect of this interaction is dispersal, which affects biodiversity, especially if rafting organisms can establish themselves in new areas and outcompete the resident species (García-Gómez et al., 2021).

Dispersal of plastic fragments affects biodiversity if rafting organisms can establish themselves in new areas.

The remaining interaction records belong to the categories coverage or contact, entanglement and other types of interactions (Section 5.2.5).

The effects of microplastics on sediment-dwelling and epibenthic animals from soft-sediment environments was investigated in the Oslofjord, Norway: all of the analysed species of fish, bivalves, echinoderms, crustaceans and polychaetes had ingested microplastic (Bour et al., 2018). Microplastics smaller than 200 µm accounted for 58% of all microplastics found in the organisms, highlighting once again the underestimation of microplastic levels in studies, which rely on methods that can only detect larger particles. During experiments, microplastic ingestion by marine worms caused reduced feeding activity, prolonged gut residence of ingested microplastics, and inflammation (Wright et al., 2013).



Right: A new deep-sea species named for the plastic that contaminates it. © BBDO; Left: Computer tomography scan, showing a plastic fibre in the amphipod crustacean termed Eurythenes plasticus from the Mariana Trench. © Alan Jamieson

The common mussel

Species:	The common mussel or blue mussel (*Mytilus edulis*) is an edible clam from the Mytilidae family and widely consumed in Europe, both as wild and farmed mussels.
Distribution:	Intertidal areas attached to hard substrates, often in dense mussel beds along most European coasts; also introduced to the Pacific and southern hemisphere.
Food:	Mussels filter detritus and plankton but also perform an important ecosystem function by removing bacteria, metals and toxins from the water.
Conservation status:	Least concern.

Interaction with plastic pollution

As a common and widespread filter feeder of commercial importance, it comes as no surprise that the common mussel has become a 'model organism' for investigating the effects of microplastics in the field as well as in laboratory studies. Since mussels are consumed in whole, any contamination most likely leads to human consumption of microplastics. Ingestion of microplastics by blue mussels has been demonstrated throughout most of its natural and introduced range, e.g. Nova Scotia, Canada (Mathalon and Hill, 2014), China (Li et al., 2016; Qu et al., 2018), Belgium, Denmark, France, Germany, Netherlands and the UK (12 studies in LITTERBASE). The rates of plastic ingestion ranged widely from 0.2 to 7.6 microplastic particles per mussel from coastal sites off the North Sea, French Atlantic and Channel and the UK (Hermabessiere et al., 2019; Li et al., 2018b; Phuong et al., 2018; Scott et al., 2019; Van Cauwenberghe et al., 2015). Very high numbers of fibres and particles were reported from the Belgian coast and in three European 'hotspots' where mussels contained 0.4–8.1 fibres and 0.5–3.4 microplastics per 10 g tissue, respectively (De Witte et al., 2014; Vandermeersch et al., 2015).

A total of 43 studies investigated the interactions of plastic with the common mussel. The highest number of studies (38) dealt with plastic ingestion. In half of these studies, mussels were exposed to plastic particles in experiments. The other half examined the microplastic burden of mussels collected in the field. Common mussels also colonise plastic items (4 studies) as observed in Iceland, north Spain, the Baltic Sea and two German rivers (LITTERBASE).

Common mussels found entwined with dolly rope strands beached on the Belgian coast in 2013. © Melanie Bergmann/AWI

Oyster

Species: Oyster is the common name for several families of bivalve molluscs, which live in marine or brackish habitats. Most but not all oysters belong to the superfamily of the Ostreoidea. Wild and farmed oysters are consumed globally by people.

Distribution: Worldwide along coastlines except very cold waters. Because of their beneficial ecosystem functions, such as improving water quality, there are efforts around the world to restore oyster reefs.

Food: As filter feeders, oysters feed on detritus, plankton, bacteria and nutrients and can filter up to 5 L of water per hour. By removing vast amounts of nutrients from the water they perform important ecosystem functions, improving water quality and clarity and increasing biodiversity. Because oysters also remove heavy metals and toxic phytoplankton, eating large numbers of oysters can cause shellfish poisoning.

Conservation status: Least concern.

Interaction with plastic pollution

Oysters are commercially important filter feeders, which are consumed in whole. Therefore, microplastics can be passed on to humans. The Pacific oyster (*Magallana gigas*) is the most widely farmed and commercially important oyster in the world. Pacific oysters purchased on Taiwanese markets contained 1.1 microplastics per 10 g tissue (Chen et al., 2020).

Four oyster species farmed along the Chinese coast contained on average 3 microplastic particles per oyster, with 84% of individuals being contaminated (Teng et al., 2019). In the laboratory, Pacific oysters ingested microplastics but also released 84% of them within three days (Graham et al., 2019). During experiments, larvae also ingested micro- and nanoplastics readily, but no negative effect on their development was observed (Cole and Galloway, 2015). In another experiment, however, Pacific oysters exposed to 2 and 6-µm sized microplastics caused significant decreases in oocyte diameter, number of sperms and sperm velocity and slowed larval development (Sussarellu et al., 2016). Similarly, the ingestion of nanoplastics caused a significant decrease in fertilization success and lead to impaired development of oyster embryos and larvae (Tallec et al., 2018). Eastern oysters (*Crassostrea virginica*) from Florida contained on average 17 microplastics per individual (Waite et al., 2018) and micro- and nanoplastics accumulate inside their tissues, which could carry adsorbed toxins directly into cells (Gaspar et al., 2018). In a Chinese estuary, the microplastic burden on hooded oysters (*Saccostrea cucullata*) was 1.4–7.0 microplastic particles per oyster, and positively correlated with microplastic pollution in the water (Li et al., 2018a). An experiment using black-lip pearl oysters (*Pinctada margaritifera*) demonstrated negative effects on energy balance and reproduction (Gardon et al., 2018). In the laboratory, Sydney rock oysters (*Saccostrea glomerata*) ingested microplastics, which passed into the blood (Scanes et al., 2019).

Since oysters are sessile and ingest microplastics, they may be suitable monitoring species. In an experiment, European flat oysters (*Ostrea edulis*) and the associated community were subjected to regular doses of microplastics. As a result, the number of individuals and species in the communities decreased, indicating that chronic exposure to microplastics can alter benthic community structure.

The Norway lobster

Species: The Norway lobster or langoustine (*Nephrops norvegicus*) is a lobster-like crustacean 20 cm in size and the most important commercial crustacean in Europe, caught by trawl and creel (Bell et al., 2006).

Distribution: Northeast Atlantic Ocean, North Sea and parts of the Mediterranean Sea. It lives in burrows in muddy sediments.

Food: Predator, scavenger and suspension feeder, consuming fish, invertebrates and organic matter.

Conservation status: Least concern.

Interaction with plastic pollution

An early mention of the ingestion of nylon threads, probably from trawl gear, came from Norway lobsters caught in the Mediterranean in 1994–1995 (Cristo and Cartes, 1998). A later study showed that 83% contained microplastic, with an average abundance of 5.5 particles per individual (Cau et al., 2019). In Scottish waters, 29–83% of *Nephrops* contained plastics (Murray and Cowie, 2011; Welden and Cowie, 2016a).

To test the effects of contamination in the laboratory, *Nephrops* were fed microplastics over eight months. The result was a reduction in the feeding rate, body mass, metabolic rate and catabolism of stored lipids of the plastic-contaminated animals (Welden and Cowie, 2016b). It was suggested that moulting is the main route of microplastic loss by this species. In another experiment, no effect on the nutritional state of *Nephrops* was observed after they were fed with microplastics for only three weeks, but such a short time period does not exclude long-term effects (Devriese et al., 2017). The study also showed that there was a limited uptake of PCBs in *Nephrops* tail tissue after ingestion of PCB-loaded microplastics. Small *Nephrops* tails are not necessarily gutted, so that microplastic could be transferred to humans.

Six studies recorded ingestion of microplastic, one study reported entanglement and four studies recorded ingestion of plastic items (all cited above). The non-selective feeding strategy of *Nephrops* may render this species more susceptible to plastic ingestion (Cau et al., 2019).

Norway lobster inhabiting burrows in muddy grounds.
© IMAGO/McPHOTO/Bäsemann

The lugworm

Species: The lugworm (*Arenicola marina*) is a large marine worm (10–40 cm) of the phylum Annelida.

Distribution: Tidal flats of the northeast Atlantic, particularly abundant in the Wadden Sea.

Food: Living in U-shaped burrows in sandy sediments, lugworms swallow and filter up to 25 kg of sand a year and digest the organic matter. As an ecosystem engineer, the lugworm is a keystone species of tidal flats.

Conservation status: Least concern.

Interaction with plastic pollution

The lugworm is an ecosystem engineer because of the tremendous amounts of sand and organic matter that the millions of individuals digest and move within the tidal flat ecosystem. This is essential for oxygenating sediments, nutrient cycling and primary productivity. Along several North Sea sites, an average of 1.2 microplastics per lugworm was reported (Van Cauwenberghe et al., 2015). An experiment also showed that lugworm feeding activity moves microplastics into the sediments (Gebhardt and Forster, 2018). Microplastics added in realistic concentrations to the sediments, caused lower feeding activity, higher egestion time and immune cell activity, and up to 50% less available energy, affecting the survival of the organism (Wright et al., 2013). Increasing microplastic concentrations in sediments led to lower worm activity (Green et al., 2016). In another experiment, adsorbed pollutants or additives of microplastics leached into the lugworm's gut tissues, which led to lower feeding and survival rates.(Browne et al., 2013). Worms exposed to microplastics with PCBs accumulated more PCB in their tissues than worms exposed only to PCBs (Besseling et al., 2013), but microplastic ingestion contributes very little to the overall PCB bioaccumulation of worms (Besseling et al., 2017). However, it should be noted that these pollutants are transferred into food, sediment, and water by leaching from plastics, which may lead to a growing contamination of the environment (Section 5.3). In total, 11 studies recorded ingestion of microplastic by lug worms in an experiments (LITTERBASE).

Lugworm and its cast at Morecambe Bay. © IMAGO/Ardea

5.5 Impacts of plastic pollution on populations and endangered species

There are hundreds of studies reporting plastic ingestion across different taxa, but the identification of the impacts of plastic pollution on populations is a more complicated task for species that are affected by various marine threats. Therefore, only few studies attempted to assess population-level impacts of plastic pollution. A global review of air-breathing megafauna (see Glossary) highlighted that the population-level effects of plastic pollution are largely unknown (Senko et al., 2020). Most of these species are migratory, which complicates the assessment of a distinct man-made stressor, whether it be plastic or one of the many other kinds of pollution. Furthermore, some species, such as sea turtles, change their habitat or foraging strategy as they mature. Apart from obvious cases, for such entangled animals, that are either injured or have died, it is often difficult to identify the actual cause of death by necropsies. These methodological challenges complicate the analysis of population-level effects in marine species.

In this section, the studies on populations will be reviewed. Moreover, a number of studies reported the interaction rates among the examined organisms of distinct species groups, which can be used as an indicator for populations (Figure 16, 17). However, firm conclusions for global populations cannot be inferred based on the results obtained from a limited number of individuals (Provencher et al., 2017). Therefore, an approach of combining empirical data, modelling and simulations appears to be the best way to provide projections, estimations and risk assessments (Chapter 7) on the population level.

Out of 690 species which encountered marine debris (92% of individual encounters were with plastic debris, 8% with other material), 17% are listed in the IUCN Red List as near threatened or with a higher threat status (Gall and Thompson, 2015).

Galapagos fur seal (Arctocephalus galapagoensis) pups playing with plastic sheet, Galapagos. © naturepl.com/ Tui De Roy/WWF

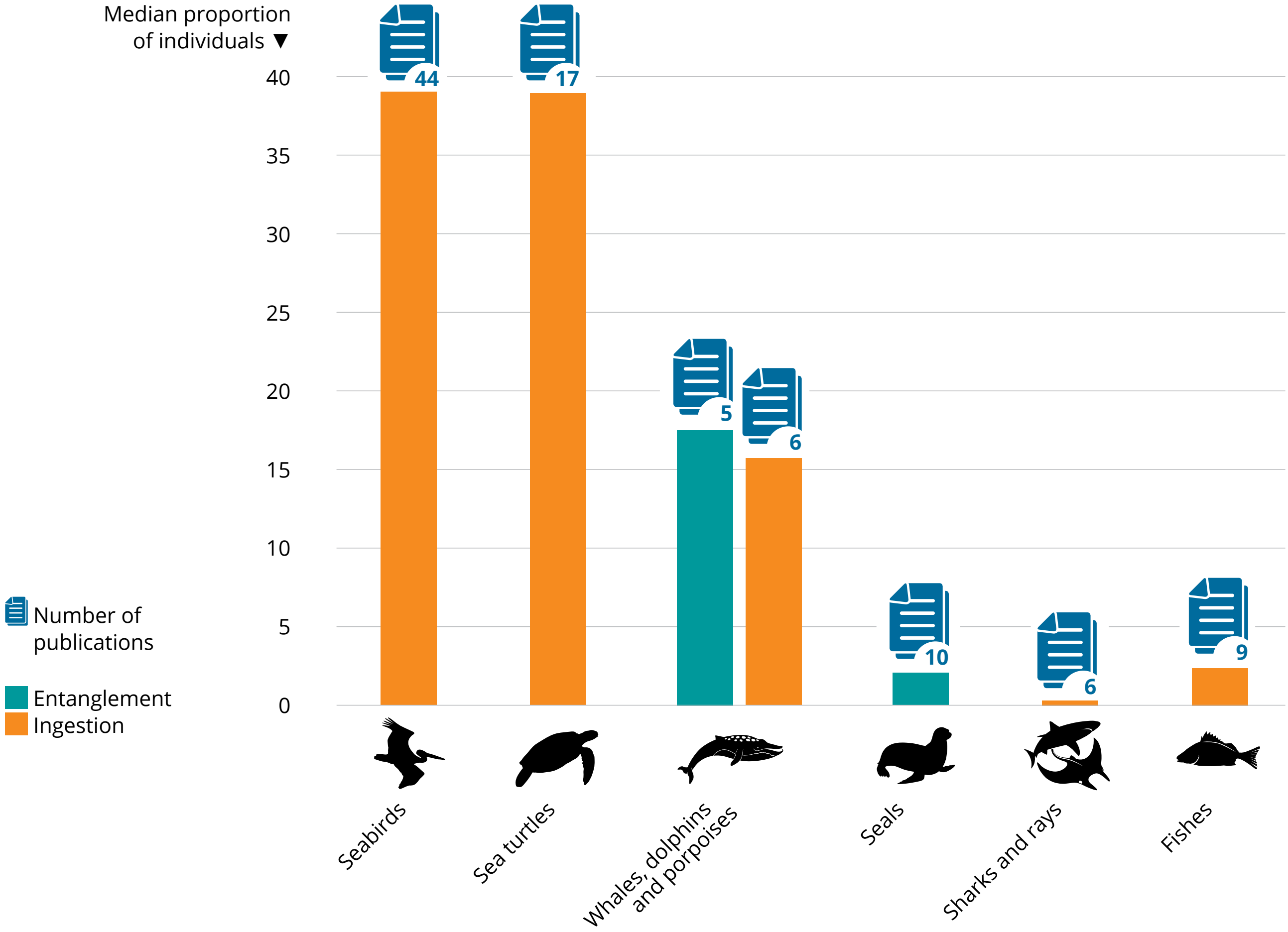


Figure 16: The median percentages for individuals that interacted with macroplastic debris, within the same taxa of examined organisms. The data were extracted from 105 studies on macroplastic entanglement and ingestion by charismatic megafauna (LITTERBASE). The blue thumbnails above the bars show the total number of studies from which data were analysed for this figure.

A spatial risk analysis for seabirds was carried out using the global distribution of plastic debris and adjusting the model with the actual rates of plastic ingestion (Wilcox et al., 2015). It concluded that, between 1962 and 2012, 59% of seabird species and 29% of seabird individuals had ingested plastic. If plastic pollution increases at the current rate, 99.8% of all seabird species (not necessarily individuals) could ingest plastics by 2050.

Our analysis shows that a median of 39% of all examined individuals of seabirds had ingested macroplastics, and a median of 33% had ingested microplastics. Unlike ingestion, entanglement with a median of 1% does not yet appear to be a threat to most seabirds. These findings concur with the conclusions of a recent global assessment (Rodríguez et al., 2019). However, spatial and temporal variations in plastic pollution are reflected in the proportion of negatively impacted seabirds and should be considered as a factor when assessing the population-level effects (Section 5.4.1).

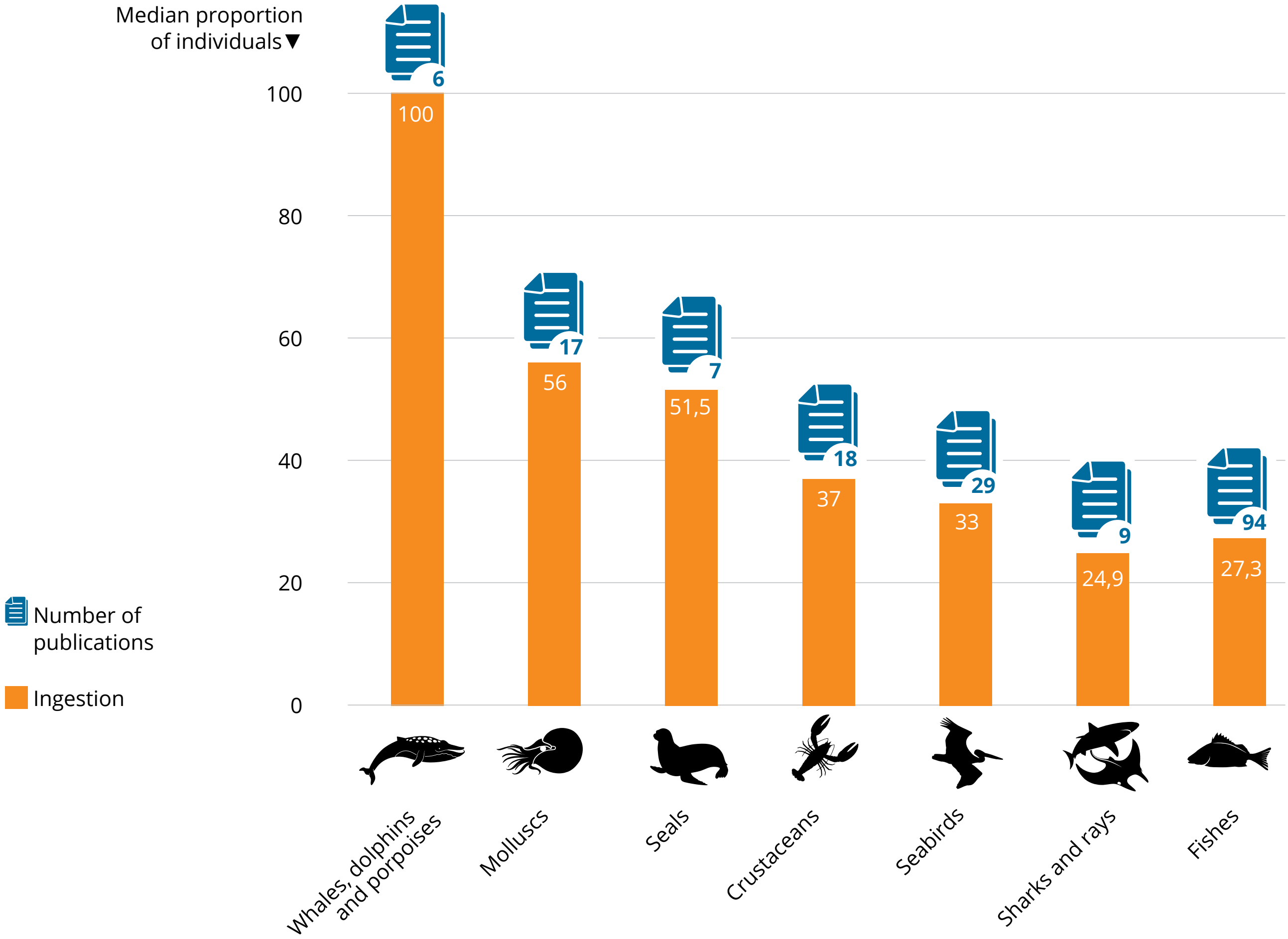


Figure 17: The median percentages for individuals that ingested microplastic debris, within the same taxa of examined organisms. The data were extracted from 180 studies on microplastic ingestion (LITTERBASE). The blue thumbnails above the bars show the total number of studies from which data were analysed for this figure.

An analysis of a global dataset of 50,000 birds, provides a list of under-researched species that may be vulnerable to plastic ingestion. Based on their ecology and knowledge of other threats, it was estimated that 90% of the global population of the critically endangered magenta petrel (*Pterodroma magentae*), endangered black-capped petrel (*Pterodroma hasitata*), endangered Newell's shearwater (*Puffinus newelli*), vulnerable Hawai'ian petrel (*Pterodroma sandwichensis*), decreasing little shearwater (*Puffinus assimilis*) and stable long-tailed jaeger (*Stercorarius longicaudus*) may already ingest plastic (Avery-Gomm, 2020).

A global analysis for sea turtles estimates that 52% (340,000 individuals) of all turtles, for which population estimates exist, have already ingested plastics (Schuyler et al., 2016). Predicted high-risk areas for sea turtle populations include the US east coasts, Australia, South Africa, the east Indian Ocean and Southeast Asia (Figure 18). In addition, both entanglement and plastic ingestion have been reported from around the world. Six out of seven sea turtle species are listed as endangered (Section 5.4.2). Among the thousands of sea turtles that strand every year, 6% were found entangled in marine debris, of which 91% were dead (Duncan et al., 2017). More than 100 experts from 43 countries rated entanglement and plastic ingestion as a greater risk to sea turtles than oil pollution, climate change or direct exploitation (Duncan et al., 2017). According to the 17 studies captured in LITTERBASE, the median incidence rate of macroplastic ingested by sea turtles was 39% (Figure 16). While population-level implications remain inconclusive, plastic pollution has been highlighted as a serious threat to sea turtles (Duncan et al., 2017).

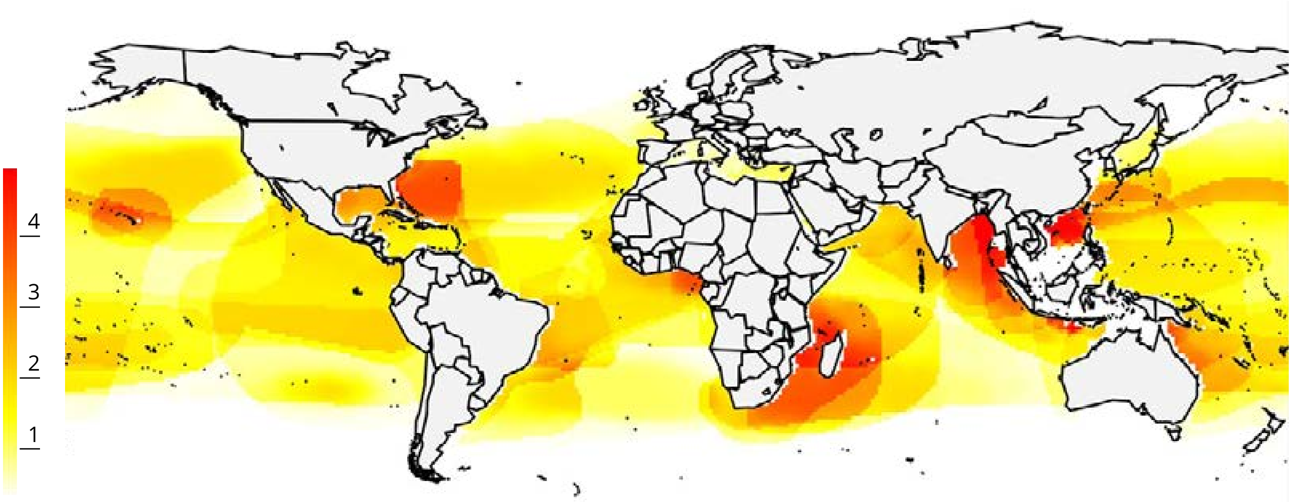


Figure 18: Predicted probability of debris ingestion risk for sea turtles. Red indicates geographic areas, which pose a higher cumulative likelihood of risk. This figure represents the sum total of the risk to all species within a given location. Red areas are particularly risky due to a combination of factors. They may have high debris loads, fall within the habitat distribution for several species, be home to particularly vulnerable species, or a combination of all of these (from Schuyler et al., 2016).

Individuals of whales, dolphins and porpoises have been subjected to both entanglement and ingestion of macroplastics, at a median rate of 18% and 16%, respectively (Figure 16). However, the population-level effects of these interactions are unknown except for estimates for some species in certain areas. For example, 60% of sperm whales in Greek waters had plastics in their stomach, which can impair digestion and be fatal (Alexiadou et al., 2019). The necropsies of whales stranded between 1990 and 2015 along Irish coasts revealed that 9% of whales had eaten plastic debris (Lusher et al., 2018).

A global review reported that 0.4% of pinniped individuals became entangled with plastic debris (Jepsen and de Bruyn, 2019). Scaling up to the known pinniped population of 23 million individuals (IUCN Red List data) results in 85,000 entangled individuals worldwide. Our analysis of data in LITTERBASE resulted in an even higher median percentage of 2%, which results in an estimated 460,000 entangled individuals. Although this figure may be considered minor in terms of populations, it may well pose a threat for endangered species. For example, the Mediterranean monk seal (*Monachus monachus*) is listed as endangered with a population of only 500–600 individuals (Karamanlidis and

Dendrinos, 2015), and the Hawai‘ian monk seal (*Neomonachus schauinslandi*) population comprises only 1,200 individuals (Littnan et al., 2015). For such small populations, even a few entanglements may impact their survival (Jepsen and de Bruyn, 2019). The populations of the vulnerable northern fur seal (*Callorhinus ursinus*) in the North Pacific are under a risk from plastic pollution, as this area is very polluted (Gelatt et al., 2015; Jepsen and de Bruyn, 2019).

A quarter of the 1,041 species of sharks, rays and chimaeras are threatened according to the IUCN Red List.

A quarter of the 1,041 species of sharks, rays and chimaeras are threatened according to the IUCN Red List. Overfishing poses the biggest threat, with large-bodied, shallow-water species at greatest risk (Dulvy et al., 2014). Population declines are strongest in the Indo-Pacific and Mediterranean areas. A review of 139 blue sharks from the Mediterranean reported that 25% of the examined animals ingested plastics and highlighted the importance of further research into the impacts of plastic pollution on its population (Bernardini et al., 2018). Another review pointed out the Pacific and Atlantic Ocean as those areas where the highest percentages of entanglements of sharks, skates, rays and chimaeras occur (Parton et al., 2019).

Our analysis of the available data for examined individuals of fishes (other than sharks and rays) showed a median of 2% for macroplastic (Figure 16) and 27% for microplastic ingestion (Figure 17). While only nine studies referred to macroplastic ingestion, 94 studies dealt with microplastic ingestion. A compiled dataset on 171,774 individuals of 555 species reported that the incidence of microplastic ingested by fish was 26% (Savoca et al., 2021) and mobile predatory species had the highest rates of ingestion.

In the Mediterranean, plastic particles were identified in the stomachs of 18% of the top predators, namely Atlantic bluefin tuna (*Thunnus thynnus*), Albacore tuna (*Thunnus alalonga*) and swordfish (*Xiphias gladius*) (Romeo et al., 2015). The highest percentage of plastic ingestion (31%) was observed for bluefin tuna, which is listed as endangered by the IUCN because of intense fishing pressure (Collette et al., 2011). As one of the top predators in the oceans and one of the most valuable commercial fish species, the ecotoxicological effects of plastic ingestion on its populations and repercussions of consumption by people merit further investigation.

Ecosystem outputs or 'ecosystem services' are often beneficial or even essential to human societies.

6. Effects of plastic pollution on marine ecosystems

6.1 Introduction

To really understand how ecological systems (= ecosystems) work, a solid understanding of what constitutes a 'system' is required. Systems, and especially complex systems such as our bodies or ecosystems, have several essential features.

1. Several functionally and structurally different components form an integrated whole by having interdependent functional and structural relationships. For example, the heart supplies the organs with blood, while the brain controls the heart pressure and heart rate, and so on; most of our bodies' organs cannot live without the contributions of the others. Likewise, a coral reef ecosystem cannot survive without the corals, fishes or invertebrates who all depend on each other for the survival of the whole.

2. Systems and system components have complex structures, which give them their varied functions. For example, we could put the water and all the elements of a living body into separate containers. The atoms would still be the same, but they would not be in the complex, structural arrangement, which allows the body to function. Similarly, a coral reef ecosystem has highly complex structures: first of all, all the organisms in it are complex, but the fractal structure of the ecosystem itself is important, too. For example, all the nooks, crannies, crevices, holes and tunnels of different size and shape within the coral skeleton allow different species to hide from predators, which explains why so many species can survive. In turn, this biological diversity (= biodiversity) gives the system its complexity and stability.

3. Systems and system components exhibit behaviours, which involve inputs, processing and outputs. A coral reef ecosystem has inputs in the form of energy and nutrients, constantly processes them by turning them into cells and organisms and creates outputs, such as cleaner water, oxygen, or reef structures.

These ecosystem processes are often called 'ecosystem functioning' (Loreau et al., 2002; Naeem et al., 2009; Schulze and Mooney, 1994). It reflects the collective life activities of all the life forms within the ecosystem, such as feeding, producing waste, moving, growing, reproducing (that is, all the natural processes that sustain an ecosystem) and the resulting effects on their environment. Ecosystem outputs are referred to as 'ecosystem services', which are often beneficial or even essential to human societies (Daily et al., 1997; Díaz et al., 2020; IPBES, 2020; Millennium Ecosystem Assessment, 2005). The ecosystem functions and services of coral reefs, for example, include (Barbier et al., 2011; Brandl et al., 2019; Woodhead et al., 2019): Providing food, medicines and aquarium fishes for fishing communities and all of humanity. Corals have been used to treat cancer, ulcers, HIV and cardiovascular diseases (Chivian and Bernstein, 2008). Further functions are water purification; carbon sequestration, which dampens climate change; structure for coastal protection against waves, storms, floods and erosion; biodiversity and complexity of the system itself.

Plastic pollution is an additional and increasing stressor to already stressed ecosystems.

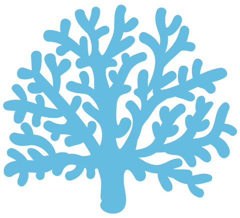
When it comes to plastic pollution, the question remains how (and how much) plastic pollution interferes with the functioning of the affected ecosystems and the services they provide to people. The accumulated evidence in this report and many other publications clearly shows that plastic pollution is an additional and increasing stressor to already stressed ecosystems (Lartaud et al., 2020). However, it is very difficult to quantify by how much ecosystem functions are impaired.

The first challenge is to agree on what an ecosystem function is and then how to quantify the scale and extent of an ecosystem (Brussard et al., 1998). For example, both the whole earth and a mudflat can be considered an ecosystem. The second challenge is to be able to finance and organize large-scale long-term studies of ecosystems that are also influenced by other factors, which need to be considered. These challenges are not insurmountable, as ecologists have also studied the large-scale influences of habitat loss, climate change, or chemical pollution on ecosystem functions and services (Bonin et al., 2011; Freedman, 2013; Pratchett et al., 2011).

However, only about 5% of the examined studies explicitly extrapolated their findings of plastic intake on individual species to the impact on ecosystem functioning. More importantly, even studies, which claim to have studied the effects of plastic pollution on ecosystem functioning often only deduce ecosystem effects from either laboratory studies or from effects on a single or a few species. The few studies, which investigated effects in natural ecosystems were all conducted at small scales (e.g. the size of a plastic bag or a plot of a few metres) so that ecosystem effects are inferred from small parts of the ecosystem.

Systems, especially complex systems, have great in-built resilience to deal with harmful events such as oil spills or freak weather events and repair themselves over time. However, if pushed too far, too often or too quickly, a system will either be completely destroyed or enter a new state. This new state is often a simplified system with fewer species, lower biodiversity and crucially, lower productivity and stability (Jackson, 2008; Pal and Bhattacharyya, 2017; Worm et al., 2006; Yadav et al., 2018). Such a decrease in productive ecosystem services means lower economic gains and fewer societal benefits.

Unfortunately, the multiple stressors affecting marine ecosystems nowadays, which increasingly include the harmful effects of plastic pollution do not bode well for the future as marine life is already greatly diminished (Damalas et al., 2015; Jackson, 2008; Luypaert et al., 2020; McClenachan et al., 2012; Pacoureau et al., 2021; Rosenberg et al., 2005; Thurstan et al., 2010; Zeller et al., 2006). This chapter focuses on four marine ecosystems and how plastic pollution affects their functioning and services. As with the effects of plastic pollution on individuals and species, the effects on entire ecosystems vary greatly depending on the type of ecosystem, its species, location, properties of the pollutant (size range, type, associated chemicals) and the amount and duration of the exposure.



6.2 Coral reefs

A coral reef is a marine ecosystem characterized by reef-building corals. While tropical coral reefs are located in the tropics (see Glossary), cold-water coral reefs can also occur outside of the tropics. Coral reefs cover less than 1% of the ocean floor (Spalding and Grenfell, 1997), but are one of the most productive and diverse ecosystems on Earth. Since some 25% of all known marine species live in coral reefs (700 coral and 4,000 fish species) (Plaisance et al., 2011), they are considered the "rainforests of the sea" (Reaka-Kudla, 1997).

A coral reef is formed when colonies of coral polyps extract calcium carbonate from the water to build a hard exoskeleton and grow to a substantial size. They grow on the skeletons of their dead ancestors over decades and millennia. Some corals depend on symbiotic unicellular algae or zooxanthellae to provide energy via photosynthesis. Others catch small marine life with their sticky tentacles. Cold-water corals, extend to deeper and darker parts of the oceans, with temperatures as cold as 4°C. Therefore, their growth is slower, so that some corals may be hundreds of millions of years old (Lumsden et al., 2007; Williams et al., 2006).

Coral reefs face many stressors besides plastic pollution.

Coral reefs face many stressors besides plastic pollution (Lartaud et al., 2020): climate change causing heat stress and acidifying waters making it harder to build their skeletons (Mollica et al., 2018); rising sea levels, more frequent and severe storms (Hughes et al., 2017); increasing pollution with sediments, fertilizers, oil and toxic chemicals (Jones et al., 2016; Silbiger et al., 2018; van Dam et al., 2011; Zaneveld et al., 2016); overfishing, including destructive methods (Fox, 2004; MacNeil et al., 2020; Madeira and Calado, 2019; Zaneveld et al., 2016); damage from tourism (Al-Jufaili et al., 1999; Lamb et al., 2014; Saphier and Hoffmann, 2005) and habitat loss (Jackson, 2008). Tropical corals will likely disappear within a few decades unless drastic action is taken (Hoegh-Guldberg et al., 2007; Jackson, 2008). Although currently less impacted than tropical reefs, cold-water corals have been particularly affected by bottom trawling, the hydrocarbon industry, overharvesting for jewellery (Roberts and Cairns, 2014) and climate change (Roberts and Cairns, 2014).

Macroplastics

Macroplastic debris gets easily caught in the spiky three-dimensional structure of the reefs and can smother large parts of coral colonies (Lartaud et al., 2020). While some reefs are already smothered with macroplastic (Lamb et al., 2018), others are still relatively pristine. One third of the investigated 159 coral reefs in the Asia-Pacific region were polluted with macroplastics (Lamb et al., 2018): in 2010, 11.1 billion plastic items were entangled in these reefs, a figure that will likely rise to 40% by 2025. Entangled corals were 20 to 89 times more likely to contract disease. Although the exact mechanism is unknown, tissue abrasion and injury likely promote disease (Lamb et al., 2015), especially if plastic carries pathogens. Plastic waste could also harm the coral's immune system and wound healing process (Mydlarz et al., 2006). Shading effects and oxygen deficient conditions due to smothering could also favour disease (Lamb et al., 2018).

Plastic net covering a faviid coral (location: Mayotte, Indian Ocean, date: 24.09.2018). © BIORECIF – Thierry Mulochau

Typical pollution in Red Sea coral reefs (location: Eilat, Gulf of Aqaba, Israel, date: 20.06.2020; water depth: 5 m). © Guilhem Banc-Prandi/WeSea

Macroplastic has infiltrated coral reefs of all oceans. In the Mediterranean, lost fishing gear was found at densities of 3 items/100 m^2 (Consoli et al., 2019). A third of this litter affected corals of conservation concern. Coral reefs in Jordany even had litter densities as high as 280–304 items/100 m^2. Plastic and fishing gear dominated at 31–42% (Abu-Hilal and Al-Najjar, 2009; Al-Najjar and Al-Shiyab, 2011), some of which were entangled in corals, and continued to catch fish. Lost fishing gear may remain on a reef and cause damage for decades. Ghost-fishing nets had killed crustaceans, fishes, turtles, cetaceans and other marine wildlife, with one net still catching fish seven years after its abandonment (Al-Jufaili et al., 1999).

Sugiyanta of WWF Indonesia Fisheries programme takes off a trash rice sack choking a plate coral. Wanci underwater, Wakatobi, South Sulawesi, Indonesia. Date: 09.11.2009. © Jürgen Freund/WWF

In the Gulf of Mannar, marine litter caused tissue abrasion and mortality of sessile invertebrates such as corals, sponges and the colonial zoanthid (see Glossary) *Palythoa* (Ganesapandian et al., 2011). An underwater survey of 21 coral islands found that lost fishing nets were the dominant debris, covering live corals (39%) (Patterson Edward et al., 2020). While half of these were fragmented, one-third had tissue loss and only 18% looked intact. In coral reefs in Mayotte, southwestern Indian Ocean, half of sites that were polluted primarily with plastic fishing lines contained broken or abraded corals, especially branch or table corals such as *Acropora* (Mulochau et al., 2020).

Already in 1998 in a popular cast fishing site in Hawai'i, 65% of coral colonies had monofilament fishing lines, and 80% of the colonies were entirely or partially dead (Yoshikawa and Asoh, 2004). The percentage of entanglement was positively correlated with the percentage of partially or entirely dead colonies. In other Hawai'ian coral reefs, lost ghost-fishing gear killed endangered monk seals (*Monachus schauinslandi*), corals and other wildlife, and thus posed a persistent threat (Donohue et al., 2001). It was shown that cleaned areas accumulate new debris, mostly derelict fishing gear at a rate of 0.6 metric tons/km^2 per year (Dameron et al., 2007).

At two coral reefs in Ecuador, coral damage caused by intermediate pollution levels was negatively correlated with structural reef complexity and diminished the abundance of various reef species, including fish, affecting ecosystem functions and services such as food provision (Figueroa-Pico et al., 2016). A synthesis of the available knowledge on interactions between marine litter and reef organisms and how this affects ecosystem functions and services highlighted that 418 reef species and more than 36,389 individuals interact with derelict fishing gear, mostly through entanglement and ghost fishing, which affects hard corals and reef fish hardest (de Carvalho-Souza et al., 2018).

Biogenic reefs are small reefs created by coral, bivalves, tubeworms and other species, which bind dead and living matter together to build reefs. They play a key role in benthic ecosystems, enhancing biodiversity and ecosystem functioning from shallow to deeper waters (Buhl-Mortensen et al., 2010). Biogenic reefs create elevation above the seabed and structural complexity with small crevices that provide an important habitat for other species. A review on the impact of marine debris on Mediterranean reefs (Angiolillo and Fortibuoni, 2020) showed

Left: A fishing net smothering a coral reef (Los Ureles, Jaramijo, Manabi, Ecuador, 2019). © Juan Figueroa Pico
Right: A starfish (Phataria unifascialis) in contact with a net covering a coral reef (Los Ureles, Jaramijo, Manabi, Ecuador, 2019). © Antonio Santos Medranda

A coral (Acropora) broken because of a fishing net (location: ringing reef near Hainan Island, date: 22.09.2019). © *Zhi Zhou*

that many species were impacted by marine litter, including endangered species such as corals, gorgonians and sponges. Entanglement of lost fishing gear in corals and sponges was the most frequently reported impact resulting in breakage, injury and disease. Ghost fishing of 15 species of arthropods, fish and one mollusc species was also reported.

Microplastic can affect the health of corals in many ways.

Microplastics

Microplastics are directly captured by the corals' tentacles or ingested indirectly when corals consume plastic-polluted zooplankton and can then be transferred to the polyp tissues where they potentially disturb physiological functions (Lartaud et al., 2020). The odour of particles could drive the consumption of microplastics (Allen et al., 2017). Corals in the Great Barrier Reef, Australia, ingested microplastics, some probably originating from ship paint and fishing floats (Hall et al., 2015), which could affect coral health. Likewise, corals and other species from the South China Sea accumulated microplastics in their bodies, which caused cell death. This can affect the corals and their symbiotic algae and thus the community structure (Tang et al., 2021). In laboratory studies, microplastic exposure inhibited coral feeding efficiency (Savinelli et al., 2020) and growth (Hankins et al., 2021), and activated a stony coral's stress response (Tang et al., 2018). Laboratory exposure of staghorn coral (*Acropora formosa*) caused the release of symbiotic algae, bleaching and necrosis (Syakti et al., 2019). Microplastics also disturbed the relationship between symbiotic algae and two of their anthozoan and coral host species as they occupied the spaces of the symbiotic algae, especially in corals already bleached due to rising temperatures (Okubo et al., 2018; 2020). Microplastic exposure of symbiotic algae (*Cladocopium goreaui*) suppressed nutrient uptake, photosynthesis and increased cell death leading to a decreased density and size of the algal cells (Su et al., 2020). Lower photosynthetic rates were also observed in a hood coral (*Stylophora pistillata*) (Lanctôt et al., 2020). What is more, anemones bleached due to global warming seem less capable of microplastic removal (de Orte et al., 2019).

Another type of interaction is particle adherence to corals. The extensive reefs of the Red Sea were shown to be a major sink for microplastics, as some microplastics were removed by the feeding actions of the corals, but forty times more were removed by sticking to the outsides of the corals' bodies (Martin et al., 2019b). In experiments, mushroom (*Danafungia scruposa*) and zonanthid corals (*Zoanthus sociatus*) also removed microplastics from the water through passive adhesion (Corona et al., 2020; Rocha et al., 2020). This altered the coral's physiology, which could, in the long term, lower its energy reserves (Rocha et al., 2020). Microplastic also entered the body of button polyps (*Protopalythoa* sp.), where it had toxic effects on cells (Jiang et al., 2020). Some species of corals that were exposed to realistic levels of microplastic for six months showed signs of compromised health, likely due to increased energy demands (Reichert et al., 2019). In another experiment, corals experienced bleaching and tissue necrosis, with up to 40% of corals affected (Reichert et al., 2018). Some species responded with cleaning via mucus production and others by overgrowing particles, which imposes additional energetic cost and could lower survival and reproduction.

If corals accumulate microplastics, this pollution could be transferred to animals of the associated ecosystem, but this has only been investigated in a few studies on reef fish from Saudi Arabia's Red Sea coast (Baalkhuyur et al., 2018), the South China Sea (Ding et al., 2019; Nie et al., 2019), French Polynesia (Garnier et al., 2019) and the Great Barrier Reef (Jensen et al., 2019). While microplastic ingestion was high in some cases, it is unclear if this was an effect of the coral sink or due to locally high pollution levels.

Close-up of the reef-building cauliflower coral Pocillopora damicornis. After experimental microplastic exposure for four weeks, necrosis and bleaching (white areas) were observed in some of the corals, which might be caused by toxic substances or pathogens that can adhere to the surface of the microplastics (location: Justus Liebig University Gießen, Germany, date: 01.08.2015) (Reichert et al., 2018). © Jessica Reichert

The planktivorous fish *Acanthochromis polyacanthus* is widespread in Indo-Pacific coral reefs (Critchell and Hoogenboom, 2018). Exposure experiments showed that these fish ingested many more particles, when offered small rather than larger sizes of microplastic (125–300 versus 2 mm), although these were in range with their natural prey. Both the growth and body condition of fish suffered. This suggests that, with time, microplastics could become a more and more pressing issue when legacy plastic continuously breaks down to sufficiently small sizes.

Left: Bleached sea anemone (Aiptasia pallida) after ingesting plastic microfibers in the laboratory. The fluorescent orange items are the microfibers inside the anemone (de Orte et al., 2019). © Manoela Romanó de Orte; Right: The reef-building hood coral Stylophora pistillata ingests black polyethylene microplastic particles. After minutes to hours, the indigestible material is egested again (location: Justus Liebig University Gießen, Germany, date: 17.05.2018). © Jessica Reichert

Leached chemicals

In a remote coral reef atoll of the Maldives, widespread contamination with microplastics was shown along with appreciable levels of phthalate esters in corals (Saliu et al., 2019). More than 95% of the examined coral species contained phthalate esters (Montano et al., 2020). Although hood corals (*Stylophora pistillata*) exposed over five days to flame retardants bioaccumulated these pollutants it showed no negative effects except consistent polyp retraction (Aminot et al., 2020).

Chemical pollution could push coral species and ecosystem health over critical thresholds in the long run.

Impacts on foundation species of reefs such as coral and sponges or important fish predators that control population dynamics of prey species, will inevitably affect ecosystem function and services although the current scale is unclear. It is clear, however, that increasing pollution levels will exacerbate the threat. Added to stressors such as climate change and overfishing, this could push species and ecosystem health over critical thresholds in the long run. This will affect biodiversity, ecosystem functions and services such as provision of fish stocks.

6.3 Seagrasses

Seagrasses are flowering marine plants, which form extensive underwater meadows down to 60 m and constitute a unique, productive and highly diverse ecosystem found on all continents but Antarctica (Boström et al., 2006). They form a critical habitat for endangered dugongs, manatees and sea turtles (Orth et al., 2006), and provide various ecosystem services: disease control, fertilizer and food production, carbon sequestration, coastal protection, nutrient cycling, sediment production, water purification and recreation (Barbier et al., 2011; Himes-Cornell et al., 2018; Luisetti et al., 2013; Mtwana Nordlund et al., 2016; Ondiviela et al., 2014; Ruiz-Frau et al., 2017). Together with coral reefs and mangroves, they are one of the most productive coastal habitats (Short and Wylie-Echeverria, 1996). Seagrass ecosystems face a combination of stressors besides plastic pollution (Ceccherelli et al., 2018; Griffiths et al., 2020; Unsworth et al., 2015): worsening water quality due to runoff of sediments, nutrients, changing salinity and toxic chemicals (Orth et al., 2006); climate change (Jordà et al., 2012; Nowicki et al., 2017; Orth et al., 2006); invasive species, disease and physical disturbance due to dredging and boating (Unsworth et al., 2015), and habitat loss (Jackson, 2008; Short and Wyllie-Echeverria, 2000; Waycott et al., 2009) due to coastal development. Maintaining seagrass ecosystems requires drastic changes in human activities and widespread conservation measures (Bonanno and Orlando-Bonaca, 2020; Cullen-Unsworth and Unsworth, 2018; Orth et al., 2006; Tan et al., 2020; Unsworth et al., 2019).

Shallow water seagrass Mataking Island, Semporna, Sabah. © Mazidi Abd Ghani/WWF-Malaysia

Seagrass habitats may become an important sink for plastic debris.

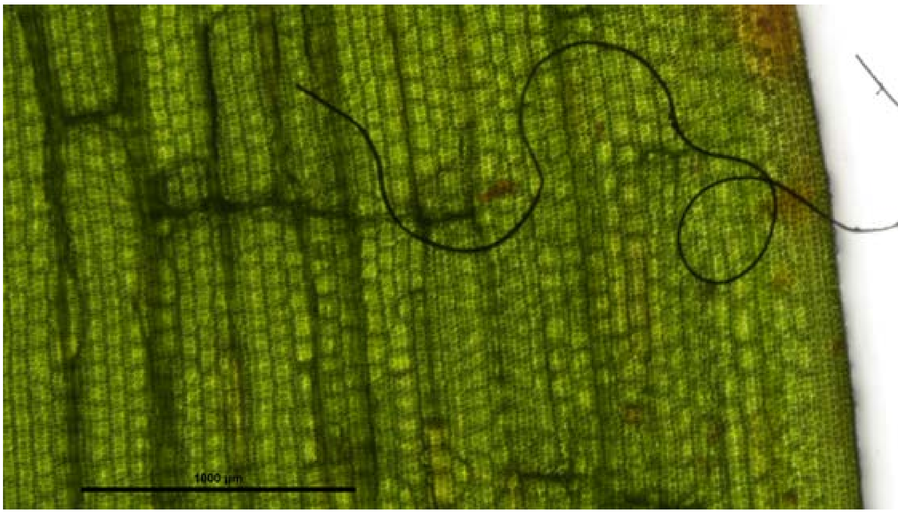
Macroplastics

In the Gulf of Mannar between India and Sri Lanka, marine litter negatively affected seagrass ecosystems (Ganesapandian et al., 2011). In a Philippine seagrass area, which is an important feeding ground of dugongs (*Dugong dugon*), the mean litter density was 6 items/100 m^2, with plastics accounting for 95% (Abreo et al., 2018). A study of seagrass habitats in Portugal showed that macro- and microplastics were trapped in the canopies and sediments of these habitats to varying degrees depending on plastic size, habitat and tidal position (Cozzolino et al., 2020). Seagrass habitats may thus become an important sink for plastic debris that may leak to nearby beaches. The Mediterranean seagrass *Posidonia oceanica* forms extensive meadows but loses its leaves in autumn, which wash ashore as loose deposits or ball-shaped agglomerates. Half of the investigated loose deposit and 17% of the agglomerate samples contained plastic items (Sanchez-Vidal et al., 2021). A mesocosm experiment, which placed plastic bags on the Mediterranean seagrass *Cymodocea nodosa* for six months showed that the bags lowered the pH and oxygen content of sediments and altered plant growth (Balestri et al., 2017).

A typical example of a seaball with entangled plastic (location: Mallorca beach, Balearic Islands, 2019) (Sanchez-Vidal et al., 2021). © Anna Sànchez Vidal/ Barcelona University

Microplastics

Several studies have demonstrated that seagrass meadows trap microplastics and could thus become a sink for microplastics. Near an urban centre of Belize, microplastics were found on 75% of all blades of the turtle grass *Thalassia testudinum*, with 81% of microplastics being fibres (Goss et al., 2018). Microplastics were also detected on 55–63% of the surfaces of intertidal seagrasses growing around Singapore, with one microplastic item per seagrass blade (Seng et al., 2020). Seagrass meadows (*Enhalus acodoides*) in Hainan, China harboured 80–885 particles per kg of dry sediment, with fibres being the dominant shape (Huang et al., 2020). Sediments with seagrass growing on them had 2.5 times more microplastics than bare sites indicating a trapping effect.



A plastic microfibre stuck on a blade of seagrass Thalassia hemprichii (location: Tanah Merah, Singapore, date: September 2018) (Seng et al., 2020). © Nicholas Seng, Muhammad Faiq Saleh and Clement Cheng

In a common eelgrass species *Zostera marina* bed in Orkney, Scotland, microplastics were found in 94% of samples of seawater, sediments and on eelgrass blades, as well as on the associated biota of sediments and blades (Jones et al., 2020). Again, seagrass sediments (113,000 microplastics/m^3) trapped more microplastics than sandy sediments without vegetation (68,000 microplastics/m^3). Results from an experimental study corroborated this trapping effect and showed that the probability of retention increased with plastic and canopy density and decreased with the water velocity (Carmen et al., 2021).

Since microplastics are found on the vegetation and within the invertebrates living on it, any herbivores or predators feeding on them likely also ingest microplastics as shown for seaweed (Gutow et al., 2016). Thus, microplastics enter marine food webs. An analysis of the invertebrate community inhabiting the seagrass *Posidonia oceanica* near Corsica showed that 27% of the invertebrates contained viscose fibres (see Glossary) (Remy et al., 2015). Microplastics were also found in samples of seawater, sediments, fishes and benthos collected in several seagrass ecosystems in South Sulawesi, Indonesia (Tahir et al., 2019; 2020).

Leached chemicals

Examining the sediments of seagrass ecosystems in the Saudi Arabian Red Sea, various metals and PAHs were detected, but concentrations of both contaminant groups were low (Ruiz-Compean et al., 2017). Laboratory studies showed that environmentally relevant concentrations of BPA impact the photosynthetic activity and thus the growth of the seagrass *Cymodocea nodosa* (Adamakis et al., 2018; 2021; Malea et al., 2020).

Plastic pollution contributes to other threats, causing a global decline of seagrasses.

While the available evidence shows clearly that seagrass habitats accumulate plastic debris, and that this pollution infiltrates the associated food web, the scale of the resulting effects for ecosystems is unclear. Although the extent is unknown plastic pollution likely contributes to the litany of threats, causing a global decline of seagrasses of 110 km^2/yr since 1980 (Waycott et al., 2009).

6.4 Mangroves

Mangrove forests consist of specialized salt-tolerant shrubs and trees, which tolerate brackish or saline water and inhabit the coastal intertidal zone of the tropics and subtropics. There are 2,000 mangrove forests that cover approximately 138,000 km² in 118 countries on all continents except Antarctica (Giri et al., 2011).

Rubbish littering the ground in a dead mangrove forest, Vanua Levu, Fiji. © Brent Stirton/Getty Images

Mangrove ecosystem services include coastal protection (e.g. against storm surges and tsunamis), food and wood production, carbon sequestration, nutrient cycling, water purification, and recreation (Alongi, 2002; 2012; Barbier et al., 2011; Brander et al., 2012; Dahdouh-Guebas et al., 2005; Danielsen et al., 2005; Friess et al., 2020; Hamilton and Friess, 2018; Himes-Cornell et al., 2018; Hochard et al., 2019; Sievers et al., 2019).

Mangroves face a combination of stressors (Turschwell et al., 2020) besides plastic pollution: Habitat loss and fragmentation is probably the most important one as up to 35% of all mangroves have already been destroyed by deforestation and sea-level rise (Alongi, 2002; Bryan-Brown et al., 2020; Friess et al., 2019; Valiela et al., 2001; Worthington et al., 2020). Climate change induced increased storm frequency and severity are additional stressors and are on the rise, causing erosion and land subsidence (Alongi, 2002; Gilman et al., 2008; Lovelock et al., 2015; Sippo et al., 2018). Further threats include altered hydrological regimes, eutrophication, pollution, exotic species and the overharvesting of wood (Alongi, 2002; Biswas et al., 2018). Drastic changes in human activities and widespread conservation measures are needed to maintain mangrove ecosystems (Friess et al., 2019; Romañach et al., 2018; Turschwell et al., 2020).

Macroplastics

Mangrove habitats are particularly prone to plastic pollution.

As rivers form a major pathway of land-based plastic to the ocean, ecosystems of river mouths can be exposed to high volumes of plastic debris. Since 54% of mangrove habitats are located within 20 km of a river mouth, they are particularly prone to plastic pollution (Harris et al., 2021). Mangroves are considered traps for marine debris because the complex aerial root systems can intercept and entrap marine debris (Luo et al., 2021).

Indeed, by the 2000s, macroplastic debris was already widespread on a Red Sea island with mangrove forests (Saleh, 2007). In the 2010s, mangrove forests along the Red Sea and Arabian Gulf had a litter density of 66 items/100 m^2, of which more than 90% was plastic (Martin et al., 2019a). Nearby beaches had lower debris densities and denser mangroves trapped more debris highlighting that mangroves are a significant sink of marine debris. Plastic was also recorded in mangroves near Mumbai, India (Singare, 2012) where it was captured in the root structures of mangrove trees, causing obstruction to water flows which, in turn, can alter feeding sites of animals (Kantharajan et al., 2018). Very high macrodebris densities (215–7,312 items/100 m^2) were reported from urban and near-urban mangrove forests of the Malaysia island of Penang, 93% was made up of plastics (Yin et al., 2020). In Indonesian mangrove forests, macrodebris density even ranged from 2,000–53,300 items/100 m^2, the vast majority being plastic (van Bijsterveldt et al., 2021; Suyadi and Manullang, 2020; Hastuti et al., 2014). Denser mangrove trees *Avicennia marina* entrapped more macrodebris (Hastuti et al., 2014). In Papua New Guinea, the mean debris load, mostly plastic, ranged from 120–7,830 items/100 m^2 at mangrove-dominated sites, compared with 1,200 and 11,800 items/100 m^2 at beach and open-shore areas (Smith, 2012). However, compared to other habitats it is not always the case that

Example of macroplastic items caught in the roots and branches of mangrove forests (location: Sahiat (close to Dammam), Saudi Arabia, date: 03.04.2017) (Martin et al., 2019a). © *Cecilia Martin* there are higher levels of plastic debris in mangroves. The abundance of marine litter in Jakarta Bay, Indonesia, was higher at sandy beaches and beach forests than in mangrove forests (Ivonie et al., 2021), which could reflect different input and accumulation rates of debris. Intermediate densities of marine debris were reported from mangrove forests in Colombia (Garcés-Ordóñez et al., 2021; Riascos et al., 2019) and a Brazilian estuary (Cordeiro and Costa, 2010).

The density of plastic debris negatively correlated with mangrove health (Suyadi and Manullang, 2020). On Java, mangrove trees suffered significant leaf loss and increased mortality as plastic pollution approached 100% coverage of the forest floor (van Bijsterveldt et al., 2021).

Example of macroplastic items caught in the roots and branches of mangrove forests (location: Mati, Davao Oriental, Mindanao, Philippines, date: December 2017) (Abreo et al., 2020). © Neil Angelo S. Abreo

In terms of impacts, smothering and entanglement of tree seedlings with marine debris can hamper the survival and rehabilitation of mangrove forests (Gorman and Turra, 2016; Smith, 2012). So far, few effects on animals inhabiting mangroves have been documented. In an Indian mangrove forest, the noise that plastic bags produce during strong winds scare off water birds temporarily or permanently (Sandilyan and Kathiresan, 2012). In Panama, an increase in the percentage of mangrove surface covered by garbage was significantly correlated with a decrease in active crab holes (Bulow and Ferdinand, 2013).

Microplastics

A study in Colombia reported microplastic levels between 31–2,863 items/kg of forest soil with highest levels found closer to sources near urban centres (Garcés-Ordóñez et al., 2019). It was said to affect the environmental quality of the lagoon. Sediments from mangroves in Singapore and Iran contained lower concentrations (mean of 37 and 27 microplastics/kg of dry sediment, respectively)(Naji et al., 2019; Nor and Obbard, 2014). The latter receives insufficiently treated discharges from the surrounding cities, thus sewage discharges were suggested as the main source of the fibres. In a Brazilian estuary, mangrove creeks harboured 5–26 microplastics/100 m^3 (Lima et al., 2015a; 2015b). Microplastics were also consumed by three resident species of catfish (17–33% of the fish; 1–10 microplastics per fish) (Possatto et al., 2011). In the same estuary, 64% of all individuals of the commercially important Acoupa weakfish (*Cynoscion acoupa*), had ingested microplastics, 97% of which were plastic fibres (Ferreira et al., 2016).

While the available evidence suggests that mangroves accumulate plastic debris, little is known about the extent of effects both on mangroves and the species of this vanishing ecosystem.

6.5 Deep-sea benthic ecosystems

The deep sea has been defined as regions deeper than the continental shelf break at 200 m depth and is Earth's largest habitat by area supporting very diverse ecosystems (Gage and Tyler, 1991). Much of it remains unexplored because of technological challenges. Although these ecosystems are by and large out of reach of direct human influence, chemical and plastic pollution could be important stressors besides impacts from climate change, deep-sea fishing, mining and the hydrocarbon industry, invasive species and noise pollution (Paulus, 2021; Ramirez-Llodra et al., 2011; Roberts and Cairns, 2014).

One of the foremost ecosystem services pertains to the long-term storage of carbon fixed in the upper waters and exported to depth through the biological pump thus buffering climate change (Thurber et al., 2014). The deep sea also provides nutrients for production processes in the upper ocean including fisheries and supports a wealth of resources such as fish stocks, energy reserves, rare elements and a high biodiversity endowing substances of pharmaceutical interest (Ramirez-Llodra et al., 2011; Thurber et al., 2014).

Plastic debris does not move or degrade on the deep seafloor.

Macroplastics

It has been suggested that the deep seafloor constitutes a sink for marine litter (Galgani et al., 2015; Kaandorp et al., 2020; Tekman et al., 2017) since 50% of the plastic from municipal waste is heavier than seawater and sinks directly to the seafloor (Engler, 2012). If not intercepted by land the remainder also descends to the seafloor in the long run, due to ocean currents, material degradation and ballasting processes (van Sebille et al., 2020). In the absence of strong currents and sunlight, plastic debris does not move or degrade much as indicated by 30-year old plastic recovered from the Sea of Japan without any sign of deterioration (Kuroda et al., 2020). Debris on the seafloor has thus been observed in most surveys, including the oceans' deepest point, the Mariana Trench (Chiba et al. 2018), various regions across Europe (Pham et al., 2014), the Atlantic and Indian Oceans (Woodall et al., 2014), Arctic seafloor (Bergmann and Klages, 2012), Nordic Seas (Buhl-Mortensen et al., 2017), South China Sea (Peng et al., 2019; Song et al., 2021), off Japan (Kuroda et al., 2020), central and western Pacific Ocean (Amon et al., 2020), Dutch Caribbean (Debrot et al., 2013), off California (Schlining et al., 2013; Watters et al., 2010) and the Kuril-Kamchatka trench in the northwest Pacific (Fischer et al., 2015). The amounts of marine litter on the seafloor vary greatly and plastic accounts for 62% of the debris reported from the seafloor globally (Canals et al., 2021). Particularly high concentrations were recorded from the Xisha Trough in the South China Sea (Peng et al., 2019), as well as from the Mediterranean and the Arctic Ocean, where quantities have increased over time (Parga Martínez et al., 2020; Pierdomenico et al. 2019; Gerigny et al., 2019). This was correlated with shipping and fishing activities (Gerigny et al., 2019; Tekman et al., 2017). In addition to proximity to sources, water currents and bottom topography affect the distribution of debris on the seafloor. For example, submarine canyons are known pollution hotspots (Pham et al., 2014).

Debris on the seafloor originating from populated area near Banda Neira, Moluccas, Indonesia, date: 09.12.2009. © Jürgen Freund/WWF

The deep sea is still largely unknown, therefore our knowledge of human impacts including those of plastic debris is limited, too. A recent review suggested that the most distinct impacts of plastic pollution on the seafloor are the entanglement and coverage of sessile animals and soft-sediment environments, and the introduction of artificial substrata (Canals et al., 2021).

Plastic objects can be used for the attachment of encrusting and sessile organisms in otherwise homogeneous muddy environments with few hard substrata. In submarine canyons west of Portugal, many litter items were colonized by sea anemones, coral and other invertebrates or used as refuge (Mordecai et al., 2011). In the Arctic deep sea, plastic debris was also often colonised by sea anemones, incapable of settling on the surrounding sediments (Tekman et al., 2017). Macrodebris recovered from the Xisha Trough harboured 49 different fungi and invertebrate species acting as new biodiversity hot spots (Song et al., 2021). However, while the overall number of species increases, it may cause the numbers and functions of species adapted to this particular environment to decrease, and thus change biodiversity.

Entanglement of sponges from the Arctic deep sea increased in parallel with growing litter intensities.

As with coral, litter drifting in the water currents above the seafloor is intercepted by sessile suspension feeders. Therefore, they were proposed as an indicator for the monitoring of marine debris (Galgani et al., 2018). Indeed, up to 28% of sponges from the Arctic deep sea were entangled with litter, and entanglement increased over 10 years in parallel with growing litter densities on the seafloor (Parga Martínez et al., 2020). As with coral, such entanglements could inflict injury, disease, starvation and death on animal forest species, too, but this is currently unknown. Ghost fishing of abandoned or lost fishing gear has also been observed on the deep Mediterranean seafloor where a derelict fishing net had caught Geryon crabs (Ramirez-Llodra et al., 2013).

Vast areas of the deep seafloor are characterised by muddy environments, which are inhabited by a diverse host of burrowing animals. Plastic items lying on sediments can affect biogeochemical processes at the sediment-water interface, with effects on bottom-dwelling communities. While no data exist for the deep sea, experiments in the intertidal zone produced oxygen-deprived conditions underneath plastic bags, a reduced availability of food and resulted in lower densities of sediment-inhabiting invertebrates (Green et al., 2015). As pollution increases, this could interfere with ecosystem functions and decrease biodiversity.

Left: Plastic bag colonised by orange sea anemones; Right: Plastic debris entangled in sponges on the deep Arctic seafloor, 2,500 m depth (location: Fram Strait, dates: 21.07.2012 and 23.06.2014). © Melanie Bergmann/AWI

Given the paucity of food in the deep sea larger animals such as fish may be particularly prone to the ingestion of debris, whose biofilms exude an attractive odour (Savoca et al., 2017). The little information available points to ingestion by four species of deep-sea sharks from the Mediterranean (Carrassón et al., 1992; Valente et al., 2020) and Greenland sharks, which reach an age of

400 years (Leclerc et al., 2012; Nielsen et al., 2014). While no internal injuries and only low burdens were recorded, a false feeling of satiation may affect slow-growing animals in a food-limited environment such as deep-sea sharks. As top predators many sharks fulfil important ecosystem functions but are threatened with extinction by overfishing (Pacoureau et al., 2021).

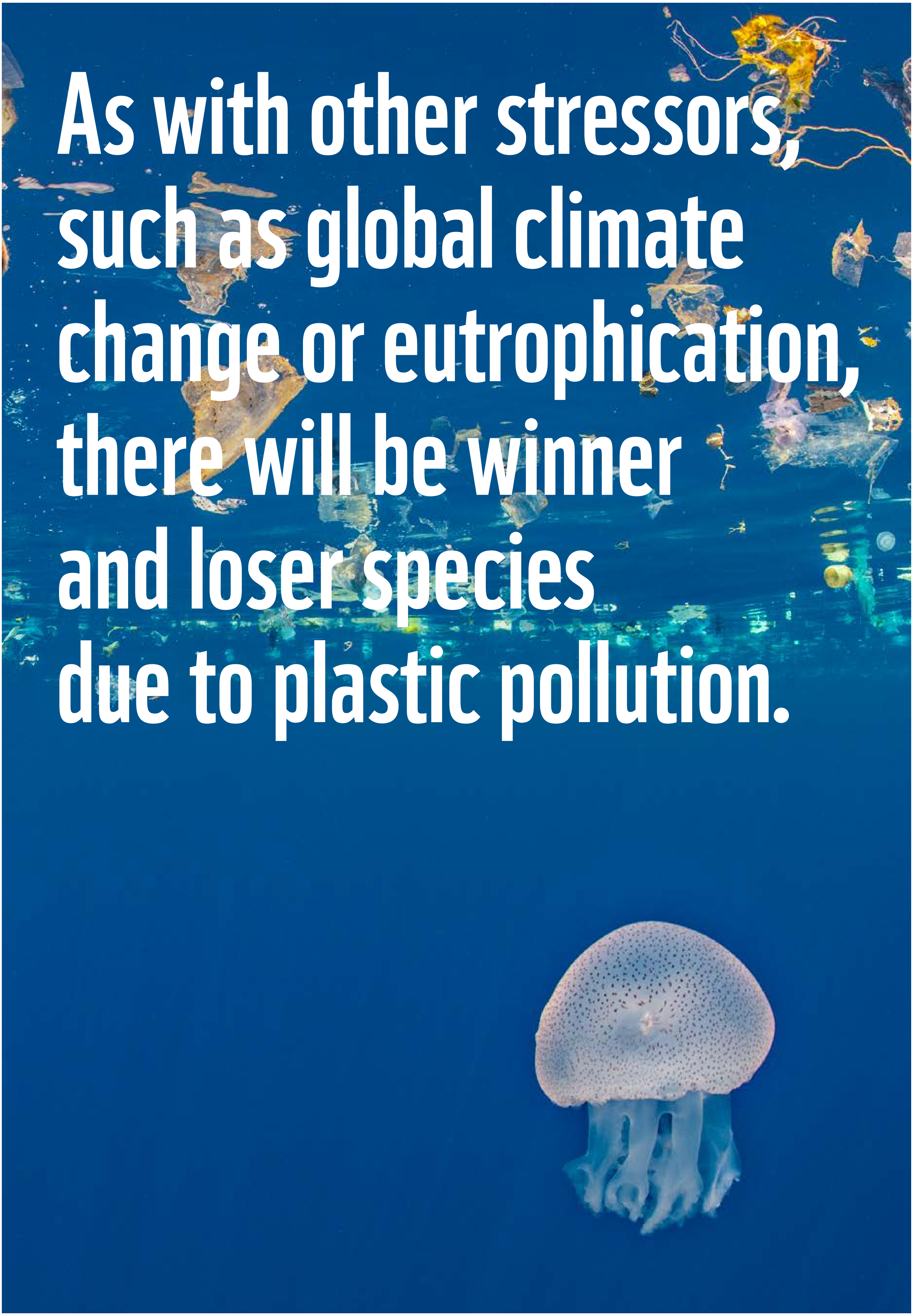
Microplastics

Microplastic pollution of the deep ocean floor has become global and widespread down to the Mariana Trench (Kane and Clare, 2019; Peng et al., 2018). This is helped by the fact that smaller-sized particles sink to the seafloor more rapidly because their higher surface to volume ratio promotes fouling of their surface, which makes them heavier and thus accelerates sinking (Fazey and Ryan, 2016). Being incorporated in biological matter from microbes, algae and faeces adds to this, as do water currents (van Sebille et al., 2020). Microplastics in deep-sea sediments occur in similar or even higher concentrations than their intertidal and shallow counterparts, whereby submarine canyons and ocean trenches harbour the highest microplastic densities (Kane and Clare, 2019). Bottom currents can carry microplastics on the seafloor to accumulation areas that also happen to be biodiversity hotspots (Kane et al., 2020). It has been argued that deep-sea sediments constitute a time-integrated sink for microplastics (Woodall et al., 2014). Indeed, in the Arctic deep sea, levels of up to 13,000 microplastic items/kg sediment were 16,000 times higher in sediment than in the overlying water (Tekman et al., 2020).

Microplastic was also recorded in marine species from the deep sea.

Microplastics were found in invertebrates from the Mariana Trench (Jamieson et al., 2019), mid-Atlantic and SW Indian Ocean (Taylor et al., 2016), North Pacific (Hamilton et al., 2021) and the Rockall Trough in the north Atlantic (Courtene-Jones et al., 2017), including museum specimens from 1975 (Courtene-Jones et al., 2019). It could be argued that frequent ingestion of microplastics could lower the energy reserves even further of animals living in already food-limited ecosystems such as the deep sea. However, since it is extremely difficult to conduct laboratory experiments on deep-sea animals the effects of this are unknown. Microplastics were also recorded in 36 species of 1,984 lantern fishes (Savoca et al., 2021), deep-sea fish from the South China Sea (Zhu et al., 2019) and the northeast and south Atlantic (McGoran et al., 2021; Pereira et al., 2020). While fish that swim on a regular basis from the upper waters to the seafloor enhance the transportion of microplastics to the deep sea (Wieczorek et al., 2018), the ecological effects of microplastic ingestion on deep-sea fish are currently unknown.

The available evidence shows that plastic pollution small and large has become widespread in deep-sea ecosystems, which likely constitutes a sink. Given the vast extent of the deep ocean floor, which covers ~50% of the Earth (Ramirez-Llodra et al., 2011), the effects are likely overall moderate although this may be different in hot spots such as canyons and depressions. Going by current trajectories, this can be expected to change as more plastic pollutants sink to the seafloor. Our current lack of knowledge of the effects of ingestion makes it difficult to judge effects on ecosystem health and services.



As with other stressors, such as global climate change or eutrophication, there will be winner and loser species due to plastic pollution.

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7. Evaluation of the impacts of plastics on species, ecosystems and biodiversity

The levels of plastic pollution are highly variable, ranging from almost no pollution to severe pollution.

There are some marine regions that still experience relatively low levels of plastic pollution. Then there are hotspots, such as ocean gyres (see Glossary) or some coastal regions that harbour high loads of plastic debris. Plastic pollution has even been reported from the most remote parts of the planet, highlighting that plastic pollution is carried over vast distances by atmospheric and ocean currents (Bergmann et al., 2019; Brahney et al., 2021; Lavers and Bond, 2017; Nichols et al., 2021; Ryan et al., 2021).

The varying degrees of plastic pollution in different ecosystems also appear to be reflected in the number of affected species in these. The highest pollution levels are found in coastal areas and on the seafloor (Chapter 4). Similarly, the highest number of species to encountering plastic debris inhabit the benthic compartment (Figure 19).

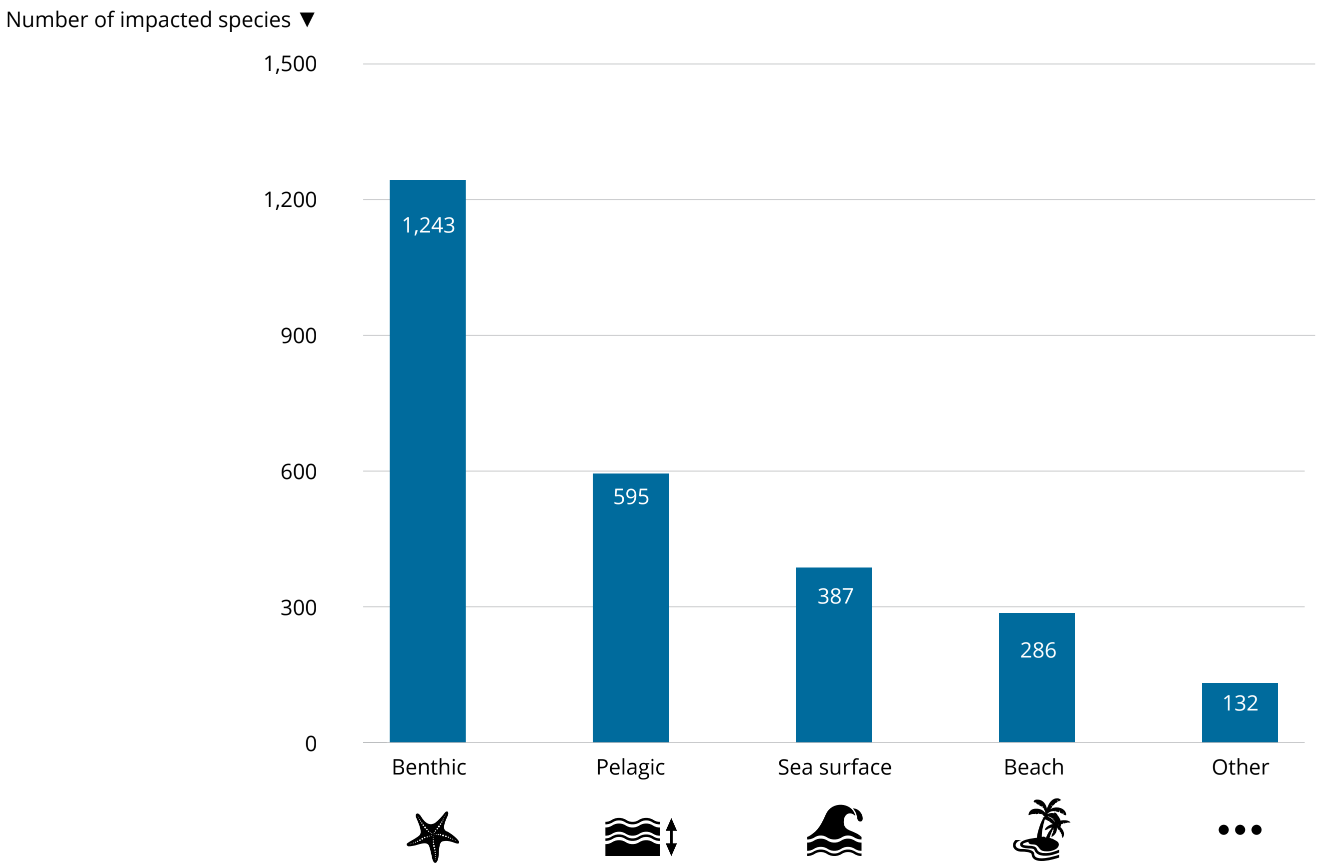

Figure 19: Number of species affected by plastic pollution based on the sphere that they inhabit (this refers to scientific studies compiled in LITTERBASE).

Marine plastic debris scattered across a beach on Phu Quoc Island, Vietnam. © WWF-Vietnam/Denise Stilley

The overall level of plastic pollution is projected to increase.

If we do not change consumption patterns and our current rate of virgin plastic production, plastic pollution is set to increase in the foreseeable future (Borrelle et al., 2020). Business-as-usual scenarios predict a four to 50-fold increase of plastic production and emission. Even the most optimistic scenarios, which rely on a massive increase of source reduction, improved waste management, recycling and removal, will mean further increases in marine pollution, albeit at much lower rates (Borrelle et al., 2020; Lau et al., 2020). Despite recent examples of effective policies, which have reduced sources, improved waste management and recycling rates, most of them have been enacted at local or national level (Karasik et al., 2020; Vince and Hardesty, 2018; Walther et al., 2021b). While some studies suggest plastic pollution levels have stabilized in recent years, a consistent global trend cannot be concluded (Chapter 3). In fact, even if all inputs of plastic pollution stop now, legacy plastics already in the ocean would continue to break down, with the mass of microplastics in oceans and on beaches more than doubling by 2050 (Lebreton et al., 2019).

The impacts of plastic pollution on species are highly variable.

Clearly, there are still many species that have not been investigated for the impacts of plastic pollution. Consequently, the number of 2,141 species, which interact with plastics in the wild and 902 species in experimental studies (LITTERBASE) is likely a vast underestimate. The negative effects on the species have hardly been assessed in the wild, often due to methodological challenges. Experimental studies have mostly focused on confirming plastic ingestion at different exposure levels. Therefore, we should bear in mind that the research on the effects of plastic pollution is still in its infancy. For example, plastic ingestion has been reported for 1,254 species in field and experimental studies, yet adverse effects on organisms have been assessed (in field studies) and investigated (in experimentals) only for 15% (190 species) of them and adverse effects were confirmed for 83% (158 species) of these (LITTERBASE).

Plastic pollution in its various forms poses an additional and increasing threat to vulnerable species.

An increasing threat from plastic pollution, added to the pressure from other anthropogenic stressors, may well be what pushes species to endangerment. The scale of this contribution is unknown and hard to establish. Slow-reproducing species are particularly vulnerable, many of them are also top predators or large herbivores (see "Megaherbivore" in the Glossary), and experience other threats. Since some of these vulnerable species are declining and globally or regionally threatened, plastic pollution in its various forms poses an additional and rapidly increasing threat to them.

Most certainly, ingestion of macro- and microplastics as well as chemical pollution negatively impact several seabird species or some of their subpopulations. It has been estimated that 90% of seabird species nowadays ingest plastic, a figure that is expected to rise to 99% by 2050 (Wilcox et al., 2015). Typical examples include albatrosses, fulmars, and shearwaters, who all feed on small prey items seized from the ocean's surface. There is considerable geographical variation of plastic pollution and ingestion by seabirds, as the examples for the northern fulmar and the flesh-footed shearwater demonstrate (Section 5.4.1). Nevertheless, certain species are already impacted by frequent entanglements or ingestion rates higher than 90%, with some studies reporting negative effects on their populations (Bond and Lavers, 2011; Hutton et al., 2008; Lavers et al., 2014; Werner et al., 2016). Plastic pollution also contributes substantially to threats, which can cause turtle populations to plunge towards extinction, probably because they experience all four types of interactions: entanglement, ingestion, smothering of nests and feeding areas and uptake of leached chemicals (Chapter 5). Mediterranean sperm whales are already classified as endangered while the sperm whale's global conservation status ranks in the lower category of vulnerable. In the Mediterranean, sperm whales ingest macroplastics, which can lead to starvation and death (Alexiadou et al., 2019; de Stephanis et al., 2013; Deudero and Alomar, 2015; Roberts, 2003) and also suffer from high chemical pollution (Bartalini et al., 2019; Mazzariol et al., 2011). Where hotspots of other threats (e.g. climate change, overfishing, chemical pollution) and hotspots of plastic pollution overlap (e.g. Mediterranean, East China and Yellow Seas), the impact of plastic pollution will be exacerbated, especially for already threatened species or regional subpopulations (Deudero and Alomar, 2015; Ford et al., 2022; Gissi et al., 2021; Mazaris et al., 2019; Ramírez et al., 2018).

An increasing number of studies have demonstrated the translocation of micro- and nanoplastics into various organs of organisms.

It is also important to emphasize that the impact of plastic pollution varies greatly with type, size and concentration of plastic items encountered. Although usually (but not always) confirmed only at high concentrations, some of the effects and impacts of micro- and nanoplastics are indeed concerning, both in marine biota (Chapters 5–6) and humans (Box 3). For example, an increasing number of studies have demonstrated the translocation of micro- and nanoplastics into various organs of organisms, including animal brains (Crooks et al., 2019; Haave et al., 2021; Mattsson et al., 2017) and human placenta (Ragusa et al., 2021).

Commercially important fish, such as cod and herring are also impacted by plastic pollution, but apparently to a smaller degree. For example, 1–30% of Atlantic cod, 0–52% of Atlantic herring, and 12–96% of sardines contain microplastics. While this highlights great geographic variation in contamination levels, each fish only contained a few particles (Section 5.4.5). Other impacts, such as entanglement and chemical pollution, are also much less severe for these lower trophic level and faster reproducing species of fish. However, the overall impact of plastic pollution on natural populations used as seafood is presumably relatively small because in most locations, microplastic concentrations have not yet reached critical levels (Everaert et al. 2020).

Where hotspots of plastic pollution converge with other threats, the negative impacts of plastic pollution will likely be exacerbated.

Coral reefs are already seriously threatened by global change (IPCC, 2019). Plastic pollution is a serious additional stressor through entanglement and smothering of corals causing tissue abrasion, breakage, disease and death of colonies. Entangled corals are 20 to 89 times more likely to have disease than non-entangled corals (Lamb et al., 2018). Uptake of microplastics can also cause coral bleaching (Soares, 2020) and led to decreased food uptake and growth, increased cell death, necrosis, mortality and immune response in experiments (Chapter 6). Again, spatial variation is important: Where hotspots of plastic pollution converge with other threats, e.g. in the South China Sea (Ding et al., 2019; Nie et al., 2019) or the Indonesian archipelago (Lamb et al., 2018), the negative impacts of plastic pollution will likely be exacerbated as numerous factors add up.

Some of the world's highest plastic densities have been recorded from mangrove forests. Higher tree densities appear to trap more macroplastic debris and this in turn deceases the health of mangrove trees (Debrot et al., 2013; L uo et al., 2021; Martin et al., 2019; Smith, 2012; Suyadi and Manullang, 2020; van Bijsterveldt et al., 2021). In Columbia, microplastic levels entrapped in mangrove sediments exceed the assumed safe concentration of sedimented microplastics (Everaert et al. 2018; Garcés-Ordóñez et al., 2019), highlighting the risk for these diverse ecosystems in certain areas.

Plastic waste in a nature reserve of an island in the Con Dao archipelago (Vietnam). Some 5,000 cubic meters are washed up on the shores of the islands every year.
© Bernhard Bauske/WWF

To our current knowledge, other ecosystems, such as the dynamic water column or seafloor sediments, currently experience on the whole lower pollution levels such that species of these ecosystems also incur lower risks (Everaert et al. 2018). However, in certain regions such as the deep Arctic seafloor or the Norwegian Fjord systems (Haave et al., 2019; Tekman et al., 2020) ecosystems already exceed safe microplastic levels putting their species at risk.

As with other stressors, such as global change or eutrophication, there will be winner and loser species due to plastic pollution, which in turn means that community composition and ecosystem functioning may change. In some cases, this may just mean species substitutions, but the overall functioning of the ecosystem will remain relatively intact. However, in other cases, biodiverse, productive and resilient ecosystems will be replaced with simpler, less productive and more fragile ecosystems, especially if several stressors interact (Graham et al., 2013; Hughes et al., 2003; Hughes et al., 2010; Unsworth et al., 2015; van de Koppel et al., 2015). Such ecosystems provide fewer benefits and services, which in turn means fewer economic returns as well as less security and well-being for human societies (Beaumont et al., 2019; Jang et al., 2014; McIlgorm et al., 2011; Shen et al., 2019; Wyles et al., 2016). Much more research is needed not just on the effects of plastic pollution on ecosystem functioning and productivity, but also on the effects on ecosystem services and human well-being. Furthermore, much more research is needed on the additive, combinatory, or synergistic effects of plastic pollution and other stressors on ecosystems. However, lack of research should not lead us to conclude that we can cut back efforts to stop plastic entering the environment until further research has been done.

Northern gannet (Morus bassanus) nesting on cliffs covered with fisheries-related plastic debris on the island of Helgoland (Germany). The cliffs are cleaned up on a regular basis. © Bernhard Bauske/WWF

The assessment of the impacts of plastic pollution on biodiversity requires a more complex approach than just evaluating species-level effects. Although we already have data on the interactions of plastic with thousands of species, a reliable assessment of the effects on biodiversity requires the measurements of more parameters, such as multi-species data, biogeochemical data and life history traits. One tool is ecological risk assessment, which estimates how biodiversity is and will be affected by plastic pollution, as well as what risks there are to human health (Besseling et al., 2019; Booth and Sørensen, 2020; Burns and Boxall, 2018; Compa et al., 2019; Everaert et al., 2018; 2020; Gouin et al., 2019; Jung et al., 2021; Senathirajah et al., 2020; Xu et al., 2018). These assessments need to be developed further and for this, the relevant data must be collected.

Because of the highly variable concentrations of macro-, micro-, and nano-plastics obtained by different sampling and analytical techniques, which vary in quality and accuracy, it is difficult to establish environmentally realistic concentrations of plastic pollution, for both risk assessments or realistic laboratory experiments (Booth and Sørensen, 2020; Carbery et al., 2018). Rather than using a single concentration, laboratory research and risk assessments should use a range of concentrations with the aim of identifying the functional relationships between plastic pollution levels and impacts (Koelmans et al., 2017). This approach enables us to identify risks for the same species inhabiting different regions and for changes in plastic concentrations over time. Moreover, standard parameters should be identified, such as plastic types and sizes, and these parameters should be assessed using the same methods for different species, by also focusing on their life stages. Such detailed assessments can be used for stranded animals, to assess the impacts of plastic pollution on megafauna (Byrd et al., 2014), especially on endangered species.

No-effect levels of microplastic concentration have already been exceeded in some areas of the Mediterranean and Yellow sea.

This area of research is still developing and only a few studies have been carried out so far. The ecotoxicological risks of floating microplastic on marine biota was evaluated by integrating 23 species-specific effect-threshold concentrations (Everaert et al., 2020). The no-effect level of microplastic concentration was estimated at ≤ 121,000 items per m^3 with a large confidence interval of 7,990–1,490,000 items per m^3. An earlier study had identified a much lower threshold of ≤ 6,650 items per m^3 (Everaert et al., 2018), and another recent study (Jung et al., 2021) also determined a lower safe threshold level of ≤ 12,000 items per m^3. The microplastic pollution levels of some areas of the Mediterranean and Yellow Seas already exceed these threshold levels (Everaert et al., 2018; 2020) (Figure 20). Given that there are more than 8,500 macroscopic species (see Glossary) in the Mediterranean, which account for 4–18% of the world's marine species (Bianchi and Morri, 2000), high levels of plastic pollution in the Mediterranean Sea alone would already pose a risk to global marine biodiversity. Considering the projected increase in plastic pollution in the oceans, the ecological risks of microplastic pollution on the global ocean surface are expected to spread considerably by the end of the 21st century (Everaert et al., 2020).

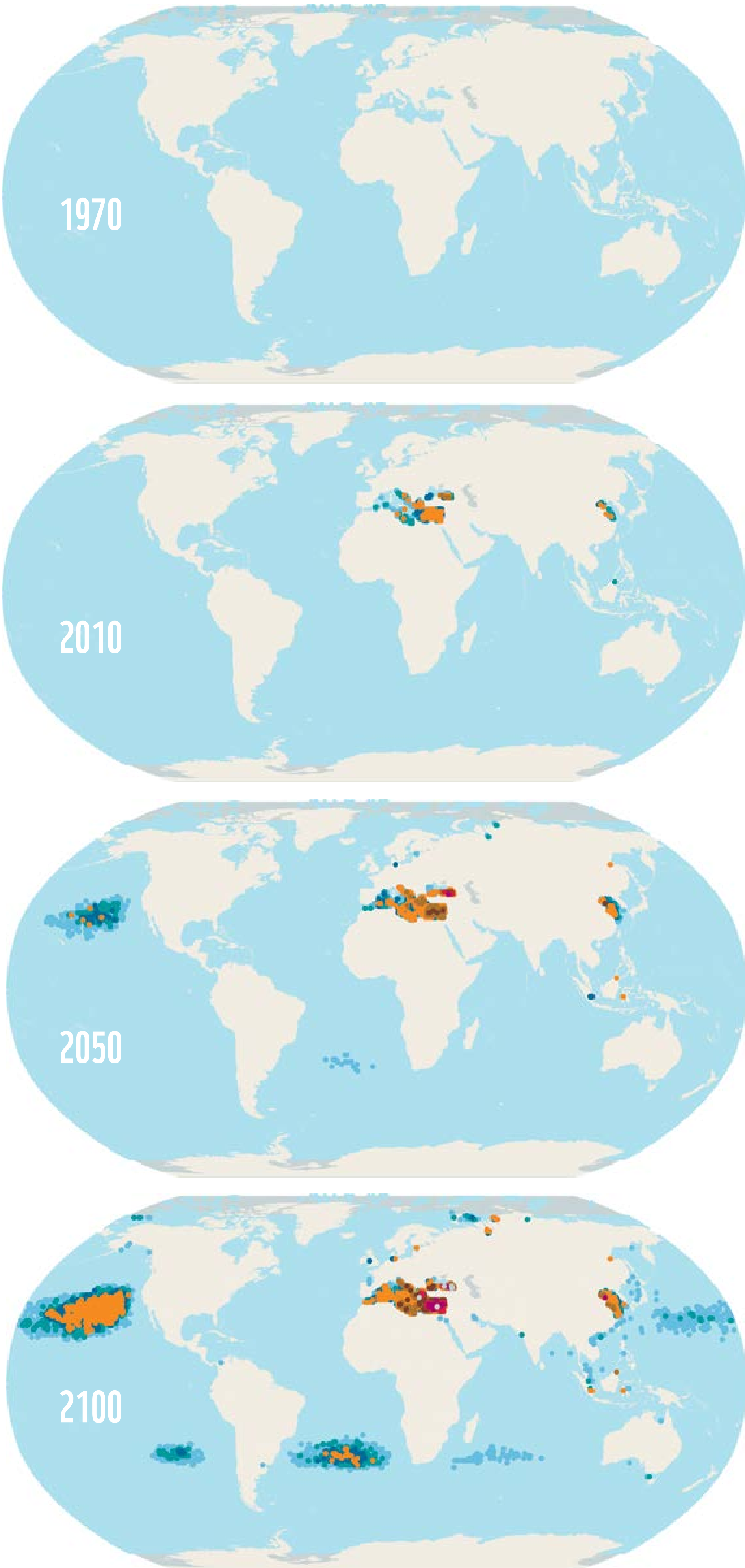

Figure 20: Global risks of microplastic pollution based on a worst-case scenario (unacceptable level (PNEC) = $7.99 * 10^3$ MP m^{-3}) displayed in a four-panel plot, in which each panel corresponds to a specific year. For this, cell-specific (1° by 1°) risk estimates were calculated and a visualization of the data was generated. The risk estimates were represented using colour codes. As long as the risk quotient remains lower than the value of 1 (bluish tones), policy makers consider there to be no risk due to microplastics. If the risk quotient exceeds the value of 1 (reddish tones), there is a risk (Everaert et al., 2020)

Risk Quotient

- no data
- 0.00 – 0.25
- 0.25 – 0.50
- 0.50 – 0.75
- 0.75 – 1.00
- 1.00 – 6.00
- 6.00 – 15.00
- 15.00 – 27.00
- 27.00 – 41.00
- 41.00 – 70.00
- 70.00 – 200.00

Relating micro- and nanoplastic concentrations to the risk of toxicity for marine organisms is complicated (Besseling et al., 2019; Burns and Boxall, 2018; Gouin et al., 2019). For example, the threshold level defined for certain species may not be realistic in some circumstances, but this does not guarantee that these impacts are not being observed in other circumstances, that they will not be dynamic over time or pose a risk in the future. A risk assessment for sea turtles modelled the global hotspot areas for debris ingestion (Schuyler et al., 2016) (Figure 18). The areas of highest debris ingestion risk were around Hawai'i, Southeast Asia, along the southeastern African coast and eastern US coast. A risk assessment for microplastic pollution in the seas around South Korea concluded that based on our present state of knowledge, current levels are ecologically safe but would be far exceeded by 2100 (Jung et al., 2021). The results of a risk assessment for Mediterranean biodiversity showed that coastal species have a higher risk of debris ingestion than open-sea species, so coastal species probably face dangerous concentration levels sooner (Compa et al., 2019). Species with a large home area, such as loggerhead sea turtles, sperm whales and Atlantic bluefin tunas have a higher risk.

An exponential increase in plastic pollution will have adverse effects on ecosystem function and structure, as well as affecting populations, changes in genetic diversity and evolutionary paths.

An exponential increase in plastic pollution will have adverse effects on ecosystem function and structure, as well as affecting populations, changes in genetic diversity and evolutionary paths (Everaert et al., 2020), which play out in small populations (Groom et al., 2006; Soulé, 1986). A better knowledge of population-level impacts is thus needed to link plastic pollution to wildlife conservation (Avery-Gomm et al., 2018).

The impact of the colonisation of floating plastic debris by animals should be evaluated from multiple perspectives. For the organism itself, rafting to a different climate zone may lead to death. However, if it survives, it could become invasive at the destination area and may thus cause changes to the ecosystem and biodiversity. A total of 738 species travelled in the oceans or were found on beached debris, including exotic species and pathogens (LITTERBASE).

The most recurrent organisms found on drifting plastic were potentially invasive and toxic, which are capable of causing great damage in places far away from their origin (García-Gómez et al., 2021). Because of their persistence, plastic rafts seem to transport animal groups like Arthropoda, Annelida and Mollusca more efficiently than natural rafts (García-Gómez et al., 2021). Thus, colonised plastic debris may pose a risk to ecosystems with a high endemism, such as ecosystems of remote islands. For example, exotic species were found on plastic pieces on beaches of Rapa Nui, which came from the South Pacific Subtropical Gyre (Rech et al., 2018).

Coral pathogens were distributed with floating plastics in the North Pacific (Goldstein et al., 2014) as was the bacterium *Vibrio parahaemolyticus* on microplastic from the North and Baltic Seas (Kirstein et al., 2016). Possible dispersal of the pathogens *Aeromonas salmonicida* on microplastics was documented from the Adriatic Sea. It is listed as one of the most harmful invasive bacteria on the exotic invasive species inventory for Europe as it infects fish, including salmonids, cyprinids, flatfish and sea bass (Viršek et al., 2017).

Numerous species use plastic items as substrates for settlement, as refuges from predators, or to disperse into new areas. These species are the winners of the habitat change caused by plastic pollution. While the concept of winners and losers of anthropogenic habitat change has been discussed in ecology for several decades (Cavole et al., 2016; Dutkiewicz et al., 2013; Mace et al., 2010; McKinney and Lockwood, 1999) it should be borne in mind that increases in the number of these winners usually mean that the functioning of the natural ecosystem changes, for example by lowering productivity or resilience. Other species, often range-restricted or rare species, suffer from the increased abundance of these winners. A potentially deleterious threat of plastic pollution is that it allows exotic species or diseases to invade new areas, where they may spread and cause ecological upheaval.

It is crucial to identify and agree on future research priorities that inform efficient change.

115 experts from 29 countries identified the following research priorities, which could inform policies aimed at reducing the harm plastic pollution does to marine life (Provencher et al., 2020):

1) What are the sources of plastic debris in the aquatic environment?

2) What policy tools have been successful at reducing ingested plastics in aquatic biota?

3) What are the chemical effects on aquatic biota from ingesting plastics?

4) What are the best methods for standardised sampling and reporting of ingested plastics?

5) Where are the highest concentrations of plastics in the aquatic environment?

Ghost fishing net discarded by fishermen causing widespread damage to a coral reef in the Indian Ocean, Zanzibar. © Shutterstock/ Aqua Images/WWF-Peru

Related to these priorities, numerical model simulations should be improved to characterise the distribution and pathways of plastic pollution (Hardesty et al., 2017).

Standardisation of methods for quantifying plastics and their effects is one of the highest research priorities.

One of the highest research and monitoring priorities is the standardisation of methods for quantifying plastics and their effects, as this currently hampers global assessments of plastic pollution and the determination of threshold risk levels (e.g. GESAMP, 2015, 2019; Haseler et al., 2018; Renner et al., 2018; Serra-Gonçalves et al., 2019).

In addition, further suitable bioindicator species are needed to assess ecosystem health (Fossi et al., 2018). So far, the northern fulmar has been used for monitoring the levels of plastic pollution in the North Sea by OSPAR (van Franeker et al., 2021). Filter feeders such as whales or mussels have been proposed for monitoring microplastic levels (Germanov et al., 2019; Li et al., 2019). However, species of different habitats and feeding types should complement each other so that we can collect information on the spatiotemporal variation of pollution and its impacts in different spheres (Bonanno and Orlando-Bonaca, 2018). The thresholds of plastic ingestion risks should be determined in standardised settings for different species, doses and polymer types and shapes to improve risk assessments (Besseling et al., 2019; Burns and Boxall, 2018; Everaert et al., 2018; 2020; Jung et al., 2021).

Wildlife beach stranding response networks should be set up at least for pollution hotspots or high-risk areas, and the results of necropsies should be shared in a central database (Williams et al., 2011). The time-series data obtained should be analysed to update risk assessments and assess the efficiency of regulations. Necropsies should be standardised to assess plastic ingestion across species (Alexiadou et al., 2019; Avery-Gomm et al., 2013; Provencher et al., 2017). Assessments of plastic debris in bird nests can also provide valuable information.

The clear-cut cases of harm documented for certain species, ecosystems and locations are ominous warning signs of much more common and widespread damage to come.

Conclusion

While there have been scientists who have argued that the threat of microplastic pollution is overstated (Burton Jr, 2017; Backhaus and Wagner, 2020), and some take the middle road (Gouin et al., 2020; Rist et al., 2018; Wardman et al., 2020), this is a conclusion others disagree with (Kramm et al., 2018; Leslie and Depledge, 2020). There are the clear-cut cases of harm documented for certain species, ecosystems and locations. These cases are ominous warning signs of much more common and widespread damage to come unless the looming trajectory of plastic pollution is drastically changed “to avoid [the] risk of irreversible harm” (Rochman et al., 2016). With continued plastic pollution, all of the documented harmful effects it has will also continue and increase, which could very well mean crossing dangerous thresholds for some subpopulations, species or ecosystems (MacLeod et al., 2021).

The impacts of continuously accumulating plastic pollution will likely grow, especially in combination with the many other severe and growing man-made stressors such as climate change, overharvesting, habitat degradation, ocean acidification, eutrophication, deoxygenation, and chemical and noise pollution. Without a doubt, unchecked plastic pollution will become a contributing factor to the ongoing sixth mass extinction (Barnosky et al., 2012; Ceballos et al., 2015; Pereira et al., 2010), ultimately leading to widespread ecosystem collapse (Barnosky et al., 2012; Jackson, 2008; UNEP, 2016) and transgression of safe planetary boundaries (MacLeod et al., 2021; Steffen et al., 2015b; Villarrubia-Gomez et al., 2018). Adopting the precautionary approach means that action to reduce plastic pollution must begin now, despite large remaining gaps in our scientific knowledge of marine plastic pollution and its effects on marine populations, species and ecosystems.

Given that numerous harmful impacts have now been documented in the scientific literature, we suggest that the problem of plastic pollution of the environment in general and of the marine environment specifically, is approximately at the point where the problem of man-made ozone depletion and climate change was in the 1990s (Borrelle et al., 2017).

What makes plastic pollution an especially concerning threat is that it is almost impossible to remove.

What makes plastic pollution an especially concerning threat is that, once it is out there, it is almost impossible to remove. Therefore, plastic pollution is another legacy burden for future generations. On current trajectories, our children and grandchildren will likely be saddled with oceans full of plastics.

If we consider such future trajectories, we should perhaps also consider the effects of future plastic pollution levels on human health. Only a few studies have yet explored how human health and quality of life is affected by marine and coastal plastic pollution, but they all point to serious repercussions economically, socially and regarding quality of life (Beaumont et al., 2019; CBD, 2016; Jang et al., 2014; Krelling et al., 2017; Thushari and Senevirathna, 2020; Watkins et al., 2017; Wyles et al., 2016). This topic has of course received massive attention from the media, which often show beaches full of plastic debris or animals suffering from plastic pollution to catch people's attention (e.g. Geary, 2019; Walther et al., 2021b). Obviously, concern for animal welfare is less of a scientific and more of a moral issue, but whether we act on plastic pollution or not is also a moral decision.

Any truly sustainable solution has to be based on principles such as the non-polluting zero-waste materials economy, which, by definition, means the end of most, but not all plastics, (Benyus, 1997; Leonard, 2010; McDonough and Braungart, 2008), clean zero-carbon energy (Green, 2018; Ripple et al., 2020) and protection of biodiversity and ecosystems (Díaz et al., 2020; Wilson, 2016).

8. Author contributions and disclaimer

M. B. T. and M. B. designed the report with the contributions of B. A. W. and L. G. in collaboration with WWF. M. B. T. and B. A. W. contributed equally to the writing of the report. Specifically, B. A. W. wrote Chapters 1, 2, 6, and the section 'Chemical interactions' and all the species' accounts in Chapter 5 with inputs from other authors. M. B. T. wrote Chapters 4 and 5 with input from the other authors. Chapter 7 was written equally by M. B. T. and B. A. W. with input from M. B.. M. B. T. performed the computations, analyses and interpretations of the LITTERBASE data and produced the data for the resulting graphs. M. B. T. and C. P. discussed the results of the data analyses with the contribution of M. B. and L. G.. All authors contributed to the literature research. C. P. completed the data input of records into LITTERBASE. B. A.W. collated many of the photos. M. B. T. and M. B. revised and commented on the report.

Disclaimer: Almost all of the information in this report was drawn from scientific publications. Although we carefully double-checked all information, mistakes can be made. Therefore, if in doubt, readers should consult the original publications for information. Of course, readers are also strongly encouraged to consult the original publications because they contain a vast amount of additional information.

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10. Annex

10.1 Plastic litter distribution data in LITTERBASE

Analysis of the data
Litter concentrations extracted from peer-reviewed publications and reports are collected in LITTERBASE. For this report, only marine plastic debris concentrations were considered. For sampling locations, where the coordinates were not stated in the study, latitude and longitude were estimated based on the availability of location information given in the publication. Concentrations of plastic debris found at a location were calculated by summing up the concentrations of different types of plastic debris. Unless it was strictly specified as plastic (e.g. plastic fishing nets, nylon fishing line), fisheries debris was not included in the data analysis, which has most likely caused an underestimation of current concentrations.

The following plastic categories were included into our data analysis: Fisheries plastics, plastic items and fragments, cigarette butts, fibres, films, pellets and styrofoam items. Since it would lead to erroneous results to compare abundances reported in different units of measure (e.g. kilometre versus cubic metre), firstly, the data were grouped according to the units used. For Figure 5, the median concentrations of size classes and ecosystem compartments were used, as there is a high variability among the plastic concentrations reported from different publications. Scientifically, median values should be represented within a range of values (minimum, 1st, 3rd quartiles and maximum) to describe the skewness (see Glossary) of the data. For simplification, only median values were shown in Figure 5. As Table 1 shows, there is a high variability between the values reported from different studies, which prevents us from reaching certain conclusions. The number of sampling locations taken into account for the analysis is large enough to be representative, as shown in Table 1.

List of publications
The figures in Chapter 4 (Figures 4–6) were produced based on the data extracted from the publications listed in distribution_studies_list.pdf file.

10.2 The impacts of plastic pollution on species in LITTERBASE

Analysis of the data
LITTERBASE holds records of interactions of marine litter with species reported by peer-reviewed publications and reports. The sampling locations and methods, ecosystem compartments inhabited by the affected species, type of interactions and consequent effects of those interactions, type and size of the litter encountered and taxonomical information of the species were included in LITTERBASE.

If the coordinates were not specified for sampling locations in the study, latitude and longitude were estimated based on the available information in the publication. In the current report, only marine plastic litter interactions were considered. Unless it is specified as plastic, fisheries debris was not included in the data analysis. The following marine litter encounters with species were analysed: Fisheries' plastics, plastic items and fragments, cigarette butts, fibres, films, pellets and styrofoam items. Some studies reported multiple types of interactions and/or effects for one species or a species was reported for encountering several interactions and/or effects with/due to marine litter in different publications. Therefore, the sum of the numbers in some bars of Figure 12–14 may represent a higher number of species than specified in the text. For species counts, only species which were identified to species (and some up to genus) taxonomic level were included in the data analysis. Because of the data structure of LITTERBASE, it was not possible to distinguish interactions with plastic debris only, if multiple types of interactions and litter were reported for a single species. Therefore, those records on 234 species were not included in the data analysis.

Effects of interactions

The evaluation of the effects recorded in LITTERBASE is rather complicated. Mostly because of methodological challenges, the direct effects of interactions cannot necessarily be assessed or distinguished. For example, even if stranded whales or seabirds had a lot of plastic in their intestines it is often not possible to link this ingestion explicitly to the effect 'mortality' by necropsies. Effects of interactions were only added to LITTERBASE, when they were specifically confirmed in studies or shown in pictures. Whenever a solid reasoning was provided, the related effect due to plastic debris encounter was entered. The following categories of effects were assessed for this report:

» Behaviour/locomotion: A change in behaviour, e.g. different swimming movements or no movement possible at all
» Breathing/Oxygen uptake: No breathing possible, either after entanglement or ingestion
» Dispersal: Distribution of species by rafting on litter pieces
» Food uptake: Prohibition or decrease of food uptake caused by litter, change in food uptake
» Growth: All kinds of changes in growth, size and/or weight
» Injury (internal/external): External injuries (from entanglement), internal injuries (e.g. of digestive organs from ingesting/egesting plastic pieces)
» Mortality: Death of single organisms, which is obviously caused by litter; higher mortality rates in populations
» No effect: If effects were searched for, but none were found
» Other: For every effect, which does not fit in any of the categories described here
» Physiological change: All physiological changes, photosynthetic rates, metabolic changes, adaptions, changes of transcription of genes, etc.
» Reproduction: Changes in the rates of reproduction, failed reproduction, oviposition, malformed embryos
» Toxicity: Proven toxicity of litter in the environment/medium for the organisms caused by plastic itself or hazardous substances on plastic debris
» Translocation: Passage of particles from the intestinal tract to the blood or organs (other than digestive organs)

Species groups

The number of species in different groups (seabirds, sea turtles, marine mammals, sharks and rays, fishes and corals and sponges were obtained by the analysis of the taxonomic information stored in LITTERBASE. LITTERBASE uses the Phylum of the species for a high-level species categorisation. Apart from the well-known groups mentioned above, the following categories were summarized in the group 'Other', for which the data for interaction and effects were analysed accordingly:

» Anemones, jelly fish and comb jellies (Anthozoa, Hydrozoa, Scyphozoa, Ctenophora)
» Bacteria and blue-green algae (Bacteria and Cyanobacteria)
» Crustaceans (Crustacea, Branchiopoda, Copepoda, Ostracoda, Euphausiacea, Peracarida, Decapoda, Leptostraca, Cirripedia, Mystacocarida, Thecostraca)
» Echinoderms (Echinodermata, Crinoidea, Echinoidea, Holothuroidea, Ophiuroidea, Asteroidea)
» Green, red and brown algae (Chlorophyta, Rhodophyta, Phaeophyceae)
» Molluscs (Polyplacophora, Gastropoda, Cephalopoda, Bivalvia)
» Moss animals (Byrozoa)
» Tunicates (Tunicata)
» Unicellular eukaryotic organisms (Haptophyta, Dinophyta, Bigyra, Cryptophyta, Ciliophyta, Protozoa, Chrysophyta, Foraminifera, Bacillariophyta)
» Vascular plants and mosses (Tracheophyta, Bryophyta)
» Worm-like animals (Annelida, Nematoda, Platyhelminthes, Nemertea, Sipuncula, Priapulida)

Calculation of the interaction rates for species groups

The percentages of plastic debris interactions with individuals of sampled species is stored in LITTERBASE, if such data are available in the studies. LITTERBASE was analysed for these impact rates and a species-level list of impacted individuals (as percentages) was obtained for entanglement with macroplastic and ingestion of macro- and microplastic (Figure 16, 17). The species were grouped according to the species groups in this report and the representative impact rates for each species group were calculated. Median values were used as the representative values since there is a high variability in impact rates among studies.

The list of publications

The figures in Chapter 5 (Figures 9–14) were produced based on the data extracted from the publications listed in impact_studies_list.pdf file.

11. Glossary

Androgen receptor antagonist: A substance, which prevents the binding of male sex hormones to the receptors, blocking the effects of the hormones.

Anthropocene: Nicknamed the 'Great Acceleration' because various socio-economic and Earth-System related indicators experienced a continuous and often exponential growth after the Second World War (McNeill and Engelke, 2016; Steffen et al., 2015a; Steffen et al., 2018). One indicator of the Anthropocene is the sudden emergence of plastic pollution, which was almost non-existent before the Second World War. Currently, geologists are proposing to define the Anthropocene as a distinct geological age (or epoch), which is characterised by the commencement of a significant human impact on the Earth's climate, geology and ecosystems.

Anti-androgenics: Substances, which prevent or reverse the effects of male sex hormones.

Benthic: The zone of the bottom of the ocean, including the sediment and some sub-surface layers. Organisms living in this zone are called benthos and usually include microorganisms and larger invertebrates.

Bioaccumulation: The gradual accumulation of pollutants, e.g. endocrine disruptors, in an organism. Bioaccumulation occurs when the rate of absorption from all sources (air, water, food, etc.) exceeds the rate of elimination via catabolism and excretion. Therefore, the longer the biological half-life of a toxic pollutant, the greater the risk of chronic poisoning, even if the environmental concentrations of the pollutant are very low.

Biodegradable: Biodegradable by definition refers to material, which degrades by the action of micro-organisms into simple inorganic molecules, water, carbon dioxide and methane. Such materials are expected to decompose under natural conditions. In the context of plastics, there are multiple interpretations of these "natural" conditions. For example, the biodegradability of Mater-Bi (Balestri et al., 2017) was tested under composting conditions on the laboratory scale. Test material was mixed with mature compost and kept at a high temperature under aerobic conditions, at a proper level of humidity (Rutkowska et al., 2004).

Biodegradation: Defined as the biologically catalysed breakdown in complexity of chemical compounds, usually organic matter, by microorganisms, mostly bacteria and fungi. In other words, it is the process by which organic substances are broken down into smaller compounds, with the end products often being minerals. The speed and pathways of the process depend on external factors (temperature, humidity, etc.) and on the microbes involved.

Biodiversity: Biodiversity is the variety of living organisms, including plants, bacteria and animals in an ecosystem, in a region or around the globe. Generally, three levels of biodiversity are recognized: (1) genetic diversity, which is the variation in genes, e.g. within a population or a species; (2) species diversity, which is all the different species in a location; and (3) ecosystem diversity, which is the different ecosystems; in the case of marine biodiversity this would include coral reefs, kelp forests, seagrass meadows, etc. As biodiversity covers a wide variety of species and ecosystems, assessment of the impacts of plastic pollution on biodiversity is a complex task.

Bio-fouling: The colonisation (or overgrowth) of underwater pipes and other surfaces (in this report, the surfaces of plastic objects) by organisms such as algae, bacteria, and barnacles.

Biological pump: The biological pump is the process by which photosynthetically produced organic matter is transported to the deep ocean in the form of sinking particles. During the sinking process, they are subject to water currents, feeding by animals and defecation (Turner, 2015). Also known as the marine carbon pump, it is part of the oceanic carbon cycle and consists of several different processes, which all move carbon within the ocean.

Bisphenol A (BPA): An organic synthetic compound, which has the chemical formula $(CH_3)2C(C_6H_4OH)2$. BPA is a colourless solid, which is soluble in organic solvents, but poorly soluble in water. It serves as an important precursor to several plastics, especially certain polycarbonates and epoxy resins. BPA-based plastics are made into many different common consumer goods, such as plastic bottles (including baby bottles), food storage containers, sports equipment, CDs, and DVDs. Epoxy resins made from BPA line water pipes, coatings inside of food and beverage cans and thermal paper used for sales receipts. In 2015, about 4 MMT of BPA-derived chemicals were produced. BPA has been shown to be a xenoestrogen, exhibiting oestrogen-mimicking, hormone-like properties. Even though the effect is relatively weak, the pervasiveness of BPA-containing materials is concerning, and has led to reductions in its use or even bans for certain products.

Brominated flame retardant: These increase the time between ignition of a fire and flash over, which is the point at which enough heat is generated to cause combustion of flammable materials. A typical example of a brominated flame retardant is Tetrabromobisphenol A.

Buoyancy: Also called upthrust, it is an upward force exerted by a fluid that opposes the weight of an object. Inside a fluid, pressure increases with depth. Therefore, the pressure at the bottom of an object is greater than at the top of the object, causing it to experience an upward force. If the object has a density, which is greater than that of the fluid, gravitation is stronger than buoyancy, and the object sinks. However, if the object is less dense than the liquid, the buoyancy can keep the object afloat.

Congener: Refers to one of many variants or different configurations of a common chemical structure (e.g. PCBs occur in 209 different congeners) and are thus related, similar chemical substances.

Copepod: A group of small crustaceans living in nearly every freshwater and marine habitat. There are benthic and planktonic species, and some are parasites.

Cryptorchidism: Condition in which one or both testes fail to descend from the abdomen into the scrotum.

Disease vector: Any agent which carries and transmits an infectious pathogen from an infected host to another host, e.g. a mosquito carrying the malaria pathogen from one human to another. Most vectors are organisms, and most of those are arthropods or microbes.

Disease vector control: Limiting or eradicating animals, which transmit pathogens to humans.

Ecosystem: All the individuals of all the species within a distinct and somewhat homogeneous species assemblage (e.g. a coral reef or a mangrove forest) and how they interact with all the abiotic factors (water, light, temperature, soil, air, wind, wave action, fire) in the same space; the interactions of all the non-living (or abiotic) and living (or biotic) components then determine how energy, water and nutrients move through the ecosystem. The most important marine ecosystems are: coral reefs, open oceans and deep sea, and coastal marine ecosystems such as estuaries, mangrove forests, salt marshes.

Egestion: The excretion of indigestible material.

Endocrine disruptor: An endocrine disruptor (also endocrine-disrupting chemical or EDC) is a substance that interferes with the normal hormonal mechanisms, which are vital for the functioning of a biological organism in its natural environment (e.g. to regulate growth, develop sex organs, or to determine food and water intake). Typical examples of endocrine disruptors are bisphenol A and phthalates.

Entanglement: In the context of this report, entanglement refers to a marine organism enrapping itself in an item (or several items) of plastic debris, which often results in impaired movement or growth, or even death.

Eutrophication: The enrichment of a body of water with nutrients and minerals, e.g. by agricultural runoff and untreated waste water.

Exotic species: A species, which was moved by human activities from its natural range (or distribution) to a new location where it previously did not exist is defined as an exotic (or alien) species. If it has little ecological impact, it remains an exotic species; if it has a significant ecological impact, it becomes an exotic invasive species.

Fourier Transform Infrared Spectroscopy (FTIR): One of the most reliable laboratory techniques to distinguish plastic materials from non-plastic materials. It measures the infrared spectrum of a sample material, and this spectrum is then compared to known spectra of various plastic polymers and other materials.

Ghost nets: Also called ghost-fishing nets. These nets (and sometimes traps) have been "abandoned, lost, or [otherwise] discarded" in the ocean (Richardson et al., 2019; WWF, 2020). These nets may be entangled in some bottom substrate (e.g. reefs) or drifting in the open ocean. Their distinguishing feature is that they continue to catch target and non-target species, and occasionally even human divers, causing stress, injury, or death. This feature distinguishes them from nets which do not catch any species anymore, but nevertheless continue to pollute the marine environment, e.g. by smothering the substrate below them (see 'lost fishing gear').

Gyre: Any large system of circulating ocean currents, whereby the five largest and most important ones are the Indian Ocean Gyre, North Atlantic Gyre, North Pacific (Subtropical) Gyre, South Atlantic Gyre and South Pacific (Subtropical) Gyre. All of them have been accumulating and concentrating plastic debris (macro-, micro- and nanoplastics) (Eriksen et al., 2016).

Individual: Defined as a discrete organism, e.g. one individual coral, fish, or dolphin.

Habitat: Defined as the type of natural environment or natural home in which a species preferentially lives because it can survive and/or reproduce there.

Hepatosomatic index: The ratio of liver weight to total body mass. It indicates the energy reserves of an animal, especially in fish that use the liver to store fat.

Invasive species: A species, which was moved by human activities from its natural range (or distribution) to a new location where it previously did not exist is defined as an exotic (or alien) species. In the new location, it may quickly die without reproducing or reproduce very slowly and not spread and thus have little ecological impact. However, if it successfully spreads and has a significant impact on the ecosystem, then it is defined as an invasive species.

Ingestion: The process of taking foods, drinks or other substances into the body by swallowing them.

Karyotype: An individual's collection of chromosomes.

Lost fishing gear: Fishing gear is lost for various reasons, which has led to the somewhat cumbersome use of the term "abandoned, lost, or [otherwise] discarded" fishing gear which, at times, has been abbreviated to ALDFG (Macfadyen et al., 2009; Richardson et al., 2019; World Animal Protection International, 2014). Other terms, which have been used are derelict or left fishing gear. For simplicity, we simply used the term 'lost fishing gear', which encompasses all the various reasons why fisheries equipment ends up in marine environments. Obviously, lost fishing gear includes ghost nets (or ghost-fishing nets) but includes many other items as well (e.g. non-catching nets, which simply smother the substrate below them, lost plastic buoys, etc.).

Macroplastics: Macroplastics are commonly defined as any plastic object or fragment whose longest linear dimension exceeds 25 mm. For ease of writing, we include mesoplastics (5–25 mm) into the category of macroplastics.

Macroscopic species: A species that can be observed by the naked eye.

Marine organism: In this report, a marine organism is defined as any living entity, which lives in the marine realm and thus includes organisms from all biological domains (or superkingdoms, which are the highest taxonomic rank of organisms and which include archaea, bacteria and eukaryotes).

Marine snow: A continual fallout of mostly organic material in the oceans from the upper layers of the water column to the seafloor. It has an important role in carbon cycling by transporting energy from the light-rich photic zone to the aphotic zone below.

Marine Strategy Framework Directive: A strategy adopted by the European Union in June 2008, which aims to protect more effectively the marine environment across Europe.

Median: In statistics, the median is the value separating the higher half from the lower half of a sample or population. In other words, it is the middle value. Unlike the mean, the median is not skewed by a small proportion of extremely small or large values, and therefore provides a better representation of a typical value in samples and populations with such outlying data values.

Megafauna: Refers to the largest animal species of an area or ecosystem. There is no commonly agreed lower weight threshold, but some biologists use > 40 kg and others use > 1,000 kg, but none of these are universally agreed. However, in the marine world, megafauna can also refer to the largest invertebrates (> 1 cm), e.g. among the benthos.

Megaherbivore: Refers to very large herbivores, which means the largest herbivore species in their respective ecosystems, and which often have a profound influence on ecosystem functions (Owen-Smith, 1988).

Metalloid: A metalloid is a chemical element, which has properties in between those of metals and nonmetals. However, there is no standard definition of a metalloid and no complete agreement on which elements are metalloids. Examples include antimony, arsenic and germanium, and antimony and arsenic are especially toxic.

Metric ton (or tonne): One metric ton (MT) is defined as 1000 kg. In this report, we regularly use the abbreviation of MMT for one million metric tons.

Microplastics: Microplastics are commonly defined as any plastic item whose longest linear dimension is ≤ 5 mm or < 5 mm (unfortunately, these two slightly different definitions have both been used, and recently, a different boundary of < 1 mm was proposed (GESAMP, 2015, 2016; Hartmann et al., 2019). While this upper bound is almost universally accepted, the lower bound has not been satisfactorily defined so far. However, the lower bound is certainly where the upper bound for nanoplastics begins.

Mutagenic effect: Certain substances trigger mutations, i.e. changes in the DNA of the organism.

Nanoplastics: Nanoplastics have been defined as any plastic object or fragment whose longest linear dimension is ≤ 1 µm (or 1000 nm) or < 1 µm (or 1000 nm), although another upper bound was also proposed, namely ≤ 100 nm or < 100 nm (GESAMP, 2015, 2016; Gigault et al., 2018; Hartmann et al., 2019). Furthermore, a lower bound of 1 nm was proposed (Gigault et al., 2018; Koelmans et al., 2015). According to the International Organization for Standardization (ISO, 2015), the nanoscale is indeed defined as 1–100 nm.

Observation bias: As is the case for studies on plastic pollution, usually the sampling and analysis between studies differ to the extent that observations are not strictly comparable.

Oceanic garbage patch: Commonly referred to areas (or patches) of higher plastic pollution (macro-, micro- and nanoplastics), which are found within the major ocean gyre systems. The most famous is the so-called 'Great Pacific garbage patch' because it was discovered first and has become famous due to extensive media coverage, which uses it as an exceptional example of marine pollution. The general perception of these oceanic garbage patches by the public is of a literal 'garbage island'. However, this perception is not correct. The distribution of floating marine debris is patchy in these areas, and surface sampling surveys revealed high abundances of microplastic particles, so that such a garbage patch may perhaps be more accurately referred to as a 'plastic soup' denser than it is in other parts of the ocean.

Oesophagus: A muscular tube, which connects the throat with the stomach of vertebrates.

Oestrogen receptor agonist: A substance, which binds to oestrogen receptors and activates the release of hormones.

Oestrogenic activity: Oestrogen is a sex hormone that plays an important role in reproduction. Some substances have a similar molecular structure and trigger oestrogenic activity, when they enter the body, affecting the sexual development or reproduction of the organism.

Pelagic: The water column of the open ocean, the sphere between the sea surface and the seafloor. It is further subdivided into epipelagic (0–200 m), mesopelagic (200–1000 m), bathypelagic (1000–4000 m), abyssopelagic (4000–6000 m) and hadopelagic (> 6000 m).

Persistent organic pollutants (POPs): Also known as 'forever chemicals', POPs are organic compounds that are highly resistant to environmental degradation through chemical, biological, and photolytic processes. Consequently, POPs bioaccumulate with potential adverse impacts on animal and human health and ecosystem functioning. Some POPs are used in the manufacture of plastics (e.g. PBDEs, PCBs). Many POPs are also classified as PBT (Persistent, Bioaccumulative and Toxic) substances, which is similar to the POP classification. For example, POPs do not include dangerous metallic elements such as mercury; however, the PBT classification includes mercury. There are also substances classified as vPvB (very Persistent, very Bioaccumulative).

Phthalate: Phthalates are esters of phthalic anhydride and are used predominantly as plasticizers, which increase the flexibility, transparency, durability and longevity of plastics. For example, they are used to soften polyvinylchloride. Because of concerns about their effects as endocrine disruptors, lower-molecular-weight phthalates have been gradually replaced in many products with higher-molecular-weight phthalates or other plasticizers.

Plastic: Plastics are a wide range of synthetic or semi-synthetic organic compounds that are malleable and therefore can be moulded into solid objects of almost any shape or size (Kutz, 2011; Wypych, 2016). While the vast majority used today is made from petrochemicals, various new plastics have recently been invented that are made from renewable materials such as polylactic acid from corn, cellulosics from cotton linters, and even chicken feathers.

Plasticizer: A substance, which is added to plastic to make it softer and more flexible or pliable.

Polycystic ovary syndrome: A disorder, which causes infrequent, irregular or prolonged menstrual periods, and is often associated with elevated levels of male (androgen) hormones.

Polymer: A polymer is a material or substance that consists of very large molecules (so-called macromolecules). They are usually composed of many repeating subunits. There are many natural, biological polymers (e.g. proteins) and many synthetic, non-biological polymers (e.g. plastics) (Kutz, 2011; Wypych, 2016). In this report, we consider non-fibre polymers and resins to be synonymous (Geyer et al., 2017).

Population: All of the interacting individuals of the same species within a defined habitat or ecosystem (e.g. all of the sea otters in a kelp forest ecosystem). A global population is then all the individuals of the same species on the Earth (e.g. the global human population of almost eight billion people). See also subpopulation.

Scenario: In the context of this report, a scenario refers to a feasible future 'storyline' about how plastic production, waste management and waste emission may play out in the next few decades. Another useful definition is 'a postulated sequence or development of (future) events.'

Sessile: Usually refers to organisms, which cannot move, but remain in one place (sessile), e.g. because they have roots or are otherwise attached to a surface (e.g. barnacles, coral).

Skewness: It is the degree of the asymmetry in a probability distribution. A normal distribution has a skew of zero.

Source reduction: Refers to activities, procedures and regulations whose purpose it is to reduce the volume, mass or toxicity of products throughout their life cycle. Therefore, the design and manufacture, use, and disposal of products are altered in such a way as to reduce (or even eliminate) the environmental impacts of the products and to prevent pollution of the natural environment. Source reduction can be achieved through improvements in design, production, use, reuse, recycling, and through Environmentally Preferable Purchasing (EPP). For example, one of the most effective ways to reduce plastic pollution is source reduction through bans of single-use plastics (Prata et al., 2019; Schnurr et al., 2018; Walther, 2019; Walther et al., 2020; 2021b) (Box 6).

Species: There are several competing definitions of what a species is (Zachos, 2016). For sexually reproducing species, the most common definition remains the biological species concept, which defines a species as all the individuals that can potentially interbreed and produce fertile offspring (Beurton, 2002). For non-sexually reproducing species (e.g. bacteria or viruses), several different phylogenetic species concepts have been proposed. For the purposes of this report, we simply use the definition of each species as it was used in the primary literature (e.g. the Mediterranean fin whale defined and used in the study by Fossi et al., 2012).

Stockholm Convention on Persistent Organic Pollutants: An international environmental treaty (signed in 2001), which aims to eliminate or restrict the production and use of POPs. The criteria for listing a chemical as a POP include a chemical's persistence, bioaccumulation, potential for long-range environmental transport and toxicity. Currently, over 30 chemicals are listed as POPs (status for July 2019).

Stressor: A stressor is a biological or chemical agent, environmental condition, external event or stimulus (or any other internal or external effect), which causes stress to a system (which can be an individual, population, ecosystem, or the entire biosphere). Sometimes we also refer to pressures when we describe stressors, e.g. "the rapid accumulation of atmospheric greenhouse gases from human activities as well as multiple direct man-made pressures (plastics, marine traffic, overfishing, habitat alteration.) are having profound effects on the very fundamental processes that regulate how (the ocean) functions" (Ziveri, 2019).

Subpopulation: Defined as a subset of a larger population. In this report, we use this term to refer to geographical subpopulations; e.g. the Mediterranean subpopulation of a species is more exposed to plastic pollution than an Antarctic subpopulation of the same species.

Synergistic effects: Also called multiplicative effects. For example, the exposure to one chemical substance causes a dramatic increase in the effect of another substance that is much larger than the simple addition of the individual effects of each substance acting by itself. In other words, the interaction of two substances produces a combined effect greater than the sum of their separate effects. Of special concern is toxicological synergy because the exposure level to a chemical substance, which is considered safe for an organism, for that substance alone, might pose an unacceptable health or ecological risk when the organism is also exposed to other harmful substances. A practical problem is that the responses of organisms are hardly ever tested for the additive, combinatorial, synergistic, or antagonistic effects of several substances acting together. Therefore, the potential for synergistic effects is usually completely unknown. This lack of information applies to many of the chemical combinations to which humans are regularly exposed, including residues in food and water, indoor air contaminants, and other exposures (e.g. through the skin). Some researchers have suggested that the rising rates of various health problems (e.g. cancer, autoimmune diseases) may be caused by these combination exposures.

Tropics: Or tropical zone, is the region south of the Tropic of Cancer in the northern hemisphere and north of the Tropic of Capricorn in the southern hemisphere. About 4% of the Earth's surface is covered by the tropics.

Viscose fibres: Also called rayon, a synthetic fibre made of cellulose from wood or agricultural materials, often used for clothing.

Xenobiotics: Substances that are not natural for animal life, such as drugs, pesticides or chemical additives.

Zoanthid: They are marine animals of the class Anthozoa, generally colonial with polyps and often referred to as encrusting anemones. They can commonly be found in tropical and subtropical seas but are distributed in most marine environments, including the deep sea below 5000 m (Irei et al., 2011).

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Why we are here
To stop the degradation of the planet’s natural environment and to build a future in which humans live in harmony with nature.

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