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

SUMMARY OF A STUDY FOR WWF BY

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

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SUMMARY

A new report commissioned by WWF provides the most comprehensive account to date of the extent to which plastic pollution is affecting the global ocean, the impacts it's having on marine species and ecosystems, and how these trends are likely to develop in future. The report by researchers from the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) reveals a serious and rapidly worsening situation that demands immediate and concerted international action:

- **Today almost every species group in the ocean has encountered plastic pollution, with scientists observing negative effects in almost 90% of assessed species.**
- **Not only has plastic pollution entered the marine food web, it is significantly affecting the productivity of some of the world's most important marine ecosystems like coral reefs and mangroves.**
- **Several key global regions – including the Mediterranean, the East China and Yellow Seas and Arctic sea ice – have already exceeded plastic pollution thresholds beyond which significant ecological risks can occur, and several more regions are expected to follow suit in the coming years.**
- **If all plastic pollution inputs stopped today, marine microplastic levels would still more than double by 2050 – and some scenarios project a 50-fold increase by 2100.**

WWF calls the world governments to urgently negotiate and adopt a global treaty to tackle this pervasive and ever-growing threat to life in our oceans

INTRODUCTION: A PLANETARY CRISIS

Plastic pollution is everywhere in the global ocean, and levels have grown exponentially

The UN calls it a 'planetary crisis'.[1] From the poles to the remotest islands, from the surface of the sea to the deepest ocean trench, the marine plastic pollution problem has grown exponentially, plastic pollution is now ubiquitous and is projected to increase even if current corporate and government commitments are met.[2] Global and systemic actions are needed urgently in response.

Plastic pollution is a relatively new threat. Plastic only began to be widely used after World War II, but already the mass of all plastic ever produced is twice as high as the overall mass of all terrestrial and marine animals combined.[3] Production has rocketed in the last two decades, with as much plastic being produced between 2003 and 2016 as in all the preceding years combined.

By 2015, 60% of all plastic ever produced had already become waste,[4] a significant part of which has ended up in the ocean. Estimates vary widely, but it's thought that between 86-150 million metric tonnes (MMT) of plastic have accumulated in the oceans by now,[5] at a continuously increasing rate: in 2010, 4.8-12.7 MMT of plastic waste pollution were estimated to enter the ocean from land,[6] while a more recent study suggests that 19-23 MMT entered our waterways in 2016.[7]

Oceanic plastic pollution is not evenly distributed. Planetary hotspots include the five large ocean gyre systems (where the 'garbage patches' accumulate floating plastic debris), coastal and ocean areas near major emission points such as the deltas of large rivers that run through urban centres, coral reefs, mangroves, and the deep seafloor, especially canyons.

Where is all this plastic in the world's oceans coming from? Many of the sources are known, but not all of them. The rise of single-use items is a major factor: in 2015, half of all plastic waste was from packaging alone;[8] while according to a 2018 estimate, single-use plastics account for 60-95% of global marine plastic pollution.[9] Land-based sources near coastlines and rivers further inland contribute the large majority of marine plastic pollution: a recent analysis estimated that Europe, for example, releases 307-925 million litter items into the ocean annually, of which 82% are plastic.[10] But there are also significant marine-based sources, with one study estimating that at least 22% of marine litter comes from fisheries.[11] The air, too, is a vector for plastic pollution: wear of vehicle tyres and brakes are a major source of microplastic emissions,[12] as is wind abrasion from plastic-coated surfaces, waste processing, roads and agriculture.

Figure 1: Nanoplastics particles are ten times smaller than fine clay.

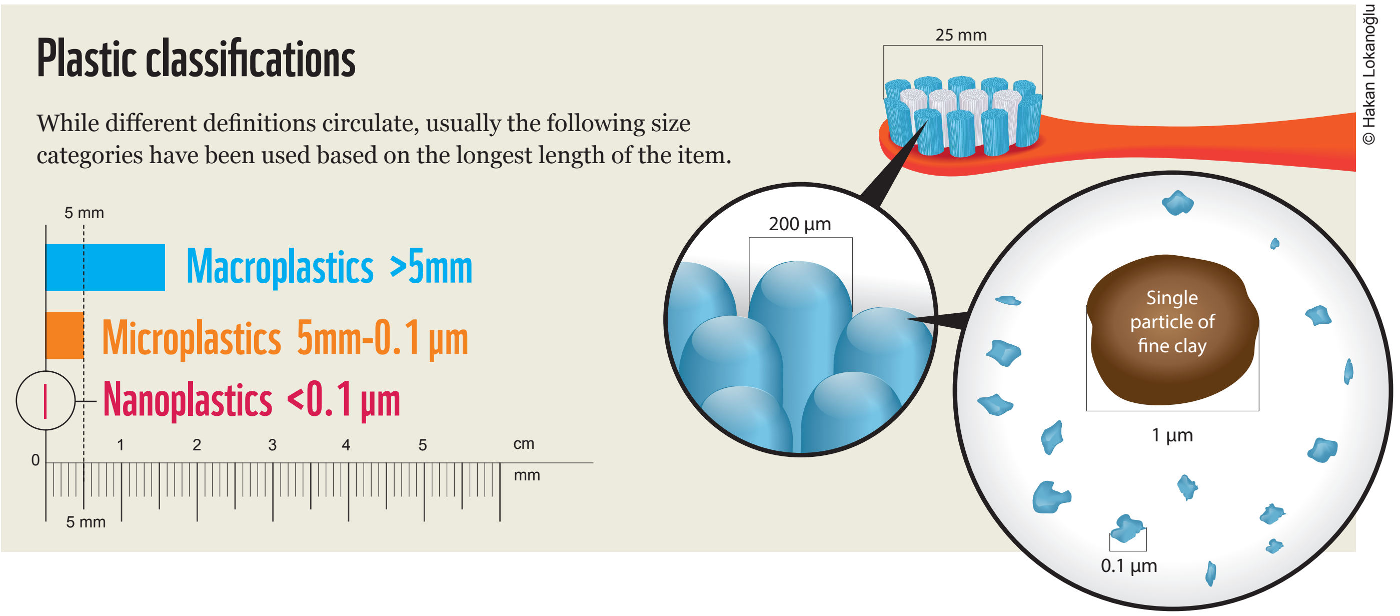


Figure 2: Plastic and waste pollution in the eastern Caribbean between the islands of Roatan and Cayos Cochinos in front of the coast of Honduras.

THE RISE OF MICROPLASTICS

As plastics continue to break down in the ocean, the threats they pose multiply

Due to the challenges of collecting ocean plastic and the persistent nature of plastic in the environment,[13] once plastic is in the ocean it's almost impossible to remove it. Moreover, once it has entered the ocean, it continues to break down: macroplastics become microplastics, and microplastics become nanoplastics, making recovery even more unlikely. Even if all plastic pollution inputs into the ocean were to stop today, this process of degradation means the mass of microplastics in oceans and beaches will more than double between 2020 and 2050.[14]

And there's little evidence of plastic pollution inputs stopping or even slowing in the near future. While 'business-as-usual' projections vary a great deal, they all predict substantial further growth in waste output. The plastics industry has invested US$180 billion into new factories since 2010.[15]

Plastic production is expected to more than double by 2040 and plastic pollution in the ocean is expected to triple.[16] This could lead to a four-fold increase in oceanic macroplastic concentrations by 2050,[17] and an alarming 50-fold increase in oceanic microplastics by 2100.[18]

Microplastic concentrations of 1.21×10^5 items m^{-3} have been proposed as a threshold level, above which significant ecological risks occur[19]. This threshold has already been exceeded in certain pollution hotspots including the Mediterranean, the East China Sea, the Yellow Sea[20] and in Arctic sea ice[21]. Ecological risks of microplastic pollution at the global ocean surface are expected to spread considerably by the end of the 21st century:[22] even the most optimistic scenarios see further significant increases, while a worst-case scenario suggests that dangerous pollution thresholds will be exceeded across an ocean area more than twice the size of Greenland.

INTERACTIONS WITH NATURE

Plastic pollution harms marine life through entanglement, ingestion, smothering and chemical leaching

Plastic pollution is now found everywhere in the ocean, and almost every marine species is likely to have encountered it. According to a conservative assessment of current research, a total of 2,141 species have so far been found to encounter plastic pollution in their natural environments.

The large majority of these interactions were related to ingestion, entanglement or smothering, with a further 738 species observed to colonize plastic items, enabling the spread of these species to new areas.

Studies – carried out both in the laboratory and the field – have also researched interactions with plastics under experimental conditions for 902 species. These included microplastic ingestion studies with different microplastic levels, and the deployment of ghost nets to quantify entanglements. While an assessment on how species come in contact with plastic was done for 902 species, some studies went further and not only tested interactions but also investigated negative effects. Some of these studies assessed effects such as injury or death, restricted motion, altered food uptake, growth, immune response, reproduction and cell function. Observable effects were studied for 297 species, and of these 88% were considered to be adversely affected.[23] While this percentage comes only from a limited sample of species and hence cannot be more broadly applied, a strong tendency is nevertheless clear: plastics have negative effects on most marine life.

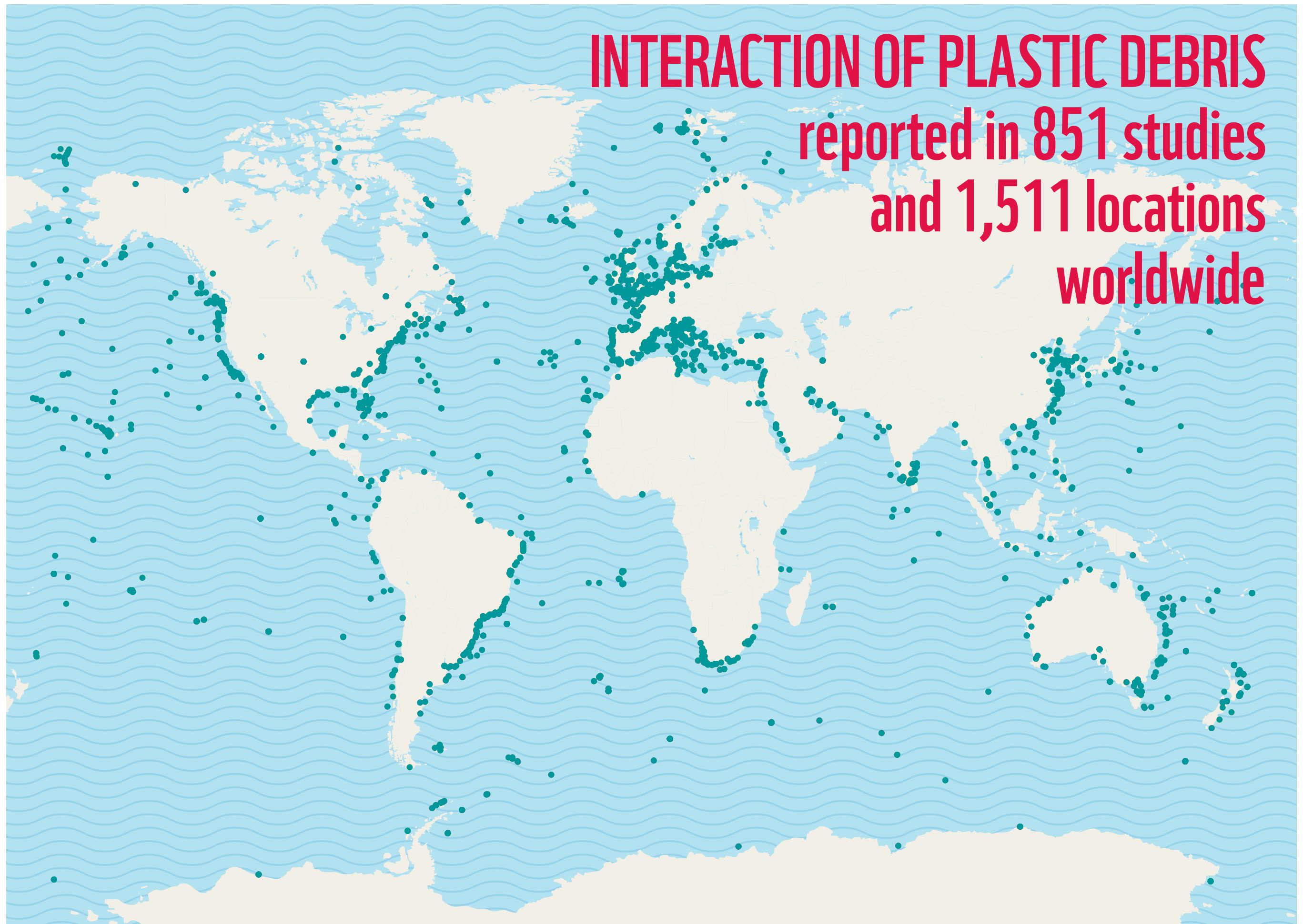


Figure 3: Map of encounters between plastic pollutants and marine life. The dots on the global map refer to 1,511 locations reported in 851 studies (LITTERBASE).

The main negative effects of plastics are:

Entanglement – Items like ropes, nets, traps and monofilament lines from abandoned, lost or discarded fishing gear wrap themselves around marine animals causing strangulation, wounds, restricted movement and death. Birds also use marine debris for their nests, which can entrap parents and hatchlings. Fishing lines entangled 65% of coral colonies in Oahu, Hawaii,[24] and 80% of these colonies were entirely or partially dead. Even in the remote Arctic deep sea, up to 20% of sponge colonies have been entangled with plastic, and entanglements increased over time[25]

Ingestion – Marine animals of all kinds – from apex predators down to the plankton at the base of the food chain – ingest plastic. This can cause serious harm to the animals, affecting food uptake by creating a false sense of satiation or blockages in digestive systems, as well as leading to internal injuries. Laboratory experiments have shown reduced growth in fish when their food is contaminated by high volumes of microplastics;[26] while at the other extreme a single plastic drinking straw in its digestive system likely caused the death of a whale shark in Thailand.[27] Plastic ingestion in seabirds is global, pervasive, and increasing[28]. It has been estimated that up to 90% of all seabird [29,29] and 52% of all sea turtle individuals nowadays ingest plastics.[30] Many emaciated whales and dolphins found stranded are also found to have ingested macroplastics.[31, 32, 33, 34] Some studies have shown altered or decreased food uptake, and negative impacts on growth,[35, 36, 37, 38] immune response, fertility and reproduction as well as altered cell functions and behaviours in the impacted species; with levels of harm directly related to exposure concentrations.[39]

Smothering – Plastic pollution deprives corals, sponges and bottom-dwelling animals of light, food and oxygen, making sediment oxygen-deficient and reducing the numbers of organisms in the sediment.[40,41] This can negatively affect ecosystems and give pathogens a foothold, which can have detrimental effects on marine life. Smothering is particularly harmful in coral reefs and mangroves (see below).

Chemical pollution – Not all the ingredients in plastics are harmful, but many of them are and can leach from plastics[42] into the marine environment. The smallest plastic particles can cross into the body cells and some of them can even reach the brains of marine animals.[43,44]

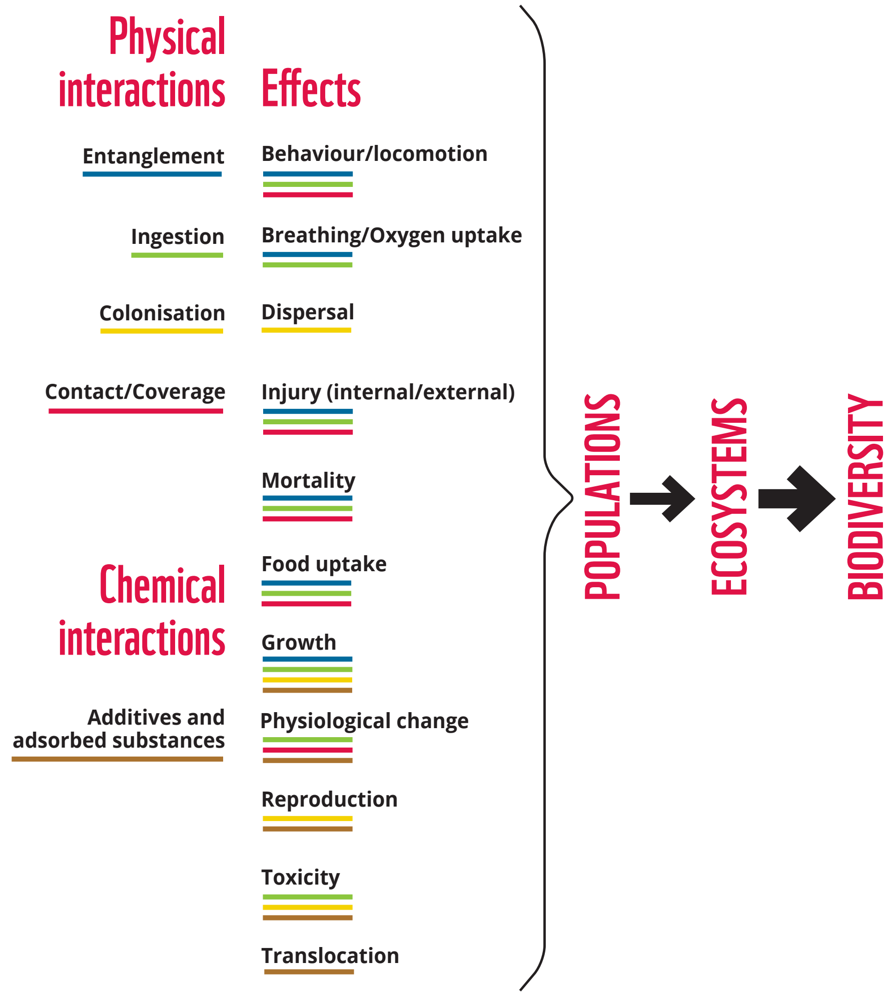


Figure 4: Diagram of the most frequently reported interactions and their effects on organisms (LITTERBASE). The colours represent the respective interactions.

Some of the most concerning chemical pollutants found in plastic can include:

Endocrine disruptors – these interfere with hormones, disrupting breeding, development and behaviour in many kinds of marine life.[45] Even some plastics that are labelled as food-safe can be highly toxic to aquatic animals and people alike.[46,47]

Persistent organic pollutants – these long-lasting substances, such as polychlorinated biphenyls (PCBs), affect organisms and environmental health.[48] Because they don't degrade, they can be transported over long distances by wind and water, eliciting long-lasting impacts far from their origin.

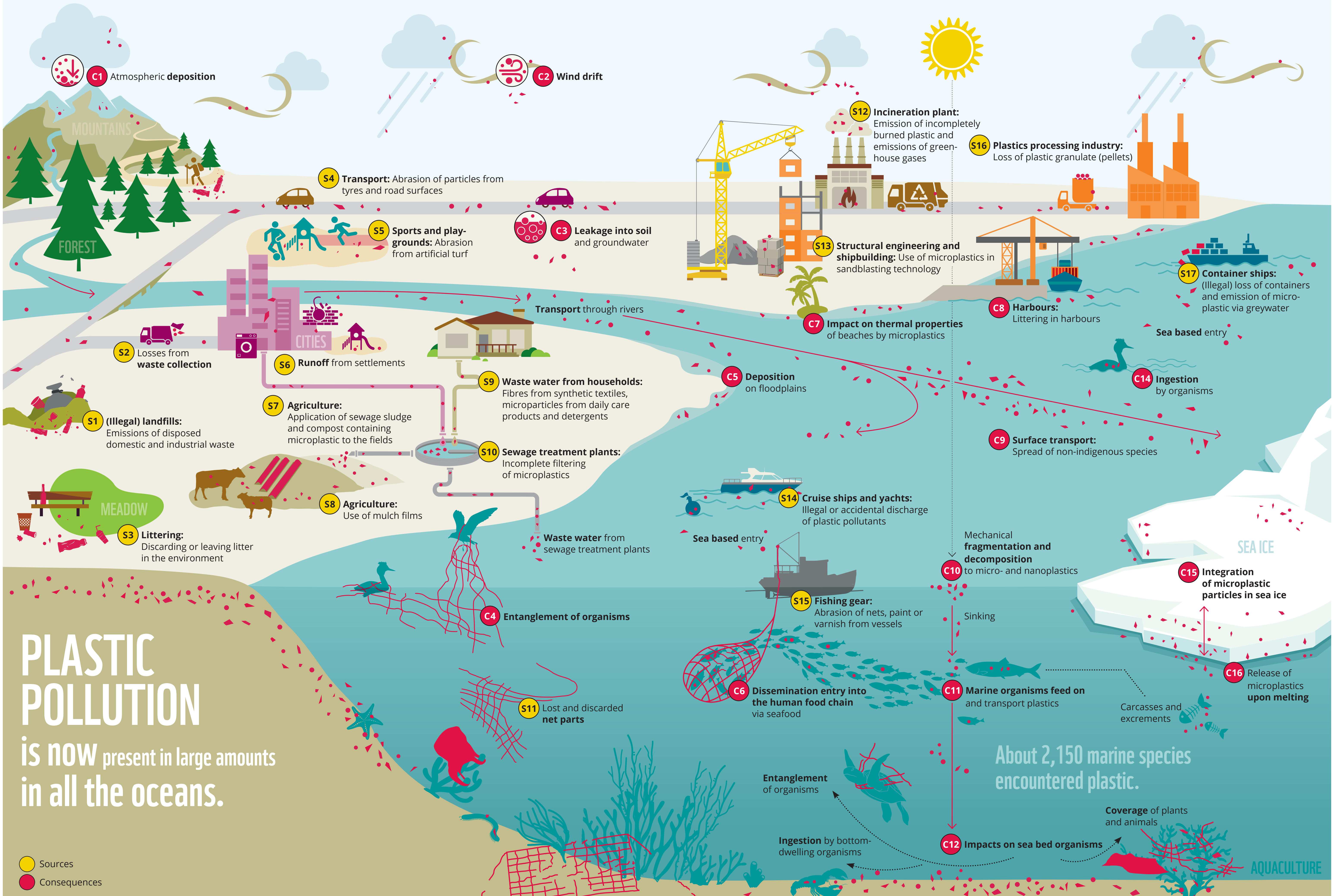


Figure 5: Pathways of plastics into the ocean

POLLUTING THE FOOD CHAIN

Ingested plastic can move right up the marine food chain – and is now found in human diets, too.

When marine animals ingest plastics, field and laboratory studies have demonstrated that those plastics – and their associated chemical pollutants – can pass further up the marine food chain.

Studies have confirmed the existence of microplastics in the water column and the incorporation of these particles into sinking aggregates.[49, 50, 51] These sinking particles are consumed partly or completely by plankton and other tiny organisms, which form the base of marine food webs.[52, 53, 54, 55] Disruptions in the efficiency of biological processes due to ingestion of plastic could affect the amount of food reaching the seafloor, which can cause changes in food-limited seafloor ecosystems. This was demonstrated by a recent study, which exposed salps to concentrations of microplastic likely to occur in the future.[56]

There's widespread concern over the potential dangers of nanoplastics, about which not a great deal is known to date. Experimental exposure of the water flea *Daphnia magna* to nanoplastics reduced its survival dramatically, in some cases causing mortality of up to 100% within the studied population. When these water fleas were then fed to fish, the nanoplastics were found to cross the blood-brain barrier and caused behavioural changes including lower feeding and movement rates.[57] As these impacts spread through the food chain, they could harm the functioning of the broader ecosystem.

Despite a recent surge of research on their effects on organisms, surprisingly little is currently known about the potential impacts of plastics on human health – but it's safe to say people are inhaling and ingesting them. Ingestion of microplastics by blue mussels, for example, has been demonstrated through most of their natural and introduced range[58, 59, 60] and the same is true for oysters. Since both are consumed whole by humans, there's no way of avoiding the plastics they contain.[61] Similarly, four out of 20 brands of canned sardines and sprats were found by researchers to contain plastic particles.[62]

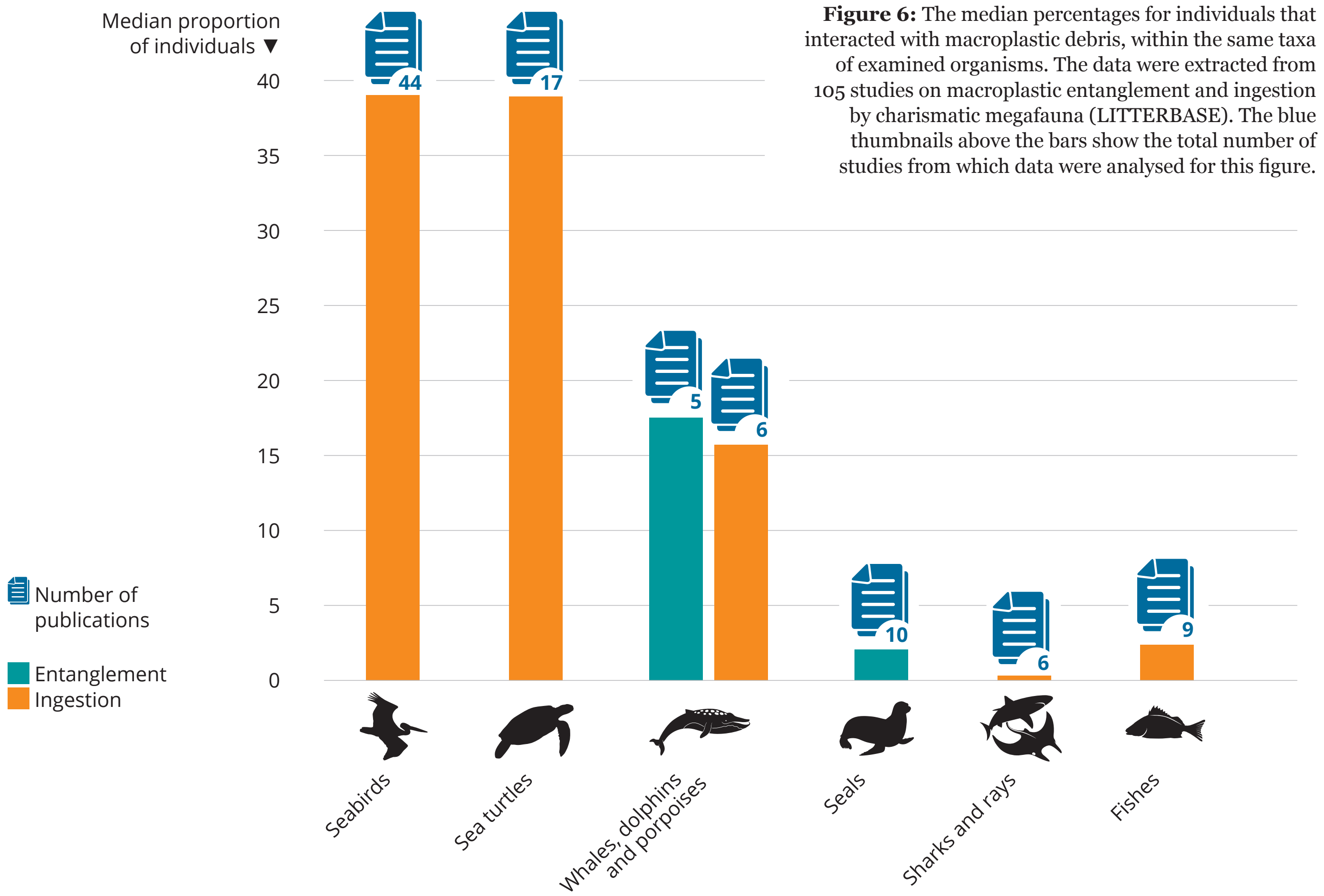


Figure 6: The median percentages for individuals that interacted with macroplastic debris, within the same taxa of examined organisms. The data were extracted from 105 studies on macroplastic entanglement and ingestion by charismatic megafauna (LITTERBASE). The blue thumbnails above the bars show the total number of studies from which data were analysed for this figure.

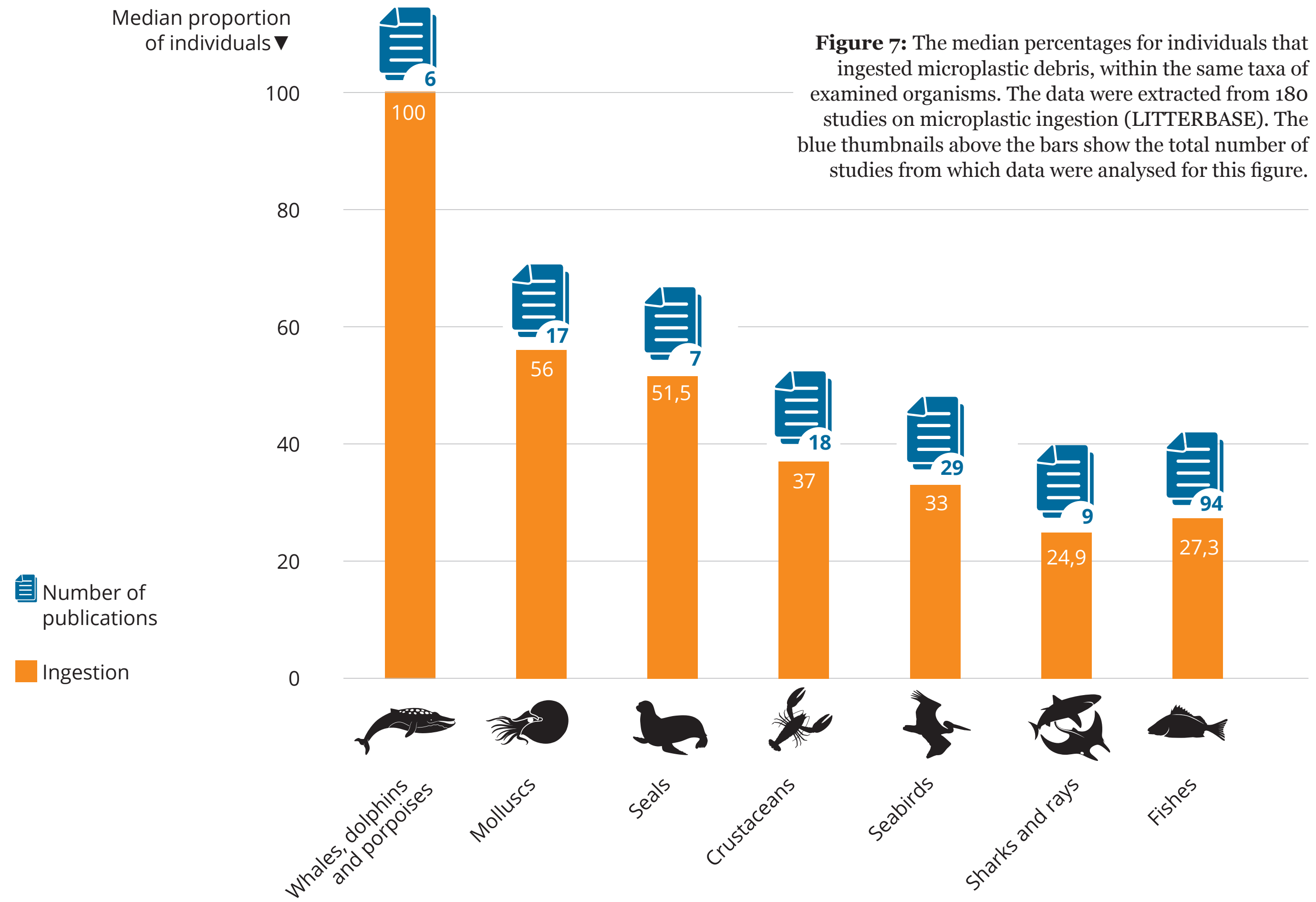


Figure 7: The median percentages for individuals that ingested microplastic debris, within the same taxa of examined organisms. The data were extracted from 180 studies on microplastic ingestion (LITTERBASE). The blue thumbnails above the bars show the total number of studies from which data were analysed for this figure.

KEY ECOSYSTEMS AT RISK

Plastic pollution is hitting coral reefs and mangroves particularly hard

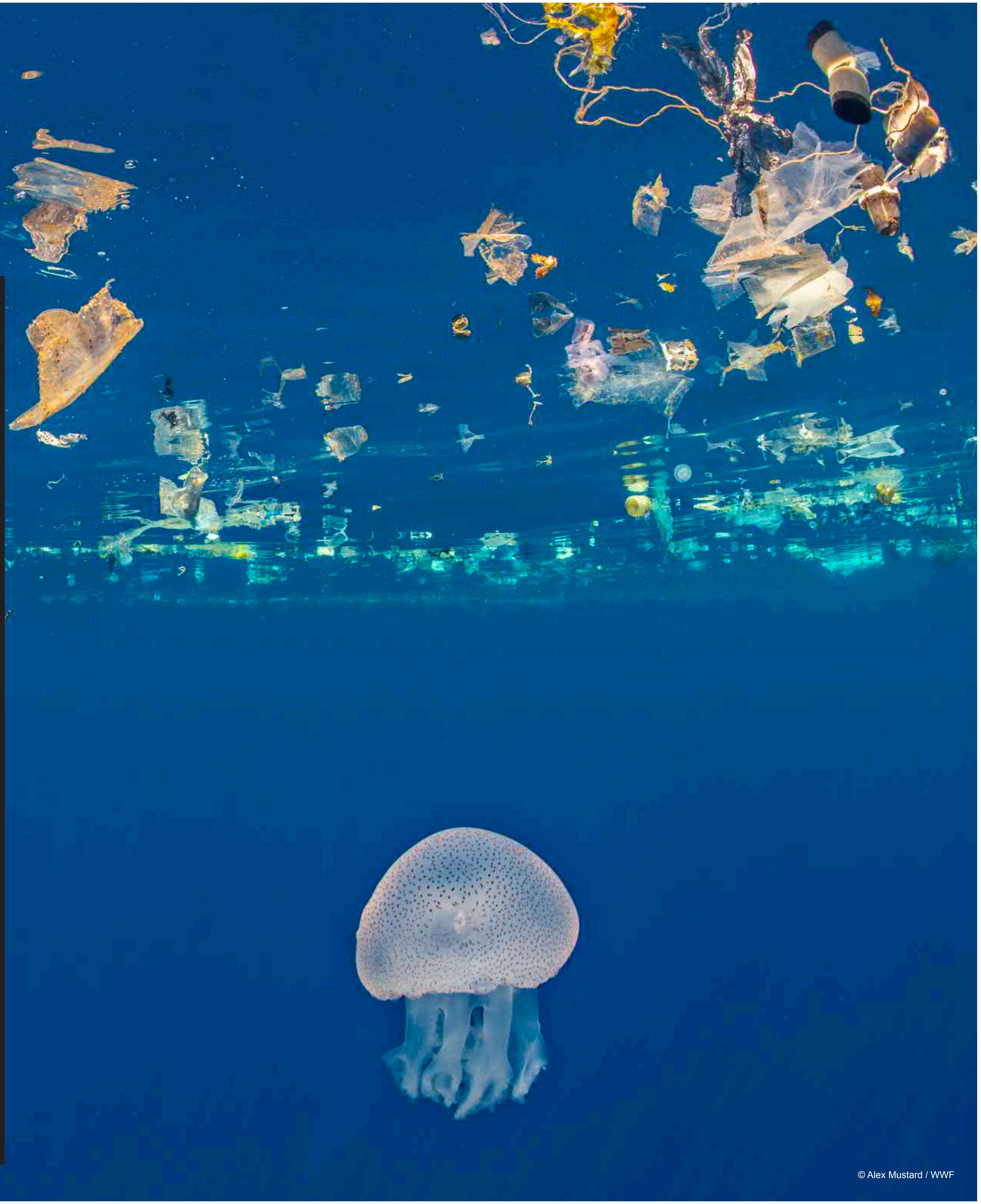
While plastic pollution is now found everywhere in the global ocean, certain key marine and coastal ecosystems are particularly at risk as they are already facing multiple threats in addition to growing levels of plastic pollution. These ecosystems – coral reefs and mangroves are notable examples – provide vital services to people as well as marine life, so humans are directly affected when plastic negatively affects how they function.

The scale of the threat plastic poses to coral reefs – already in crisis due to global warming– is alarming. In the Asian Pacific region, it's estimated that 11.1 billion plastic items were entangled in the region's coral reefs in 2010,[63] with this pollution projected to grow by 40% by 2025. Particularly worrying was that entangled corals were 20 to 89 times more likely to contract disease.[64]

Lost or abandoned fishing gear, often referred to as ghost gear, is also a serious threat to corals all over the world and can remain entangled on reefs for decades, smothering, breaking and abrading the structures, sometimes killing entire reef systems.[65, 66] Corals also accumulate microplastics in and on their polyps, negatively impacting the corals themselves and their symbiotic algae, and altering reef community structures.[67]

Mangroves – which provide many coastal communities with food security and flood defences among other services – are often close to river mouths where plastic pollution accumulates and gets trapped in their complex root systems that become plastic sinks. Some of the world's highest litter densities have been recorded in mangrove forests, with higher pollution levels correlating with lower tree health.[68, 69, 70, 71, 72, 73] A recent study of Javan mangrove forests found a density of 2,700 plastic items per 100m², with plastic covering up to 50% of the forest floor at several locations.[74] In an experiment, trees whose roots were completely covered with plastic had a lower leaf area index and survival rate.[75] Furthermore, efforts to rehabilitate degraded mangrove areas can be less effective when tree seedlings are smothered by plastic.[76]

Plastic pollution has been found more than 10 km beneath the surface in the Mariana Trench, the deepest point on Earth.[77, 78] Conditions here are relatively stable, so the waste could lie undisturbed for centuries. In some cases, it creates an artificial hard substrate in the mud on the deep seafloor for new organisms to colonize.[79] While plastic is thus beneficial for these species, its presence can alter the community structure of the native ecosystems.[80, 81]



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THE ADDITIVE EFFECT

Plastic pollution combines with other threats to marine life to form a precarious cocktail

The effects of plastic on marine ecosystems should not be considered in isolation. Plastic pollution is one of several manmade threats including ocean warming, overharvesting, ocean acidification, eutrophication, deoxygenation, shipping and underwater noise, invasive species, habitat destruction and fragmentation, as well as other forms of chemical pollution.

It's usually very difficult to pinpoint a single decisive factor behind a decline in marine life,[82] but where particular threats overlap, negative impacts will be exacerbated, especially for species that are already threatened. Further study is needed before we fully understand the 'additive' or 'synergistic' effects that occur when multiple stressors combine,[83, 84, 85, 86, 87, 88] but it's likely that the consequences may be severe – and this trend will probably become worse in future. Many experts agree that the planet is already undergoing a mass extinction,[89, 90, 91, 92] and unchecked plastic pollution will undoubtedly be a contributing factor as the crisis worsens.

There's another critical point to bear in mind when looking to the future. As plastic pollution continues to accumulate in the oceans, all the harmful effects that have been documented will increase – and there's a real possibility that this will mean crossing threshold levels of risk[93] for many more subpopulations, species and ecosystems. If plastic pollution continues growing at current rates, researchers predict that 99.8% of all seabird species will ingest plastics by 2050, [94] while evidence of ingestion and/or entanglement has already been found in all marine turtle species.[95]

ATTACKING THE ROOTS OF THE PROBLEM

Targeting the causes of plastic pollution before it happens is far more effective than cleaning it up afterwards

Similar to the climate crisis, this issue affects the entire planet: plastic pollution levels are continuously increasing, and only global and systemic solutions will succeed in response. Encouragingly, public attention is now focused on the issue, and calls are growing for decisive international action to turn the tide before plastic pollution overwhelms the resilience of a critical number of marine species and ecosystems.[96]

One solution that is often proposed is the collection and removal of plastic pollution from the ocean. In the same way that carbon-capture technology has been promoted by some groups to alleviate climate change, large-scale removal technologies for marine plastic pollution – with futuristic technological and yet unproven solutions – are increasingly being promoted.[97, 98, 99, 100] However, even if they were shown to be theoretically possible, the widespread use of such technological solutions would likely have significant economic costs and would not sufficiently turn the plastic pollution tide.[101, 102] Furthermore, the impact of removal on marine ecosystems has not been adequately assessed:[103] such removal solutions could do more harm than good if they amplify the mortality of bycaught marine life and continuously remove substantial amounts of biomass in the middle of the food-limited ocean, especially when scaled up. They are also likely to have significant carbon footprints, and would almost certainly not remove the smaller plastics from the ocean. There are some removal methods for microplastics, but most of them are currently only applicable for wastewater treatments.[104]

A far more important approach is simply to prevent plastic waste entering the environment in the first place, which also implies a major reduction in primary plastic production. Such an approach would have additional benefits including reduced resource use and pollution from manufacturing, transportation and disposal of plastic waste.

After decades of delays, the world is finally beginning to come together to act collectively and decisively on the climate crisis. The global plastics crisis, too, should be everybody's urgent business. There's no time to waste: action must begin now.

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CALL TO ACTION

A BINDING INTERNATIONAL TREATY IS URGENTLY NEEDED

A new global treaty on plastics must be binding, ambitious and hold states to a common standard of action. The treaty should contain specific, clear and universally applicable rules and obligations across the lifecycle of plastics that allow for an effective response to the global plastic pollution crisis. It must include provisions to ensure that those rules can be evaluated and gradually strengthened over time and shaped in a way that promotes global equity and incentivizes participation and compliance.

The treaty should include:

- **A clearly formulated vision of eliminating direct and indirect discharge of plastic into nature, based on the precautionary principle and in recognition of the devastating impacts of plastic pollution**
- **An obligation to develop and implement ambitious and effective national action plans, on prevention, control and removal of plastic pollution**
- **Common definitions, methods, standards and regulations for an efficient and harmonized global effort to combat plastic pollution across the lifecycle of plastic, including specific requirements to ensure circularity and bans on certain plastic products deemed to pose a particular risk to the environment, such as certain single-use plastic products and intentionally added microplastics**
- **Explicit bans on certain acts considered to defeat the object and purpose of the treaty, including deliberate dumping of plastic waste in river systems and internal waters**
- **An agreed measurement, reporting and verification scheme for tracking plastic pollution discharges and the progress made to eliminate them at a national and international level**
- **A specialized and inclusive international scientific body with a mandate to assess and track the scale, scope and sources of plastic pollution, harmonize scientific methodologies and collate state-of-the-art knowledge to provide inputs for decision-making and implementation**
- **A global financial and technical arrangement, as well as technology transfer assistance, to support the effective implementation of the treaty by all parties**
- **A commitment to update, revise and develop these measures and obligations over time**

Endnotes

1 MacLeod, M., Arp, H. P. H., Tekman, M. B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373 (6550), 61–65

2 Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G. H., Hilleary, M. A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L. R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C. M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369 (6510), 1515–1518

3 Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M., Milo, R., 2020. Global human-made mass exceeds all living biomass. Nature 588 (7838), 442–444

4 Geyer, R., Jambeck, J. R., Law, K. L., 2017. Production, use, and fate of all plastics ever made. Sci Adv 3 (7), e1700782

5 Ocean Conservancy, *Stemming the Tide: Land-based strategies for a plastic-free ocean*. 2015, McKinsey & Company and Ocean Conservancy.

6 Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., Law, K. L., 2015. Marine pollution. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

7 Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G. H., Hilleary, M. A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L. R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C. M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369 (6510), 1515–1518

8 Geyer, R., Jambeck, J. R., Law, K. L., 2017. Production, use, and fate of all plastics ever made. Sci Adv 3 (7), e1700782

9 Schnurr, R. E. J., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., Srain, H. S., Thavarajah, V., Xanthos, D., Walker, T. R., 2018. Reducing marine pollution from single-use plastics (SUPs): A review. Mar Pollut Bull 137, 157–171

10 González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., Barceló, D., Bessa, F., Bruge, A., Cabrera, M., 2021. Floating macrolitter leaked from Europe into the ocean. Nat Sustain 4 (6), 474–483

11 Morales-Caselles, C., Viejo, J., Martí, E., González-Fernández, D., Pragnell-Raasch, H., González-Gordillo, J. I., Montero, E., Arroyo, G. M., Hanke, G., Salvo, V. S., Basurko, O. C., Mallos, N., Lebreton, L., Echevarría, F., van Emmerik, T., Duarte, C. M., Gálvez, J. A., van Sebille, E., Galgani, F., García, C. M., Ross, P. S., Bartual, A., Ioakeimidis, C., Markalain, G., Isobe, A., Cózar, A., 2021. An in shore–offshore sorting system revealed from global classification of ocean litter. Nat Sustain 4 (6), 484–493

12 Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., Stohl, A., 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nat Commun 11 (1), 3381

13 MacLeod, M., Arp, H. P. H., Tekman, M. B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373 (6550), 61–65

14 Lebreton, L., Egger, M., Slat, B., 2019. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci Rep 9 (1), 12922

15 www.theguardian.com/environment/2017/dec/26/180bn-investment-in-plastic-factories-feeds-global-packaging-binge

16 PEW and SYSTEMIQ, 2020. Breaking the plastic wave. Pew Charitable Trusts, 1–154.

17 Lebreton, L., Egger, M., Slat, B., 2019. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci Rep 9 (1), 12922

18 Everaert, G., Van Cauwenberghe, L., De Rijcke, M., Koelmans, A. A., Mees, J., Vandegehuchte, M., Janssen, C. R., 2018. Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. Environ Pollut 242 (Pt B), 1930–1938

19 Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C. R., Backhaus, T., Mees, J., van Sebille, E., Koelmans, A. A., Catarino, A. I., Vandegehuchte, M. B., 2020. Risks of floating microplastic in the global ocean. Environ Pollut 267, 115499

20 Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C. R., Backhaus, T., Mees, J., van Sebille, E., Koelmans, A. A., Catarino, A. I., Vandegehuchte, M. B., 2020. Risks of floating microplastic in the global ocean. Environ Pollut 267, 115499

21 Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nature Communications 9 (1), 1505

22 Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C. R., Backhaus, T., Mees, J., van Sebille, E., Koelmans, A. A., Catarino, A. I., Vandegehuchte, M. B., 2020. Risks of floating microplastic in the global ocean. Environ Pollut 267, 115499

23 M.B. Tekman, L. Gutow, C. Peter, M. Bergmann, 2021. *LITTERBASE: Online Portal for Marine Litter*, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, litterbase.org

24 Yoshikawa, T., Asoh, K., 2004. Entanglement of monofilament fishing lines and coral death. Biol Conserv 117 (5), 557–560

25 Parga Martínez, K. B., Tekman, M. B., Bergmann, M., 2020. Temporal trends in marine litter at three stations of the HAUSGARTEN observatory in the Arctic deep sea. Front Mar Sci 7, 321

26 Naidoo, T., Glassom, D., 2019. Decreased growth and survival in small juvenile fish, after chronic exposure to environmentally relevant concentrations of microplastic. Mar Pollut Bull 145, 254–259

27 Haetrakul, T., Munanansup, S., Assawawongkasem, N., Chansue, N., 2009. A case report: Stomach foreign object in whaleshark (Rhincodon typus) stranded in Thailand. Proceedings of the 4th International Symposium on Seastar 2000 and Asian Bio-Logging Science, 83–85

28 Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proceedings of the National Academy of Sciences 112 (38), 11899-11904

29 Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proceedings of the National Academy of Sciences 112 (38), 11899-11904.

30 Schuyler, Q.A., Wilcox, C., Townsend, K.A., Wedemeyer-Strombel, K.R., Balazs, G., van Sebille, E., Hardesty, B.D., 2015. Risk analysis reveals global hotspots for marine debris ingestion by sea turtles. Global Change Biology.

31 Kasteleine, R. A., Lavaleye, M. S. S., 1992. Foreign bodies in the stomach of a female harbour porpoise (Phocoena phocoena) from the North Sea. Aquat Mamm 18, 40–46

32 Baird, R. W., Hooker, S. K., 2000. Ingestion of Plastic and Unusual Prey by a Juvenile Harbour Porpoise. Mar Pollut Bull 40 (8), 719–720

33 Barros, N. B., Odell, D. K., Patton, G. W., 1990. Ingestion of plastic debris by stranded marine mammals from Florida. In: Shomura, R. S., Godfrey, M. L. (Eds.), Proceedings of the Second International Conference on Marine Debris. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Honolulu, Hawaii, USA, 746

34 Lusher, A.L., Hernandez-Milian, G., Berrow, S., Rogan, E., O'Connor, I., 2018. Incidence of marine debris in cetaceans stranded and bycaught in Ireland: Recent findings and a review of historical knowledge. Environmental Pollution 232 (Supplement C), 467-476

35 Byrd, B. L., Hohn, A. A., Lovewell, G. N., Altman, K. M., Barco, S. G., Friedlaender, A., Harms, C. A., McLellan, W. A., Moore, K. T., Rosel, P. E., 2014. Strandings as indicators of marine mammal biodiversity and human interactions off the coast of North Carolina. Fish Bull 112 (1), 1–23

36 De Stephanis, R., Gimenez, J., Carpinelli, E., Gutierrez-Exposito, C., Canadas, A., 2013. As main meal for sperm whales: plastics debris. Mar Pollut Bull 69 (1–2), 206–214

37 Dickerman, R. W., Goelet, R. G., 1987. Northern Gannet starvation after swallowing styrofoam. Mar Pollut Bull 18 (6), 293

38 Macedo, G. R., Pires, T. T., Rostán, G., Goldberg, D. W., Leal, D. C., Garcez Neto, A. F., Franke, C. R., 2011. Anthropogenic debris ingestion by sea turtles in the northern coast of Bahia, Brazil. Cienc Rural 41 (11), 1938–1941

39 Prokić, M. D., Radovanović, T. B., Gavrić, J. P., Faggio, C., 2019. Ecotoxicological effects of microplastics: Examination of biomarkers, current state and future perspectives. Trends Analyt Chem 111, 37–46

40 Green, D. S., Boots, B., Blockley, D. J., Rocha, C., Thompson, R., 2015. Impacts of discarded plastic bags on marine assemblages and ecosystem functioning. Environ Sci Technol 49 (9), 5380–5389

41 Balestri, E., Menicagli, V., Vallerini, F., Lardicci, C., 2017. Biodegradable plastic bags on the seafloor: A future threat for seagrass meadows? Science of The Total Environment 605–606, 755-763.

42 Rochman, C.M., 2015. The complex mixture, fate and toxicity of chemicals associated with plastic debris in the marine environment. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Berlin, pp. 117-140.

43 Mattsson, K., Johnson, E.V., Malmedal, A., Linse, S., Hansson, L.-A., Cederwall, T., 2017. Brain damage and behavioral disorders in fisch induced by plastic nanoparticles through the food chain. scientific reports 7, 11452

44 Prüst, M., Meijer, J., Westerink, R.H.S., 2020. The plastic brain: neurotoxicity of micro- and nanoplastics. Particle and Fibre Toxicology, 17:24.

45 Porte, C., Janer, G., Lorusso, L.C., Ortiz-Zarragoita, M., Cajaraville, M.P., Fossi, M.C., Canesi, L., 2006. Endocrine disruptors in marine organisms: Approaches and perspectives. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 143, 303-315.

46 Hamlin, H.J., K. Marciano, and C.A. Downs, *Migration of nonylphenol from food-grade plastic is toxic to the coral reef fish species Pseudochromis fridmani*. Chemosphere, 2015. **139**: p. 223-228.

47 Muncke, J., Andersson, A.-M., Backhaus, T., Boucher, J.M., Carney Almroth, B., Castillo Castillo, A., Chevrier, J., Demeneix, B.A., Emmanuel, J.A., Fini, J.-B., Gee, D., Geueke, B., Groh, K., Heindel, J.J., Houlihan, J., Kassotis, C.D., Kwiatkowski, C.F., Lefferts, L.Y., Maffini, M.V., Martin, O.V., Myers, J.P., Nadal, A., Nerin, C., Pelch, K.E., Fernández, S.R., Sargis, R.M., Soto, A.M., Trasande, L., Vandenberg, L.N., Wagner, M., Wu, C., Zoeller, R.T., Scheringer, M., 2020. Impacts of food contact chemicals on human health: a consensus statement. Environmental Health 19 (1), 25.

48 Geyer, R., Jambeck, J. R., Law, K. L., 2017. Production, use, and fate of all plastics ever made. Sci Adv 3 (7), e1700782

49 Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., Soudant, P., 2015. Interactions between microplastics and phytoplankton aggregates: impact on their respective fates. Mar Chem 175, 39–46

50 Tekman, M. B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., Bergmann, M., 2020. Tying up loose ends of microplastic pollution in the Arctic: Distribution from the sea surface through the water column to deep-sea sediments at the HAUSGARTEN observatory. Environ Sci Technol 54 (7), 4079–4090

51 Zhao, S., Ward, J. E., Danley, M., Mincer, T. J., 2018. Field-Based Evidence for Microplastic in Marine Aggregates and Mussels: Implications for Trophic Transfer. Environ Sci Technol 52 (19), 11038–11048

52 Brandon, J.A., A. Freibott, and L.M. Sala, Patterns of suspended and salp□ingested microplastic debris in the North Pacific investigated with epifluorescence microscopy. Limnol. Oceanogr. Lett., 2020. 5(1): p. 46-53

53 Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T. S., 2013. Microplastic ingestion by zooplankton. Environ Sci Technol 47 (12), 6646–6655

54 Davison, P., Asch, R. G., 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Mar Ecol Prog Ser 432, 173–180

55 Katija, K., Choy, C. A., Sherlock, R. E., Sherman, A. D., Robison, B. H., 2017. From the surface to the seafloor: How giant larvaceans transport microplastics into the deep sea. Sci Adv 3, e1700715

56 Wieczorek, A. M., Croot, P. L., Lombard, F., Sheahan, J. N., Doyle, T. K., 2019. Microplastic Ingestion by Gelatinous Zooplankton May Lower Efficiency of the Biological Pump. Environ Sci Technol 53 (9), 5387–5395

57 Mattsson, K., Johnson, E. V., Malmendal, A., Linse, S., Hansson, L. A., Cedervall, T., 2017. Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. Sci Rep 7 (1), 11452

58 Mathalon, A., Hill, P., 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. Mar Pollut Bull 81 (1), 69–79

59 Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016a. Microplastics in mussels along the coastal waters of China. Environ Pollut 214, 177–184

60 Qu, X., Su, L., Li, H., Liang, M., Shi, H., 2018. Assessing the relationship between the abundance and properties of microplastics in water and in mussels. Sci Total Environ 621, 679–686

61 Zeytin, S., Wagner, G., Mackay-Roberts, N., Gerdts, G., Schuirmann, E., Klockmann, S., Slater, M., 2020. Quantifying microplastic translocation from feed to the fillet in European sea bass Dicentrarchus labrax. Mar Pollut Bull 156, 111210

62 Karami, A., Golieskardi, A., Choo, C. K., Larat, V., Karbalaei, S., Salamatinia, B., 2018. Microplastic and mesoplastic contamination in canned sardines and sprats. Sci Total Environ 612, 1380–1386

63 Lamb, J. B., Willis, B. L., Fiorenza, E. A., Couch, C. S., Howard, R., Rader, D. N., True, J. D., Kelly, L. A., Ahmad, A., Jompa, J., Harvell, C. D., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460–462

64 Ibid.

65 Al-Jufaili, S., Al-Jabri, M., Al-Baluchi, A., Baldwin, R. M., Wilson, S. C., West, F., Matthews, A. D., 1999. Human Impacts on Coral Reefs in the Sultanate of Oman. Estuar Coast Shelf Sci 49, 65–74

66 Angiolillo, M., Lorenzo, B. D., Farcomeni, A., Bo, M., Bavestrello, G., Santangelo, G., Cau, A., Mastas-cusa, V., Cau, A., Sacco, F., Canese, S., 2015. Distribution and assessment of marine debris in the deep Tyrrhenian Sea (NW Mediterranean Sea, Italy). Mar Pollut Bull 92 (1–2), 149–159

67 Tang, J., Wu, Z., Wan, L., Cai, W., Chen, S., Wang, X., Luo, J., Zhou, Z., Zhao, J., Lin, S., 2021. Differential enrichment and physiological impacts of ingested microplastics in scleractinian corals in situ. J Hazard Mater 404 (Pt B), 124205

68 Luo, Y. Y., Not, C., Cannicci, S., 2021. Mangroves as unique but understudied traps for anthropogenic marine debris: a review of present information and the way forward. Environ Pollut 271, 116291

69 Suyadi, N., Manullang, C. Y., 2020. Distribution of plastic debris pollution and it is implications on mangrove vegetation. Mar Pollut Bull 160, 111642

70 Martin, C., Almahasheer, H., Duarte, C. M., 2019a. Mangrove forests as traps for marine litter. Environ Pollut 247, 499–508

71 van Bijsterveldt, C. E., van Wesenbeeck, B. K., Ramadhani, S., Raven, O. V., van Gool, F. E., Pribadi, R., Bouma, T. J., 2021. Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. Sci Total Environ 756, 143826

72 Debrot, A. O., Meesters, H. W., Bron, P. S., de Leon,R., 2013a. Marine debris in mangroves and on the seabed: largely-neglected litter problems. Mar Pollut Bull 72 (1), 1

73 Smith, S. D., 2012. Marine debris: a proximate threat to marine sustainability in Bootless Bay, Papua New Guinea. Mar Pollut Bull 64 (9), 1880–1883

74 van Bijsterveldt, C. E., van Wesenbeeck, B. K., Ramadhani, S., Raven, O. V., van Gool, F. E., Pribadi, R., Bouma, T. J., 2021. Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. Sci Total Environ 756, 143826

75 Ibid.

76 Smith, S. D., 2012. Marine debris: a proximate threat to marine sustainability in Bootless Bay, Papua New Guinea. Mar Pollut Bull 64 (9), 1880–1883

77 Taylor, M., 2017. $180 bn investment in plastic factories feeds global packaging binge. The Guardian

78 Taylor, M., Plastic pollution discovered at deepest point of ocean, in The Guardian. 2018.

79 Tekman, M. B., Krumpen, T., Bergmann, M., 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep-Sea Res Part I 120, 88–99

80 Song, X., Lyu, M., Zhang, X., Ruthensteiner, B., Ahn, I.-Y., Pastorino, G., Wang, Y., Gu, Y., Ta, K., Sun, J., 2021. Large plastic debris dumps: New biodiversity hot spots emerging on the deepsea floor. Environ Sci Technol Lett

81 Katsanevakis, S., Verriopoulos, G., Nicolaidou, A., ThessalouLegaki, M., 2007. Effect of marine litter on the benthic megafauna of coastal soft bottoms: a manipulative field experiment. Mar Pollut Bull 54 (6), 771–778

82 Werner, S., Budziak, A., van Franeker, J., Galgani, F., Hanke, G., Maes, T., Matiddi, M., Nilsson, P., Oosterbaan, L., Priestland, E., Thompson, R., Veiga, J., Vlachogianni, T., 2016. Harm caused by marine litter. MSFD GES TG Marine Litter – Thematic Report. JRC Technical report EUR 28317 EN. European Union

83 Landos, M., Smith, M. L., Immig, J., 2021. Aquatic pollutants in oceans and fisheries. International Pollutants Elimination Network, National Toxics Network

84 Gunderson, A. R., Armstrong, E. J., Stillman, J. H., 2016. Multiple stressors in a changing world: The need for an improved perspective on physiological responses to the dynamic marine environment. Ann Rev Mar Sci 8, 357–378

85 Orr, J. A., Vinebrooke, R. D., Jackson, M. C., Kroeker, K. J., Kordas, R. L., Mantyka-Pringle, C., Van den Brink, P. J., De Laender, F., Stoks, R., Holmstrup, M., Matthaei, C. D., Monk, W. A., Penk, M. R., Leuzinger, S., Schafer, R. B., Piggott, J. J., 2020. Towards a unified study of multiple stressors: divisions and common goals across research disciplines. Proc Biol Sci 287 (1926), 20200421

86 Coe, M. T., Marthews, T. R., Costa, M. H., Galbraith, D. R., Greenglass, N. L., Imbuzeiro, H. M., Levine, N. M., Malhi, Y., Moorcroft, P. R., Muza, M. N., Powell, T. L., Saleska, S. R., Solorzano, L. A., Wang, J., 2013. Deforestation and climate feedbacks threaten the ecological integrity of south-southeastern Amazonia. Philos Trans R Soc Lond B Biol Sci 368 (1619), 20120155

87 Kroeker, K. J., Kordas, R. L., Harley, C. D., 2017. Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. Biol Lett 13 (3), 20160802

88 McComb, B. C., Cushman, S. A., 2020. Synergistic effects of pervasive stressors on ecosystems and biodiversity. Front Ecol Evol 8, 398

89 Pereira, H. M., Leadley, P. W., Proenca, V., Alkemade, R., Scharlemann, J. P., Fernandez-Manjarres, J. F., Araujo, M. B., Balvanera, P., Biggs, R., Cheung, W. W., Chini, L., Cooper, H. D., Gilman, E. L., Guenette, S., Hurtt, G. C., Huntington, H. P., Mace, G. M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R. J., Sumaila, U. R., Walpole, M., 2010. Scenarios for global biodiversity in the 21st century. Science 330 (6010), 1496–1501

90 Barnosky, A. D., Hadly, E. A., Bascompte, J., Berlow, E. L., Brown, J. H., Fortelius, M., Getz, W. M., Harte, J., Hastings, A., Marquet, P. A., Martinez, N. D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J. W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D. P., Revilla, E., Smith, A. B., 2012. Approaching a state shift in Earth's biosphere. Nature 486 (7401), 52–58

91 Ceballos, G., Ehrlich, P. R., Barnosky, A. D., Garcia, A., Pringle, R. M., Palmer, T. M., 2015. Accelerated modern human-induced species losses: Entering the sixth mass extinction. Sci Adv 1 (5), e1400253

92 Jackson, J. B., 2008. Colloquium paper: ecological extinction and evolution in the brave new ocean. Proc Natl Acad Sci USA 105 Suppl 1, 11458–11465

93 Everaert, G., De Rijcke, M., Lonneville, B., Janssen, C. R., Backhaus, T., Mees, J., van Sebille, E., Koelmans, A. A., Catarino, A. I., Vandegehuchte, M. B., 2020. Risks of floating microplastic in the global ocean. Environ Pollut 267, 115499

94 Wilcox, C., Van Sebille, E., Hardesty, B. D., 2015b. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc Natl Acad Sci USA 112 (38), 11899–11904

95 M.B. Tekman, L. Gutow, C. Peter, M. Bergmann, 2021. *LITTERBASE: Online Portal for Marine Litter*, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, litterbase.org

96 Walther, B., Nation engulfed by plastic tsunami, in Taipei Times. 2015. p. 8

97 Barcelo, D. and Y. Pico, Case studies of macro-and microplastics pollution in coastal waters and rivers: Is there a solution with new removal technologies and policy actions? CSCEE, 2020. 2: p. 100019.

98 Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., Virdin, J., Dunphy-Daly, M. M., 2020. Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. Environ Int 144, 106067

99 Helinski, O. K., Poor, C. J., Wolfand, J. M., 2021. Ridding our rivers of plastic: A framework for plastic pollution capture device selection. Mar Pollut Bull 165, 112095

100 Slat, B., How the oceans can clean themselves: a feasibility study. 2014, Ocean Cleanup Foundation

101 Hohn, S., et al., The long-term legacy of plastic mass production. Sci. Total Environ., 2020. 746: p. 141115

102 Cordier, M. and T. Uehara, How much innovation is needed to protect the ocean from plastic contamination? Sci. Total. Environ., 2019. 670: p. 789-799.

103 Morrison, E., et al., *Evaluating The Ocean Cleanup, a marine debris removal project in the North Pacific Gyre, using SWOT analysis.* Case Stud. Environ., 2019. 3(1): p. 1-6.

104 Padervand, M., et al., *Removal of microplastics from the environment. A review.* Environ. Chem. Lett., 2020. 18(3): p. 807-828.

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