

PLASTIC POLLUTION
BIODIVERSITY UNDER THREAT



X. Cousin, G. Darmon,
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Plastic pollution, biodiversity under threat

Xavier Cousin, Gaëlle Darmon, Marie-France Dignac, Franck Lartaud, Gaël Le Roux, Gaëlle Mathieu-Ernande, Claude Miaud (eds)

Preface by Angèle Préville and Philippe Bolo

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The BiodivOc project was born from an initiative by the Occitanie Region to support research into the functioning and dynamics of biodiversity. This work was conducted at a regional scale, but its implications are much broader. Indeed, it would be futile to attempt to understand biodiversity within a restricted geographical space. It would be equally futile to neglect such research amidst the current erosion of biodiversity. The drivers of this decline are well-known and scientifically identified: major climate change, land-use change due to urbanization and agriculture, invasive species, and, of course, pollution in all its forms.

When discussing "pollution", one cannot ignore plastic—ubiquitous and massive, as Angèle Préville and Philippe Bolo remind us in the preface to this book. Yet our knowledge of plastic's impact on biodiversity, species and ecosystems remains limited and all too often overlooked. This led the *Défi Clé* BiodivOc to organize the symposium entitled "Biodiversity and Plastic Pollution: From Impacts to Solutions" in Banyuls-sur-Mer in January 2023. This event brought together a panel of scientists, policymakers, businesses, associations, and citizens to review current knowledge and explore potential ways forward. It is from this symposium that this book was created as a collective endeavour, a principle well worth upholding today.

Our primary thanks go therefore to the Occitanie Region for granting us complete freedom of choice and action; to the University of Montpellier for their unfailing support, without which this work would certainly not have seen the light of day; and to the Banyuls Oceanological Observatory (Sorbonne University) for hosting the symposium.

We also thank the thirty authors who contributed to this work. By drawing on concrete examples from recent scientific studies, they provide the reader with the keys to understanding the major challenges and risks posed by plastic pollution.

Sincere thanks are also due to the members of the coordinating committee—X. Cousin, G. Darmon, M.-F. Dignac, F. Lartaud, G. Mathieu-Ernande, G. Le Roux and C. Miaud—for their dedication. Under the tenacious and exacting leadership of G. Mathieu-Ernande, they ensured the coherence and quality of this work, and (nearly) succeeded in keeping us to the schedule.

I would like to extend a special thanks to Angèle Préville and Philippe Bolo for kindly writing the preface, and for their long-standing commitment alongside the scientific community to alert public authorities to the gravity of plastic pollution.

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Preface

What kind of world do we want for tomorrow? What kind of world do we wish to leave to future generations?

This work provides some answers to these essential questions. Supported by the extensive research of scientists and specialists in plastic pollution and its impacts, it represents a tremendous effort to raise awareness, which is essential for strong engagement of both citizens and policymakers.

As part of our report, "Plastic Pollution: A Ticking Time Bomb?"[1], submitted to OPECST (Parliamentary Office for the Evaluation of Scientific and Technological Choices) in 2020, we interviewed many scientists working on this subject. They drew up an alarming assessment!

Since then, their research, experiments, and observations have continued, providing us with additional knowledge and an increasingly refined understanding of pollution and its effects. Sharing this knowledge is vital to ensuring that everyone understands this insidious and widespread pollution. It is a necessary prerequisite for initiating both individual and collective action. In this light, we commend the authors' generous and responsible initiative to share their scientific expertise.

The "revelations" contained in this book are likely to raise awareness, shake things up, and provoke reactions and actions that challenge our certainties and habits. Just as our report for OPECST was a landmark publication, this volume aims to be equally pivotal. It provides irrefutable evidence of the urgency with which we must address this subject. Our collective responsibility is to ensure that the state of the planet is no worse than it was before we came along.

Our various projects for OPECST—the aforementioned 2020 report, the 2023 public hearing summary on the scientific stakes of the international treaty to end plastic pollution[2], the 2023 note on plastic recycling[3], and the 2024 public hearing summary on the impacts of plastics on human health[4]—have allowed us to measure, sometimes with dread, the considerable long-term effects of this pollution. It is already so unacceptably extensive, disseminated and scattered across every part of the Earth, and within the organisms that inhabit it. It exists in all forms and at all scales, sometimes in fragments so small—micro- and nanoplastics—that they become invisible.

1. "Pollution plastique, une bombe à retardement ?", https://www2.assemblee-nationale.fr/content/download/320346/3119124/version/2/file/2020_0063_rapport_pollution_plastique-compress%C3%A9.pdf
2. https://www.senat.fr/rap/r22-641/r22-6411.pdf
3. https://www.philippe-bolo.fr/wp-content/uploads/2024/01/opecst_note_recyclage_plastiques_vf2.pdf
4. https://www.senat.fr/rap/r24-141/r24-141-syn.pdf

We have a responsibility to stem this massive and uninterrupted flow and to halt an accumulation that has, unfortunately, been going on for far too long.

Despite the warnings, plastic production continues to grow exponentially. Contrary to what one might imagine given the shocking pictures of seals entangled in discarded plastic fishing nets or turtles injured by straws lodged in their nostrils, plastic consumption has not decreased. "Ghost nets"—which are anything but ethereal—cause the death of marine animals. This is not a marginal phenomenon but a cruel and appalling reality, extremely detrimental and a primary driver of biodiversity decline.

As parliamentarians, we utilized the "Circular Economy and Anti-Waste" law (*loi AGEC*) to incorporate several measures aimed at curbing the negative impacts of the irrational use of plastics. Among the robust measures of this law, we should specifically mention the implementation of Extended Producer Responsibility (EPR) for fishing gear, the obligation to limit the leakage of virgin plastic pellets at production, transport and storage facilities, and the ban on plastic packaging for fruit and vegetables.

All these virtuous legislative intentions were met with circumvention by active lobbying, which is unscrupulous and indifferent to the urgency of preserving the planet, its biodiversity, and our collective health. These actions have delayed the law's implementation.

In many respects, certain plastics are no longer "fantastic", but horrific. Misplaced in nature, they do not decompose; they fragment. They become laden with the organic pollutants they encounter. They are colonised by numerous microorganisms that are potentially invasive and pathogenic. Finally, throughout their extensive life cycle, they leach the additives, plasticisers and other chemicals they contain. Some of these molecules are endocrine disruptors that continuously accumulate in every environmental compartment, in water, soil and in our bodies. Even low doses put our health and our ecosystems at risk.

This book documents, with scientific evidence, each of these phenomena and their consequences. It helps show that pollution from surface macrolitter on the oceans is merely the tip of the plastic pollution iceberg. It is beneath the visible surface, down to the seabed, that the problem is far more significant. Knowing that our beautiful Mediterranean Sea—the *Mare Nostrum* so dear to our hearts—is one of the most polluted marine areas on earth must serve as a stark wake-up call, demanding a forceful and immediate response.

Our hyper-consumerist society has made plastic omnipresent in our daily lives, creating habits and conveniences associated with "disposable" and pre-packaged culture. The problem of plastic pollution is far more complex than the simple abandonment of packaging in the environment. It touches upon our lifestyle habits, the very organization of our society, and our consumption model. The pace is still accelerating, as shown by the recent and emblematic phenomenon of ultra-fast fashion: the frenetic and massive consumption of synthetic fibre clothing purchased online at very low prices.

It should be shouted loud and clear: polyester and fleece fabrics are plastic! It is said that the quantity of clothing already manufactured and available in the world could clothe 12 billion human beings for four generations! With the rampant production

of synthetic textiles, the health risks and deleterious effects on ecosystems lie in the dissemination of plastic microfibres into the air and water during machine washing and daily wear.

We expect a great deal from the forthcoming United Nations treaty on plastic pollution currently under negotiation. We attended the second session of the Intergovernmental Negotiating Committee in Paris in May 2023. This legally binding instrument represents a formidable opportunity to push for solutions that must be taken on a global scale.

Within these negotiations, we have seen the influence of lobbies and the overly large number of countries hostile to a reduction in production, whether for economic and strategic interests or through a lack of understanding of the impacts of plastic pollution.

In the debates surrounding this international treaty, the issue of additives is emerging, which is a welcome development. However, while further scientific research is indeed necessary on these, for some—make no mistake—it serves as a pretext to further delay the binding decisions that would apply to them.

There is still a long way to go, and we need to see more initiatives of all kinds to reverse this trend. This is everyone's responsibility.

The strength provided to us by the scientific community lies in the power of knowledge and understanding, which allow us to act as informed citizens. Our sincere thanks go to all those who have dedicated their time and shared their expertise to make this vast subject accessible.

Expectations are high, and it is optimism that must sustain us.

We hope you enjoy the book!

Angèle Préville[5] *and Philippe Bolo*[6]

5. **Angèle Préville** is a former senator of the Lot department, member of the Committee on Regional Planning and Sustainable Development, and member of the Parliamentary Office for the Evaluation of Scientific and Technological Choices (*Office parlementaire d'évaluation des choix scientifiques et technologiques*) (2017-2023).

6. **Philippe Bolo** is the mayor of Avrillé, Vice-President of Angers Loire Métropole, former Member of Parliament (député) for Maine-et-Loire, former member of Economic Affairs Committee, Parliamentary Office for the Evaluation of Scientific and Technological Choices (2017-2026).

General introduction

Fabienne Lagarde and Pascale Fabre

Plastic: a revolutionary material

Plastics entered our lives on a massive scale starting in the 1960s, carrying the image of inert, resistant, and safe materials. What we call "plastic" is primarily composed of polymers, which are very long chains made of small molecules (or monomers) linked together. Additives are also included in their composition, though in smaller quantities, to grant them specific properties such as plasticity or resistance to ageing. These exceptional qualities constituted a true revolution in materials chemistry, as evidenced by the fact that several Nobel Prizes were awarded in the second half of the 20th century to researchers who discovered or studied them. Due to their very low cost, plastics have democratised access to consumer goods and technology and have improved medical care worldwide. They have quite simply revolutionised our lives. Yet, sixty years later, they are considered a global scourge and have become the central focus of international negotiations under the auspices of the United Nations to try to halt their proliferation.

The plastic bag perfectly illustrates this paradigm shift: the first polyethylene bag was patented in 1965 by the Swedish company Celloplast and, 25 years later, occupied more than 80% of the bag market in Europe (Figure I.1). These bags, presented as being



Figure I.1. From the first disposable polyethylene bag (patented in 1965) to plastic-filled landscapes (2011).

clearly superior to paper bags or reusable bags, entered the American market in the early 1980s and, following a meteoric success, brought us into the "fully-disposable" era. In barely 20 years, the world was invaded by plastic, including the famous disposable bags, and following the first alerts from explorers and scientists, some states began to act. Bangladesh was the first country in the world to ban plastic bags in 2002, after discovering during catastrophic floods that they were clogging drainage systems. Other countries followed suit, but without truly reversing the trend. In 2011, it was estimated that one million plastic bags were consumed every minute worldwide! To date, nearly 100 countries have partially or totally banned the use of disposable plastic bags, and numerous restrictions on the use of single-use plastics have emerged. Nevertheless, global production of plastic materials continues what seems to be an inexorable progression, with nearly 460 million tonnes produced in 2019.

⏩ Plastics at the confluence of the triple planetary crisis of climate, pollution and biodiversity

Thus, in less than sixty years of existence, plastics have become the third most produced material in the world after cement and steel, representing absolutely considerable volumes. This massification of production and usage now places plastics at the confluence of the triple planetary crisis we are experiencing—that of climate, pollution, and biodiversity loss (Figure I.2).

The consequences of human activity on the environment are difficult to predict and even harder to quantify. The concept of "planetary boundaries" was recently proposed to quantify human-caused disturbances to the Earth system in ecological, biogeochemical, and climatic processes. It is throughout their entire life cycle—from raw material extraction to production, consumption, treatment, or release into the environment—that plastics have an environmental impact and contribute to exceeding planetary boundaries. At present, six of the nine planetary boundaries have been exceeded; plastic contributes directly to one of them—the introduction of novel entities into the biosphere—and indirectly to five other boundaries already exceeded, the main ones being climate change and biodiversity loss. Among the five chemical products most produced in Europe and responsible for approximately 50% of the impacts on planetary boundaries are two plastic materials: polypropylene and high-density polyethylene, in addition to styrene, a toxic monomer precursor to polystyrene.

To cite only a few of the main effects of plastic production on the environment, we note the greenhouse gas emissions during the extraction of fossil resources for the production and synthesis of polymers, the vast majority of which are derived from petrochemistry. These emissions currently represent 3% of total CO_2 emissions; projections predict this proportion will reach 15% in 2040 (Karali *et al.*, 2024). Thus, plastic production contributes to climate change and ocean acidification, which becomes less and less effective for carbon sequestration, creating a vicious circle. Furthermore, there is not one plastic, but many plastics, with more than 16,000 chemical molecules that can enter their formulation as components or additives to give them specific properties: fire-retardants, antioxidants, plasticisers… Some of these additives produced in very large quantities are toxic and invade our daily lives and our environment. Moreover, through their growing presence in the soil, the atmosphere, and aquatic environments, plastics and their additives also alter habitats and ecosystems, contributing to the modification of biodiversity.

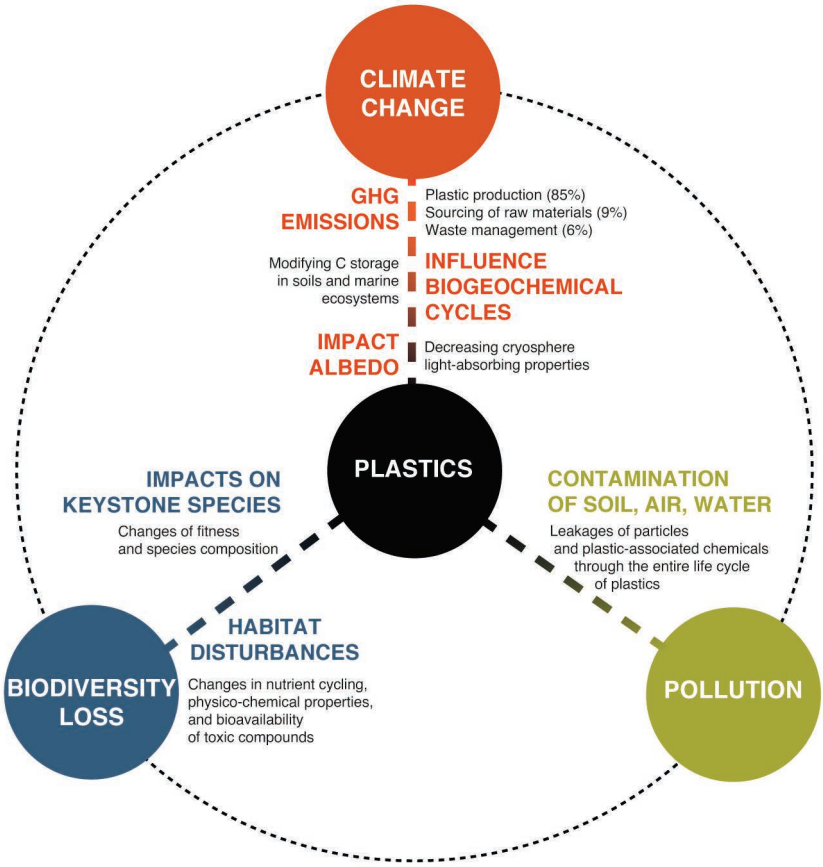


Figure I.2. Plastics are at the centre of the three planetary crises: climate change, biodiversity loss, and pollution.

GHG: greenhouse gas; C: carbon.

But of all the stages of its "life", it is in its "end of use" that plastic effectively turns into a problematic pollution, today clearly identified by the general public. Indeed, given the quantities produced and the fact that 40% of plastics are intended for short-term use, the volume of plastic waste generated is considerable and increases at the same rate as production. In its reference scenario, the Organization for Economic Co-operation and Development (OECD) predicts that the volume of plastic waste will further increase considerably in the coming decades, rising from 353 million tonnes (Mt) in 2019 to 1,014 Mt in 2060. These flows and the diversity of plastics that compose them make the management of these mountains of waste complex.

Recycling, presented as the essential link in this management, despite the efforts and costs incurred, is not living up to expectations. At present, worldwide, barely 10% of end-of-use plastics are actually recycled. More than 30% are still destined for landfills that are often poorly controlled, and it is estimated that every year, several tens of millions of tonnes of plastics enter the environment, quantities that could triple by 2040.

Like their production and usage phases, all plastic end-of-life stages have repercussions on the environment, but poorly managed waste that enters it directly and uncontrollably raises particular concerns, notably regarding its possible impacts on biodiversity.

It is estimated that every year, 8 to 12 million tonnes of plastics reach the world's oceans and seas via rivers and coastal areas. While the "plastic continent"[7] is the most infamous and constitutes the first giant plastic dump brought to public knowledge, we know today that plastic is present in all compartments of the environment: seabed, rivers, soil, atmosphere, and even in clouds. The presence of plastic in large quantities in the soil is less visible and publicised but is starting to be very well documented.

The durability of plastics is, in fact, both too great and not great enough: primarily under the effect of solar ultraviolet (UV) rays—much like the plastic chair on our terrace after several years—it crumbles and turns into smaller particles of a few millimetres: microplastics. These very light particles are easily transported by wind over great distances: they have been found even in remote regions of the Arctic. Until recently, it was even thought that microplastics could be used as a marker for the Anthropocene, had this era been validated: the depth of the sedimentary layers in which they are found was supposed to give us the starting point of the "all-plastic" era. But irony of fate: researchers have recently shown that the smallest particles slip deeper and deeper into the sediments, reaching zones corresponding to periods when plastic had not even been invented! Thus, it invades our present… and remodels the past.

However, the story does not end with microplastics: these particles can indeed continue to degrade into objects 1,000 to 10,000 times smaller: nanoplastics. Like all other nanoparticles, these are probably small enough to cross cell barriers and penetrate to the interior of organs, potentially causing much greater and more lasting damage than larger particles.

⏩ From plastic presence to plastic impacts

Not a day goes by without hearing about the loss of biodiversity, but what exactly does this term cover? Scientists speak of "biodiversity" at three levels: genetic diversity within a population or species, species diversity in a given location, and ecosystem diversity. For example, marine biodiversity includes coral reefs, kelp forests, seagrass beds, etc. Insofar as biodiversity covers a wide variety of species and ecosystems, assessing the consequences of plastic pollution on biodiversity is a very complex task. Furthermore, many factors influence biodiversity, and it is not easy to identify those specifically linked to polymers and their additives. To overcome this difficulty, scientists often reproduce environmental conditions as best as possible—but in a simplified way—in their laboratory. Another difficulty is linked to the complexity of plastic formulations, generally kept secret, and which range from ten to a hundred components: consequently, how can "the" culprit of an effect be isolated, especially as each plastic is different and different types of plastics are generally found in the places where they accumulate. Thus, it is difficult to prove that a given pollutant has an impact in such a multifactorial environment, and to convince the public, businesses, or the political world of this causality.

7. Discovered in 1997 by the American oceanographer Charles Moore, the "7th continent", also known as the "Great Pacific Garbage Patch", is situated between Hawaii and California; it currently spans over 1.6 million square kilometres, an area three times the size of mainland France (Lebreton *et al.*, 2018).

Despite all this complexity, three major classes of phenomena are now considered to have an impact on biodiversity: entanglement, ingestion, and the "rafting" effect.

Today, the observation is simple: wherever we look for plastic, we find it. Plastics have thus been identified by the scientific community in very varied environments and in a vast number of organisms at different levels of the trophic chain[8]. As oceans are a final receptacle for many pollutants including plastics, one of the first victims of plastic pollution is marine biodiversity. More than 1.5 million marine animals die every year because of plastic pollution, including 100,000 marine mammals caught or entangled in plastic waste. The accumulation of macroplastics (such as fishing gear or single-use plastics) in the environment can also cover and deteriorate important ecosystems, durably altering heritage or landscapes but also leading to the destruction of certain natural habitats such as coral reefs and mangroves.

Depending on their size, these wastes can also be ingested. A recent study (Darmon *et al.*, 2022), for example, showed the presence of plastic in the digestive tracts of nearly 70% of turtles found dead around the Mediterranean, although it cannot be stated that their death was solely linked to the presence of this waste. In the bird species *Ardenna carneipes* from Lord Howe Island, Australia, the link between plastic ingestion and a new disease, ironically named plasticosis and consisting of a fibrosis of the digestive tract, was recently highlighted (Charlton-Howard *et al.*, 2023).

At micro- and nanometric sizes, plastic particles also affect smaller organisms that ingest them, right down to the fundamental bases of food chains such as plankton. By passing through their digestive system, these particles have deleterious effects on organisms by altering certain biological functions, such as filtration activities and digestive processes, with repercussions on the animal's energy metabolism and major physiological functions, such as growth or reproduction. Furthermore, certain chemical additives in plastics have also been identified as having negative effects on reproduction and development in mammals, birds, fish, invertebrates, insects, and, at the end of the chain, humans.

At a larger scale, the great variety of microorganisms, named the "plastisphere" (see Part 3, Chapter 4), which colonises plastic debris in the environment could lead to significant modifications of ecosystems. For example, five years after the tsunami that took place in Japan in 2011 on the Pacific coast of Tōhoku, hundreds of new species of bacteria and microorganisms that had travelled on plastic debris (rafting effect) from the Japanese coasts were found on the American coasts. These exotic species can become invasive and thus disrupt the balance of local ecosystems by competing with native species.

Even soils and their biodiversity are not spared. We know today that soils are also the receptacle for very large quantities of plastic waste via direct contamination (illegal dumping, agricultural tarps, etc.), but also in a more indirect way through the spreading of sludge from wastewater treatment which itself contains microplastics. The presence of these particles can lead to changes in soil properties and thus modify not only the bacterial communities found there, but also the entire soil biodiversity, which now constitutes a major concern for the agricultural sector.

8. We also talk about the "food web", which describes the totality of trophic interactions between organisms within an ecosystem. Within a food web, various trophic levels are identified, defining, for instance, predator-prey relationships.

This work aims to explore the different facets of a problem that has become global and complex. Through some examples of in-depth analyses and recent case studies, we will examine the multiple effects of plastic pollution on different terrestrial and aquatic ecosystems, as well as on the species that depend on them for their survival.

Throughout the book, you will better understand the challenges posed by the massification of plastic in our lives, as well as the urgency of putting in place innovative solutions and better practices to limit their use and their impacts on biodiversity and the environment. Finally, we will reflect on the individual and collective actions necessary to face this environmental crisis and preserve the richness and diversity of life on Earth, indispensable for long-term human survival.

Part 1

A world wrapped in plastic

Introduction

Jean-François Ghiglione

In 2020, a study published in the journal *Science* showed that the **mass of plastic produced since the creation of this material in the 1950s (8 billion tonnes) is twice as large as the biomass of animals living on Earth** (Elhacham *et al.*, 2020). Four years after this study, the weight of plastics has already exceeded 10 billion tonnes and it will surpass 20 billion tonnes in 2040 (5 times more than the global biomass of animals) if no significant action is undertaken (Baztan *et al.*, 2024). It is estimated that 30% of the plastic materials produced since 1950 are still currently in use, 7% have been recycled, 10% incinerated, and approximately 50% are now dispersed in the environment (Geyer *et al.*, 2017).

"Scientific knowledge is an indispensable foundation for assessing the risks associated with the plastic lifecycle [*author's note*: from the extraction of resources to their end-of-life] and for devising adequate solutions to this major form of pollution", as highlighted by Luis Vayas Valdivieso (Chair of the Intergovernmental Negotiating Committee, INC[9]) at the opening of the international negotiations for a global treaty to combat plastic pollution in Ottawa (INC-4, April 2024).

The impact of plastics is manifold, **contributing to the triple planetary crisis of climate change, pollution, and biodiversity loss**:

– **climate change:** most greenhouse gas emissions (primarily in the form of CO_2) linked to plastics result from the energy used at different stages of its life cycle, notably during the extraction of fossil fuels, the production of monomers, resins, and additives (15% of oil production is intended for the production of plastics; International Energy Agency [IEA, 2018]), during the processing of plastics, and during their end-of-life "management" (incineration, recycling, landfill, and leakage into the environment). **The majority of greenhouse gas emissions occur during plastic production** (85%). Other emitting phases, though to a lesser degree, are the initial stages of raw material supply (9%) and waste management (6%, primarily during incineration) (Cabernard *et al.*, 2022). Taking into account the economic losses associated with climate change, environmental degradation, and effects on organisms and human health, the global cost of CO_2 emissions from plastic production has been estimated at 341 billion dollars per year (Landrigan *et al.*, 2023);

– **ecosystem pollution:** plastics contribute to the pollution of all the planet's ecosystems, from the world's highest peaks to the deepest oceans, but they are also present in our food or in the air we breathe (Stubbins *et al.*, 2021). The great diversity

9. The United Nations Environment Programme (Unep) is a specialized agency of the United Nations, established in 1972, that aims to coordinate United Nations activities in the field of the environment, strengthen environmental governance and law, safeguard ecosystems, and provide evidence-based data to inform policy decisions.

of chemicals present in marketed plastics (more than 16,000) poses an obvious problem, since more than 3,000 of them have shown toxic effects for certain organisms (Wagner *et al.*, 2024). **Pollution is present throughout the life cycle of plastics**: during the extraction of fossil materials (greenhouse gas emissions, discharges of fracking water, petroleum products, and other chemicals), the production of plastics (release of chemicals, micro- and nanoplastics, and additives), in transport (leakage of pellets or finished products), in their use (voluntary or involuntary release), and in waste management (including recycling). Furthermore, plastics are constantly ageing, contributing to the release of smaller particles or molecules (microplastics, nanoplastics, oligomers, monomers, as well as additives and their degradation products) throughout their life cycle (Arp *et al.*, 2021);
– **effects on biodiversity:** the effects of plastic pollution on biodiversity are visible at every level of the food chain (including humans). Landfills and illegal dumping, as well as the dispersion of plastics as they transform into microplastics and nanoplastics, contribute to the **alteration of all habitats on Earth (soil, air, water)**. For example, abandoned fishing nets or debris from packaging or single-use plastics can have an impact on species, particularly for keystone species and/or endangered species, through ingestion or entanglement (Manullang, 2020). Effects have been observed up to the mortality of the analysed species, but also on the regulation of their growth, on reproduction, on blood pressure, on blood glucose, and on homeostasis in connection with the presence of numerous chemicals in plastics (Leistenschneider *et al.*, 2023). Plastic pollution also constitutes a threat to human health due to multiple pathways of exposure (e.g. contaminated food or the inhalation of particles) and cumulative impacts (Landrigan *et al.*, 2023).

Plastic pollution results from a dynamic process that can be diagrammed in three main successive stages (Figure 1.1):
– losses and leakages of plastics into the environment throughout their life cycle;
– their dispersion in the environment, notably via wastewater or stormwater networks, air and wind, atmospheric fallout (rain, snow), watercourses, and marine currents;
– the accumulation of plastics in the various compartments of continental waters, soil, air and oceans.

During the last decade, the scientific community has deployed considerable efforts to create an inventory of plastic pollution in the environment. Research, which began with the inventory of plastic waste in the ocean, has more recently turned towards continental waters, soils and the air, attempting to obtain the most precise image possible of the quantities of plastics in the air-land-sea continuum.

However, the diversity of polymers and the multiplicity of formulations make the quantification and characterization of plastics in the environment difficult. To this diversity is added the variability of the plastic life cycle, whose degradation and fragmentation depend on the conditions of the medium and the environmental factors to which they are subjected (ultraviolet rays, oxygen, water, microorganisms etc.).

Numerous fields of research remain to be explored further to understand the life cycle of plastics, their dispersion and their persistence in the different compartments of the environment. This knowledge is essential to measure the scale of the challenges associated with this pollution and to evaluate the numerous impacts on ecosystems and organisms.

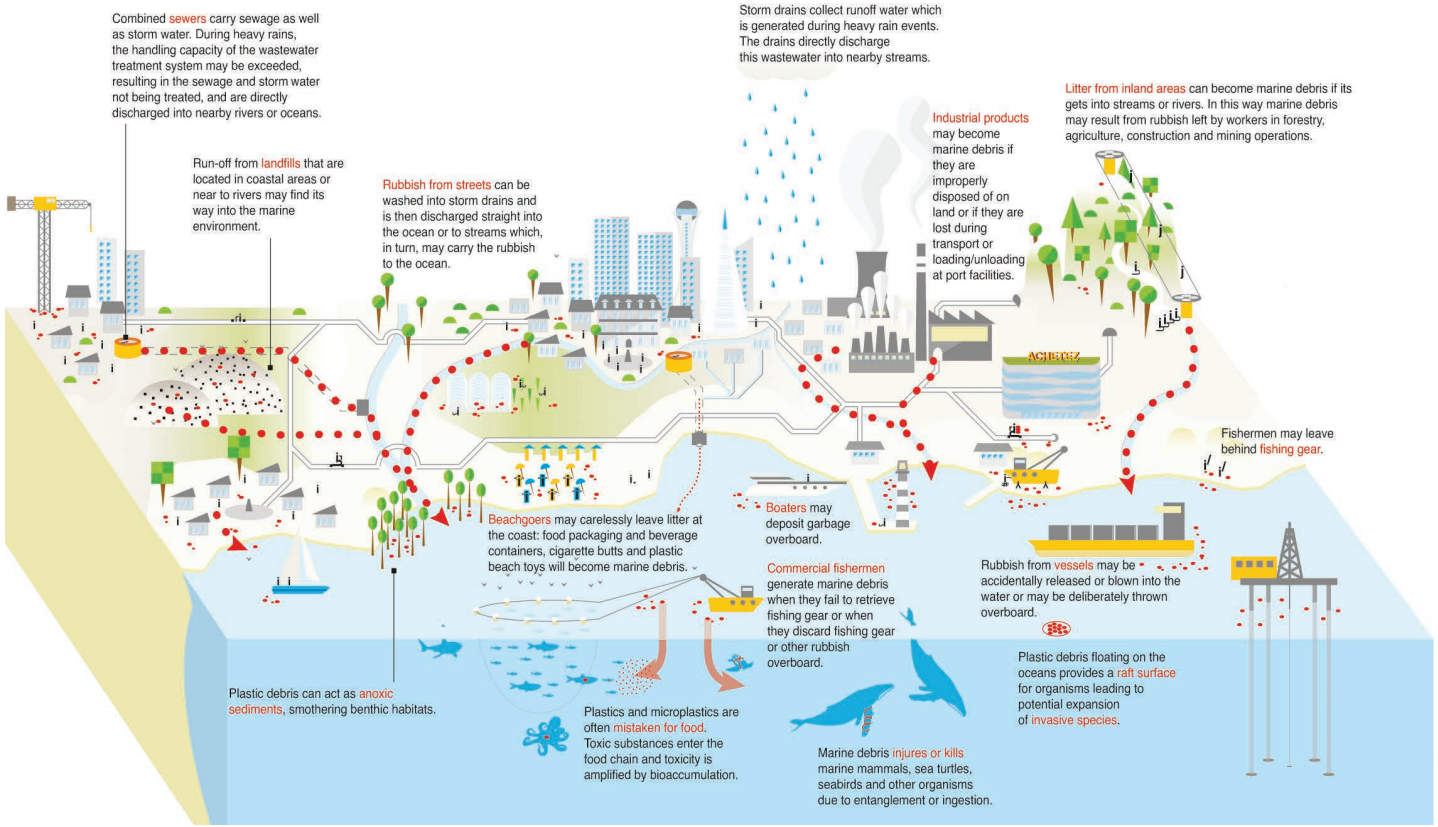


Figure 1.1. The origins of plastic and their dispersion routes in the environment.

All leakages of plastic debris into the environment and, ultimately, into the ocean, result from human activities. Three main sources of release are at the origin of these leakages: residues generated by any type of human activity, leading to their release into the environment; poor management and "illegal dumping" of waste, whether industrial, commercial or domestic; unintentional releases, which come from regular and uncontrolled procedures linked to the processes of extraction, manufacture, distribution and use of plastics. Atmospheric transport of particles can be added to these forms of circulation (see Chapter 2 and Figure 1.2.4).

Chapter 1

What are plastics and their debris?

Roxane Danquigny, Cloé Veclin, Javier Jimenez-Lamana, Bruno Grassl and Stéphanie Reynaud

Plastic materials: history, production and uses

The first plastics were invented in the mid-19th century. They were derived from natural raw materials, such as Parkesine, a thermosetting materiel made from cellulose and presented at the London International Exhibition in 1862, and celluloid, a thermoplastic produced on a large scale from 1872 onwards. It was not until the early 20th century, with associated advances in chemistry, that the production of fully synthetic plastics became possible (Figure 1.1.1). Bakelite appeared in 1907, followed by polyvinyl chloride (PVC) which was invented in 1912, although its widespread use did not begin until the late 1920s with the discovery of plasticisers. Plastic production

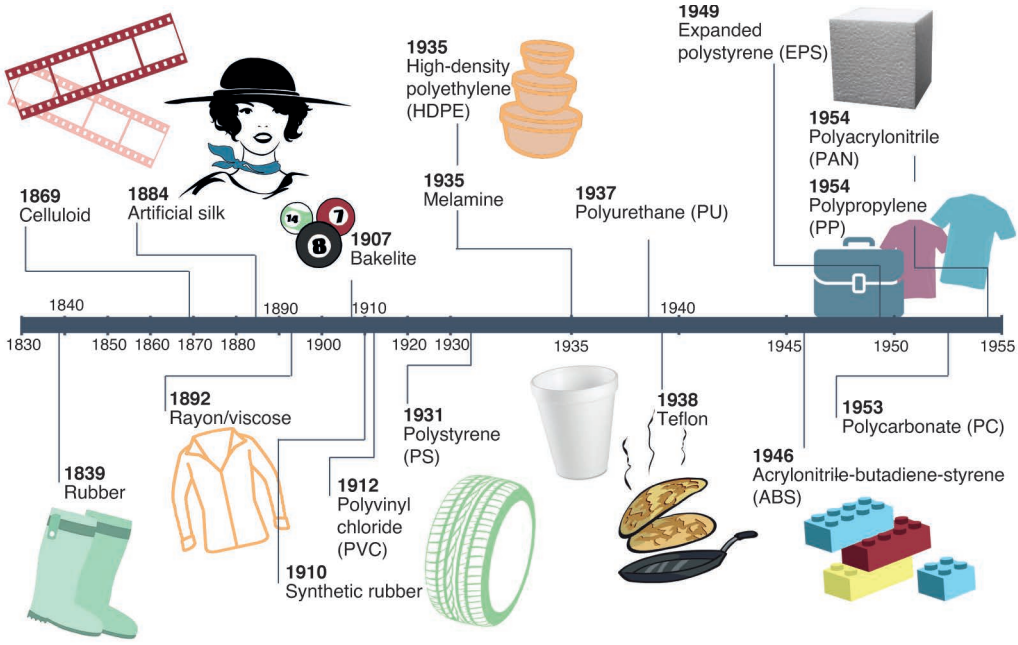


Figure 1.1.1. The history of plastic.

intensified during the Second World War with the development of polyethylene (PE), polystyrene (PS) and polyethylene terephthalate (PET). Since the 1950s, the uses and diversity of plastics have continued to grow, and, between 2000 and 2019, annual global production doubled reaching 460 million tonnes.

Plastics are designed to be resistant, inert, durable, lightweight and malleable, while remaining inexpensive for the producer and the consumer. As a result, they have spread across virtually every sector of society: from packaging to construction, including electronics (Figure 1.1.2). Most plastics are used for packaging, which, according to 2021 data, accounted for more than 40% of global production, followed by construction (18%) and transport (8%). However, it is important to note that certain categories are not included in the data; for example, textiles are excluded, even though they alone accounted 10% of plastic production according to the 2019 report.

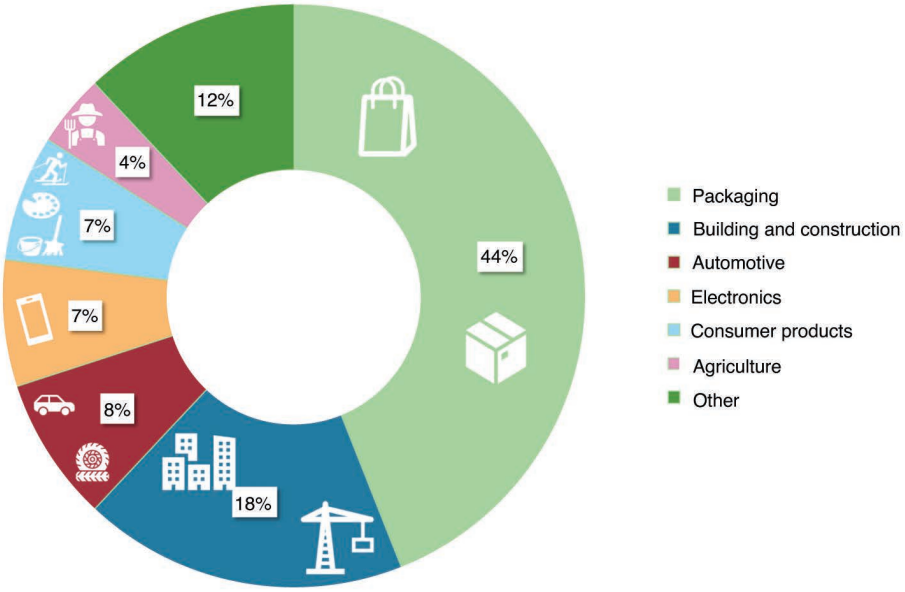


Figure 1.1.2. Distribution of plastic materials use by sector in the European Union (including Switzerland and Norway) in 2021.

The "Other" category includes household appliances, mechanical engineering, furniture, medical applications, etc. (based on data from Plastics Europe "Plastics—the Facts 2022", 2022).

Today, for everyday use in industrial and domestic sectors, six types of plastics dominate the market. They represent around 80% of plastic demand in Europe: low-density polyethylene (LDPE, used, e.g., for plastic bags), high-density polyethylene (HDPE, for shampoo bottles), polypropylene (PP, for food packaging), polyvinyl chloride (PVC, for window frames), polystyrene (PS, for certain yoghurt pots or in its expanded form, EPS, for construction insulation), polyurethane (PUR, for furniture foams) and polyethylene terephthalate (PET, for mineral water bottles).

Polymers are the basis of plastics. They are macromolecular chains made up of monomer units linked together by covalent bonds. For example, polystyrene is formed from styrene units. In most cases, plastics are commonly named after the polymer,

or one of the polymers, that constitutes them, even if they have very complex chemical formulations. Behind such a simplified name, a mixture of polymers may in fact be present, for example, high-impact polystyrene can contain up to 10% polybutadiene, while still being referred as polystyrene. The composition of plastics does not stop there; additives are added to the polymer(s), making it possible to improve the final properties, such as stability (thermal stabilisers, antioxidants, flame retardants, fungicides etc.), mechanical properties (plasticisers, fibres etc.), aesthetics (pigments, dyes etc.) or even surface properties (antistatic, non-slip etc.). Other additives are used to reduce production costs (inert fillers) or facilitate processing (lubricants). To this list are potentially added unreacted starting substances (monomers, catalysts etc.) and non-intentionally added substances (degradation products, impurities etc.). A recent report (Wagner *et al.*, 2024) estimated the number of chemical products present in plastics at more than 16,000; a quarter of them are used even though they are known to be toxic, while toxicological data are unavailable for 67% of them (10,726 substances).

When plastics become waste

Considering the average duration of use of plastic products across different sectors, it is estimated that more than two-thirds of the waste produced comes from plastic products with an average lifetime of less than 5 years (Geyer *et al.*, 2017). In 2019, 353 million tonnes of plastic waste were produced, equivalent to more than three-quarters of the plastics produced in the same year (Figure 1.1.3). Such a volume cannot be managed effectively by collection methods, recycling or by the infrastructure in charge of managing plastic end-of-life. Thus, in 2019, of the 353 million tonnes of plastic waste, around half ended up in landfill and only 9% were recycled. Recycling can be carried out in a "closed loop", where the recycled product is the same as the original one. In an "open loop", the recycled product is different from the original one (e.g. the recycling of a PET bottle into fleece fibre). This is referred to as "downcycling". Furthermore, the very great diversity of chemical formulations of plastics, whose exact compositions are rarely disclosed by manufacturers, complicates the reuse, sorting and recycling of plastic objects at the end of their life.

It has been estimated that around 20% of plastic waste is (re)thrown into the environment. The total fraction of plastics released into the environment (landfill + releases) would represent a little more than 250 million tonnes of plastics for the year 2019 and adds up to the more than 5,300 million tonnes accumulated between 1950 and 2017 (Geyer, 2020). A simulation, based on a constant economic model, shows that this quantity could reach 12,000 million cumulative tonnes in 2050 (Jambeck *et al.*, 2015; Geyer *et al.*, 2017).

Plastic waste: from macroplastics to nanoplastics

Environmental degradation processes

During their lifetime, under the action of different factors such as solar radiation, temperature, mechanical stress or biological activity, plastics undergo degradation processes.

In the environment, the main factor is photodegradation, a chemical process due to UV and visible solar radiation. At the molecular scale, these radiations, associated with oxygen, induce changes in the macromolecular chains that constitute polymers.

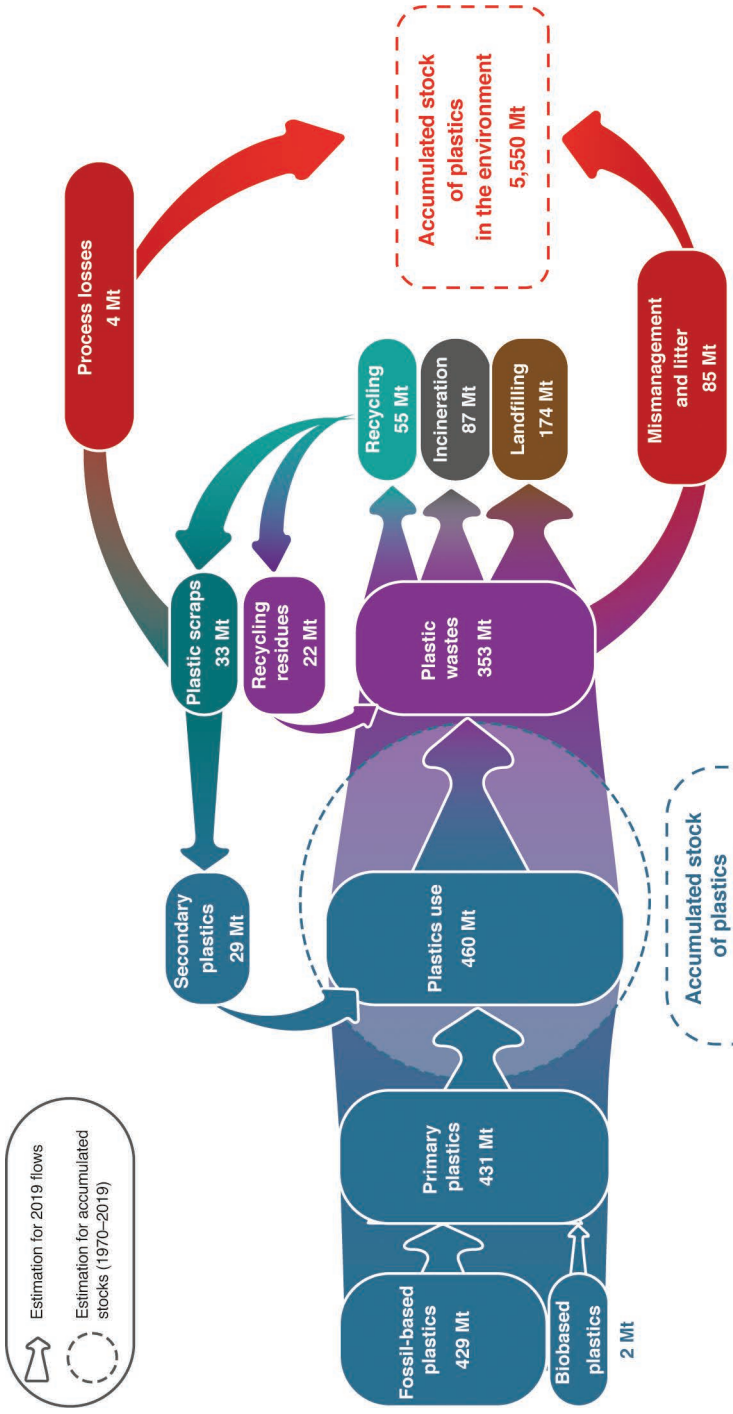


Figure 1.1.3. Global plastic production and plastic waste in 2019 and their fate.
Mt: million tonnes.

This may involve the formation of shorter chains (oligomers) and/or new chemical groups, markers of plastic oxidation, such as carboxyl groups. At the macroscopic scale, cracks and fragmentations are observed, in particular on parts of plastic debris exposed to the sunlight.

The fragmentation of plastic waste can also be caused by mechanical degradation processes, via the action of waves, for example, or biodegradation through the action of microorganisms living on the surface of debris. In both cases, degradation is enhanced by UV irradiation which reduce the size of macromolecular chains making them more readily bioassimilable (Gewert *et al.*, 2015).

Macro-, micro- and nanoplastics: classification and definitions

Degradation processes, whether chemical or physical, make materials fragile, leading to the release of smaller and smaller debris, as illustrated in Figure 1.1.4. The situation is not recent; the first publications reporting the presence of small plastic debris (<5 mm) in the oceans were published in the early 1970s (Carpenter, Smith, 1972; Wong *et al.*, 1974).

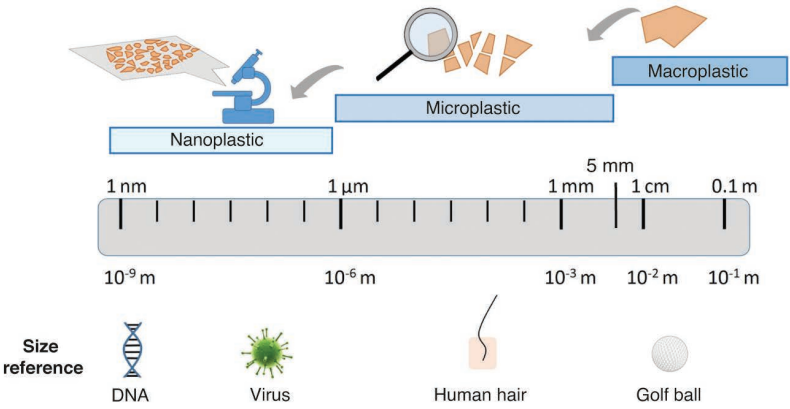


Figure 1.1.4. Classification of plastic particles according to their size (based on data from Hartmann *et al.*, 2019).

The different types of plastic debris are generally defined primarily by their size, but the nomenclature used to classify them sometimes vary among authors and publications, notably regarding the size threshold between nanoplastics and microplastics. A widely accepted classification indicates that nanoplastics are particles smaller than 1 µm, microplastics are between 1 µm and 5 mm and macroplastics are larger than 5 mm.

Moreover, microplastics and nanoplastics are described as "primary" when they are intentionally manufactured for use in specific products (e.g. cosmetics or paints) and "secondary" when they result from the degradation of larger plastic waste.

Microplastics

Microplastics have been observed all around the globe, as far as remote areas such as the Arctic Ocean, in deep waters or even in snow at the top of mountains. This highlights not only their transport in aquatic environments but also their atmospheric transport, and therefore their probable ubiquity.

However, understanding their transport and estimating their quantity in various compartments remains a challenge due to the many parameters involved. In the ocean, for example, the distribution of microplastics in the water column is complex and depends on many factors, such as buoyancy, which can itself be influenced by processes such as the formation of a biofilm on the plastic debris surface. Different estimates have been made to assess microplastic distribution in the environment. The number of microplastics floating on the surface of the oceans has been estimated at more than 170 trillion particles, equivalent to more than 2 million tonnes of microplastics, but these calculations only account for plastic debris that can be sampled by nets (generally Manta trawls) at the very surface (generally 25 cm) and with cut-off sizes between 53 and 505 µm (Eriksen *et al.*, 2023). Therefore, the sampling methods should be considered as an important factor in the interpretation of environmental concentrations. Consequently, in many environments, living organisms are exposed to microplastics and these small debris have been detected in a wide variety of species such as benthic organisms, fish and marine mammals.

In addition to exposure through the environments in which they evolve, organisms are also likely to be exposed to plastic debris via their diet. Trophic transfer phenomena have indeed been observed on several occasions, for example between zooplankton and salmon (Desforges *et al.*, 2015).

Nanoplastics

Although studies are less numerous than for microplastics, mainly due to analytical difficulties, nanoplastics have been detected in the environment on several occasions (Table 1.1.1). As with microplastics, sampling methods may not cover the full-size range of nanoplastics (1 nm-1 µm) and concentration values must be considered with caution.

Nanoplastics have been detected in multiple environmental samples (Table 1.1.1) such as seawater, freshwater, or even in secluded areas like the Alps (Materić *et al.*, 2020), Greenland and Antarctica (Materić *et al.*, 2022b). As for microplastics, this highlights their ubiquity.

The quantification of nanoplastics in aquatic environments is already challenging and it becomes even more difficult in complex matrices such as organisms in the natural environment. This is why, at present, we do not yet have a clear picture of the contamination of fauna and flora by nanoplastics.

Beyond their quantification, for which analytical protocols are still under development, nanoplastics are a major concern because their size makes translocation phenomena possible. Nanoplastics are likely to cross cell walls and be assimilated within organisms. However, today, there is no consensus on the size threshold of plastic debris' translocation.

Even in the absence of a translocation phenomena, nanoplastics could in principle be a source of toxicity during their transit through organisms, as are microplastics. This toxicity could be direct or indirect, through the transfer of toxic substances present within or on the surface of plastic debris. This phenomenon is called the "Trojan horse effect".

Among the toxic substances that nanoplastics can transport and transfer to organisms, there are, first of all, the additives listed above, which are present from the

Table 1.1.1. Summary of nanoplastic concentrations measured in aquatic environments.

Sample type	Country	Type	Size (nm)	Mean concentration (µg/l)	Reference
River water	United Kingdom	PS	<450	241.8	(Sullivan *et al.*, 2020)
Snow	Austria	PET, PP, PE, PS	<200	15.1 (PET); 29.5 (PP); 25 (PE); 5 (PS)	(Materić *et al.*, 2020)
River water	China	PP, PE, PET, PS, PVC, PMMA	<200	0.283-0.793 (0.117-0.389 PP; 0.088-0.242 PE; 0.011-0.079 PET; 0.007-0.058 PS; 0.006-0.057 PVC; 0-0.046 PMMA)	(Xu *et al.*, 2022)
Ice	Denmark	PE, PET, PS, PVC, PP/PC, Tire wear	<200	13.2 (6.5 PE; 2.7 PET; 0.57 PP/PC; 0.11 PS; 0.11 PVC; 3.2 Tyre wear)	(Materić *et al.*, 2022b)
Fresh water	Sweden	PVC, PE, PET	<200	122 (PVC); 276 (PE); 61 (PET)	(Materić *et al.*, 2022c)
Fresh water	Russia	PVC, PS	<200	109 (PVC); 15 (PS)	(Materić *et al.*, 2022c)
River water	Thailand	PS, PVC, PET, PE, PP, PS, Others	<20-450	336 (189-488)	(Wibuloutai *et al.*, 2023)
Sea water	China	PS, PMMA	<1,000	7.35 (PS); 9.25 (PMMA)	(Zhou *et al.*, 2019)
Sea water	Netherlands	PS	<200	4.2 (2.7-6.5)	(Materić *et al.*, 2022a)
Sea water	Antarctica	PE, PP, PET	<200	52.3 (19.8-38.0 PE; 9.0-20.7 PP; 8.3-8.9 PET)	(Materić *et al.*, 2022b)

PET: polyethylene terephthalate; PP: polypropylene; PE: polyethylene; PS: polystyrene; PVC: polyvinyl chloride; PMMA: polymethyl methacrylate; PC: polycarbonate.

design and production of the plastics. To these additives can be added environmental pollutants, such as organic compounds (e.g. pesticides, endocrine disruptors) and inorganic pollutants (e.g. metals), which are adsorbed by nanoplastics during their residence in the environment. The presence of pollutants on plastic debris has already been highlighted on several occasions, for example on polyethylene debris from the North Atlantic gyre (Prunier *et al.*, 2019), or on microplastics sampled on a beach in Guadeloupe (El Hadri *et al.*, 2020). With their high specific surface area, nanoplastics have greater capacity to accumulate pollutants through adsorption phenomena on their surface, or absorption phenomena within the bulk of the particle debris (Aynard *et al.*, 2023). These aspects will be detailed in Chapter 4 of Part 3.

Whether due to their intrinsic toxicity, or their capacity to transport toxic compounds or pathogenic organisms, nanoplastics represent a major risk for living organisms. For the moment, the size of nanoplastics, their concentration in the environment and the presence of other compounds such as organic matter, salts and microorganisms make their detection, quantification and sampling difficult. The use of nanoplastic model materials makes it possible to study their behavior in laboratory experiments. Tracers (e.g. metals, fluorescent molecules or isotopes) can be added to the model material nanoplastics to facilitate their quantification in complex media such as organisms. This technique enables the quantification at very low concentrations, similar to those expected in natural samples. However, particular attention must be paid to the choice of labelling, to the conditions of production of the nanoplastic model material and to the analytical protocols in order to obtain reliable and representative results. All these aspects are currently at the heart of scientific research and require multidisciplinary projects involving chemists, biologists, ecotoxicologists, physicists and physicians.

Chapter 2

Environmental monitoring: how to quantify, characterise and track plastic pollution?

Marie-France Dignac, Wolfgang Ludwig, Philippe Kerhervé, Bruno Charrière, Gaël Le Roux, Gaëlle Darmon, Franck Lartaud and Jean-Christophe Auguet

⏩ Microplastics in soils: sources, levels and fate

Marie-France Dignac

Many soils are polluted by pesticides, heavy metals and organic pollutants, some of which are persistent. Agricultural soils, in particular, are also affected by, are also polluted by micro- and nanoplastics. However, their presence there has only been documented for about ten years (Rillig, 2012). Yet these plastics can persist in soil for decades to centuries, and their concentrations may even exceed those found in oceans—at least for microplastics.

Recent studies show that contamination levels depend on land use (Büks, Kaupenjohann, 2020). Agricultural soils are more contaminated (with an average of 1,200 particles in a kilogram of dry soil) than forest soils and natural grasslands. Nizzetto *et al.* (2016) estimated that between 107,000 and 730,000 tonnes of microplastics may be deposited annually on agricultural soils in the United States and Europe.

How do microplastics get into the soil?

Microplastics can be deposited onto soils from the air. Indeed, the lightest fraction of microplastics can circulate in the atmosphere and be deposited with rain, particularly when these consist of fibres originating from our clothes. In agricultural soils, a significant proportion of plastics originates from agricultural activities (Nizzetto *et al.*, 2016), such as the use of plastic films for soil mulching, the effects of wear and tear on agricultural equipment (nets, polytunnels etc.), the use of encapsulated mineral fertilisers (Cusworth *et al.*, 2024) or organic fertilizers, whether these come from urban waste composts (Colombini *et al.*, 2022) or agricultural waste (Weber *et al.*, 2022). A study on the soils of the long-term experiment at the Rothamsted Research centre in the United Kingdom, which has collected and stored soil samples since 1840, revealed an increase in microplastics in plots amended with manure, probably due to the increasing use of plastics on farms (Cusworth *et al.*, 2024).

Organic fertilizers derived from waste treatment represent an essential source of organic matter for agricultural soils, but they can also introduce contaminants.

These organic fertilizers can result from the composting of waste of urban or agricultural origin or from the solid fraction resulting from the anaerobic treatment of waste (methanization), known as "digestate". The mechanical treatment of deconditioning or unpacking that is employed to separate the compostable organic fraction from packaging, plastic bags and other materials present in waste, can lead to the release of plastic particles. Sorting biowaste at the source should limit the quantity of plastics present in composts.

Sewage sludge is the residue obtained after wastewater treatment. It contains microorganisms, organic matter and pollutants trapped during the water treatment. Approximately 10 million tonnes of sewage sludge are produced in Europe each year, of which about 40% is spread on soils, which brings 40,000 tonnes of microplastics onto European agricultural land each year (Lofty *et al.*, 2022). In particular, sewage sludge contains large quantities of plastic fibres, concentrated in this solid fraction during wastewater treatment. These fibres in wastewater originate from the washing of synthetic clothes or from wipes thrown into the wastewater collection system.

Plastics are also used directly on farms. Each year, 7.4 million tonnes of plastics are used in the agricultural sector (FAO, 2022), for polytunnels, nets, non-woven textiles or even plastic mulching with plastic films, which are applied directly to the soil. These plastics release micro- and nanoplastics, as well as toxic chemicals into the soils. Most plastics used in agriculture are used for less than a year before becoming waste; this is therefore a short-term use of plastics. Biodegradable plastic films are increasingly replacing conventional plastic mulching, but they also release micro- and nanoplastics and chemicals during their use and are not completely degraded in the soils (Zhou *et al.*, 2023). According to the European standard EN 17033, 90% of the biodegradable mulching film must be degraded after 2 years in the soil. However, the tests are carried out under optimal conditions of temperature and humidity, and only concern the biodegradation of the polymers, not that of the chemicals they contain. These ideal conditions are never found in real soils, and the plastic mulching film will not degrade completely. Furthermore, there are sometimes two applications of plastic mulching per season; considering the 2 years necessary for degradation, there is clearly a problem of accumulation of these materials in the soil. The paradox should also be pointed out, of using plastic mulching in agriculture in response to climate change. The greatest threat today to food security, which will increase in the years to come, is indeed climate change, causing water shortages, rising temperatures, extreme weather events, drought, floods, etc. Locally, agricultural plastics may help to alleviate the effects of climate disruption, whereas, on a global scale, they accentuate this disruption due to the fossil origin of the materials that make them up.

Contamination levels

Microplastics brought in by urban waste composts accumulate in the soil over the years (Colombini *et al.*, 2024). A study on agricultural soils that received applications of compost derived from the residual fraction of household waste (unsorted waste) for 22 years showed that this practice had led to the accumulation in the soil of more than 400 kg per hectare of microplastic particles sized between 2 and 5 mm (Colombini *et al.*, 2022). Soils that received compost from green waste or biowaste sorted at the source presented the lowest microplastic levels. A mass of 400 kg per hectare is equivalent to the mass of 80,000 plastic bags or 1,400 water bottles, which would be

fragmented and distributed over a surface area of one hectare. Until 2020 and the AGEC law (French Anti-Waste for a Circular Economy law), the spreading of these composts derived from organic waste not sorted at the source (mechanical-biological treatment, or MBT) was a very common practice in France. This practice could be banned in 2027. Soils where these composts have been spread for years may have high levels of microplastics, with impacts on biodiversity, plant growth and on the surrounding terrestrial and aquatic natural environments.

Quantification of microplastics in soils

The variety of polymers, and of sizes and shapes of plastics encountered in the environment makes their analysis difficult. Although a wide range of techniques is used for monitoring microplastics in marine environments and sediments, the detection of microplastics in solid matrices (soils and organic residual products) remains a challenge. There is currently no ideal analytical method available, but rather pioneering methods needing to be explored and adapted. Different quantification methods have been proposed, but none is currently standardized. These include FTIR, Raman spectroscopy, DSC thermal analysis, Rock-Eval® and pyrolysis-GC/MS. Reference plastics and plastics at different stages of degradation must be analysed by these different methods to facilitate their identification in soils where they have been fragmented and weathered.

To assess the microplastic contamination of a soil requires three stages: collecting a sample, treating this sample, and making the analysis itself, which is generally done on just a few grams. Each of these stages must follow a rigorous protocol to avoid contamination by plastic particles that are present everywhere in the environment and to work on a sample representative of the studied medium. Field sampling consists of taking several clods or cylinders of soil distributed over the entire surface to be assessed and mixing them to obtain an average sample of a few kilograms, considered representative of the studied site. Drying, sieving and soil particle mixing stages make it possible to reduce the sample size while maintaining its representativeness. The location of the plastics within the soil matrix is important information. Indeed, their environmental impacts, particularly their toxic effects on soil organisms, will be different if they are trapped in organo-mineral aggregates or mixed with coarser soil debris (Guo *et al.*, 2020). Dividing up the sample by separating particles according to their size (Watteau *et al.*, 2018) gives us access to this information. A separation of particles according to their density allows the isolation of plastic particles that are not included in the aggregates: being less dense than minerals, they will float and be separated from the soil matrix. Quantification is done either by weighing isolated particles for the largest particles (2-5 mm) or by indirect methods employing infrared analysis or pyrolysis coupled with gas chromatography and mass spectrometry (pyrolysis-GC/MS), which makes it possible to estimate polymer concentrations through calibrations. Some studies quantify the number of particles for each polymer, others the distribution of sizes and shapes, or the masses of microplastics.

Fate of microplastics in soils

Once introduced into the soil, plastics can undergo fragmentation processes resulting from physical actions such as ploughing, wetting/drying or freeze/thaw cycles, and chemical processes, notably oxidation and hydrolysis caused by the action of UV

radiation, oxygen and water. Finally, they can be attacked by microorganisms present on their surface or by small organisms living in the soil that can ingest them and contribute to their fragmentation and their further association with microorganisms.

Microplastics present on the soil surface can be ingested by earthworms and carried into the deep soil. Microplastics have been found throughout the soil profile, sometimes as deep as 90 cm (Weber *et al.*, 2022). Furthermore, the activities of earthworms aerate the soil and increase its porosity, facilitating the migration of microplastics towards the deep soil with water. Other small soil animals, such as springtails (*Collembola*) and mites, can contribute to the circulation of microplastics in the soil.

Microplastics can be found within soil aggregates, formed by the aggregation of organic and mineral particles. Protected in this way, they can remain in the soil for a long time (Watteau *et al.*, 2018) and accumulate there.

With soil erosion, microplastics, whether free or trapped within aggregates, can be carried towards other soils or towards aquatic environments. Thus, microplastics present in soils represent a major source of contamination for riverbanks, sediments and continental waters.

Plastics therefore pollute soils in various forms (nano- and microplastics, diffusion of toxic chimicals and vectors of other contaminants etc.); they are present throughout the full depth of soils and remain there for a long time. Their diffusion into inland environments greatly increases their impact on the environment, ecosystems and biodiversity, far beyond the soil itself.

⏩ Plastics in rivers: tracking their transport and measuring inputs into the sea

Wolfgang Ludwig, Philippe Kerhervé and Bruno Charrière

Are rivers the main source of plastic in the oceans?

The awareness of the extent of plastic pollution in the oceans strongly increased in the years 1990s and 2000s when sailors and scientists began systematic observation and countings of plastic debris during cruises. Especially the formation of accumulation (hot spots) in the middle of the great oceanic gyres—commonly designed as "plastic continents"—and on our coastlines highlights the issue of the pollution's origin. Where does all this plastic waste come from? From land-based discharges or from activities at sea?

When studying natural biogeochemical cycles on Earth, researchers got aware that the riverine transport of particulate and dissolved elements into the sea resulting from the erosion of continents play a key role in the functioning of the oceans. In addition to natural elements, there are nowadays also many chemical contaminants resulting from human activities, as plastic waste, either in the form of large plastic litter or small degraded and fragmented plastic debris (microplastics). Even though we lack of data on a global scale, it is accepted that approximately 80% of plastics in the oceans are of terrestrial origin and that their main source is via rivers.

The first studies, which were based only on a few measurements, came to the conclusion that the annual transport of plastics by rivers should amount to millions of tonnes (e.g. Lebreton *et al.*, 2017). These estimates far exceed those of the plastics stocks

present on the surface of the oceans, which implies a very short residence time on the ocean surface and exchanges with other oceanic compartments, such as the deep ocean or living biomass. This worrying finding reinforced the idea of a major threat to marine ecosystems. More recent studies (e.g. Weiss *et al.*, 2021) however questioned these short residence times. All these studies nevertheless converged to the conclusion that, while initial studies were primarily dedicated to the oceans, a better understanding of the plastic cycle in marine environments also requires deeper knowledge of their mobilization and transfer from land-based sources (both terrestrial and fluvial).

How should we quantify the transport of plastic waste by rivers?

Any quantification of the transport of materials by rivers is based on a dual approach. On the one hand, an estimation of the total water flux that reaches the oceans is needed, typically quantified on an annual scale. On the other hand, the estimation of the average concentration of a transported element as a function of the variable hydrological conditions (low flow vs peak flow) is needed as well. Today, the water fluxes of the world's rivers are mostly monitored by hydrological services and are relatively well documented. The estimation of solid fluxes, that is to say the fluxes of natural suspended particles such as sands, silts and/or clays, is more complex because concentrations can be highly variable depending on river discharge. Nevertheless, scientists have been able to establish reliable models for these solid fluxes and overall budgets for many rivers as well.

The precise quantification of plastic concentrations according to the various hydrological conditions remains however a much more laborious challenge. The plastic debris floating in rivers represents an extremely heterogeneous group of particles, and this type of debris cannot be determined using the same methods as for natural particle debris. We generally differentiate microplastics (MP) from macroplastics (MaP) because the methods used to estimate their number are completely different. Microplastics are recovered by water filtration, whereas macroplastics can only be estimated by remote visual observation (e.g. from a bridge) and/or by trapping them in low-flow areas. It is commonly admitted that the size limit of 5 mm separates both classes.

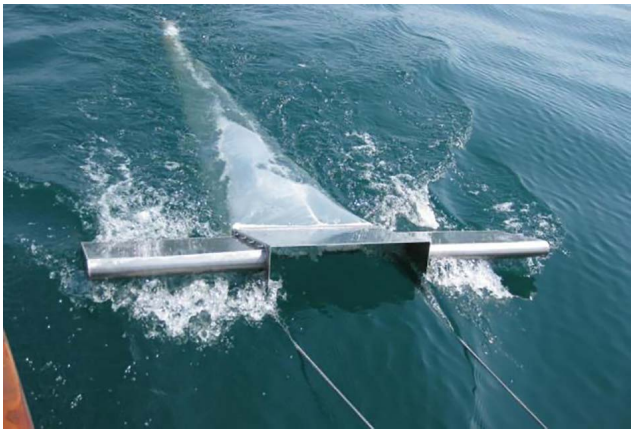


Figure 1.2.1. A Manta net in use (opening 60×20 cm, mesh size 333 µm) on the Rhône River (Arles, 2018).

To quantify microplastics in rivers, researchers initially reproduced the techniques which were used in the oceans for MP quantifications, namely the use of plankton nets and flowmeters. The most frequently used plankton net model is known as the "Manta" net, which has a mesh size of approximately 300 µm. These net-based techniques suffer from two limitations: the difficulty of using a relative fine mesh without risking rapid clogging of the net (due to higher concentrations of suspended particles in rivers than at sea) and the impossibility of working in turbulent environments such as those encountered during peak flow or floods. In short, these high-discharge conditions are very difficult, or even impossible, to sample with nets, especially as they are always associated with the presence of numerous floating plant debris (leaves, branches etc.). It is however precisely these flood conditions (and therefore high precipitation) that remobilise and transport most terrestrial particulate materials, including micro- and macroplastics, towards the sea.

The multiplication over time of studies on microplastics in rivers allowed to gradually consolidate estimates of their average concentrations, without, however, rigorously discriminating among the external factors and the mechanisms causing their mobilization. The measured concentrations often vary greatly between individual sites end rivers. A study conducted by Cefrem on a monthly scale for two consecutive years allowed a comparison of microplastic concentrations between two contrasting river systems in the south of France: the Rhône River (at Arles) and the Têt River (at Perpignan) (Constant *et al.*, 2020). Although average microplastic concentrations were higher in the Têt River, the average fluxes per unit area (in $g.km^{-2}.y^{-1}$) were quite comparable in both rivers, notably due to much wetter climatic conditions in the Rhône catchment area. Microplastic pollution could thus be widespread in French rivers, leading to reduced variabilities of specific average MP fluxes in rivers. This study also highlighted the importance of sampling during high-discharge periods to improve budgets. If one considers the few samples which could be taken during a flood of the Rhône, the average annual flux for this river increases approximately four times the value which is obtained when the calculations were done on the basis of only the non-flooding samples.

Fluxes (number of waste items per unit of time) of macroplastics in rivers are generally evaluated through visual counts from bridges. This method also allows the identification of the type of waste but naturally under-estimates the counting and reduces the identification of small debris and transparent packaging. In a pilot study conducted over four years on the coastal Têt River and downstream Perpignan (Laverre *et al.*, 2023), floating macroplastics were monitored from a shallow fording (2 m). Identification of objects could be made with precision down to the size limit of cigarette butts (size: 1 cm), and all floating litter passing at the studied section could be collected using a pool net fitted on a stick. All collected waste was dried and items weighed individually. This study allowed a robust flux estimation of 350,000 floating macroplastics/year (0.65 t/year), the majority composed of cigarette butts, pieces of polystyrene and food packaging (approximately 20% for each category). Thanks to a sampling strategy targeting all climatic (dry, rain, wind) and hydrological (low, medium, high discharge) conditions, this study also showed that 70% of the macroplastics discharged by the Têt were transported during heavy rain conditions, even though these periods represent only 6% in time during the study period.

The results obtained for macro- and microplastics are interesting because they allow comparison of the respective importance of both fractions for the total plastic fluxes. For the Têt, the annual mass flux of macroplastics is seven times higher than the microplastic flux. For the Rhône, based on counts made from a bridge during another study (Castro-Jiménez *et al.*, 2019), the mass flux of macroplastics per unit area can be estimated to be approximately 70 times lower than that of the Têt, whereas the microplastic fluxes are of the same order of magnitude (see above). This large difference for the specific MaP fluxes could be explained by the greater capacity for retention and sequestration during transport in the Rhône catchment area, which is about 70 times greater than the catchment of the Têt River. This suggests that the size of the catchment area could also be a factor influencing macroplastic fluxes to the sea.

Note that indirect methods are also frequently applied to estimate the transport of plastics by rivers. A very widespread method is the counting of plastic objects deposited by running water alongside rivers. This method, initially developed for counting plastics on beaches (MSFD[10] or Ospar[11] protocol), is increasingly applied to plastics deposited on riverbanks. It has the advantage of being usable in "citizen science" approaches (Philip *et al.*, 2024), which makes it possible to collect of a large amount of data. However, even if this method allows a realistic identification of the nature of the plastics transported by rivers, it is currently difficult to use these data also for flux determinations in the absence of models that can estimate their mobility.

An important open question remains however how we can overcome the limitations inherent to extreme climatic events, which definitively play an important role in the land-to-sea transfer of plastics, but which are difficult to be monitored. Turbulence and water speed make direct visual counting of microplastics impossible and also prevent *in situ* sampling. A solution for these cases could be the use of new tools such as "remote sensing" or "hyperspectral optical cameras" fixed onto rigid structures such as bridges, which might be capable to increase observations during extreme conditions.

Which size classes should be considered? The key to improving mass balances

Unlike previous studies, which estimated fluvial inputs of microplastics to the sea at approximately one million of tonnes, a recent study decreased these estimates to several thousands of tonnes (Weiss *et al.*, 2021). This large difference can be explained by methodological differences concerning the homogenization of data across different methods, the specific size classes which were targeted by the different methods, or the mass conversion of the obtained data when only numerical countings were available. At last, for the calculation of large-scale mass balances (via extrapolation), the choice of the potential controlling factors for plastic fluxes—such as population density and/or river discharge—must be made with caution. An inappropriate choice can introduce

10. The Marine Strategy Framework Directive (MSFD) is a European directive of the European Parliament and of the Council (2008/56/EC) which establishes a framework for Community action in the field of marine environmental policy.

11. The Ospar Convention is an international treaty for the protection of the marine environment of the North-East Atlantic. It aims to prevent and eliminate marine pollution, particularly from submerged munitions, radioactive discharges and polychlorinated biphenyls.

significant errors. These potential error sources represent to some extent the "bottleneck" for large-scale mass balance estimations (Figure 1.2.2). Especially combination of these errors can introduce considerable differences in the resulting budgets. Discrepancies in these budgets do not, however, mean that the extent of plastic pollution has been largely overestimated; rather, they demonstrate the importance of comparing mass balances established using rigorously identical methods to better understand the plastic cycle.

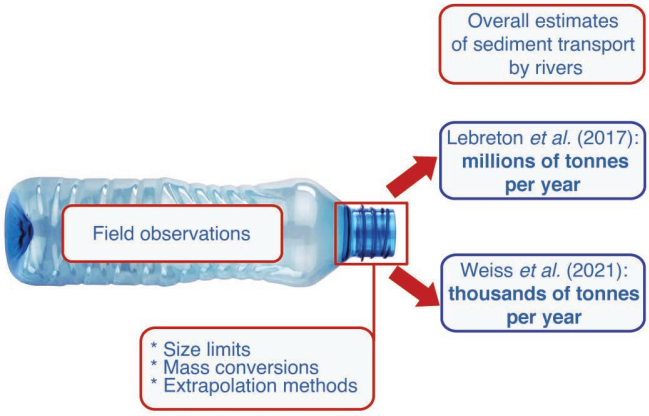


Figure 1.2.2. Diagram illustrating the sources of error that can easily introduce large differences in estimations of fluvial microplastic transport at the global scale.

MP: microplastic.

Among MPs, the presence of small fibres is also subject to numerous analytical limitations. The chemical removal of organic matter from a sample can be aggressive and induce the loss of a portion of these plastic microfibres. Contamination by allogenic microfibres as airborne MPs in the field and in the laboratory also poses a problem. If these fibres are abundant within the samples, they can also agglomerate, rendering their enumeration impossible. In short, the identification and quantification of small microplastics remain a constant analytical challenge.

To overcome the analytical biases inherent to the simplified classification of macro- versus microplastics, and consequently to improve the estimation of these fluvial fluxes, many studies consider it necessary to introduce sup-size classes within these fractions. They frequently discriminate between macroplastics (5 mm), large microplastics (0.5-5 mm), small microplastics (0.001-0.5 mm), and nanoplastics (<0.001 mm), although the applied size thresholds in some cases can vary between studies.

One solution to overcome the biases or limitations associated with numerical quantification and mass conversion relies on thermal techniques associated with chromatographic separation, such as pyrolysis coupled with gas chromatography and mass spectrometry (Py-GC/MS). This technique can directly provide mass concentrations of plastics. Studies with this technique have shown that small microplastics in rivers are predominant in terms of number, but very likely also in terms of mass concentration (Landebrit *et al.*, 2024). Recent studies using more traditional methods (such as μ-FTIR analysis, Stratmann *et al.*, 2024) also confirm these findings.

Consequently, even if the initial estimations of the global transport of large microplastics by rivers had to be revised downwards, it is highly probable that this decrease in mass budget fluxes is largely compensated by the mass budget fluxes of small microplastics, or even nanoplastics, which are still poorly quantified. This is especially alarming since the potential impact of plastics on the marine ecosystem increases as the size of the debris decreases.

How best can we reduce plastic pollution: clean up or avoid using them?

Despite the uncertainties that persist in the budgets of riverine inputs, there is little doubt about the terrestrial predominance of plastic litter at sea. To reduce these inputs, it is therefore evident that the plastic pollution problem has to be tackled at its source, for example at the level of the catchment areas. A clean-up of the oceans (twice the continental surface area!) is unrealistic; these heavy operations at sea would have a prohibitive environmental cost (carbon footprint) and would be economically or even practically unfeasible (although approaches in this direction still exist, see https://theoceancleanup.com/). Furthermore, tackling the consequences at sea without reducing the continental source would condemn us to an endless battle against plastic pollution.

The best waste is waste which is not produced! While European regulations increasingly prohibit the production of single-use plastic products, studies on plastic waste in rivers and at sea show the emergence of new, far more frequent plastic objects (sanitary masks, gloves, textiles, etc.). All socio-economic sectors are affected: for example, the construction industry with its widespread use of expanded polystyrene insulation and agriculture where plastic sheets and stakes are now omnipresent in winegrowing, market gardening and tree crops.

A major problem comes from waste that escapes collection systems. It ends up in the environment and is then washed towards the sea by rivers and streams during intense rainfall events. The trapping of floating plastic litter on rivers and streams have several difficulties. They are incompatible with river navigation and the conditions that prevail during extreme events such as floods. Consequently, to reduce the amount of waste transferred into the sea, the trapping must be carried out as far upstream as possible by targeting, for example, urban outfalls and drainage ditches or canals. These artificial systems are less subject to high flow variations or to regulations on the protection of living species. Their dense network across the country allows a targeted approach on "hotspot" areas with high waste concentrations, such as shopping centres, leisure parks or roads. The objective would be for all municipalities from a same catchment area to identify with the help of their technical services the major "hotspot" zones on their territories in order to place waste collection or trapping systems should be simple to use and economical for a municipality. The support of local authorities is rarely or never based on environmental considerations, but on economic ones. However, the accumulation of waste harms the image of the municipality whereas the installation of efficient trapping systems contributes to a good image within its fellow citizens.

The Roussillon plain in the Pyrénées-Orientales is a pioneering area for the study of measures on waste flux reduction (Kerhervé *et al.*, 2023). Several communes and joint catchment area unions, as well as the Department (county), have financed waste

trapping installations. Two main trapping device types have thus been set up on the Roussillon plain (Figure 1.2.3) in collaboration with a local company (Clean Up Rivers):
– trapping in ditches, mostly by means of a net that limits the potential risk of log jam or entanglement: the height of the device is no taller than half the depth of the ditch and a spring-loaded flap allows the net to lower (and close) in the event of excessive pressure. A simple net directly fixed to an urban stormwater outfall also exists in certain cities (e.g. Brest, Rouen);
– trapping in canals, which are mostly full of water, by means of a floating device fixed across the two banks.

These devices require regular maintenance and monitoring throughout the year, particularly after major rainfall events. This is undeniably their weak point. The lack of staff and the work overload make them unpopular among city staffs, as well as the "degrading" aspect for municipal personnel in handling these piles of waste.



Figure 1.2.3. "Upstream" waste trapping device set up in the Pyrénées-Orientales (Roussillon plain). **a)** Floating boom across the canal collecting drainage of water from the plain (la Llabanère, 2020); **b)** Clean Up Rivers nets installed in a ditch (Canet-en-Roussillon, 2020).

A proposed solution is the transfer of maintenance responsibilities to the installing company. The additional cost in the Pyrénées-Orientales is low as rainfall events are become increasingly rare!

⏩ Mass balance and the mountainous critical zone: quantification in an experimental catchment area

Gaël Le Roux

Europe's mountains are an essential geographical zone, playing a key role in the water cycle and serving as major tourist destinations and biodiversity hotspots. Mountain soils act as transfer pathways, channeling water from peaks to Europe's great rivers, while also functioning as buffer zones through ecosystems such as peatlands and forest soils. Often perceived as pristine, these landscapes carry a historical legacy shaped by diverse human activities, from pastoralism and mining to more recent tourism.

They also receive long-range transported pollutants, including heavy metals (e.g. mercury, lead) and persistent organic pollutants. Under the Human-Environment Observatory (Labex DRIIHM) in the Haut Vicdessos[12]—located on the Andorra-Ariège border—interdisciplinary research examines the impact of past and present human activities on mountain ecosystems. Research focuses on lacustrine and peatland ecosystems, where multi-year climatic, geochemical, and hydrological data are collected. Key study sites include the Bernadouze peatland and Lake Arbu, both influenced by human activities such as logging and fish stocking.

Presence of macroplastics and microplastics

The PlasticoPyr project revealed that even isolated areas such as the Bernadouze peatland, a Natura 2000 zone, contain microplastic macrowaste (e.g. tires) and high quantities of microplastics. Analysis of winter snow from 2017-2018 detected micro- and nanoplastics of various shapes and polymer types, including polystyrene, polypropylene, and polyethylene, originating sources tens to hundreds of kilometres away. Microplastics deposition rates at Bernadouze (365±69 particles/m^2/day) are comparable to those in major cities like Paris or Dongguan, China (100-300 particles/m^2/day).). By reconstructing air mass trajectories during periods of stable snow cover—when soil-aggregated microplastics cannot be remobilized—we demonstrated that that these particles originate from sources located several hundreds of kilometres away.

Environmental archives

One strength of the Human-Environment Observatory of Haut Vicdessos is its environmental archives—peatlands and lakes—which enable reconstruction of ecosystem trajectories over hundreds to thousands, of years. While microplastic contamination does not extend as far, sediments and peat of the Lake Arbu catchment reveal initial microplastic detection in the 1970s and a rise in deposits since the 2000s. By compa-

12. This publication was supported by the CNRS MITI 80'Prime initiative, the ANR-20-CE34-0014 ATMO-PLASTIC project, and the Plasticopyr project within the framework of the Interreg V-A Spain-France-Andorra programme, as well as the Pyrenees Haut Vicdessos Human-Environment Observatory (OHM)—LABEX DRIIHM ANR-11-LABX-0010.

ring peatlands, which act as purely atmospheric collectors, with lakes, which record signals from the entire catchment, we find that peatlands contain higher microplastic deposits than lacustrine sediments. This suggests distinct accumulation processes: aquatic transport carries plastics toward lake outlets without retention, whereas peatland vegetation captures atmospheric microplastics.

Transfer of microplastics to biota

Margenat *et al.* (2024) demonstrated the presence of microplastics in biofilms and trout, indicating a transfer from the soil to biofilms and into living organisms. However, the transfer mechanisms remain unclear, particularly due to differences in the polymer signatures between sediments and fish. For instance, fish exhibit a dominance of polypropylene, whereas sediments are characterized by plastics derived from electronic products.

Ultimately, where do micro- and nanoplastics in mountains come from? And what is their impact?

Recent work shows that microplastics can have two origins: one distant (via atmospheric transport) and one local (from human activities in the mountains; Figure 1.2.4). At the catchment scale, atmospheric input provides a continuous flux of plastic particles, but local mismanagement of macrowaste—which degrades into fine particles—also contributes, even in a protected ecosystem. Our current research aims to distinguish microplastics of a more local origin from those transported over long distances, for example by analyzing their chemical signatures or geometries.

While microplastic presence and their integration into aquatic organisms like trout have been demonstrated, their environmental impact in the mountain ecosystems remains unquantified.

⏩ Identifying sentinels of environmental plastic pollution

Gaëlle Darmon, Claude Miaud, Franck Lartaud and Jean-Christophe Auguet

The concept of bio-indicators

What is a bio-indicator?

A "bio-indicator", or "sentinel species", is a species or group of species whose presence (or absence), health status, or a function such as growth, behaviour or physiology reacts significantly to changes in its habitat or its diet, for example due to pollutants. Through its presence over the medium or long term, a bio-indicator provides valuable information on a possible degradation of environmental quality. Monitoring by bio-indicators (biomonitoring) can therefore show the evolution of pollution in a habitat or the effectiveness of measures implemented to restore the good ecological status of an environment. One example is lichens, which serve as excellent bioindicators of air quality because they absorb atmospheric pollutants.

The reliability of the information provided by bio-indicators nevertheless depends on the operational means of applying the biomonitoring. To be able to carry out a rapid

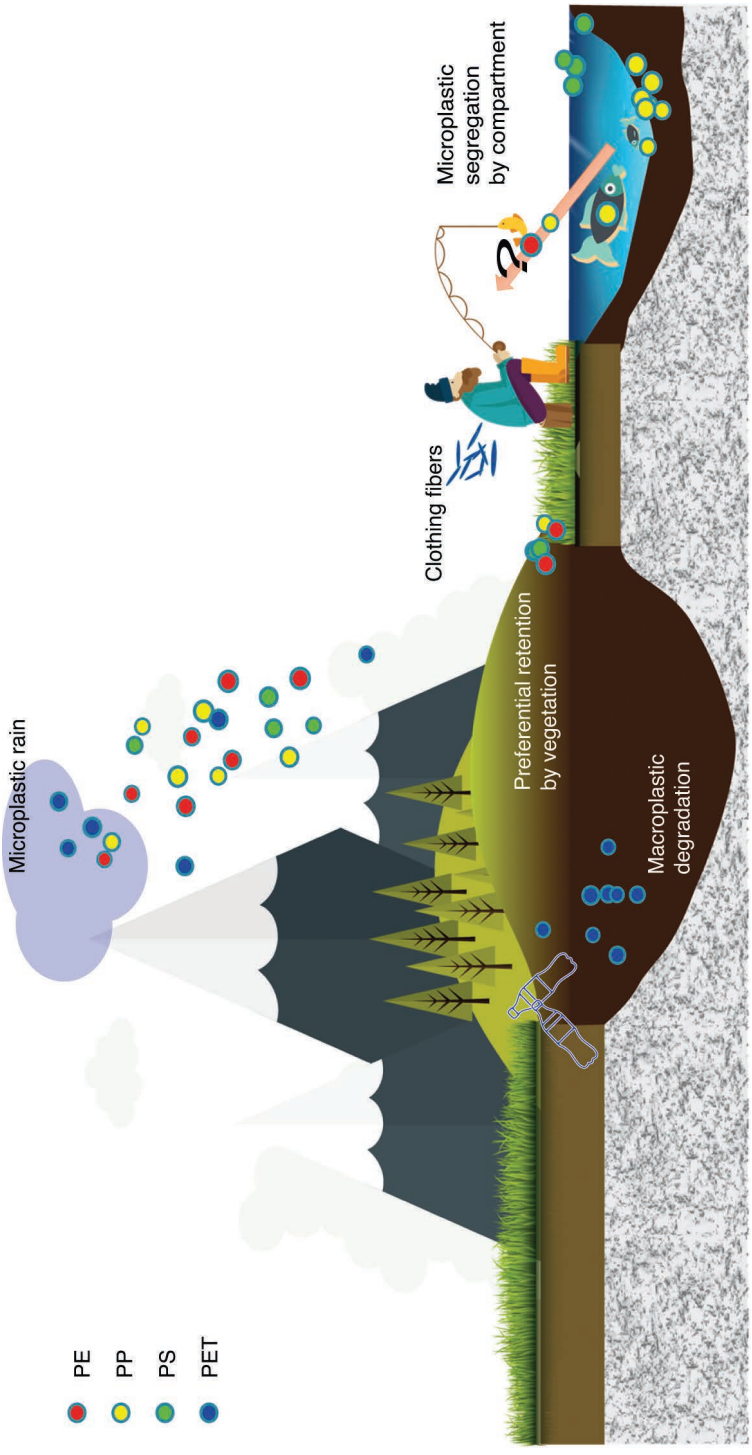


Figure 1.2.4. Diagram illustrating the dispersion of microplastics and their sources in a mountain environment.
PE: polyethylene; PP: polypropylene; PS: polystyrene; PET: polyethylene terephthalate.

and reliable assessment of environmental quality or of a pressure on biodiversity, it is necessary, on the one hand, to select a relevant bio-indicator species: its distribution must cover the area to be sampled and it must react significantly to variations in environmental conditions caused by the pollution to be monitored—in this case, plastic pollution. On the other hand, monitoring by bio-indicator has to rely on a network of actors trained to apply a series of harmonised procedures, based on a standardised protocol, which is fundamental for collecting comparable data capable of detecting the spatio-temporal variations of the pressure from the pollution and the long-term effectiveness of the solutions established between regions. The interpretation of results is carried out according to spatio-temporal trends and regulatory standards. These latter correspond to pollution thresholds beyond which the pollution is likely to have impacts on the viability of populations. Monitoring by bio-indicator therefore consists of continuously checking the compliance of observed levels with regard to these thresholds.

What should we measure? The differences between risk, pressure and impact

The terms "risk", "pressure" and "impact" are concepts that are easily muddled, being related yet distinct. For the biomonitoring of plastic pollution, these concepts must be clearly differentiated in order to effectively interpret results and propose appropriate management and remediation measures. "Risk" here refers to the probability that pollution from plastic waste will cause harmful effects on living organisms or ecosystems. "Pressure" designates the quantities and distribution of plastic waste as well as, in the context of bio-indicators, their interactions with the species concerned (notably ingestion or physical entanglement). This pressure can provoke physiological, behavioural or ecological responses: this is the "impact" (the effects of the pressure), which can be measured at various levels (molecular, individual, population, ecosystem). Thus, the response of bio-indicators (e.g. physiological, anatomical, the presence/absence of the sentinel species, density) reflects the health status of the ecosystem. However, assessing impacts and defining regulatory thresholds in relation to their severity, judged from scientific and regulatory perspectives, is not easy, as the form of the dose-response relationship can be varied and difficult to measure. Thus, the relationship between the quantity of plastics ingested and the repercussions for health (e.g. a decline in body condition or reproductive capacity) also depends on multiple environmental factors. The direct effect (e.g. perforation of the digestive wall) or indirect effect (e.g. endocrine disruption) of plastic ingestion is not always easy to demonstrate (e.g. in sea turtles, see Part 2 Chapter 2).

Advantages of using bio-indicators to monitor environmental pressure and the impacts of plastic pollution

Monitoring by bio-indicators is valuable because it compensates for the impossibility of making an exhaustive count of plastic waste in the environment, given that its distribution is so extensive and subject to significant environmental and seasonal variability. Direct observation campaigns of plastics in the environment, conducted, for example, on foot, by aircraft or by boat, provide "snapshots" at a given moment and for a given locality. However, they cannot provide an exhaustive census and they provide limited insight into temporal variations and longer-term biological impacts. Indeed, the logis-

tical and financial cost of large-scale counts generally does not permit these operations to be repeated very regularly. To date, for example, only a single large-scale census of marine waste has been conducted in the Mediterranean Sea, carried out during an aerial census of marine megafauna covering almost its whole area (Samm censuses[13], 2018). Flying at an altitude of approximately 180 m, only animals and waste items of at least 20 cm could be detected by observers from the aircraft. Biomonitoring offers a complementary approach to these visual censuses and one that is potentially more holistic, as it collects data both on the distribution of plastic waste in the environment and on its pressure on biodiversity.

The "Marine Strategy Framework Directive" (MSFD), which concerns European marine waters, and the regional sea conventions with which it harmonises its efforts—Ospar (North-East Atlantic), Barcelona (Mediterranean) and Helcom[14] (Baltic Sea) (Figure 1.2.5)—rely on harmonised monitoring of marine plastic pollution impacts established via bio-indicators. In its objective to restore the "good ecological status" (GES) of the marine environment (defined by preserved, ecologically diverse, dynamic and productive seas), the MSFD implements these bio-indicators with the aim of diagnosing the marine environment and monitoring the effectiveness of the measures established for its protection. To this end, it establishes coordinated monitoring programmes between the member countries of the MSFD and/or the regional sea conventions in order to coordinate their efforts.

The tenth among the eleven descriptors of the ecological status of the marine environment (including, e.g., biodiversity, fish stocks, contaminants and noise pollution) concerns marine litter (D10). The objective of D10 aims to ensure that "properties and quantities of marine litter do not cause harm to the coastal and marine environment" (Directive 2008/56/EC). It relies on a monitoring programme on the state of pollution by waste, defined by different criteria: criteria D10C1 and D10C2 for environmental damage, and D10C3 and D10C4 for the impacts of waste on organisms. These latter two are evaluated by bio-indicators related to the ingestion of micro- (particles <5 mm) and macrowaste by marine fauna and to other types of interactions such as entanglement in waste. A scientific assessment, based on standard protocols disseminated among networks of actors trained to apply them, allows for a status report on pollution and the pressure on fauna. A reappraisal of the situation and the distance from the thresholds (GES) is planned in six-year cycles. However, environmental objectives concerning marine litter are not yet all established for the MSFD, as the state of knowledge is not yet judged to be sufficient. The threshold could be defined according to a "clean" zone, without any waste. This is unfeasible today, as plastic waste has become ubiquitous in all ecosystems and compartments of the biosphere. Reflections on the definition of a threshold therefore focus on levels compatible with the protection of species and the environment. The aim is to absolutely avoid reaching levels that would engender negative, or even irreversible, impacts on the organisms concerned (red zone, Figure 1.2.5). For the MSFD, only one threshold has been proposed, for the indicator "number of litter items on beaches". While scientific data are insufficient to quantify ecological and socio-economic damage, a preventive threshold of

13. Samm: *Suivi aérien de la mégafaune marine* (Aerial monitoring of marine megafauna).
14. The acronym "Helcom" refers to the International Commission that manages the Helsinki Convention, which aims to protect the marine environment in the Baltic Sea area. The nine countries surrounding the Baltic Sea are parties to the Helsinki Convention, as is the European Commission.

20 litter items/100 m of beach length has been instituted. For the other indicators, in the absence of thresholds, the objective is to observe a statistically significant decrease in the number of litter items or in their associated pressure on fauna.

Fulmars and loggerhead turtles, bio-indicators of marine plastic pollution

The fulmar *Fulmarus glacialis* is a bird species very widespread in the northern seas and is recognized for its waste ingestion behaviour, to such an extent that it is considered a bio-indicator within the framework of the Ospar convention (Figure 1.2.5). Thus, the temporal and spatial variations in the quantities of waste items (predominantly plastics) larger than 1 mm extracted from the digestive systems of individuals found dead show the effectiveness of restoration measures implemented.

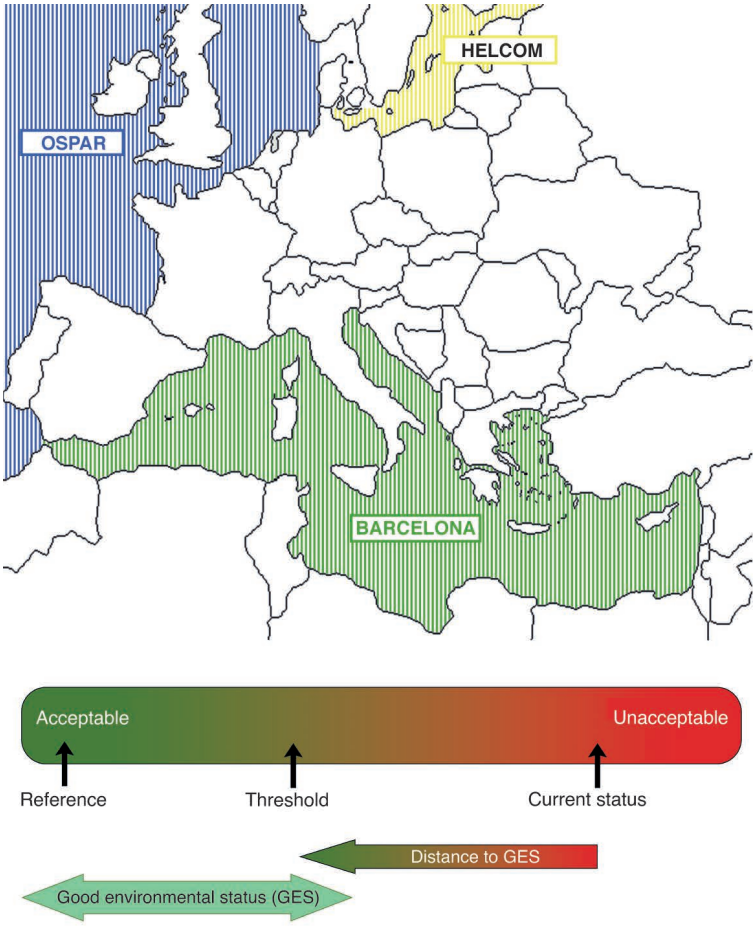


Figure 1.2.5. Above, boundaries of the Ospar, Helcom and Barcelona regional sea conventions. The Marine Strategy Framework Directive harmonises Member States' efforts to monitor the impact of marine litter and achieve good environmental status. Below, good environmental status (GES) is defined as the absence of harm to organisms. The environmental objectives aim to reduce the distance to this threshold in order to keep the environment in a healthy and sustainable state (arrows as an example).

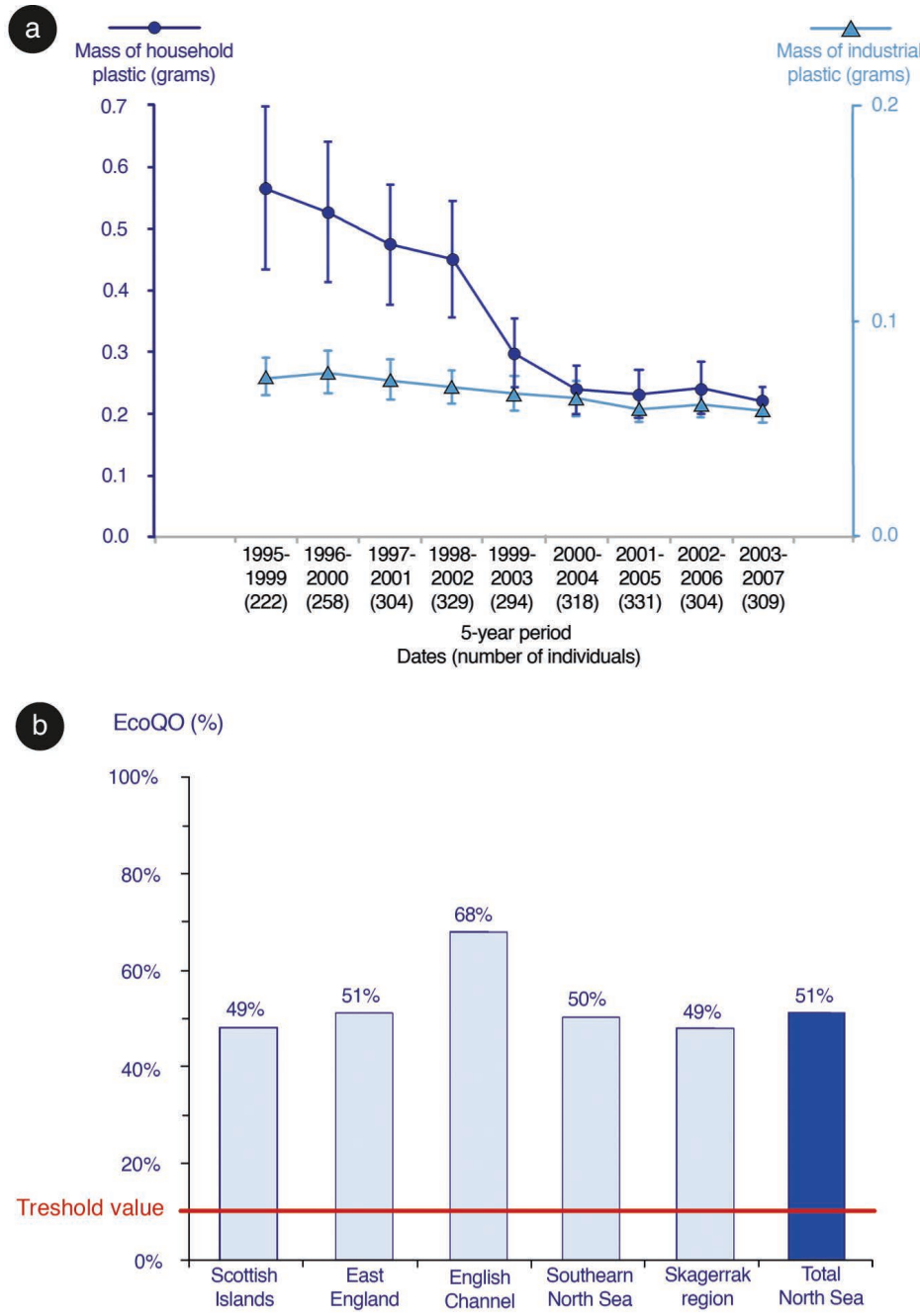


Figure 1.2.6. a) Temporal variations in quantities of industrial and household plastics in the Netherlands between 1995 and 2007—five-year average ± standard error for the two main categories of plastic in the stomachs of stranded fulmars in the Netherlands; **b)** Comparison of the occurrence (in percentage) of ingestion of plastics larger than 1 mm among fulmars monitored in the sub-regions of the Ospar area over the period 2014-2018. The red line corresponds to the regulatory threshold for good ecological status.

The occurrence of plastic ingestion among fulmars and the quantities found in their digestive systems vary according to sub-regional pollution levels and the efforts being made to reduce discharges of industrial and consumer plastics (Figure 1.2.6). The ecological quality objective (EcoQO, the equivalent of the MSFD GES) is defined as follows: "There must be fewer than 10% of northern fulmars containing more than 0.1 g of plastic particles in the digestive systems of 50 to 100 fulmars washed up on beaches over a period of at least five years." The Fulmar bio-indicator was recently integrated into the MSFD, where a threshold assessment method was proposed (van Franeker *et al.*, 2021). This is based on a zone of the Canadian Arctic, virtually pristine of marine waste, where 10.1% of fulmars exceed the 0.1 g level of ingested plastic, which corresponds to the EcoQO that had been arbitrarily proposed. However, this 10% threshold remains largely exceeded today. Data collected between 2012 and 2016 show that this threshold is reached in none of the sub-regions in the North Sea. Out of 51 fulmars, 95% had ingested plastic, on average 31 particles or 0.28 g per individual. Occurrence frequencies vary from 50% in the Skagerrak to 75% in the English Channel, and it is only in the Canadian Arctic that plastic ingestion levels truly approach the EcoQO. However, temporal analyses considering data since 2007 show a significant reduction in the mass of ingested plastic as well as in the percentage of birds containing more than 0.1 g of plastic in their digestive systems, and this is found to be the case in all 5 sub-regions of the Ospar zone[15].

As the fulmar is absent from the Mediterranean, it is the loggerhead turtle *Caretta caretta* that is used as a bio-indicator for plastic monitoring there for the MSFD and within the zones of the Ospar and Barcelona conventions. Approximately one hundred institutions, composed of veterinary laboratories, care centres, stranding networks and research laboratories, have been trained to apply a protocol detailing the procedures for standard data collection on the presence, dry mass, characteristics, size and colour of plastics in the digestive systems of turtles found dead. Between 2013 and 2018, 59% of the autopsied turtles (802 individuals) had ingested plastic pieces larger than 1 mm (Darmon *et al.*, 2022). While the threshold for good ecological status is not yet specified, its definition for the MSFD (Decision 2017/848) corresponds to "a quantity of waste that does not negatively affect the health of the species concerned". The impact of waste ingestion on the health of individuals is not easy to establish, but would be necessary for bio-indication, and the current state of knowledge primarily allows the effective reporting of pressure. Mortalities caused by waste ingestion are only certified in cases of digestive occlusion or perforation (14 cases out of 802 autopsies). Similarly, few data could be collected on *ante mortem* health parameters, which reduces the power of statistical tests to examine the link between waste ingestion and, for example, the size or mass of the turtles, their fat reserves or the severity of their injuries. Plastics represent an average of 39% of the mass of ingested matter, which could prevent individuals from gaining enough energy to reach the same reproductive capacity as individuals that had not ingested waste (Marn *et al.*, 2020). The data collected on the loggerhead turtle bio-indicator do not yet offer the necessary hindsight to evaluate

15. Ospar Assessment, Environmental impacts of human activities, Marine litter, Plastic Particles in Fulmar Stomachs in the North Sea, https://oap.ospar.org/en/ospar-assessments/committee-assessments/human-activities/marine-litter/plastic-particles-in-fulmar-stomachs-north-sea/

temporal trends. If measures aimed at banning single-use plastics are implemented, the quantities of waste ingested by loggerhead turtles should decrease, given that plastics from takeaway catering are amongst the waste items most commonly found in the digestive systems of autopsied individuals.

Development of new bio-indicators: a challenge for microplastics and nanoplastics

Ingestion of plastics is not the only interaction between waste and wildlife. Several bio-indicators are currently under development for the MSFD, notably related to entanglement in floating waste by sea turtles, seabirds and common seals (criterion D10C4). Entanglement can cause, in addition to direct mortalities, major impacts on the health of individuals due to a decrease in their ability to move, feed or survive (see Part 2, Chapter 2). Another major issue of plastic pollution is fragmentation into smaller particles, which accentuates the risks of ingestion of micro- and nanoplastics; these can cross the epithelial barrier of organs with neurological and physiological consequences. The detection of these very small particles requires significant technical resources. A protocol is currently under development to evaluate the quantities of microplastics (300 µm to 5 mm) ingested by marine fish (bio-indicator for criterion D10C3 of the MSFD).

Bivalves such as mussels and clams, which are already used as bio-indicators (pollution by metals, hydrocarbons and phytosanitary products) in national programmes (Rocch and Rinbio in France, Mussel Watch in the United States), are also potential sentinels for micro- and nanoplastic pollution. These abundant and sedentary species generally have a wide geographical distribution, a good tolerance of pollutants and a filtration activity of a large volume of water allowing the bioaccumulation of plastic particles in their tissues, particularly for the smaller size ranges (<1 mm). The precise characterization of the processes of ingestion, retention and rejection of microplastics by bivalves is still ongoing, but initial studies reveal a proportional relationship between the concentration in the environment and that in the tissues of certain species, such as *Mytilus edulis* (Qu *et al.*, 2018). No threshold affecting health status has been defined for the moment; nevertheless, high proportions of microplastics accumulated in mussel tissues have been reported, with great variability depending on geographical zones. The highest values come from Mediterranean mussels (*Mytilus galloprovincialis*) from the Catalan coasts (19 microplastics/individual), corresponding to an average exposure of more than 8,000 microplastics/year/adult for particles of size 20 µm or over (Expósito *et al.*, 2022).

Extending the scope: from the open sea to freshwater systems

In its action plan *Zéro plastique en mer d'ici 2025* (Zero plastic at sea by 2025), the French Ministry for Ecological Transition and Territorial Cohesion is implementing a strategy to acquire knowledge on the pathways of waste transfer from their sources to the seas. However, there is currently no monitoring programme for plastic waste in continental waters, apart from a few rare one-off actions (e.g. the Plastic-Rhône project of the *Compagnie Nationale du Rhône*). At the European level, the Water Framework Directive (WFD), which aims to restore a "good ecological status" to continental waters, certainly relies on several water quality indicators, such as the "multimetric

invertebrate" index based on the presence of benthic macro-invertebrates, or the "river fish" index to measure the species diversity of rivers. However, although it also coordinates rigorous monitoring of pollution from heavy metals (mercury, cadmium, lead, metal), plant protection products, hydrocarbons or organic compounds such as perfluoroalkyl substances (PFAS), for example, it does not currently integrate the monitoring of plastic waste pollution. Yet waste distribution models show that the vast majority of waste originates from continental environments and remains blocked there long before reaching the seas (Meijer *et al.*, 2024). Studies on plastics in freshwaters are in full development (e.g. the MacroPlast project on the Seine led by Leesu; the Redplast66 project on the Têt catchment area led by the Cefrem-UPVD laboratory and the Citeco66 association; the Plastilac study led by the Aqualti association, carried out in collaboration with the University of Savoie Mont-Blanc and the University of Paris-Est Créteil for high-altitude lakes; and the PlastiGar study conducted by laboratories of the Paul-Sabatier University in Toulouse on the plastic pollution of the Garonne) and provide necessary knowledge on the fluxes of plastic waste in these environments and on their impacts on the biodiversity of these continental environments.

Conclusion

Given the leakage of plastics into the environment throughout their lifecycle, their fragmentation into micro- and then nanoplastics and their transport over long distances, plastics are now ubiquitous in the environment. No part of the globe appears to be spared from this pollution, even the most remote such as Antarctica or protected mountain zones.

The wide variety of plastics and our still very partial knowledge of their cycle on a global scale explain the difficulty in accounting for their fate and the quantities of plastics accumulated in the environment since their invention. However, the intensification of research and the methods developed over the last decade, as well as the compilation of historical data on plastic production and waste, allow a fairly realistic estimation.

Thus, the global plastic cycle models of Sonke *et al.* (2022) evaluate that, of the 8.3 billion tonnes of plastic polymers produced since 1950, only 31% are still in use. Considerable quantities very likely remain in the form of waste on land (42%), in the sediments of the continental shelf (1.4%), on beaches (0.02%) and, following marine emissions, in the remote terrestrial surface basin (0.34%) or in the deep ocean (1%, or 82 million tonnes). Projections carried out from this model show that, even in the event of a drastic reduction in production and releases, pollution would still increase by a factor of 4 by 2050 due to a future mobilization of the terrestrial reservoir of plastic waste (3.5 billion tonnes). This model highlights the replenishment of reservoirs of macroplastics and coarse microplastics (>0.3 mm and <5 mm) over centennial timescales, while small microplastics (<0.3 mm) will continue to circulate in the air, soil and surface oceans for millennia.

Plastics decompose more or less quickly but degrade inexorably into increasingly small particles, down to the nanometre scale. A plastic bag, for example, could fragment into one million billion (10^{15}) nanoplastics based on its initial quantity of matter. Yet these nanoparticles are potentially the most dangerous for living organisms because they are liable to cross biological membranes and penetrate all the cells of the organism (the phenomenon of translocation), but also to be transmitted throughout the food chain and thus affect all life form, from primary producers to top carnivores. It is therefore necessary to better understand the mechanisms of plastic fragmentation to be able to evaluate the concentrations of particles for each size class and their impacts on ecosystems and biodiversity.

The quantity of plastic produced to date constitutes an immense reservoir for future pollution. When we reach the nanometric scale, it is too late to act. To limit this pollution, which has become uncontrollable, it is urgent to significantly reduce emissions into the environment and to remediate the vast terrestrial reserves of plastics in order to stem their dispersion into our ecosystems for hundreds, or even thousands, of years.

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Part 2

Impacts on organisms

Introduction

The impact of plastic pollution on organisms is a very broad topic and must be looked at throughout the entire life cycle of plastics. Each stage of the life cycle contributes to pollution, the toxicity of plastics and greenhouse gas emissions in various ways, from the extraction of raw materials used to manufacture plastics to their end-of-life as debris, including the production of polymers and the use of plastics. If we specifically focus on the toxicity related to the plastic itself, it is clear that there is a physical dimension to this toxicity that has to do with the plastic object itself or its fragments, as well as a chemical dimension.

Part 1 discussed the circulation of plastics, both through and between the various terrestrial and oceanic compartments on Earth. It is worth remembering that plastic pollution (macroplastics, microplastics and nanoplastics) is ubiquitous, in addition to the fact that plastics come from multiple sources and flow from the continents to the oceans. Even though plastic pollution has been studied for more than 50 years now, there is a compartment on which research was conducted only within the past decade has only focused on one compartment: soil. It is somewhat paradoxical that, for the most part, soils are used for agricultural productions that provide subsistence for humans, and yet these soils contain high amounts of plastics. In this part, we will first present the impacts on terrestrial organisms, before focusing on the marine environment, which has been studied for longer. Given the sheer number of organisms involved, we decided to illustrate this work with examples of keystone or particularly representative species and ecosystems since, in general, these processes apply to all environmental compartments and to the related biodiversity.

For terrestrial environments, we will discuss the impacts on flora and organisms living in the soil, as well as on fauna found in inland waters.

For marine environments, we will cite examples found in birds, fish, sea turtles and ecosystem engineers such as bivalves and corals. A fifth section will approach the issue of entanglement without mentioning specific groups.

In a first step, we look at the physical dimension of plastics: organisms (mostly aquatic animals such as turtles or seals, or animals living near water such as certain birds) could become entangled or be strangled by the largest size litter, for example, ghost nets (lost or abandoned fishing nets). This would consequently reduce animal's fitness[16] and could even lead to its death.

Smaller macrowaste, such as plastic bags, could be mistaken for other organisms (potential prey) and ingested by mistake. This has already been observed, particularly in aquatic environments among certain marine mammals and sea turtles.

16. The fitness of an individual describes its ability to successfully reproduce and can be measured by the proportion of its offspring that reach sexual maturity.

We have already seen that there are far more small fragments of plastic than macroplastics in the environment and that organisms, both aquatic and terrestrial, ingest these small plastics more often and more easily. It has been experimentally shown that these plastic fragments can be ingested by all organisms as long as their size is similar to that of their potential prey. Thus, in the aquatic environment, mammals and birds ingest fragments on the scale of several centimetres or millimetres, whereas fish ingest millimetre-scale or sub-millimetre fragments. Filter feeders such as bivalve molluscs ingest micrometric fragments and zooplankton ingest microplastics with a maximum size of approximately 10-20 µm. In terrestrial environments, the ingestion of microplastics by springtails and earthworms has been documented. Earthworms ingest microplastics that are mostly smaller than 50 µm in size. A recent article reported the presence of microplastics in the faeces of four small mammal species (hedgehog, vole, mouse and rat) out of seven species examined (Thrift *et al.*, 2022). Even though, in most cases, the fragments have a relatively short residence time and are rapidly egested (within several hours), the exposure to plastics is continuous given their abundance in the environment.

This continuous exposure to microplastics could induce toxic effects related to physical changes, for example, or through disturbances in the intestinal flora (microbiota), which may then influence growth (malnutrition and/or a false sense of fullness).

Airborne organisms are not only exposed to plastics through the food they eat, but also the air they breathe. The recent discovery that microplastics are present in the atmosphere has led to research being carried out on their presence in the lungs. The particle sizes observed in the lungs are directly tied to the micrometric size of the particles found in the air and range from one to several micrometres (µm).

So far, although research has mostly looked at plastic fragments larger than one micrometre, there are also smaller fragments known as nanoplastics (mentioned in Part 1). Researchers have yet to fully understand the physical toxicity of these particles, however it seems likely to be of a different nature from that of microplastics. Given their small size, nanoplastics can penetrate tissues and likely cross the intestinal barrier to spread throughout the body. It has not been possible to clearly identify the precise size limit at which nanoplastics can enter the body. However, experiments conducted on cultured cells have shown that nanoplastics alter mitochondrial functions and functionality in several types of cells, possibly as a result of their direct interaction with these organelles.

Besides this physical dimension, plastics also have a chemical dimension. Part 1 mentioned that over 16,000 chemical molecules are found in all plastics; roughly 3,000 of these molecules are known to be toxic and there is currently no reliable information available regarding their toxicity for at least half of them.

The aim of this part is to address both the physical and chemical dimensions of the environmental impacts of plastics, and to illustrate the wide variety of their effects through several examples of terrestrial and marine organisms.

Chapter 1

Impacts on terrestrial organisms

Camille Larue, Franck Gilbert, Gaëlle Darmon and Claude Miaud

⏩ Interactions between plastic particles and terrestrial plants

Camille Larue

Given the ubiquitous contamination of terrestrial environments by plastic particles, it is now vital to study their interactions with plants (especially crop plants). Ademe (Palazot *et al.*, 2023) recently conducted a study showing that agricultural soils are particularly concerned by this pollution and therefore, plants are considered as the first link in a food chain up to humans.

In 2020, a first literature review noted that fewer than twenty articles have been published on this topic (Larue *et al.*, 2021). Today, a lot more research has been carried out, with just slightly more than one hundred articles published (Zantis *et al.*, 2023; Jia *et al.*, 2024). However, despite this, the scientific community has still not been able to come to a consensus about the level of risks for plants with regard to the dispersal of plastics. The exposure scenarios for this issue are rather complex and include several different confounding factors (e.g. the physicochemical characteristics of the particles, plant species or exposure environments, etc.), which could possibly explain this lack of consensus.

Influence of the physicochemical properties of plastic particles

Size

Studies have looked at how the size of plastics (micro- and nanoplastics) influences their phytotoxicity. Literature reviews suggest that larger particle sizes have a more pronounced effect on plant development than smaller sizes (Jia *et al.*, 2024); however, other studies conclude the opposite.

A hypothesis that combines both these results would be that different toxicity mechanisms exist based on the size of the plastic particle, and therefore different toxicity profiles also exist. As an example, as nanoplastics are exceedingly small, they can enter into plant tissues and cause a direct effect. Then, above a certain threshold size, there would be less effect until a second threshold; after this point, indirect effects would appear related to altered soil Several physicochemical properties or even a change in nutrient bioavailability (Jia *et al.*, 2024). One study supporting this hypothesis found that broad bean

(*Vicia faba*) plants exposed to 100 nm and 5 µm polystyrene particles are damaged in different ways depending on the size of the particle: microparticles have a stronger negative effect on biomass and root length, whereas nanoparticles cause oxidative stress and genotoxicity (Jiang *et al.*, 2019).

Shape

In addition, the literature underscores that variations in toxicity exist based on the type of plastic: for example, plastic fibres produce stronger effects (Boots *et al.*, 2019). Synthetic microfibres (a mix of nylon and acrylic) applied at a concentration one hundred times lower than that of microparticles (0.001% versus 0.1% fragment) had similar effects on the germination rate and height of ryegrass plants (*Lolium perenne*) (Boots *et al.*, 2019).

Surface charge

The surface charge of plastic particles also seems to play a key role in controlling potential interactions between the plant surface and particles and, therefore, their toxicity. Repeated exposure to positively charged particles resulted in more pronounced toxic effects on plants than neutral or negatively charged particles (Xu *et al.*, 2022). This effect may be linked to an increased interaction between positively charged plastic particles and the negatively charged root/leaf surfaces, with a higher amount of contamination being internalized. However, this link has only been tested on polystyrene nanoplastics and needs to be confirmed on a larger scale with other types of polymers and other particle sizes.

Type of polymer

Although it is difficult to come to a clear conclusion about what effect polymers have, it seems that the two polymers that have the greatest effect on plants are PVC (polyvinyl chloride) and PET (polyethylene terephthalate) (Zhang *et al.*, 2024). These findings corroborate the impacts found in phytoplankton (Larue *et al.*, 2021). This effect might be related to the presence of specific phenyl-type functional groups in PET or chlorinated groups in PVC.

Another argument put forward in the literature to explain the toxicity of certain plastics is that they release monomers and additives, found in plastic particles, especially those of biodegradable plastics. Several studies have shown that these plastics are highly toxic, sometimes even more so than conventional plastics (Boots *et al.*, 2019; Jia *et al.*, 2024).

Ageing

Most studies were conducted on pristine synthetic particles. However, it has been demonstrated that after the particles release, they begin to age as the environmental conditions (biological, physical and chemical) modify their physicochemical properties. To date, there are only a few articles that have compared pristine and "aged" materials. These articles show contrasting effects; sometimes ageing led to a decrease in phytotoxicity, and other times it resulted in an increase (Wang *et al.*, 2024).

As ageing has a strong influence on the physicochemical characteristics of plastics, it is important for future work to focus on the toxicity of these aged materials in the environment to better understand the mechanisms explaining these toxicity differences.

Influence of environmental parameters

Plant species

Some studies suggest that the impact of plastics could be species dependent (Zantis *et al.*, 2023). In the meta-analysis conducted by these authors, the conclusion was that microplastics had a significantly higher effect on the early development (germination) of dicotyledonous species than of monocotyledonous species. That said, it was not possible to come to an overall conclusion on the differences at other developmental stages using the available data. Yet these authors were able to demonstrate that the development (after 21 days of exposure) of two dicots (carrot and lettuce) exposed to polystyrene microplastics was more disrupted than the growth of two monocots (barley and wheat). However, other studies have shown either the opposite effect (altered development in barley but no impact on cucumber after exposure to polyethylene microplastics) or differences between species but unrelated to the family. More systematic studies should be carried out to better pinpoint which parameters related to plant physiology and metabolism explain these differences in responses between different plants.

Soil type

Soil type is another determining factor when it comes to assessing the fate of plastics. It has been previously shown to be important for other types of contaminants, for example, manufactured nanomaterials (Larue *et al.*, 2018). Unfortunately, to date, not enough studies have looked at this parameter to be able to really come to a conclusion. At the very least, it seems that the structure of soil aggregates is a determining factor for toxicity (Zhang *et al.*, 2024).

Toxicity mechanisms

As mentioned above, several different mechanisms may explain the effects that plastic particles have on plants.

The presence of plastics can indirectly impact plant development by changing the physicochemical properties of soils (structure, water retention, nutrient adsorption) and their microbiology. Direct effects also exist, which may or may not be linked to the internalization of plastic particles. Thus, for larger particles (micrometric size), toxicity can be related to interactions with the root or seed surfaces (disrupted hydromineral nutrition, root damage, etc.). The leaching of monomers or additives released by the particles themselves may also cause toxicity (Jia *et al.*, 2023). Lastly, for the smallest particles which can be taken up by plants, the scientific community has mostly discussed the effects of genotoxicity and oxidative stress, with repercussions on photosynthesis and, ultimately, development (Jia *et al.*, 2023).

Trophic transfer

Xu *et al.* (2022) used fluorescent nanoplastics to demonstrate that, given their small size, nanoplastics are likely to be absorbed by plants and transported to their edible parts. Unfortunately, not much data is available regarding transfers within a terrestrial food chain, but the data that are available suggest that nanoplastics may be transferred from the exposure environment to a plant, and then to a primary consumer (snail) (Zantis *et al.*, 2024).

Simultaneously, other studies have shown that vegetables and cereals may potentially accumulate large amounts of phthalates from mulching plastic used in agriculture and therefore may be a potential risk to humans (Cui *et al.*, 2024).

Current research areas and perspectives

At present, most studies examine the exposure of plants to polystyrene particles (even though the literature tends to show that polyethylene particles are predominantly found in soils). A substantial proportion of these studies are still being conducted in hydroponic media (liquid culture media) as certain mechanisms can then be studied in greater detail; however, it is not representative of environmental interactions (plant-soil-plastic particles) (Zantis *et al.*, 2023). Future research should be directed more toward investigating the exposure of soils to aged polyethylene nanoplastics as this scenario is more representative. The doses used in the studies are relatively realistic based on what is known today. As such, the literature indicates that the presence of plastic particles on plants, especially cultivated plants (the main species studied) may present a risk of decreased yields and transfers within food chains (Figure 2.1.1).

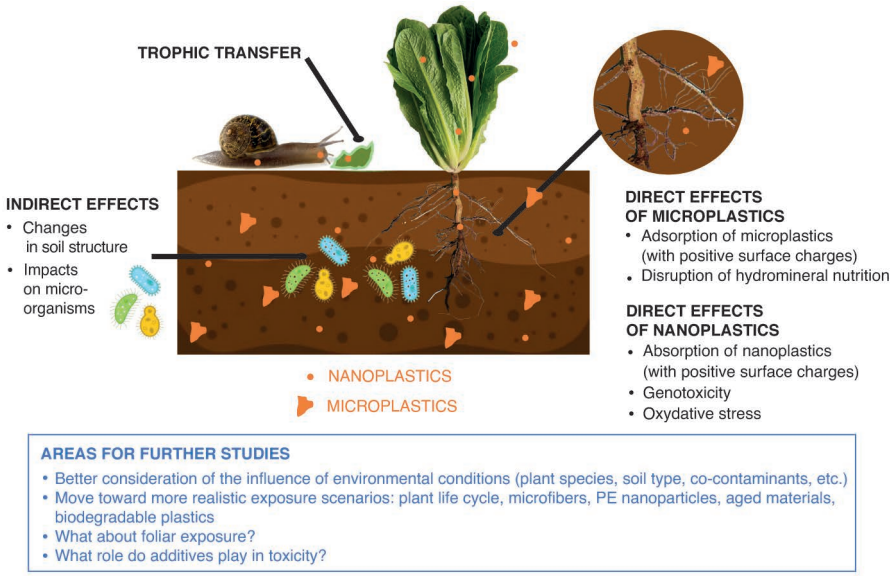


Figure 2.1.1. Summary of the main findings from the literature on interactions between plastic particles and terrestrial plants, and possible directions for future research.

PE: polyethylene.

Despite this, there is still a lot we do not know, especially regarding the influence exerted by parameters such as the physicochemical properties of plastics or environmental factors, to reach a reliable conclusion. Studies with longer exposures, over the whole life cycle of plants, also need to be conducted as some studies suggest that there may be some resilience phenomenon during exposure (Jia *et al.*, 2024). The literature review also shows that it is vital to conduct more research on biodegradable plastics. Even though it may seem that biodegradables are a more

sustainable alternative to "conventional" plastics, preliminary findings show that these types of plastic are highly toxic, which may have to do with a more rapid release of additives or being broken down more quickly into potentially more toxic nanoplastics (see Part 4, Chapter 3).

Another aspect that is still rather underexplored is the impact of microplastics after foliar exposure, i.e. the impact of air pollution or the use of plant protection products (phytosanitary products) as well as the use of polymers (e.g. to encapsulate the active ingredients). However, the few available studies have demonstrated that plastic particles can enter plants through the leaves and that it is quite difficult to remove these contaminants from the surfaces of the edible parts of plants using traditional methods (rinsing with water). This could prove to be a major problem for both animal and human health.

Other research questions touch on the influence these plastic particles have on other contaminants that may already be present in the environment (e.g. a cocktail effect with trace metals or organic contaminants). Yet once again, there are not enough studies available to be able to come to any conclusions on the toxicity of these mixtures and the possible antagonistic or synergistic effects of these contaminants.

⏩ Impacts on terrestrial and aquatic ecosystem engineers

Franck Gilbert[17]

Ecosystem engineers and bioturbation

According to Jones *et al.* (1994), ecosystem engineers are organisms that directly or indirectly modulate the availability of resources to other species by altering, conserving and creating habitats. Bioturbation is a good example of an engineering process carried out by organisms and has most recently been defined as "all transport processes carried out by animals that directly or indirectly affect sedimentary matrices" (Kristensen *et al.*, 2012) and soils, when applied to terrestrial ecosystems. Thus, bioturbation is a ubiquitous process found in all unconsolidated substrates within terrestrial and aquatic (inland and marine) ecosystems.

Bioturbation, and more specifically its particulate component (i.e. reworking) (Kristensen *et al.*, 2012) is an integrative process driven by all the activities of organisms in soft-bottom ecosystems, which are mostly related to movements on the surface and within the subsurface (for protection reasons, to search for food, for "migration", etc.) and to the construction or maintenance of burrows and tunnel networks. Therefore, it seems that biological reworking is a good marker of the overall activity of ecosystem engineers and its study can be used to characterize the effects of variations in environmental conditions (e.g. Capowiez *et al.*, 2021; Román *et al.*, 2023) or physical and chemical stresses (e.g. Cuny *et al.*, 2015; Gilbert *et al.*, 2022) on the functioning of an ecosystem.

This was the context for an experiment studying the effect the presence of microplastics in three different ecosystems—soil, freshwater sediment and marine sediment—using biological reworking quantification.

17. This sub-section was a collective effort undertaken by Soleen Bailly, Yvan Capowiez, Franck Gilbert, Stefan Krause, Camille Larue, Caroline Lise, Florian Mermillod-Blondin, Laurent Simon, Manon Vallier and Mohammad Wazne.

Preliminary experimental study of the impact microplastics on soil reworking

A joint protocol, monitoring the deposition of inert fluorescent particulate tracers (luminophores), was used to study the effect of microplastics on reworking carried out by ecosystem engineers in soil, freshwater sediment, and marine sediment (Figure 2.1.2).

Three representative species of "worms" (in the traditional sense of the word) for their respective environments were chosen for this experiment: *Aporrectodea caliginosa* (soil), *Tubifex tubifex* (freshwater sediment) and *Hediste diversicolor* (marine sediment). These three species all live in soft substrates and feed on organic matter deposited on the surface of these substrates; as such, they are all in direct contact (presence in their vicinity and ingestion) with the contaminants found in their habitats (all around them).

For each species and respective substrate, organisms were added (while respecting the natural population density conditions) to a substrate that was either contaminated or not with various microplastics (equal amounts of polystyrene, polyamide and polyamide fibre fragments with a final concentration in the substrates of 100 mg per kg of dry substrate).

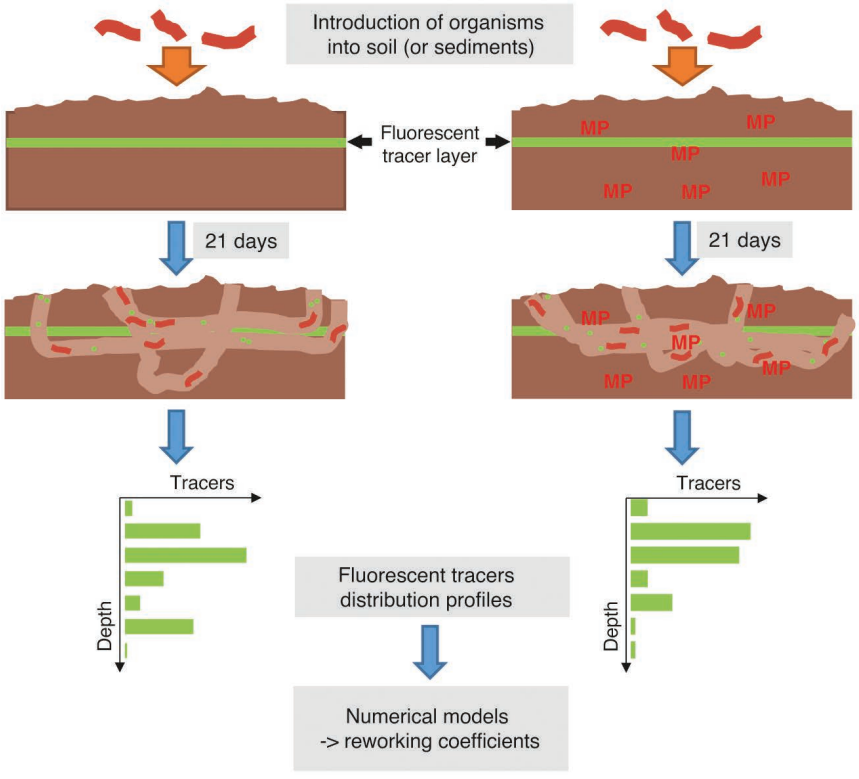


Figure 2.1.2. Protocol for measuring reworking ("particulate bioturbation") in soft substrates either contaminated or not with microplastics (MP), as part of the experiment conducted.

After 21 days under controlled experimental conditions (temperature: 20°C; alternating day/night: 12 hours/12 hours), the vertical distribution of the luminophores due to biological reworking was measured and the intensity of the corresponding reworking was calculated for each experimental unit.

The findings suggest that the presence of microplastics affects the reworking activities of the three species studied (Figure 2.1.3). However, the effects vary greatly depending on the species: there was an average increase of 9% in soil reworking activities for *Aporrectodea caliginosa*, while there was a decrease of 78% and 28%, respectively, for the two aquatic species *Tubifex tubifex* (freshwater sediment) and *Hediste diversicolor* (marine sediment).

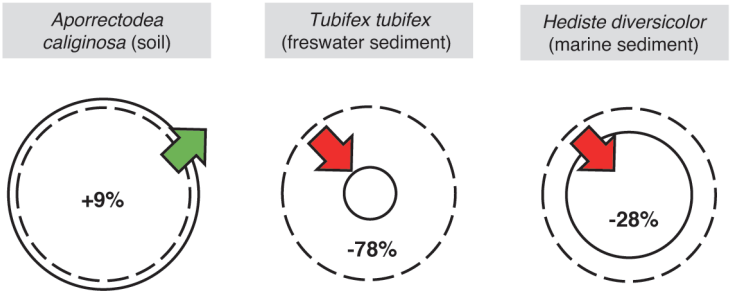


Figure 2.1.3. Average relative intensity of reworking ("particulate bioturbation") by organisms, after 21 days under the experimental conditions used.

Dashed circle: microplastics were absent from the substrate; continuous circle: microplastics were present.

At this point, it is difficult to explain both how the microplastics affected the behaviours of the species and what caused the differences in reworking activity among the various species studied. Regardless, these preliminary findings on the functioning of ecosystem engineers, and more specifically bioturbators, can be used to supplement a growing overall assessment of what impact microplastics have on species found in soils and sediments (e.g. You *et al.*, 2023; Wazne *et al.*, 2023 and other sections in this volume).

⏩ Impacts on terrestrial and watercourse wildlife

Gaëlle Darmon and Claude Miaud

Like the studies performed on macro- and microplastics in the environment, most research on interactions with fauna has been carried out in marine environments rather than in terrestrial ecosystems. Even though most macroplastics (>5 mm) accumulate in terrestrial ecosystems and on riverbanks (over 90% as per Meijer *et al.*, 2019) far upstream from the sea, the impacts of plastic debris on terrestrial biodiversity are poorly understood (Darmon *et al.*, 2020) and it is only in recent years that studies have been carried out in freshwater environments (Azevedo-Santos *et al.*, 2021). Most publications looking at interactions between wildlife and waste in terrestrial ecosystems are based on opportunistic observations. However, a literature review and observations collected from volunteers and professionals show that all terrestrial animal taxa are placed under pressure from plastic debris, just like in marine environments (Darmon *et al.*, 2020). The most documented type of interaction is

entanglement, while ingestion is not observed as often (there are fewer studies on excreta or on the analysis of digestive systems during necropsies). Plastic debris is ubiquitous in terrestrial ecosystems and accumulates on surfaces, shorelines or in vegetation. As these plastics are the only available resource, meaning that animals cannot access natural elements, thereby affecting many other behaviours such as feeding, protection, thermoregulation and nesting.

Birds in terrestrial ecosystems



Figure 2.1.4. Nest (unknown species) built with plastic sheet and string (observed in 2020 in Var, France).

Along with fish, birds are probably the most studied group; however, studies are usually conducted in coastal areas or estuaries instead of terrestrial ecosystems (Blettler, Mitchell, 2021). Observations show that quite a large variety of species are concerned, such as the osprey (*Pandion haliaetus*), various species of seagulls (e.g. the yellow-legged gull [*Larus michahellis*], lesser black-backed gull [*L. fuscus*], European herring gull [*L. argentatus*], Audouin's gull [*L. audouinii*], Mediterranean gull [*L. melanocephalus*], black-headed gull (*Chroicocephalus ridibundus*], black-legged kittiwake [*Rissa tridactyla*]), grey herons (*Ardea cinerea*), great cormorants (*Phalacrocorax carbo*), little egrets (*Egretta garzetta*), Eurasian spoonbills (*Platalea leucorodia*) or other species such as the common buzzard (*Buteo buteo*). The occurrence of plastic litter ingestion varies from 0% up to sometimes 100% depending on the species and population. In the study carried out by Gil-Delgado *et al.* (2017) in Portugal, 60% of Eurasian coots (*Fulica atra*, out of a total of 10 individuals), 45% of mallard ducks (*Anas platyrhynchos*, 40 individuals) and 44% of common shelducks (*Tadorna tadorna*, 89 individuals) had ingested various plastic debris. Different types of waste are ingested, plastic for the most part, made up of hard fragments, string or fragments of bags and foam, as well as bits of glass or metal. These studies are based on analyses of the digestive tract contents, excretions in faeces or regurgitated pellets. Some authors have also found microplastics in feather barbules.

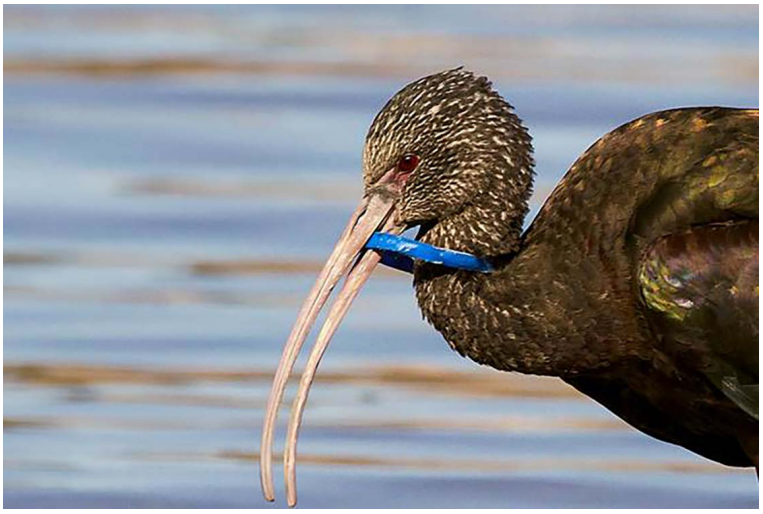


Figure 2.1.5. White-faced ibis (*Plegadis chihi*) entangled in a plastic ring used to package canned beverages (Panama River, Brazil).

Other types of interactions are commonly reported in the literature. Numerous species have been observed using man-made materials to build their nests (Figure 2.1.4), which poses a risk of entanglement, especially among young individuals. Some species are better known for using litter (e.g. grebes, cormorants, gulls and corvids), whereas other species such as the red kite (*Milvus milvus*) or the house sparrow (*Passer domesticus*) periodically use it. In 2018, Ryan documented cases of entanglement in 69 out of 676 (10%) freshwater and coastal species. This debris is often long and stringy, from fishing activities, or refuse bag strings, balloon strings, agricultural twine, electrical wires, ropes or textiles. Animals can become entangled in this very solid waste and are at risk of laceration or amputation. This has already been observed in urban environments with pigeons that have lost legs after becoming entangled in hair found near hair salons. Sometimes animals die because of entanglement or ingestion due to intestinal blockage (or internal injury) or because they are trapped by the plastic objects (Figure 2.1.5) (Blettler, Mitchell, 2021). Species that regurgitate indigestible matter as pellets might not be as affected.

Various hypotheses have been advanced to explain why birds build nests with waste, for example: cigarette butts might help repel pests, and other types of plastics might help better insulate the nest and could be used for signalling. Several published articles have highlighted a link between litter density used in nests or ingested and the loss of natural resources depending on the degree of human-induced modification, as plastic debris is sometimes the only resource available.

Freshwater fish

Research has shown that several species of freshwater fish ingest microplastics. The authors often use different methods based on the logistical capacities of their laboratories to detect very small particles in biological matrices such as digestive systems. Different size plastics have been found, with researchers usually testing for sizes of

300 or 100 µm. As per Clause *et al.* (2021), most studies concern marine species which means that studies on terrestrial ecosystems are not well represented. Observations have shown that at least 150 freshwater species have ingested plastic, with frequencies of occurrence ranging from 10% to more than 30% depending on the species and location. This includes common species found in European rivers and lakes, such as the European chub (*Squalius cephalus*), northern pike (*Esox lucius*), common roach (*Rutilus rutilus*), freshwater bream (*Abramis brama*) or European perch (*Perca fluviatilis*) (Darmon *et al.*, 2020). Fish may serve as bioindicators of the ecological health status of freshwater, however they have not yet been included in policy directives, such as the Water Framework Directive (WFD) while other pollutants such as heavy metals are taken into account. An initiative to assess microplastic ingestion in fish (as found in their digestive tracts) collected for the Water Framework Directive (WFD) is currently being conducted nationally within France. This initiative is spearheaded by HISA[18], in partnership with the CEFE and INRAe laboratories, as well as the French Biodiversity Agency (OFB) and WAO Nature & Conservation. Currently, 92.7% of the 69 chub individuals assessed had plastics larger than 100 µm in their digestive tract. The two most ingested polymers were polyethylene (PE) and polyvinyl chloride (PVC), representing 58% and 14.6% among the fish that had ingested plastics, respectively. These preliminary findings are showing that freshwater fish are exposed to plastics and that the potential effects of this pollution on the ecological status of inland waters must be considered.

Moreover, not only has it been observed that freshwater fish ingest microplastics, but these plastics also adhere to their gills, and these fish may become entangled in macrowaste from fishing activities. The wels catfish (*Silurus glanis*) is a highly opportunistic feeder and can ingest a wide range of large waste, as observed by anglers on the Rhône River (Tanzilli, Faure, 2016) who found 2.9% waste (i.e. 0.2% of the ingested mass) among all the other food ingested. Examples of this waste include plastic bags and fragments of plastic, fabrics, polystyrene fragments, aluminium fragments, flip-flops, cardboard boxes, condoms, sanitary towels and tampons, cotton ear buds, diapers, toothpaste tubes, water bottles, beer cans, etc. as well as man-made (but natural) foods such as sausage, potatoes, etc.

Land mammals

Interactions between waste and terrestrial mammals are much less studied than in birds or fish, as reflected in the number of publications involving these taxa (Darmon *et al.*, 2020; Thrift *et al.*, 2022). Published studies have reported cases of ingestion, such as in the Eurasian otter (*Lutra lutra*) in the Ticino River in Italy, or in the Amazonian manatee (*Trichechus inunguis*), sometimes causing the death of the animals involved. A study carried out in the United Kingdom demonstrated the presence of plastic in the faeces of four species with different diets (herbivores, insectivores and omnivores): the European hedgehog (*Erinaceus europaeus*), wood mouse (*Apodemus sylvaticus*), field vole (*Microtus agrestis*) and brown rat (*Rattus norvegicus*). The most common polymers (polyethylene, polyester and polynorbornene) provide information about which activities are generating this type of pollution: textiles, tyre wear, sludge spreading, etc. (Thrift *et al.*, 2022).

18. Collaborative study with Marie-Aurélia Sabatte, Human InitiativeS for Animals (HISA) association.

Moreover, cases of entanglement have also been reported (mostly in fishing gear) in various freshwater dolphin species in Asia or the Amazon River (Clause *et al.*, 2021). Some species also take refuge in litter (Figure 2.1.6).



Figure 2.1.6. *Thylamys* sp. using a plastic bottle as a refuge (South America).

Many studies have looked at the use of landfills and illegal dumping. Plastic, glass and aluminium waste have been found in the faeces of common raccoon dogs (*Nyctereutes procyonoides*), red foxes (*Vulpes vulpes*), European pine martens (*Martes* sp.) and European polecats (*Mustela putorius*). Often times, plastics are the only resource available to domestic herds of goats or cattle in countries that do not have suitable waste management structures. Several studies have shown that the ingestion of plastic bags and other debris by these animals may impact their health as well as their ability to absorb nutrients: macroscopic lesions, loss of muscle (atrophy) and body fat, organ fibrosis (spleen, liver, kidneys, etc.) and histological changes in the rumen. This could cause a decline in the animal's body condition along with trace element deficiencies and a decrease in milk production, thereby affecting both food production systems and human health.

Reptiles and amphibians

Contrary to sea turtles, few studies have been conducted on the pressure from waste on land tortoises and freshwater turtles. Clause *et al.* (2021) examined 352 non-marine turtle species and found that five aquatic species (1.4%) had ingested plastics; however, the authors did not include cases of turtles swallowing fishing lines. They also found that nine other aquatic and terrestrial species (1.7%) had ingested waste other than plastic.

In other reptiles, the primary or secondary ingestion of microplastics or even the occasional glass fragment is somewhat common. That said, studies often report cases of entanglement in fishing nets or crop protection nets, or even in the cap rings from

plastic bottles or pull tabs from juice boxes (Figure 2.1.7). These interactions can kill or injure animals, or result in wounds that turn into secondary infections, lacerations, constrictions or deformities. Sometimes, there is a decline in body condition that has an impact on individual reproduction.



Figure 2.1.7. Argentine black and white tegu (*Salvator merianae*), entangled in a plastic ring for used to package canned beverages (Brazil).

In general, studies on amphibians are based on experiments with larvae or immature individuals to test what impacts increasing exposures to plastic have on individual health. This research highlights changes in the external, mutagenic and cytotoxic morphology as observed, for example, in tadpoles of the Brazilian frog *Physalaemus cuvieri* (literature review published by Darmon *et al.*, 2020). Publications have also reported cases of entanglement, often in string-like debris such as fishing lines or crop protection nets, as seen in the common toad (*Bufo bufo*) in France, or in balloons that were released sometimes far away from where they landed.

Invertebrates

For crustaceans, insects, molluscs and members of the cnidaria family, publications are almost all based on experimental studies of exposure to plastic concentrations under controlled conditions, showing lethal or sublethal[19] effects for the individuals exposed.

Under natural conditions, it is rather common to see cases of entanglement in ghost fishing gear, for example, in the freshwater crab *Potamon fluviatile* or the European crayfish *Astacus fluviatilis*. Microplastics can become trapped in the cases built by caddisfly larvae. It appears that freshwater bivalves are more exposed to ingestion of microplastics (Figure 2.1.8), probably since they filter water to feed. For instance, Pastorino *et al.* (2021) reported an average of 0.2 particles/individual in the zebra mussel (*Dreissena polymorpha*) in Italy.

19. Causing physiological effects (sometimes severe) but not death.



Figure 2.1.8. Bivalves on a plastic toy car recovered from the Rhône River, which had probably been in the water for a long time (Lyon, 2019).

Plant vegetation and habitats

Some environments may be polluted with high concentrations of rubbish, often plastic but also glass or metal debris. These are illegal dump sites, areas that accumulate litter carried by the wind or currents, or the discharge areas of combined sewage collection systems that mix wastewater and stormwater (Figure 2.1.9). Not only does this pollution cause aesthetic damage, but it also causes a loss of resources (e.g. shelter and food) for animal life and exposes animals to risks of becoming entangled.

There is very little research on how waste impacts plants. A few articles have looked at the capture of plastics by mangroves found at the mouth of rivers. The goal of these studies is usually to record the waste discharged from rivers rather than to assess the pressure placed on plant biodiversity. Clause *et al.* (2021) report that when grown in environments with high concentrations of microplastics, algae grow more slowly than usual and present a risk for herbivorous species via secondary poisoning.

A need for specific studies

Ryan (2018) considered that the risks of entanglement[20] would be lower for freshwater species than marine species, and even lower for terrestrial birds. For example, his article mentions a rate of entanglement for sea ducks of 47% compared with 12% for freshwater ducks, geese and swans. That said, the directives for researchers working in marine environments encourage the use of a standard protocol to assess the impacts on wildlife (see Part 1, Chapter 2), whereas comparable methodologies are not always routinely

20. Entanglement is defined as the process or state of being surrounded, trapped or stuck in waste.



Figure 2.1.9. Wipes and other litter from wastewater released to the environment by stormwater drain overflows during heavy rainfalls (Lyon region, 2023).

applied to research carried out on waterways. Apart from a few systematic nest surveys, studies often rely on opportunistic observations or analysing the diets of only a few individuals. As a result, it has not yet been possible to put together an accurate overview of this pressure in inland environments. At sea, survey efforts have increased the estimated number of species likely to interact with waste. Although there are no directives for monitoring the pressure exerted by waste in territorial ecosystems, specific studies need to be carried out urgently and a monitoring system needs to be put in place; possibly one that uses relevant bioindicators, for example, birds (Masfield *et al.*, 2024).

Published studies and naturalist observations clearly demonstrate the pressure exerted by waste on territorial biodiversity. Several studies have attempted to understand the factors affecting interactions with waste, such as the dietary and ecological niche of the species or the distance from anthropized areas. In aquatic environments, riparian vegetation may help protect wildlife by retaining waste; however, this is not the case for terrestrial ecosystems where waste is a major challenge with regard to conserving biodiversity and the health of ecosystems. The accumulation of waste not only affects food resources, but it also lowers the water quality and may also impact riverbank structure and river flow. Consequently, this may have consequences for numerous species as well as the food web and could ultimately have repercussions for human health.

Chapter 2

Impacts on marine organisms

Karen D. McCoy, Marion Vittecoq, Xavier Cousin, Gaëlle Darmon, Claude Miaud, Jean-Christophe Auguet and Franck Lartaud

⏩ Seabirds as model species for plastic pollution

Karen D. McCoy and Marion Vittecoq

Among birds, seabirds are particularly exposed to plastic pollution. This exposure can have direct and obvious effects on the individual, leading to its death. Examples of this include entanglement in driftnets or other types of string-like plastics that can be found in seawater. Animals can also choke or suffocate if macrowaste is accidentally ingested. However, chronic exposure to plastic also occurs, but is more difficult to measure, especially in terms of its impacts on seabird population dynamics and associated cascading effects in the marine ecosystem.

Exposure to plastics

Like all organisms in marine ecosystems, seabirds are exposed to plastic pollution found in their habitat. Since these species are at the top of the food chain, exposure can occur in more ways than for species at the bottom of the chain:

– **environmental exposure:** birds are often exposed to plastic debris in the ecosystem as they forage or rest. Birds caught in driftnets, plastic bags, rings from beverage cans packaging, etc., may prevent them from feeding, swimming or even breathing, thereby leading to their death. These types of interactions have increased worldwide over the past three decades, with an estimated 36% of seabird species found recorded entangled in plastic debris, 83% of these incidents due to fishing gear (Ryan, 2018). Some birds also collect plastic debris for nest building, which can greatly increase the risk of entanglement and mortality, especially for chicks (Votier *et al.*, 2011);

– **by-catch:** seabirds can also mistakenly think pieces of plastic are prey. It is not uncommon to see images of dead chicks whose stomachs are full of plastic because their parents fed them these artificial elements (Figure 2.2.1a). The ingestion of plastics at sea by seabirds is influenced by the abundance and colour of the plastic pieces, as well as where this plastic is found within the water column (Lavers, Bond, 2016). How likely seabirds are to ingest plastic also varies depending on the species, due to differences in feeding ecology. For example, researchers have shown that only 12.5% of great black-backed gulls (*Larus marinus*), a specialized marine predator, were found with plastics

in their digestive tract in the Gulf of Maine (USA) (Caldwell *et al.*, 2020) compared to 50% for Newell's shearwaters (*Puffinus newelli*) in Hawaii or 86% of northern fulmars (*Fulmarus glacialis*) in Greenland; the latter two species are surface-feeders and ingest small prey at the water's surface (Kain *et al.*, 2016; van Franeker *et al.*, 2022);
– **accumulation through the food chain**: although some seabird species are less exposed to plastic waste because of their feeding behaviour, they may still ingest plastic indirectly by consuming contaminated prey (i.e., a vertical transfer of pollutants). Indeed, plastic pollution accumulates throughout the food chain, and predatory birds are exposed to the plastic particles accumulated in their prey. For example, Hammer *et al.* (2016) showed that there were numerous pieces of plastic in regurgitated pellets of great skuas (*Stercorarius skua*) that also contained the remains of northern fulmars, suggesting that these birds likely acquired the plastic via their prey; northern fulmars are well known to consume large amounts of plastic;
– **food wastes**: last, some seabirds are generalists and consume the food that is the most readily available in their environment. This is the case for many gull species,



Figure 2.2.1. a) Remains of a Laysan albatross (*Phoebastria immutabilis*) chick fed plastic by its parents; the chick was unable to regurgitate the plastic, resulting in its death by starvation or suffocation (2006); **b)** Gulls often use human food waste found in open dumps.

which have quickly learned to use the resources provided by humans, especially food wastes (Figure 2.2.1b). Because of strong competition with other birds for this resource, these birds often do not have time to separate the food from its packaging when feeding, thereby greatly increasing their exposure to plastics. A recent study looking at the diet of yellow-legged gulls (*Larus michahellis*) in 11 natural colonies of the Western Mediterranean region showed that, while exposure varied among colonies, 80% of regurgitated pellets contained at least one piece of plastic. Across all the colonies studied, the most common type of plastic was polyethylene (PE)—the main polymer used in food packaging (Nono Almeida *et al.*, 2024).

Even though seabirds are exposed to high levels of plastics in their environment, some species, such as gulls and skuas, can easily form pellets and are therefore able to get rid of at least some of this waste. Other species do not have this option. Although macrowaste do not pass through the digestive tract in this case, smaller fragments can. Therefore, it is important to differentiate between exposure, retention and accumulation of plastics in order to understand their impact. We know that a large amount of small microplastics (between 1 mm and 10 µm) can be found in the intestines of yellow-legged gulls (Nono Almeida *et al.*, 2026), but it is unclear how much of it stays there. Provencher *et al.* (2018) reported the presence of microplastics in the faeces of northern fulmars; however, in other species, it is known that very small particles (<10 µm) can cross the intestinal barrier and accumulate in other places in the body. Other unknown factors in relation to plastic exposure include the degree of absorption of additives (e.g., phthalates, brominated flame retardants, UV stabilizers), or other related pollutants (e.g. adsorbed heavy metals), by the body as plastics pass through the digestive tract and what effect this may have on various physiological functions.

Impacts of exposure to plastics on seabirds

Just like for other organisms, exposure to plastics may result in a multitude of impacts on seabirds:

– **mortality:** as outlined above, exposure to plastic may directly cause death. This is the case for species such as petrels and fulmars, as they tend to ingest large amounts of plastics, but are unable to eliminate it due to the morphology of their digestive tract. As the individual's stomach gradually becomes filled with plastic, the animal can no longer feed and will eventually die of starvation. Likewise, in various other contexts (e.g. while foraging or if plastics are found in nests, see above), birds may become entangled in pieces of plastic with the immediate result that they are either strangled, or they can no longer move and then eventually die from starvation or predation;

– **decreased fitness:** when seabirds are exposed to plastics, impacts on an individual's longevity and reproductive success may not be easy to discern or quantify. Recently, Charlton-Howard *et al.* (2023) documented a disease directly related to plastic ingestion called "plasticosis". This is an inflammatory disease caused by prolonged contact of plastics with the tissues of the digestive tract and is correlated with weight loss. Histological studies on flesh-footed shearwaters (*Ardenna carneipes*) have also shown that microplastics can penetrated into diverse organs (kidney, spleen, proventriculus) and might be related to inflammation, fibrosis and loss of organ structure (Rivers-Auty *et al.*, 2023). Various additives that are integrated into plastics are known or suspected endocrine disruptors. Exposure to halogenated organic compounds (HOCs), for example, has been associated with a disruption of thyroid hormones in

northern fulmar chicks in Svalbard (Nøst *et al.*, 2012). The immune system may also be altered by exposure to plastics, potentially rendering individuals more susceptible to infections (Loiseau, Sorci, 2022). Moreover, some plastics may even be colonized by infectious organisms, such that plastics can act as pathogen vectors. Conversely, the presence of intestinal macroparasites may help remove microplastics and associated additives from the digestive tract of seabirds; however, there have been very few studies on this potential fitness benefit of parasites. Finally, although research is only just starting to look at the seabird microbiome, exposure to plastics is known to disrupt these microbes, possibly resulting in dysbiosis (microbiota imbalance) and impacting physiological functions.

Challenges for seabirds related to exposure to plastics

The main challenge associated with seabird exposure to plastics is related to conservation; how can we conserve these long-lived species, especially when so many of their populations are in decline? For example, the strong selective pressure placed on flesh-footed shearwaters due to plastic ingestion is a contributing factor to their ongoing decline and helps explain why they were recently added to the IUCN Red List of Threatened Species[21] (Lavers, Bond, 2016). Given the uncontrolled increase in the global use of plastics, and their related accumulation at sea, it seems logical that there will be an exponential rise in this pressure over the next few decades. In this context, research should prioritize studies looking at the fitness effects of plastic exposure, and notably in combination with other pressures (e.g. reduced food availability or increased susceptibility to infections), so that appropriate conservation measures can be taken. This logic also applies more widely to all marine organisms, especially since monitoring plastic exposure in certain seabird species may serve as an indicator of exposure within the ecosystem. For example, the Convention for the Protection of the Marine Environment of the North-East Atlantic (Ospar Convention) uses the percentage of beached fulmars (dead) that contain over 0.1g of plastic as an indicator of how much pollution there is in the surrounding marine ecosystem (see Part 1, Chapter 2).

A second challenge, currently inadequately studied but whose importance is probably grossly underestimated, is understanding the dispersal of plastics by the seabirds themselves. Some seabird species collect large amounts of plastic that they bring back to their breeding or roosting sites, many of which are in relatively pristine natural areas. This is the case for species that build nests using plastics, or mistakenly feed (and kill) their young on plastics (see above). It is also a matter of concern for opportunistic species that feed in urban areas or at landfills, such as herring (*Larus argentatus*) and yellow-legged gulls. Although some of these individuals spend much of their time in human-modified environments, most reproduce and/or rest in natural areas such as coastal islets or lagoons. Thus, these birds can regurgitate large amounts of plastic within natural areas, possibly constituting a significant source of pollution in sensitive environments. Indeed, Martín-Vélez *et al.* (2024) provide an example of this in yellow-legged gulls found in Fuente de Piedra, a natural lake in Andalusia and a major breeding site for numerous birds. Their study showed that, on average, gulls brought 400 kg of plastic to the site each year with up to almost 800 kg in the year 2020! If the scale of this issue, as well as its mechanisms, were better understood more generally,

21. International Union for Conservation of Nature.

measures to limit its likely impacts on the sensitive areas could be defined. Additionally, as already mentioned, the presence of plastic pollution also may help spread pathogens within the concerned ecosystems, thereby adding another form of pressure.

Advice and recommendations for decision makers

Besides the obvious need to reduce plastic pollution in the environment in general, there are quite a few measures that can be taken immediately to reduce the impact of this pollution on wildlife, and especially on seabirds. First, food waste could be better managed to reduce exposure to associated plastics, for example by closing open-air landfill sites, by increasing the availability of larger and more tightly covered garbage bins, or by increasing the frequency of bin collection so that waste does not overflow. The sorting of plastics and other waste could also be improved by introducing more public recycling containers, providing the general public with more information and limiting the use of plastics that cannot be recycled (e.g. polystyrene) or, alternatively, developing recycling facilities to process them. In addition, public policies could provide more support for community efforts to collect plastics at sea and in coastal areas. Finally, research should aim at providing sound scientific arguments that can be used to implement appropriate policy actions to reduce plastic pollution, such as examining the impacts of different types of plastic on individual organisms, and their cumulative effects, as well as on the temporal dynamics of their populations. As high trophic level species, seabird population dynamics can reflect overall changes to marine food webs, such that these birds may be particularly valuable sentinel species for understanding both the overall ecosystem impact of plastic pollution and the effectiveness of mitigation measures.

⏩ Impacts on fish

Xavier Cousin

It is estimated that there are roughly 32,500 species of fish, in the general sense of the term, i.e. a little less than half the vertebrate species found worldwide. Fish are highly diverse, explained by the fact that there is a huge number of species occupying the same aquatic habitat, in terms of their size (from several millimetres to over 15 metres long), shape and colour, as well as the wide range of environments they have colonized. For the most part, fish are found in freshwater (lakes, rivers, etc.), marine environments and transitional waters in every region of the world, from polar waters to continental lakes with surface temperatures that sometimes exceed 30°C. Fish also have a wide range of diet types, from plankton-filtering fish such as Atlantic herring (*Clupea harengus*) or basking sharks (*Cetorhinus maximus*) to carnivorous species such as pikes or some other sharks, and grazing fish like flathead grey mullets (*Mugil cephalus*). Fish also show quite varied changes in diet depending on an individuals' age. In general, the larval stages begin by feeding on plankton (phytoplankton or zooplankton) before eventually moving on to larger prey.

All fish ingest plastic

Despite having quite diverse diets, the one point fish have in common is that they all ingest plastic. More specifically, all fish experimentally exposed to plastics were able to

ingest pieces of plastic the same size as their usual food which, for the most part, were microplastics. These experiments also showed that these microplastics were egested in faeces and that egestion removed the undigested plastic within several hours up to perhaps 10 or 20 hours, depending on the species and concentrations of microplastics used. Absence of bioaccumulation is not confined to fish and depends on the size of the particles, with very small microplastics or nanoplastics probably being translocated and thus bioaccumulated. The technical issue with this, however, is that the smaller the size of the particle, the more difficult it becomes to accurately locate it. The size threshold for translocation remains unknown.

We will now turn our focus to observations of microplastics in wild fish. A recent meta-analysis used data from 131 publications to detect the presence of microplastics in over 170,000 specimens representing 555 species. Microplastics were detected in close to 70% of the species studied (Savoca *et al.*, 2021). It is important to note that, while later studies validated these observations, they further revealed microplastic presence in 148 additional species where it was previously not detected, as reported in Savoca *et al.* (2021). Therefore, it seems very plausible that this proportion of 70% is a gross underestimation. This result is in line with experimental data and suggests that almost all fish ingest microplastics. It should also be noted that, on average, the frequency of occurrence was 0.25 (i.e. microplastics were detected in 25% of fish in these species) and in 20% of the species, microplastics were identified in 9 out of 10 specimens. Two main previously mentioned factors can explain this seemingly low average frequency: 1) it is more difficult to detect small microplastics than it is large ones and, in this type of study, the lower limit is usually above 100 µm; and 2) in almost all cases, microplastics pass through an individual's body, which means that analyses will only provide information at a specific moment in time. The number of microplastics identified per individual and the frequency of occurrence both indicate that, in natural environments, fish are constantly and continuously exposed to microplastics.

Just like in other animals, several uptake routes have been proposed to explain the ingestion of microplastics by fish (Roch *et al.*, 2020). First, microplastics may be deliberately ingested if they have been mistaken for food; they may also be passively or accidentally ingested while looking for food; and last, they may be transferred within the food chain. The contributions of these different mechanisms combined with diverse feeding strategies also explain the different levels of exposure among fish species. A detailed analysis of the species' ecology shows that the ingestion of microplastics is positively correlated with the abundance of plastic in surface waters. This analysis also shows that the habitat itself plays a part in this exposure. For example, demersal species[22] have higher levels of exposure than pelagic species. It is also more likely that predatory species that actively hunt will ingest plastic and, logically, there is a positive relationship between the trophic level[23] and ingestion of plastic.

22. Demersal species live above the sea floor. These species are highly mobile but depends heavily on the sea floor for food. Examples include sea bream, hake, whiting, cod, etc. On the contrary, a fish is called "pelagic" when it lives in waters near the surface or between the surface and sea floor. Herring, sardines, anchovies, mackerel, tuna, etc. are all pelagic fish.

23. In ecology, the trophic level is the level or position of an organism within a food web (or food chain). This concept is often used to have a much clearer understanding of the relationships between two organisms, for example: in predator-prey interactions, or to address a range of bioaccumulation issues throughout the food chain.

Last, it should be pointed out that, in addition to fish ingesting microplastics (the main route of exposure) (Roch *et al.*, 2020), they can also be exposed when these plastics come into contact with the skin and gills, and especially the gills in the case of plastic fibres.

Effects on fish health

Cui X. *et al.* (2024) recently published an analysis comparing the toxicity of microplastics for several different species and showed that fish are some of the most sensitive species. Their work also emphasized the inverse relationship between microplastics size and toxicity: toxicity increases as the plastic sizes become smaller. Just as in the above-mentioned species, the toxicity of microplastics is a combination of effects that have to do with the particles themselves and the effects caused by the chemicals they contain, in addition to any additives and adsorbed chemical contaminants (see Part 1, Chapter 1).

Fish, like other animals, must deal with several types of man-made stressors in the environment such as the presence of pollutants other than plastics, climate change associated with the acidification of water bodies, and diminished resources, especially at the bottom of the food chain, which may then affect the higher levels. Since each individual's life history and various exposures are unknown, it is difficult in natural environments to tell the difference between changes in the health of fish and their exposure to microplastics or other stressors. An integrative indicator called a condition index is often used to estimate a fish's body condition. It seems that there is no correlation between the amount of microplastics found in a fish and its condition index (e.g. see de Vries *et al.*, 2020). However, this does not mean that microplastics do not influence the health of fish. It is important to remember, as mentioned above, that this is just a representation of a specific moment in time. Furthermore, it is not possible to determine the effects on reproduction and therefore the potential effects on populations. In terms of molecular biomarkers, a recent meta-analysis sought to link microplastic detection and the level of certain biomarkers, especially biomarkers showing that the antioxidant defence system has been activated (Compa *et al.*, 2024). Based on data from several different fish species, this meta-analysis shows a weak but significant relationship between the presence of microplastics and the levels of antioxidants, catalase (CAT) and glutathione S-transferase (GST). A similar meta-analysis conducted on bivalve molluscs also showed a sustained increase in CAT levels (Li *et al.*, 2022) as well as an activation of GST, even though this is only temporary, which means that is not a robust marker. In the case of microplastics, characterized by continuous but low levels of exposure, it should be noted that it is difficult to obtain relevant biomarkers to assess the effects of microplastics on the health of fish in the environment, even more so because these biomarkers are also activated by other pollutants.

In a laboratory setting, the different parameters can be controlled to limit the sources of variation and therefore to be able to see the links more clearly, even if this comes at the expense of ecological relevance. Currently, over 500 articles have documented the effects that exposure to microplastics have on fish. As in other organisms, the earliest experiments used conditions quite different from the environmental conditions, for example, the polystyrene beads used were all the same size (homogeneous). These first experiments were key to building a knowledge base and identifying the important

aspects for future experiments, which then gradually began to use conditions more comparable to the environmental ones in terms of concentrations, varied shapes, varied sizes, etc.

Like for other species, we find a combination of approaches that use generic molecular biomarkers similar to the ones mentioned above, and more integrative approaches that assess the impacts on individuals. Molecular analyses draw attention to the activation of the antioxidant defence system, immunotoxicity, and the activation of inflammation. Sometimes, these effects are accompanied by disruptions in the intestinal barrier (Compa *et al.*, 2024). That said, these effects are not always observed, and numerous studies have not found a connection between exposure to microplastics and these responses. The reason for these variable responses probably has to do with the fact that a very wide range of these plastics is covered by just one single word: "microplastics". The analysis of individual-centred responses does not necessarily elucidate the underlying mechanisms involved; however, such data are more informative and predictive regarding effects at the population level. When fish are exposed to microplastic concentrations relatively similar to what would be found in their environment, studies have concluded that microplastics may be toxic in cases of chronic exposure over a long period of time (several months), thereby disrupting growth and reproduction (Cormier *et al.*, 2021; Cormier *et al.*, 2022). Specifically, reduced growth rates were observed in females starting in the reproductive stage and fewer eggs were produced. These effects occur with exposure to several types of microplastics (PE, PV and mixtures in the environment). No significant changes in the oxidative stress biomarkers were seen in conjunction with the physiological effects observed.

These effects may be caused by disruptions in the energy balance and a degraded state and function of the gut microbiota. The hypothesis that there is a link between microbiota and physiological responses seems to be a common thread between numerous species. Adamovski *et al.* (2021) showed that, in fish, exposure to microplastics was linked to changes in the microbiota and the composition of microbial metabolites, with impacts on host metabolisms, especially energy and lipid metabolism. These microbiome disruptions may explain the individual effects observed after exposure, especially in cases of chronic exposure. Moreover, they may also explain the activation of the antioxidant defence system, inflammation and changes in the immune system. It is important to point out that one of the microbial disturbances observed with exposure to microplastics is an increase in the abundance of pathogens (e.g. the *Actinobacillus* and *Mycoplasma* genera), but so far there is no clear direct link between these changes and disease occurrence.

Consequences for human health

Beyond their potential role in causing disease, the presence of microplastics in fish could contribute to their spread. The phenomenon of antibiotic resistance, now occurring worldwide, is related to the emergence of drug-resistant strains in some bacteria formerly susceptible to certain antibiotics. Several mechanisms have been put forward to explain why antibiotic resistance has become more widespread and what role microplastics play in this process (Stevenson *et al.*, 2024). As an example, the concentrating effects of microplastics could make it easier for resistance genes to be transferred from a resistant bacterium to a susceptible bacterium. Microplastics could

also spread agents (additives or adsorbed from the environment) that favour certain genotypes. This phenomenon could be important within an aquaculture context and may have consequences for human health.

As pointed out above, most of the time microplastics only pass through the digestive tract of fish, which is usually not consumed; therefore, they likely do not play a direct role in human exposure. However, when organisms ingest microplastics, they may also be ingesting the additives they contain and any chemical contaminants adsorbed while in the environment, some of which may accumulated along the food chain.

⏩ Plastic ingestion in sea turtles

Gaëlle Darmon, Claude Miaud and Jean-Christophe Auguet

Sea turtles are particularly vulnerable to plastic pollution

The type of interaction studied most often is the ingestion of waste by wildlife. There have been major advances in research over the past few years on the pressure waste places on marine wildlife: in the Mediterranean, the first study, published in 1988, documented the ingestion of waste in the loggerhead sea turtle (*Caretta caretta*). Between then and 2019, 23% of scientific articles studying this type of interaction focused on sea turtles (Anastasopoulou, Fortibuoni, 2022). Currently, on the global scale, it has been shown that all seven species of sea turtles[24] ingest (predominantly plastic) waste in what are sometimes huge quantities (Figure 2.2.2). The distribution models for marine debris published by Zhu *et al.* (2024) estimate that female green sea turtles transport between 7.5 and 8.2 tonnes of plastic in their gastrointestinal tracts on a worldwide scale.

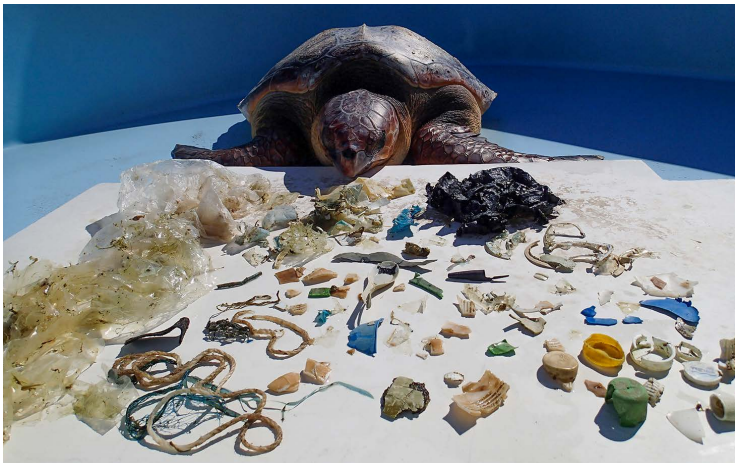


Figure 2.2.2. This 48 kg loggerhead turtle had 217 g of plastic waste in its digestive system (Reunion Island, France).

24. The seven sea turtle species are: the loggerhead sea turtle (*Caretta caretta*), leatherback sea turtle (*Dermochelys coriacea*), green sea turtle (*Chelonia mydas*), hawksbill sea turtle (*Eretmochelys imbricata*), olive ridley sea turtle (*Lepidochelys olivacea*), Kemp's ridley sea turtle (*Lepidochelys kempii*) and flatback sea turtle (*Natator depressus*). Their conservation status on the International Union for Conservation of Nature (IUCN) Red List is classified as "vulnerable" to "critically endangered".

Reviews of the scientific literature have shown that almost half of sea turtles ingest plastic waste, all species and geographic areas combined. However, certain factors, such as feeding strategy, may influence the risk of waste ingestion: herbivorous species such as the green turtle (*Chelonia mydas*) are the most affected, the large leatherback turtle (*Dermochelys coriacea*) ingests the largest quantities, whereas the loggerhead turtle, which has a more omnivorous diet, is the least affected (Zhu *et al.*, 2024). It is still unknown how much plastic waste is ingested per species; 90% of the samples in this study were found in two species inhabiting two distinct ocean regions (*Chelonia mydas* in the East Atlantic and *Caretta caretta* in the Mediterranean-Western Atlantic). In addition, the probability that sea turtles will ingest plastic waste varies geographically—some areas carry a higher risk, such as the east coast of the United States, Australia, South Africa and the Indian Ocean. As per Zhu *et al.* (2024), this may be because these regions are close to areas with less efficient waste management systems as well as areas where ocean currents converge, thereby possibly concentrating waste. More plastic waste would be ingested in highly polluted areas, for example, the Mediterranean Sea. This sea has some of the highest levels of plastic pollution in the world and is almost entirely enclosed by land (linked only to the Atlantic Ocean by the 14km-wide Strait of Gibraltar) (Darmon *et al.*, 2022b). The turtle's life stage may also be a factor: it is thought that the youngest pelagic individuals are those most exposed to waste as they are not yet strong enough swimmers to select the richest food resources. However, risk factor assessments for waste ingestion are often compromised by small sample sizes or attempt to synthesize studies with different, and therefore incomparable, methodologies.

Spatial variations in plastic ingestion among loggerhead turtles in European waters

Within the framework of the Indicit project (2017-2020), biologists from rehabilitation centres, observer networks, veterinary laboratories and researchers from France, Spain, Italy, Greece, Cyprus, Portugal, Tunisia and Turkey implemented a joint protocol with the aim to collect standardized data on the presence and amounts of litter ingested by loggerhead turtles found dead washed up on beaches or taken as by-catches. They also used autopsy reports for turtles to collect historical data on waste ingestion and the impacts on individual turtles. Since 1988, a large dataset has been collected, providing information about 1,103 turtles found in the Northeast Atlantic Ocean and Mediterranean Sea. In these eight countries, 69.2% of individuals had ingested waste, over 90% of which was plastic. If we focus on the more recent and standard data, from 2013 onwards, the year the first protocol within the Marine Strategy Framework Directive was circulated (see Part 1, Chapter 2), this number increases to 73.6% (802 individuals). The frequency of ingestion and amounts ingested vary spatially (Figure 2.2.3).

Although there are differences between the Atlantic Ocean and Mediterranean Sea, they cannot yet be explained given that fewer individuals were studied in the Atlantic Ocean. Nonetheless, a higher frequency of ingestion is seen in the Atlantic Ocean, where 68.1% of turtles were found to have ingested waste (Azores, French Atlantic coast, Canary Islands) since 2013, compared with 59% in the Mediterranean Sea (French coast including Corsica, Spanish coast including the Balearic Islands and

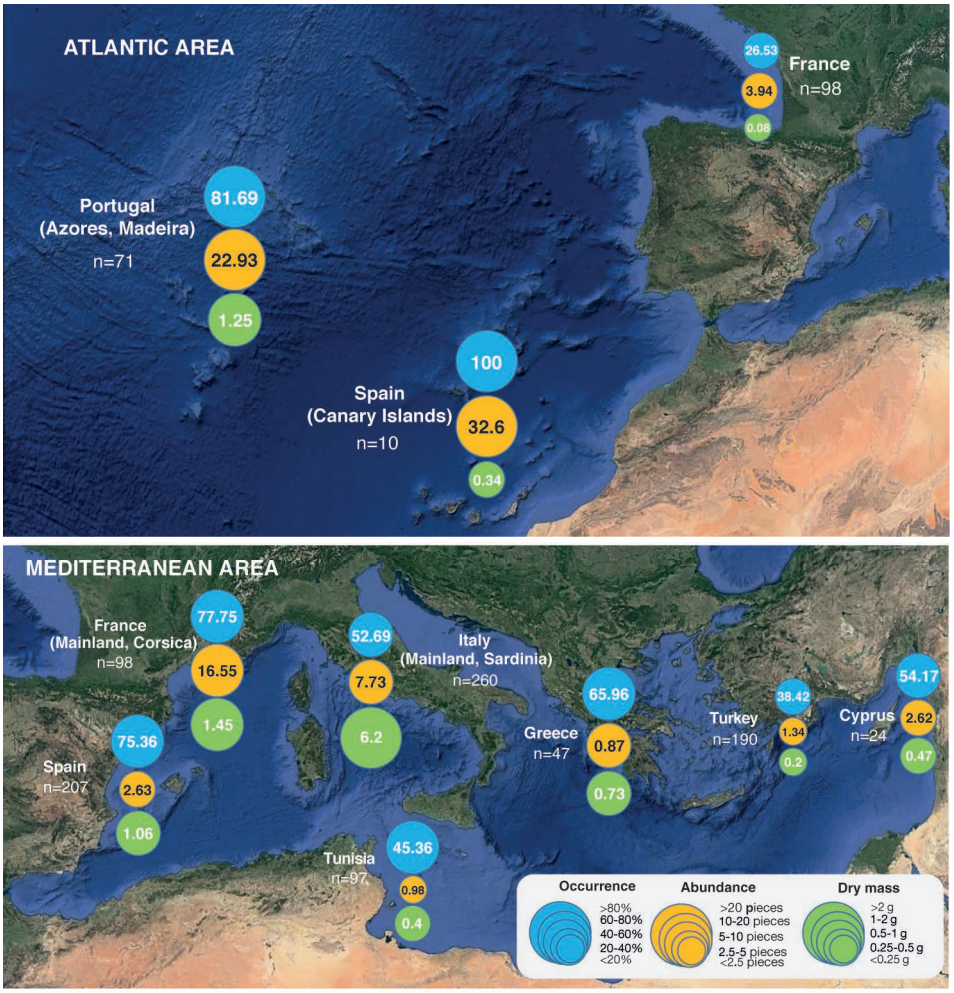


Figure 2.2.3. Spatial variations in the frequency of ingestion among autopsied turtles (blue circles) and in the amounts of plastic ingested expressed in numbers (yellow circles) and dry mass (green circles) between 2013 and 2019, where n=number of individuals.

several places in Italy, Greece, Cyprus, Tunisia and Turkey). Conversely, autopsied turtles from the Mediterranean Sea had more litter in their digestive systems, both in terms of dry mass, with an average of 0.2g (±0.1) in the Atlantic Ocean and 3.1g (±1.8) in the Mediterranean Sea, and in terms of abundance, with 2.6 (±0.5) and 8 (±0.6) items of litter, respectively. These variations are even more evident at the country level (Figure 2.2.3). For example, the lowest frequency of ingestion was in Turkey (38.4%), values over 70% were observed in Mediterranean France and Spain (77.7% and 75.4%, respectively) and even attained 80% along the Atlantic coast, in the Azores (81.7%) and Canary Islands (100% in 10 individuals). The amounts of litter ingested by loggerhead turtles were considered representative of the pressure exerted by marine litter and the effectiveness of the regulations set up to combat this menace (criterion D10C3 of the Marine Strategy Framework Directive, see Part 1, Chapter 2).

On average, the loggerhead turtles autopsied under the Indicit project had ingested 31.6g (±4.61) of litter, all kinds combined and both synthetic and natural. Plastics made up 38.7% of the total dry mass ingested (93.9±0.6% of the litter mass, 95.5±0.5% of the volume of litter).

Information about the feeding behaviours of the turtles as well as the efforts to be implemented can be gleaned by looking at the properties of the litter ingested as well as their quantities (Figure 2.2.4). Some kinds of plastic are ingested more often than others, for example: sheets of plastic (such as pieces of bags or soft food packaging), hard plastics (caps or pieces broken off from hard objects such as cups, utensils or unidentified items), as well as "string-like" objects, usually related to fishing activities (fragments of fishing line or nets) or, more rarely, textile fibres. A wide variety of objects have been found, for example: cups, cotton buds, lollipop sticks, balloons, hand wipes and even sanitary towels or filters from water treatment plants. Most of the objects found were either white or transparent (3.4±0.3 fragments on average) and usually were not either dark (1.1±0.1 fragment) or light (1±0.1 fragment) in colour.



Figure 2.2.4. Examples of plastic debris commonly ingested by sea turtles: on the left, sweet wrappers and fragments of bags, strings and balloons egested by a loggerhead turtle in a rehabilitation centre (Corse, 2021); on the right, bottle cap, phial and fragments of bags and packaging found in the digestive system of a loggerhead turtle (Corse, 2018).

How does the ingestion of litter impact the health of an individual?

The Marine Strategy Framework Directive plans to assess the effectiveness of the measures put in place using thresholds values; beyond these, plastic ingestion by sea turtles is likely to impact individual health, with implications for population viability. Various methods have been put forward to set a threshold (Darmon *et al.*, 2022a; Matiddi *et al.*, 2024) but no values have yet been officially defined. Matiddi *et al.* (2024) also determined that the litter ingested by loggerhead turtles in Italy (sample size: 459 individuals between 2017 and 2021) is above the thresholds set for all scenarios considered, for example, the scenario based on the minimum observed amount

ingested and irrespective of the individual's health (Figure 2.2.3). Their study showed that 63.4% of the individuals examined had ingested waste (an average of 10±1.1 pieces per individual, or 1.3±0.3 grams).

It is not easy to assess the health of a sea turtle, especially when the individual was found dead, and for which no blood or behavioural data exist. In any case, we still do not have enough data to be able to define the ranges for the blood or enzyme parameters that indicate whether the turtles were in good physiological health. Anastasopoulou and Fortibuoni (2022) reviewed the observations published in the literature for several species and listed which effects were cited the most often: mortality, changes in feeding behaviour or locomotion, physiological impacts, reduced body growth, translocation of microplastics or toxins from the intestinal tract to the blood or organs, and injuries. Blunt objects could in fact puncture the digestive tract, and soft objects or the accumulation of objects could obstruct it, directly causing the death of the individual. Objects in the digestive tract may also give the animal a false sense of fullness, thereby changing its feeding behaviour and thus influencing its physical condition, with repercussions for survival or the ability to reproduce. As a result, several factors will influence the health status: biochemical responses associated with the ingestion of waste (such as cell necrosis, neurotoxic effects, liver toxicity, oestrogen-like effects and decreased testosterone levels, and weakening of the immune system) all of which are further compounded by the additives used in polymer production.

It was determined for the turtles autopsied during the Indicit program that only fewer than 2% of individuals had died due to plastic debris (i.e. only 14 cases). Matiddi *et al.* (2014) consider that death is unlikely if less than 0.05g of debris is ingested. However, depending on its shape or size, even just one single object is sometimes enough to have a lethal outcome. Yet it can be quite difficult to determine the exact cause of death, which is sometimes never known; especially since this debris may indirectly lead to death or have other health repercussions. Although some ingested objects may be excreted, it usually takes 10 to 14 days, and sometimes more than one month, for the object to pass through the individual's digestive tract. Biologists at rehabilitation centres often observe turtles with buoyancy problems preventing them from diving and feeding. Other health status parameters are then studied to evaluate the direct (injuries) and indirect effects on body condition but so far, researchers have not seen any clear effects on individual masses or sizes. However, they did find that 30.5% of the individuals had ingested more plastic than natural food. It has been estimated that the average proportion of plastics in the digestive system, compared with the weight of natural food, is 38.8% (±1.3) on average per individual. As per the physiological models published by Marn *et al.* (2020), this may prevent females from becoming sexually mature and being able to reproduce as they do not have sufficient energy reserves, which may then have an impact on the population dynamics.

In the Caoua project (2022-2024), it was possible to collect faecal samples from approximately 100 live loggerhead turtles along the Mediterranean coast of Spain to determine the effect of microplastic contamination on their physiology and gut microbiota. This project showed that microplastic concentrations significantly impact faeces, both in terms of microbiota diversity (higher when microplastics are present) and composition (occurrence of pathogens when microplastics are present). Thus, plastics may act as passive vectors (i.e. fomites) of pathogens in turtles, something that has

already been seen in other marine organisms (Naudet *et al.*, 2023). In addition to this role played by fomites in plastic materials, they may potentially result in gut dysbiosis, which could also cause more insidious chronic effects. Any destabilization of the gut microbiota composition and diversity outside of natural variations is liable to interfere with the metabolic pathways, physiology and behaviour of the host (Amato, 2016), nutritional processes (Chae *et al.*, 2020), cognitive performances, and the immuno-inflammatory response at the intestinal barrier (Belkaid, Harrison, 2017). In the Caoua project, we specifically observed a significant connection between the concentration of microplastics and the immuno-inflammatory response, including an increase in the blood glucose concentration and an increase in immune cells. All these findings seem to indicate that microplastics may potentially influence the microbiota, physiology and thus the health of loggerhead turtles. That said, research still needs to be carried out on these subjects to determine if these effects are direct, indirect (via a destabilization of the intestinal microbiota) or both.

⏩ Impacts on marine ecosystem engineers

Franck Lartaud

Keystone ecosystems are particularly exposed

As seen in terrestrial environments, marine environments may host organisms that can change or create habitats. The most representative of these organisms are reef-building corals, which can create reefs spanning tens of kilometres in tropical waters (e.g. the Great Barrier Reef off the coast of Australia) and at depth (the 800m-deep *Lophelia* reefs off the coast of Mauritania), and are considered to be biodiversity hotspots. Other ecosystem engineers are present in oceans and can create three-dimensional structures ranging in size from meters to several tens of meters, such as coralligenous reefs created by red algae, *Posidonia* meadows, mats formed by honeycomb worms of the *Hermella* genus (tubeworms) or even bivalve shell middens (oysters, mussels). These structures are important for maintaining and developing biodiversity, so much so that the relevant authorities have specifically listed the "Reefs 1170"[25] habitat as a natural habitat type of community interest within the European Habitats Directive in an aim to ensure the conservation of these habitats and related wildlife.

However, ecosystems created by marine ecosystem engineers are especially vulnerable to plastic pollution. Pinheiro *et al.* (2023) observed between approximately 8,500 to 85,000 pieces of macrodebris (mostly plastic) per square kilometre in the reef waters of the Philippines, Comoros and Brazil, which is roughly equal to 520 pieces of waste in an area the size of a football field. This type of pollution is even found in deep-sea environments, especially sub-marine canyons hosting reefs of cold-water corals, sponges and deep-sea oysters. It is somewhat common to observe various types of objects made of plastic, such as plastic bags, bottles, nets and fishing lines, at depths of several

25. The Reefs habitat (EU code: 1170) includes all reefs with geogenic or biogenic substrata found on solid or soft bottoms These natural habitats are of community interest because they are able to host a rich biodiversity. The aim of the European "Habitats Directive" (92/43/EEC of 21 May 1992) is to help protect and manage natural habitats with heritage value.

hundred meters (Figure 2.2.5). In the Mediterranean Sea, Hernandez *et al.* (2022) reported a density of several tens of thousands of waste items per square kilometre in Catalan canyons (>25,000 items/km^2 for the La Fonera Canyon and Cap de Creus Canyon) as well as in southern Italy (>500,000 items/km^2 in the Messina canyon).

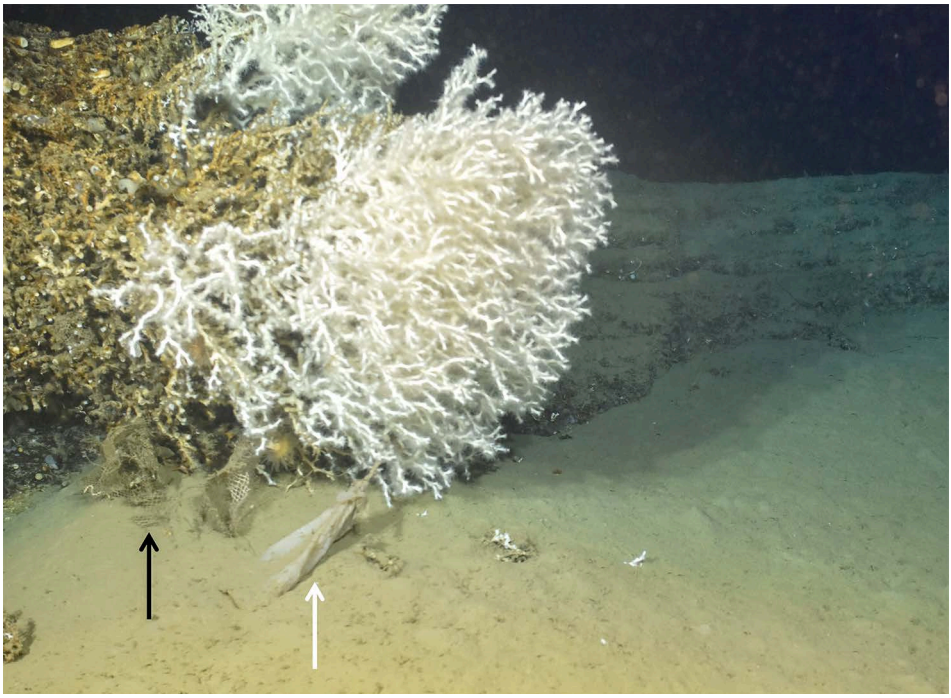


Figure 2.2.5. Plastic bag (white arrow) and fishing net (black arrow) caught in a coral reef at a depth of 500 m in the Lacaze-Duthiers Canyon (Gulf of Lion, off the coast of Banyuls-sur-Mer).

Ecosystem engineers are also highly vulnerable to pollution caused by microplastics, and act as a natural sink or filter for the environment. For example, Soares *et al.* (2023) counted 9,000 to 49,700 microparticles in corals per square meter, versus only 74 microparticles/m^2 in the water and 23 to 1,000 microparticles/m^2 in the surrounding sediment. Shell middens from the mussel genus *Mytilus* also accumulate high concentrations of microplastics, independent of the geographical area. Concentrations ranging from 1 to 7 microplastics per individual have been measured in mussels collected in China, Norway, the United Kingdom and Turkey. These concentrations may be as high as 15 to 19 particles per individual in the Mediterranean mussel (*Mytilus galloprovincialis*) from Italy or Spain (Expósito *et al.*, 2022).

Biological impacts on individual organisms…

Even though the impacts of macrowaste are better studied in megafauna such as turtles and cetaceans, this type of debris also influences marine ecosystem engineers. When plastics become entangled in corals, they may physically break the colony, result in the haemorrhaging or suffocation of polyps or even make it more difficult for the polyps to catch the zooplankton on which they feed by acting as a barrier (Lartaud *et al.*, 2020).

However, some species that live in colonies seem able to employ an avoidance strategy that would be rather energy-intensive, but which would lessen the harmful impact of macrowaste compared with microplastics over the long term (Mouchi *et al.*, 2019).

In fact, ecosystem engineers ingest large amounts of microplastics through active filtration (e.g. bivalves) or the capture of prey (e.g. corals using their tentacles), possibly helped by mucus production. Once ingested, microplastics may can migrate from the stomach cavity into all the other tissues (Al-Sid-Cheikh *et al.*, 2018; Hierl *et al.*, 2021). There are different effects depending on the species and exposure concentrations (Figure 2.2.6).

The main impacts observed in corals include: a change in behaviour (mucus production, polyp activity), reduced growth rate (e.g. by roughly 40% in deep-water corals), lower energy reserves due to reduced feeding caused by a false sense of satiety and an elevated egestion rate for energy-consuming particles, a change in the photosynthetic symbiont density and, sometimes, tissue necrosis (Lartaud *et al.*, 2020). This deterioration of organisms' health status may leave them more susceptible to other effects of stress, for example, the entry of pathogens and viruses into the body ultimately causing their death. Lamb *et al.* (2018) showed that the probability of infection increases to almost 90% in corals that are in contact with plastics. Even though it is presently difficult to demonstrate a direct link between microorganisms that develop on plastics (i.e. the plastisphere) and coral microbiomes, exposure to microparticles appears to significantly affect the balance of microorganisms associated with their host (Corinaldesi *et al.*, 2021). Last, the release of pollutants that are either found in plastics or adsorbed by them is an additional source of contamination for organisms. As an example, Saliu *et al.* (2019) determined that phthalates are present in coral ecosystems in the Maldives.

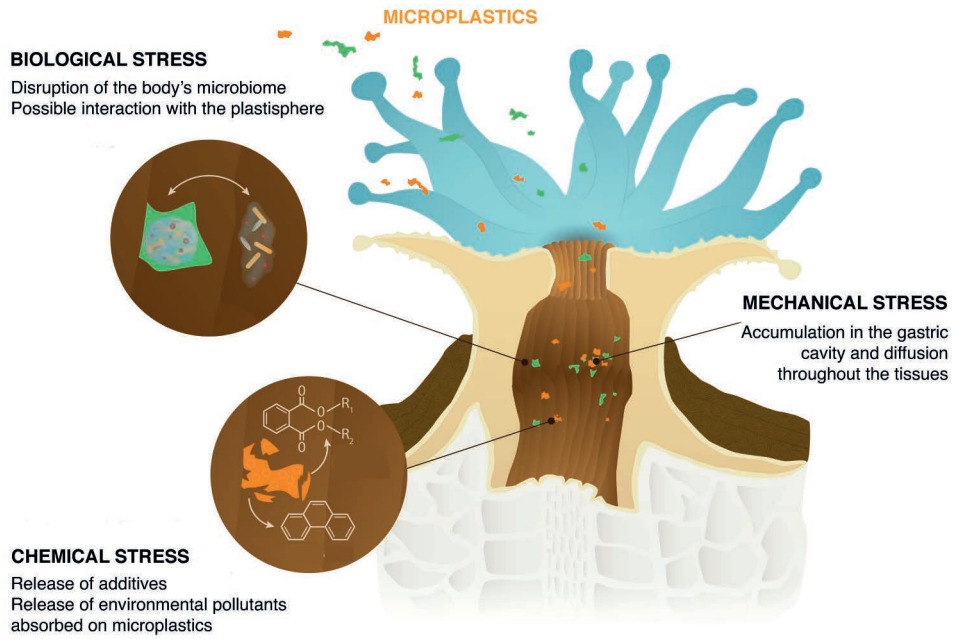


Figure 2.2.6. Synthesis of the main stress pathways to organisms exposed to microplastics.

Several authors have shown that exposure to micro- or nanoplastics may physically interact with the respiratory and digestive systems of bivalve molluscs thereby disrupting respiration and feeding activities (Sussarellu *et al.*, 2016; Maes *et al.*, 2020; Revel *et al.*, 2020). In addition, Tallec *et al.* (2022) also suggested that toxins from chemicals released onto gill cells may affect these activities in the European oyster (*Crassostrea gigas*). These disruptions may decrease the overall energy balance of the animal and have long-term implications for growth and reproduction (Bringer *et al.*, 2021). As seen in the article published by Sussarellu *et al.* (2016), when adult oysters were exposed to polystyrene microspheres over a two-month period, a decrease in gamete quality and quantity (–38%), fertilization rate (–41%) and larval growth (–20%) was observed. Once again, these effects were linked to a disrupted energy metabolism and the presence of toxic compounds. Effects have also been observed on gametes and in embryos and larvae (i.e. during early-life stages), which are very sensitive to contaminants and whose survival is central to the survival of the species (Tallec *et al.*, 2018).

...and their subsequent repercussions for the wider habitat

The actions of ecosystem engineering spread the problem throughout the entire ecosystem. The habitability of an environment revolves around these engineers and therefore it is key to keep them in good health for the sake of the related biodiversity. In addition, given that seagrass beds and reef structures tend to accumulate plastics, this means that the high concentration of species living in or near these beds and reefs (e.g. marine mammals, turtles, seabirds, fish and crustaceans) are more affected than other species found elsewhere in the ocean. As an example, it has been shown that 95% of damselfish living on the Great Barrier Reef have ingested microplastics (polyester fibres or polyethylene particles) (Jensen *et al.*, 2019).

Plastics may have quite different impacts on a habitat depending on the ecosystem engineer species considered, with possibly drastic ramifications for the morphology of future habitats. Most studies conclude that massive corals (e.g. *Porites* spp.) show greater resilience to plastic pollution than branching corals (e.g. *Acropora* spp. and *Pocillopora* spp.) (Reichert *et al.*, 2018, 2019). The latter species create three-dimensional structures that not only are more complex, but which can host a wide range of biodiversity. If they were to be replaced corals creating smaller reefs with less complex architectures, this would have an impact on the associated biological diversity. Climate change is already known to cause this type of alteration in underwater landscapes and is accompanied by the risk that the presence of plastics will accelerate this process. This would result in a much higher loss of biodiversity in addition to a loss of the services provided by these engineering organisms to humankind (e.g. a natural barrier from storms, carbon sinks and storage, fishing resources and economic activities such as tourism, etc.).

⏩ Entanglement phenomena: direct impacts on marine organisms

Claude Miaud and Gaëlle Darmon

Entanglement is defined as the process or state of being wrapped, caught or stuck in debris. Marine debris are objects (solid waste) that have been deliberately thrown away or unintentionally lost either directly at sea or transported by winds and rivers, and which are found on the surface of the water, in the water column, on the sea floor, and on the coastline.

Many marine mammal, bird, fish, turtle and invertebrate species become entangled in marine debris. An animal's behaviour, life stage and age all play a significant part in the probability it will become entangled in debris. Certain species have a higher likelihood or would be more severely affected than others. Animals may become entangled in marine debris from various land-based and marine sources, such as packaging and abandoned fishing gear. Fishing-related waste includes fishing gear that has been left behind, lost or thrown away at sea due to storms, become snagged on something under the water's surface, or entangled with other gear or in interactions with other vessels. Data on species entangled in fishing gear almost never specify whether the fishing gear had been cut and was then carried away by the entangled animal or if the animal had gotten stuck in waste from fishing activities. Different methods are used to gather information about entanglement for different taxa. Several observations have been made by wildlife rehabilitation centres that care for distressed animals (mostly mammals, birds and sea turtles), stranding networks and observers-at-sea networks, commercial fishers and scientists. If the broader public involved in nautical activities were to participate, they could also provide more data. More recently, observations shared on social media (photographs, videos) have provided a wealth of information on marine wildlife entanglement. The main sources of observations on the sea floor were made through photo campaigns and underwater explorations by professions using remote controlled vehicles.

Impacted species

Scientists have shown that over 350 marine species have become entangled in plastic debris (Kühn, van Franeker, 2020) in all parts of the world (Høiberg *et al.*, 2022). Entanglement has been reported in 51 out of the 123 marine mammal species and, at present, this phenomenon is almost ubiquitous in certain large whale populations.



Figure 2.2.7. Example of marine mammals (seals) entangled in fishing debris.

Traces of scars have been observed on humpback whales (*Megaptera novaeangliae*), indicating that 29% of individuals in North Pacific populations, over 50% of individuals in Alaska and over 78% of individuals in the North Atlantic have been entangled at least once. Numerous individuals have been observed transporting debris (11% of North Atlantic right whales) for months or sometimes even years. Entanglement in fishing gear is the number one cause of death in large whales in the western North Atlantic and plays a part in the death of marine mammals throughout the world. In Europe, entanglement in marine debris has been reported in the short-finned pilot

whale (*Globicephala macrorhynchus*), common minke whale (*Balaenoptera acutorostrata*, 5 to 19% of individuals observed in the United Kingdom), and the striped dolphin (*Stenella coeruleoalba*, 1.5% of individuals stranded in Spain). It is estimated that 300,000 whales, dolphins and porpoises die each year after becoming entangled in debris and fishing gear, although this is surely an underestimate since most animals that die go unobserved (at sea or stranded). In addition, all age groups of pinnipeds (seals and sea lions) are highly exposed to and affected by marine debris: traces or the consequences of entanglement were found in 67% (22 out of 33) of the species studied. For example, more than 50% of Steller sea lions (*Eumetopias jubatus*) in Alaska were entangled around their necks with plastic bands used to package beverage cans.

In Europe, 20 (6.5%) out of the 350 seals rescued each year by the primary rescue centre in the Netherlands are found entangled (Claro *et al.*, 2019). This happens more to grey seals (*Halichoerus grypus*) than to harbour seals (*Phoca vitulina*) and mostly involves young individuals (Figure 2.2.7).

Two hundred and sixty-five (265) species of birds have been found entangled in plastic waste, of which 147 are marine species, 69 are freshwater and coastal species, and 49 are terrestrial species, i.e., 36% of marine birds and 10% of freshwater birds. Globally, fishing gear is responsible for 83% of entanglements in these 265 entangled bird species. The pressure exerted by waste on marine birds can be evaluated by observing and analysing entanglements of species such as the great cormorant (*Phalacrocorax carbo*) and the Northern gannet (*Morus bassanus*). These species may become directly entangled in debris while fishing or even in their nests when plastic waste is used to build or strengthen them (Figure 2.2.8). In Northern gannets, the observed rate of entanglement is 0.36% in the Mediterranean, 1.9% in France (Bay of Biscay) and higher than 20% in Mauritania. Between 2012 and 2014, debris was found in 12% to 98% of cormorant nests in various colonies in France (Cadiou, Fortin, 2015).



Figure 2.2.8. Example of a dead seabird (Northern gannet) entangled in debris in its nest.

A study carried out on the major oceans inhabited by sea turtles shows that almost all (91%) of the turtles found entangled in debris die. Some may be seriously injured, with these injuries leading to mutilations, amputation or suffocation, and individuals that survive must then transport varying sizes of debris with them. A survey among authors who have published scientific articles on the effects of plastic waste on sea turtles has estimated that at least 1,000 individuals are killed each year by entanglement in anthropogenic waste (Duncan *et al.*, 2017), while keeping in mind that this number is undoubtedly greatly underestimated as the studies do not cover the whole distribution ranges of these turtles. In the Canary Islands, 45.7% of loggerhead turtles stranded between 1998 and 2003 (906 individuals) were found entangled in nets, plastic, ropes or other floating debris (Calabuig, Liria-Loza, 2007). Loggerhead and green turtles (in the Mediterranean) and leatherback turtles (in the Atlantic) have been found entangled in lost fishing nets, nylon fishing lines and plastic twine, rings used to package beverage cans, packaging, plastic packaging straps, etc. (Figure 2.2.9). Turtles have also been found entangled in all sorts of other debris such as plastic chairs, wooden crates, weather balloons and mooring lines for boats. In the Canary Islands, the most commonly found debris entangling sea turtles are plastic bags and raffia shade nets used in agriculture.



Figure 2.2.9. Example of a sea turtle (green turtle) entangled in debris (fishing nets).

Cases of entanglement in debris have been described in roughly 100 fish species, sometimes causing serious injuries in species that live a long time, such as sharks. One percent (1%) of school sharks (*Galeorhinus galeus*) in the North Atlantic population, 2.1% of nurse sharks (*Ginglymostoma cirratum*) in the Cape Verde population and 1% of blue sharks (*Prinace glauca*) in the Mediterranean Sea population show signs of entanglement, mostly in debris from fishing activities.

In Spain, juvenile blue sharks have been observed with plastic straps wrapped around their gills, causing variable degrees of injury to their dorsal muscles and pectoral fins. This was corroborated by a longline observer program in Portugal, where it was reported that thirty or so blue sharks were trapped in ring-shaped objects (rings, straps) used to package bait (e.g.). Photographs taken during this survey show that the debris left deep wounds.

Marine invertebrates may also become entangled in debris, especially those living on the sea floor such as crabs, lobsters, echinoderms, hydrozoans, corals and sponges (over 100 documented taxa). On the Italian coastlines, observations made along coralligenous outcrops (200-m long transects) show percentages of entanglement for the various coral species ranging between 2 and 18% of their respective surfaces.

Causes of entanglement

Animals may become entangled in debris for different reasons, depending on the species. For example, animals may be attracted to debris due to their specific feeding behaviour (opportunistic diet), the exploratory and playful behaviour of young individuals (marine mammals), their health status (marine mammals), their anatomical features (vision/perceptive abilities to be able to distinguish between food resources and debris) or other ecological factors (e.g. immature sea turtles that use currents are more exposed to clusters of debris found in gyres). In sessile benthic species (animals living on the sea floor), entanglement occurs when debris sinks down to the sea floor.

The age and specific behaviour of mammals could be the major factors influencing whether animals become entangled. The ratio of subadult/juvenile versus adult harbour porpoises caught in nets varies depending on the region.

Health effects

Entanglement in marine debris is a global problem that leads to death or severe welfare problems in thousands of marine animals around the world each year (Werner *et al.*, 2016). Entanglement can cause chronic or sublethal effects that alter the biological and ecological performance of an individual over time, including reduced mobility, agility, ability to ingest or digest food, as well as reduced physical fitness, which thereby affects reproductive success and survival.

Immediate death could be caused by direct asphyxiation, not being able to resurface (mostly seen in small animals trapped by heavy or large objects), ligatures around the neck or blowhole occlusions in cetaceans, a reduced ability to escape from predators or not being able to avoid collisions with ships. Tissue lesions, such as cutaneous lesions accompanied by ulceration, or the death of muscular tissue (necrotising myositis), are a widespread consequence of entanglement.

Rope and line ligatures can result in amputation or injuries with open wounds that can then become infected, thereby further reducing the chances of survival. These external injuries can also result in ingrown ligatures that cause carotid blowout, especially in seals. In addition, tissue damage this severe is responsible for the death of whales. The loss of fins and tails in whales, dolphins, porpoises or sharks is not very likely, however tail injuries and deformities have been observed. When these injuries impact the bilateral axis of symmetry along the spine (midline), they are considered very serious.

In sea turtles, entanglement could cause the animal to lose one or both flippers, which would severely limit their diving, feeding and nesting abilities. Moreover, flipper stumps are vulnerable to attacks from predators. All species of sea turtles are susceptible to entanglement. Major impacts have even been described at turtle nesting sites. For example, in the loggerhead turtle colony on the island of Cape Verde, nesting females with injuries on their hind flippers were unable to dig their nests, which meant that they could not contribute to the population dynamics of their species (Sanchez-Sierra Campillo, 2017).

Entanglement can cause reduced mobility and injury in benthic invertebrates, such as in the case of broken branches in corals.

Conclusion

Today, the harmful impacts of macroplastics on terrestrial and marine wildlife have been clearly identified. Large plastic objects can be deadly if ingested (choking) or in the case of entanglement (malnutrition). Even though there is no longer any doubt whatsoever that macroplastics harm wildlife, it is sometimes difficult to pinpoint the effects of micro- and nanoplastics in the environment as these are more subtle. That said, laboratory experiments have clearly shown that there is a link between exposure to microplastics or nanoplastics and physiological effects. When these plastics fragment into microplastics and then nanoplastics, the risks of exposure strongly increase for all living organisms and represent a more insidious threat than cannot be seen with the human eye. How toxic they are depends on the length of exposure, sensitivity of the species and the properties of the plastic materials (type of polymer, presence of additives, whether related pollutants are present, size and shape of the particles, etc.). With a smaller particle size, there is a higher risk of translocation. It has also been pointed out that many of the additives used in plastics to change their properties are related to ecotoxicity effects. Plastic micro- and nanoparticles can change the physicochemical characteristics of environments. When absorbed by animals and plants, they have both toxic and functional impacts, especially on behaviour, the immune system, development, growth, reproduction and longevity. They could even modify genes, particularly with chronic exposure. These disruptions, which differ depending on the species and types of plastics, may result in serious ecological dysfunctions (Figure 2.2.10). A number of effects appear common to several taxonomic groups (e.g. alterations to the gut microbiota), yet many unknowns remain in understanding the underlying mechanisms at play and in being able to generalize these findings. Thus, additional studies need to be carried out to determine what influence the size and chemical composition of microplastics have on their toxicity. This should then enable us to evaluate the ecological risk and to steer public policies towards appropriate measures.

In summary, this section (Part 2) has reviewed the effects that exposure to plastics (macro-, micro-, and nanoplastics) have on a broad range of organisms from many different taxa. In general, these effects observed at the individual level have an impact on functions or processes such as growth and reproduction, and it is not a hard stretch to imagine that this will have adverse consequences for the ability of these individuals to contribute to subsequent generations and thus to biodiversity (Figure 2.2.10). The next section (Part 3) looks at the effects of plastics on ecosystems.

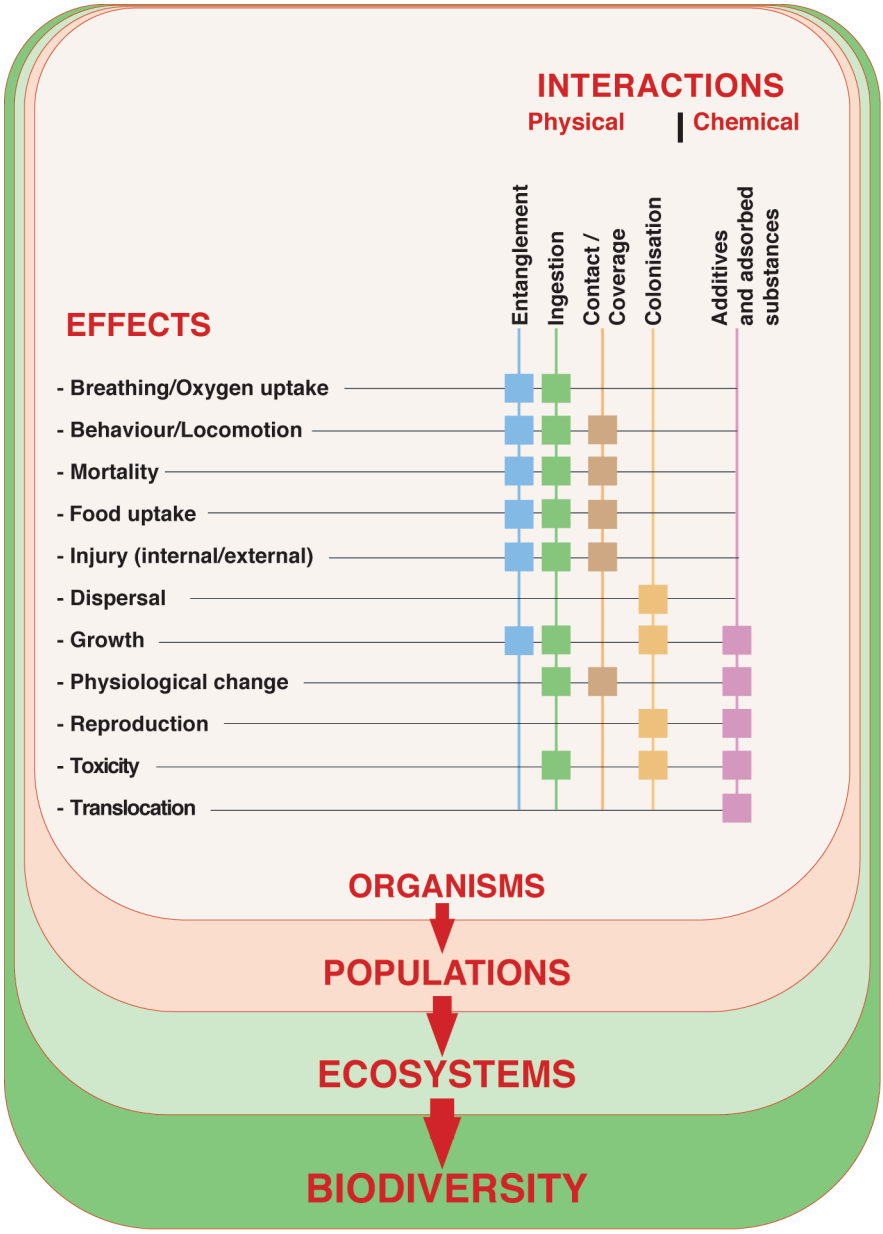


Figure 2.2.10. Diagram showing the most common interactions with plastics and their effects on organisms.

The coloured squares indicate the main effects for the different types of interactions (either physical or chemical). These individual effects all have implications for organisms, populations, ecosystems and, as a result, biodiversity.

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Part 3

Effects on ecosystems

Introduction

In ecology, an ecosystem is a natural system comprising all living organisms (animals, plants, fungi, bacteria, etc.) and the physical environment in which they reside and interact. When these interactions have to do with food systems, this is called a "trophic network" (or food web/food chain) made up of three levels: producers, consumers and decomposers. As seen previously, plastic pollution is found in all ecosystem compartments and there is a growing body of research underlining the extent of its effects and the differential consequences for living organisms, whether animal or plant and terrestrial or marine. We are still just scratching the surface: as more research is carried out, the impacts seem to be increasingly staggering. There is a domino effect that starts with disturbances in individual organisms that are passed up to the population, community and ecosystem scales which are already made fragile by other kinds of pollution, as well as human activities and climate change. These repercussions are further amplified when keystone species are involved, such as ecosystem engineers or corals, as these species are key to maintaining the balance and good ecological status of the environment in which they live.

While the ecological impacts of plastic pollution have only recently gained scientific attention, and research remains at an early stage, the profound effects documented—particularly in soil and marine environments—render ecosystem preservation a major global priority. Ecosystem destruction is an alarming threat not only to biodiversity, but also to the food security of millions of people, especially for the most vulnerable populations.

Debris and pollution generated on land first impact terrestrial ecosystems before they end up in the sea through the main transport pathways: rivers, estuaries and the air. According to the French Ministry for Ecological Transition, 75% of waste found in marine environments is plastic.

Since we cannot cover all ecosystems thoroughly, this section (Part 3) will present an overview of the numerous impacts plastic particles have on key ecosystems and functions that have been well-documented in the scientific literature; their processes and effects would probably apply to all ecosystems, whether terrestrial or marine. Therefore, our focus will be on the impact of plastics on soil functions and their toxicity for the organisms living there (1), before turning our attention to their fate in marine environments and the repercussions they have for marine food webs, from coastal ecosystems (2) to the seafloor where many plastics end up (3). Last, we will discuss the risks associated with the microbial colonization of plastic debris (the plastisphere), such as the "cargo" and "raft" effects that contribute to the transport pathogens and other pollutants (4).

Chapter 1

Impacts on soil functions

Marie-France Dignac

Soil is a thin, fertile layer on the Earth's surface that makes life on our planet possible. It provides plants with physical support as a place for anchoring their roots and the nutrients needed for their growth. Plants, in turn, nourish humans. This means that soil is a fundamental resource for global food security, environmental sustainability and the well-being of humans. Furthermore, soil health is closely related to human health.

However, soil is a non-renewable resource on a human timescale. Soil is formed over hundreds to thousands of years. It is a vulnerable ecosystem that is currently threatened in most regions around the world. It will take generations to be able to regenerate the soils we are polluting and degrading today.

One third of the planet's soils are degraded (FAO, 2023). This degradation is due to erosion, the loss of carbon and nutrients, compaction, acidification and pollution. Soil degradation leads to reduced agricultural productivity and food shortages, as well as desertification, loss of biodiversity and water shortages. Soil degradation therefore amplifies environmental planetary crises and is a major threat to the food security of millions of people, especially for the most vulnerable populations.

Ninety-five percent (95%) of our food comes from the soil (FAO, 2023). Plants grown in degraded soil can be poor in nutrients and if the soil is polluted, food may be contaminated. Soil degradation can result in malnutrition and other health issues.

Soils are the foundation for our food, and they perform numerous functions that are essential to life on Earth, as stated in the European Soil Framework Directive (2006). They filter water, mitigate climate change and host one-fourth of the world's biodiversity (Figure 3.1.1). Soils play a central role in many of the Sustainable Development Goals (SDGs) defined by the United Nations, such as "Zero Hunger" (SDG 2), "Climate Action" (SDG 13), "Life on Land" (SDG 15) and "Responsible Consumption and Production" (SDG 12; Basile-Doelsch *et al.*, 2023). The essential ecosystem services provided by soils are being degraded by the presence of microplastics. Soil health is further compromised by the breach of "planetary boundaries", which entails significant negative consequences for human well-being and health (Persson *et al.*, 2022). Six of these nine boundaries have already been exceeded, including the limit associated with the introduction of novel entities—such as plastics—into the environment.

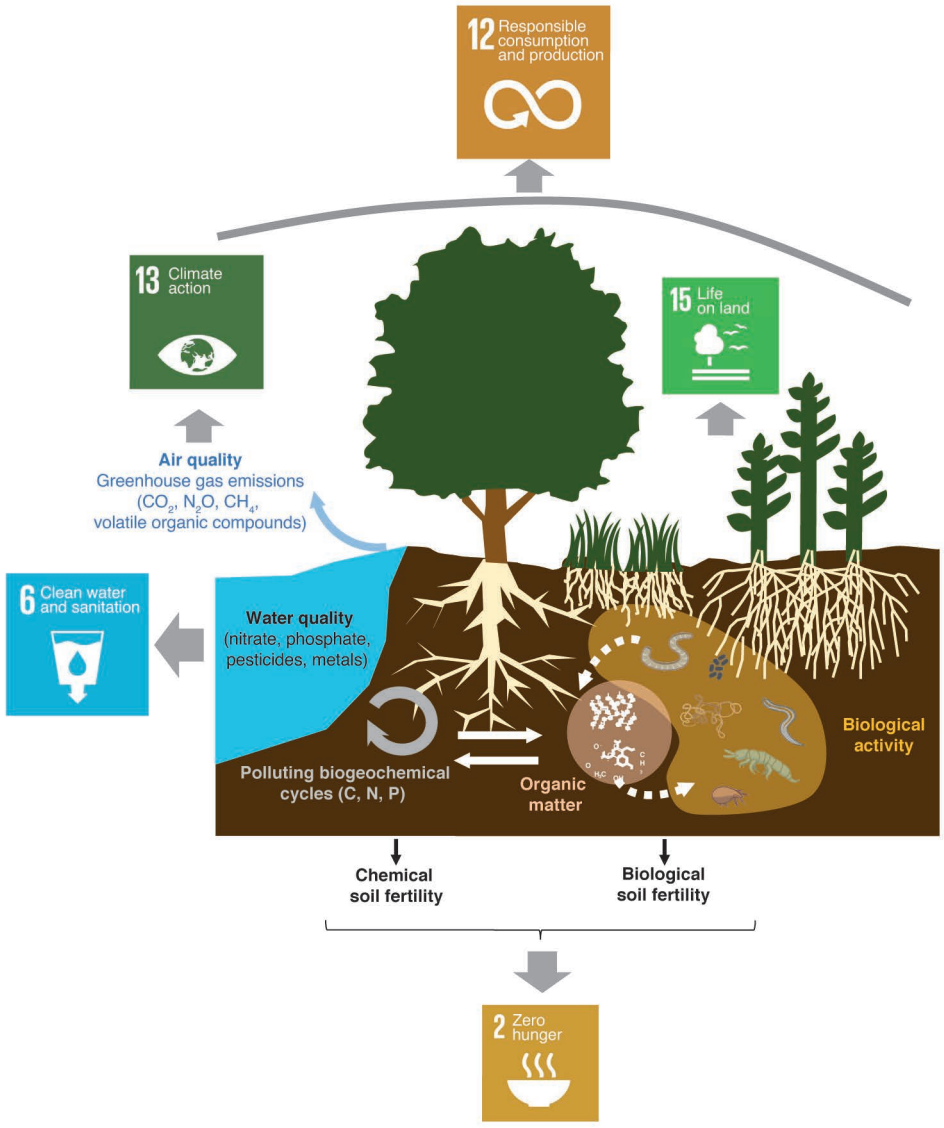


Figure 3.1.1 Functions and services performed by healthy soils and how they are related to the UN Sustainable Development Goals.

Impacts on soil biodiversity

Scientific studies have published worrying findings on the toxicity of microplastics to soil organisms (microorganisms, fauna, plants; Daghighi *et al.*, 2023). The accumulation, transfer and toxic effects of microplastics in the tissues and organs of animals in the soil all depend on the size of the particles. Microplastic particles larger than 1 mm are excreted in the faeces. They may induce intestinal lesions or oxidative stress. The smallest particles (nanoplastics) can be transferred to tissues and cells where they

accumulate. Microplastics are ingested by small and medium-sized animals in the soil, such as springtails, mites or earthworms, and they then accumulate in the trophic network and in soil organic matter expelled as excrement.

Microplastics become more toxic as they break down into smaller particles, which can be absorbed by organisms and release the toxic molecules inside them (Rillig *et al.*, 2021). The presence of microplastics in soils has harmful consequences for the soil animals that ingest them or are exposed to them, such as earthworms, springtails and snails (Song *et al.*, 2019). These effects include reduced feeding and growth, decreased reproductive rates, oxidative stress, increased mortality rates and a lower total biomass of soil fauna, resulting in changes in soil functionality.

In addition, microplastics can adsorb heavy metals, organic pollutants and pathogenic bacteria found in the surrounding environment. When ingested by soil fauna, microplastics acting as contaminant vectors exacerbate the toxic effects of these substances; these pollutants then impair animal physiology and bioaccumulate within tissues. When microplastics are colonized by microorganisms, this also increases the risk of transferring antimicrobial resistance genes.

We are only just starting to understand the impacts microplastics have on soil macroorganisms and microorganisms and plants (Wei *et al.*, 2022). Most studies look at the toxic effects of a polymer on one type of organism (e.g. earthworms, arthropods, plants, fungi or bacteria); however, not much is known about cascading (domino) effects, cocktail effects (contamination by several polymers and their related chemicals) or the indirect effects of microplastics. To better evaluate the risks of soil pollution caused by microplastics, more integrated studies must be carried out from the ecosystem to the global scale.

⏩ Impacts on plant production

It is also well known that microplastics have negative effects on plants: genotoxicity, delayed germination and impaired root development (see Part 2, Chapter 2). It has been shown that microplastics reduce agricultural yields (Gao *et al.*, 2019) and plant quality. Plants are able to assimilate nanoplastics, which have been found in their edible parts (Conti *et al.*, 2020). The presence of nanoplastics may also make it easier for other contaminants, such as heavy metals and pesticides, to be absorbed by plants.

This means that plastic pollution in the food system is found at the very beginning of the food production chain, starting with the production of crops, cereals, vegetables, and fruits, all of which are grown on soil. Moreover, food production is also affected by the impact's plastic pollution has on the functioning of soils, nutrient cycles and soil biodiversity, all of which have consequences for agriculture and food security.

⏩ Disruption of the biogeochemical cycles that affect nutrient cycles for plants

Microplastics impact the abundance, composition and functions of soil microorganisms (Seeley *et al.*, 2020). The microorganisms involved in the nitrogen cycle are especially affected. The impacts on soil biology also have consequences for nutrient cycles and on the chemical properties of soils. Many studies have shown that the

presence of microplastics causes changes in the chemical (e.g. release of nutrients useful to plants) and physical properties of soils (e.g. water and nutrient dynamics). Thus, when soils are contaminated with microplastics, this could impair the functions and services provided by the soil and decrease plant growth.

⏩ Impacts on other soil functions: water content, density, porosity

Microplastics affect the physical properties of soils and change their structure. These changes influence the soil porosity, water cycle and mobility of soil organisms and could also cause changes in the diversity and activity of the organisms living in the soil.

The physicochemical properties of the soil (bulk density or water infiltration) are affected by microplastics which, generally speaking, have hydrophobic properties (de Souza Machado *et al.*, 2018). These changes affect the root systems of plants, with implications for plant growth and, therefore, possibly crop yields.

⏩ The impact of chemicals in plastics: a lesser-known threat

Although many studies have underlined the impacts of microplastics and nanoplastics on soils, few studies have focused on the toxicity of the chemicals associated to plastics. These chemicals can be released from plastics present in the soil and affect its functioning. The latest PlastChem report identified more than 16,000 different chemicals in plastics, 4,000 of which have known hazardous effects (Wagner *et al.*, 2024). A rough calculation gives some idea of how many plastic chemicals are found in the environment. Taking into account the amount of plastic produced each year (460 million tonnes in 2019), the proportion of plastic that ends up in the environment (22% according to the lowest estimate) and the average amount of additives and plasticizers in plastics (varying from 0 to 90%, with an estimated average of 7% of the plastic's mass), we can estimate that 7 million tonnes of chemicals released from plastics end up in the environment each year. Simultaneously, about 3 million tonnes of pesticides are used on soils around the world each year (Maggi *et al.*, 2023). This means that the amount of chemicals in plastics released into the environment is potentially more than twice the total amount of pesticides used on soils. Therefore, this is a huge problem that needs to be dealt with urgently. Plastics are used directly on farms (e.g. for mulch, as materials in greenhouses or nets). Their long-term impacts on future generations must be evaluated and balanced with the short-term benefits for the agriculture today. Just as in all other sectors, it is necessary to ask if all the plastics used in agriculture are essential, safe and sustainable.

With regard to organic amendments, in many parts of the world, adding organic matter to soils is crucial to increase soil fertility. However, if we want to recycle organic matter from urban waste and manure, we must reduce its contamination by plastics, otherwise this useful agricultural practice paradoxically degrades soils by polluting them. To curb this contamination of organic amendments by plastics and to decrease plastic pollution in all environments including soils, plastic production needs to be limited to the "essential" plastics so that we can drastically reduce our consumption (Scientists' Coalition for an Effective Plastics Treaty, 2024).

Chapter 2

Impacts on coastal ecosystems and marine food webs

Ika Paul-Pont, Kevin Tallec and Arnaud Huvet

Coastal ecosystems are essential interfaces between the continent, atmosphere and ocean, and represent 7% (26,106 km^2) of the total surface of the ocean. Despite their relatively small proportion, they play a considerable part in the global marine biological productivity and in maintaining the major biogeochemical cycles. They provide a link between land and ocean and, as such, many materials from the watershed and oceanic inputs (e.g. sediments, nutrients, minerals) are exchanged in coastal ecosystems. They also support essential ecosystem services such as coastal erosion prevention, climate regulation, biodiversity conservation and nutrient production via fishing and aquaculture activities. These environments are therefore quite rich but have a fragile equilibrium. It is estimated that almost 5 billion people live on a coast or at least within 150 km of a coastline, i.e. 60% of the current global population. This percentage should reach 75% of the world's population in 2035. This means that these ecosystems must face quite a few environmental challenges related to human activity. Increasing pressure exerted by humans is causing fundamental changes that could affect the structure and functioning of these ecosystems, i.e. their capacity to maintain the diversity and functioning of biological communities at comparable levels to other similar natural habitats that are less affected. Many human-induced disturbances affect coastal areas, for example, the overexploitation of natural resources, habitat degradation, land artificialization and the release of numerous contaminants. Particular attention needs to be paid to the latter point as coastal environments become the receptacle for terrestrial man-made pollution by way of river water transfers, runoff and percolation. Coastlines are actually among the most exposed areas when it comes to the different types of recurrent pollution, such as excess organic matter causing eutrophication, pesticides, hydrocarbons, or even plastic waste which could have significant ecological impacts on these coastal environments.

⏩ Coastal ecosystems: a pathway for plastic debris to reach the sea

Fluvial input from the catchment area to the estuary constitutes the primary pathway for plastic debris entering coastal zones; this occurs alongside surface run-off and wastewater discharge—the latter of which, whether treated or untreated, represents a

significant source of micro- and nanoplastics. Coastal areas are therefore "hotspots" of macroplastic and microplastic contamination given the proximity and density of human activities in these environments (urbanization, maritime transport, tourism, aquaculture, fishing, etc.). By way of example, up to 10,200 microplastics per cubic metre have been reported at the mouth of the Yangtze River estuary in the South China Sea (Zhao *et al.*, 2014), whereas concentrations up to 15,560 microplastics per cubic metre have been observed in Jinhae Bay in South Korea (Song *et al.*, 2015). The Mediterranean Sea, a semi-enclosed sea surrounded by over 20 countries, is considered as one of the areas most contaminated by plastic debris due to the multitude of uses and anthropogenic pressures from the bordering countries. Data from the Marine Strategy Framework Directive (MSFD) show an average concentration of over 88,000 microplastics per square kilometre for this marine sub-region, with values as high as 3.6 million items per square kilometre observed in the Bay of Marseille (Gérigny *et al.*, 2022, 2024). The average concentrations on the European Atlantic coast are close to 33,200 microplastic items per square kilometre in the Bay of Biscay and 16,950 microplastic items per square kilometre in the Celtic Sea (Gérigny *et al.*, 2024). It should be noted that this pollution is not homogeneous in coastal ecosystems as it is heavily influenced by how close an area is to point or diffuse sources of pollution, by the hydrodynamic regime (currents, tides), and by meteorological conditions (rainfall, winds). As coastal environments are home to extremely rich biodiversity, plastic waste affects these environments in many different ways.

⏩ Impacts on phytoplankton, the first link in the food chain

A significant proportion of oceanic primary production (production of plant matter via photosynthesis) occurs in coastal ecosystems given their shallow waters, and thus access to sunlight, and the presence of nutrients from soil erosion. This, phytoplankton primary production is the first link in the marine food chain since it is the main source of organic matter for primary consumers (zooplankton, filter-feeding molluscs). Moreover, phytoplankton helps absorb 50% of the CO_2 in the atmosphere via its photosynthetic activity and produces 50% of the oxygen breathed. Hence, it plays a vital role in the survival of marine and terrestrial species, including human beings. Recent studies have emphasized that physical interactions between phytoplankton communities and microplastics could form aggregates, with experiments run to analyse the repercussions on their photosynthetic activity and sinking rate in the water column (Long *et al.*, 2015). If the phenomena observed under laboratory conditions occur at a significant scale in the natural environment, they would alter carbon sequestration and its export from the surface to the ocean floor. The latter process, also known as a "biological carbon pump", is a major part of the oceanic carbon cycle and helps regulate the climate. It has been estimated that this pump has allowed oceans to absorb over 40% of anthropogenic carbon since the start of the industrial age. Therefore, it is a scientific challenge to understand the incorporation of micro- and nanoplastics into marine snow (phytoplankton aggregates) and to evaluate its consequences within ecosystems given the possible consequences this interaction could have for marine biogeochemistry and the carbon cycle. Simultaneously, experiments have also shown that the nutritional quality (lipid content) of certain phytoplankton species (*Chaetoceros neogracile* diatoms) has changed following experimental exposure to nanoplastics (González-Fernández *et al.*, 2020), with suspected

impacts on the nutrition of benthic and pelagic animals feeding on phytoplankton. Among the various lipids produced by microalgae, polyunsaturated fatty acids such as omega-3s are vital to the nutrition of higher levels of the food chain. By feeding on phytoplankton, marine invertebrates incorporate these compounds into their own lipid composition and thereby become a major source of these lipids in human diets. This means that if there are changes to the fatty acid content at the bottom of the food chain, this could have implications for the nutritional quality of marine food products.

⏩ Trophic transfer

Like for other contaminants present in water, it is possible for coastal species to be directly contaminated by plastic debris by voluntarily or involuntarily ingesting it. The physical properties (colour, density) of this debris as well as the formation of biofilm on its surface could make organisms mistakenly think it is prey. The trophic transfer of contaminants is also possible; this happens when a species that has consumed one or more items of plastic waste is then consumed by a species on a higher trophic level. Given their small size, microplastics and nanoplastics may be ingested by primary consumers (e.g. zooplankton) that are then themselves ingested by secondary consumers such as fish, and so on up the chain to the top predators such as seabirds, large fish, and marine and terrestrial mammals. Various models have been used in the laboratory to demonstrate this trophic transfer, for example as seen when blue mussels (*Mytilus edulis*) contaminated ahead of time with 0.5 µm microplastics are ingested by their predator, the green shore crab (*Carcinus maenas*; Farrell, Nelson, 2013). These microplastics were found in crab tissues: haemolymph, hepatopancreas, ovaries and gills. A trophic transfer from the brown mussel (*Perna perna*) exposed to 0.1-1 µm microplastics to two predators, the Caribbean green puffer (*Sphoeroides greeley*i) and blue crab (*Callinectes ornatus*), has also been shown in laboratory experiments (Santana *et al.*, 2017). In all cases, the ingestion of plastic debris and related chemical contaminants (e.g. plastic additives) could result in bioaccumulation (accumulation of substances in tissues over time) and bioamplification (increased concentrations of contaminants along the food chain). At present, relatively few scientists have studied the trophic transfer of additives related to micro- and nanoplastics in coastal food webs, even though some compounds commonly used in plastics (nonylphenols, phthalates, polybrominated diphenyl ethers, bisphenol A) are known to be genotoxic and reprotoxic molecules even at very low concentrations (i.e. micrograms to nanograms per litre). These risks increase with each increasing level of the food web and in long-lived species (i.e. species with a long lifespan). The trophic transfer of microplastics in coastal marine species have consequences for the health and reproduction of marine organisms.

⏩ Impacts on coastal ecosystem engineers

The term "ecosystem engineer" encompasses all species that, through their presence and activity, significantly modify their environment. This includes all species that create their own habitat, such as corals, oyster reefs, honeycomb worms, mangroves, kelp forests and seagrass beds. The presence of these species creates highly productive areas and encourages a wide variety of habitats that can serve as a refuge, nursery or feeding area for local species (e.g. corals and seagrass beds), and thereby helping to establish and maintain biodiversity within coastal ecosystems. They may also help

improve water quality (e.g. filter-feeding bivalve molluscs) and reduce coastal erosion (e.g. mangroves). The toxicity of plastic waste and related chemical contaminants to these species has been shown in laboratory experiments, especially in filter-feeding molluscs and corals, raising concerns about the long-term ecological consequences of these kinds of disturbances in coastal environments. Experiments have already provided examples of domino effects, for example: a change was observed in the filtration activity of a European flat oyster (*Ostrea edulis*) reef after it had been exposed to microplastics. This change affected the diversity in related communities (microfauna and cyanobacteria) and possibly altered the biogeochemical cycles within the sediments (Green, 2016). One study also found that when coral reefs are in contact with plastic debris, the risk of disease increases by twentyfold; this could have repercussions for how the reef is structured and, therefore, the stability of the ecosystem (Lamb *et al.*, 2018). Specifically, it is difficult to evaluate the effects of plastic pollution at the scale of complex ecosystems and communities as this evaluation would have to not only include the diversity of the ecosystem but also the diversity of the plastic waste and other contaminants over the long term. This is a key focus of current research.

⏩ Seafood contamination and food safety

The contamination of coastlines by micro- and nanoplastics can disrupt not only coastal communities and marine biodiversity, but it also increases human exposure to plastics through the consumption of contaminated seafood such as fish, molluscs and crustaceans. Nevertheless, fish and shellfish are an important part of human nutrition as these products provide essential nutrients (e.g. omega-3 fatty acids), and provide livelihoods for some coastal populations, especially in overseas territories. This plastic contamination especially affects coastal species, with a prevalence rate of contamination (i.e. the number of animals in the cohort studied contaminated by at least one microplastic item) that is often higher than 50%. For instance, the latest data show that an average of 72% of Pacific oysters (Crassostrea gigas) found along the French coast are contaminated by microplastics (79% worldwide). Data for blue mussels (*Mytilus* sp.) appear to be quite similar, with 61% and 82% contaminated individuals along coastlines in France and around the world, respectively. Spatial and temporal variations go hand in hand with changes in the ambient contamination level in the surrounding water. It is also common to observe significant interspecific and intraspecific variations, sometimes even within the same ecosystem or sampling site. For the most part, these variations have to do with physiological differences between these species in terms of their feeding habits (suspension-feeders, detritivores, carnivores) and their habitats (water column, water/sediment interface). It should be noted that studies have not shown an accumulation of microplastics (>50 µm) over time in most marine species. This indicates that these particles pass right through the animal's digestive tract and therefore the microplastics are easily excreted in faeces during the depuration process in shellfish. It is rare for the contamination levels found in farmed and wild bivalves (oysters and mussels) sampled along coastlines to be higher than two particles per gram of flesh (dry weight). The reverse is true for nanoplastics and plastic chemicals, as not only can they migrate from the digestive tract to the circulatory system and other organs, but they can also accumulate over time and along the food chain. At present, there is a known link between human exposure to plastics and the consumption of seafood (either contaminated in the wild or during processing or

packaging); however, this is not considered a major route of exposure as humans are more significantly exposed through other sources such as: airborne contamination (inhalation exposure), the contamination of other industrially processed consumer products like bottled water, salt, packaged foods (ingestion exposure) or textiles (contact or inhalation exposure). Human exposure to microplastics is a growing public health problem, and early studies have shown a link with inflammation, damage in the intestines and gut dysbiosis (microbiota imbalance). However, it is currently difficult to accurately evaluate the risks to human health as more comprehensive data needs to be collected on the long-term effects of this broad range of contaminants (high number of polymers, additives, shape, size, roughness, etc.).

Chapter 3

Impacts on seafloor

François Galgani

Recent assessments of large floating plastic debris and microparticles by the United Nations Environment Programme have shown that, relative to the amount of plastic produced worldwide, not a great deal plastic waste is found on the surface of the oceans. Seafloor cover a surface area of 361,220,420 km^2 (300,875,000 km^2 of which are found in the deep sea) and are therefore an important part of marine environments. The geomorphic features of the ocean floor include the continental shelf, continental slope, abyssal environments including abyssal plains and mid-ocean ridges, and the hadal zone below depths of 6,000m. Given that half of the plastics produced are heavier than seawater, the seafloor is a major sink that accumulates marine macro- and microplastics over the long-term (Galgani *et al.*, 2022) (Figure 3.3.1). Recent analysis of the marine plastic cycle has highlighted that the quantity of plastic on the seafloor exceeds 90% of all marine debris (Sonke *et al.*, 2022). This is quite worrying given that the degradation of most polymers occurs in sunlight and that microbiological processes require oxygen, an element only found in low concentrations at depth.

It is difficult to assess the amount of waste on the seafloor because this area is hard to access and it is expensive to implement observational or collection tools. Consequently, opportunistic sampling utilizing scientific trawls on soft-bottom seafloor and underwater vehicles in rocky or very deep areas is the established norm (Canals *et al.*, 2021). In 2014, based on large-scale studies, it was estimated that there was between 71.5 and 116 billion objects (in total) in the three major oceans (Pacific, Atlantic, and Indian) and the Mediterranean Sea, roughly 80% of which are plastic (review in Galgani *et al.*, 2022). When empirical data on microplastics are extrapolated to a global scale, it appears that up to 14.4 million tonnes of microplastics may be found in the first nine centimetres of ocean sediment worldwide (Barrett *et al.*, 2020). In other words, the seafloor would contain a much larger amount of plastic waste (between 282 and 450 times higher) than what is observed on the surface, even though many accumulation sites still need to be pinpointed.

⏩ A heterogeneous distribution

Recent data show that waste is unevenly distributed on seafloor (benthic). The composition and abundance of debris are heavily influenced by both natural and anthropogenic factors linked to the sources, transport and deposition mechanisms

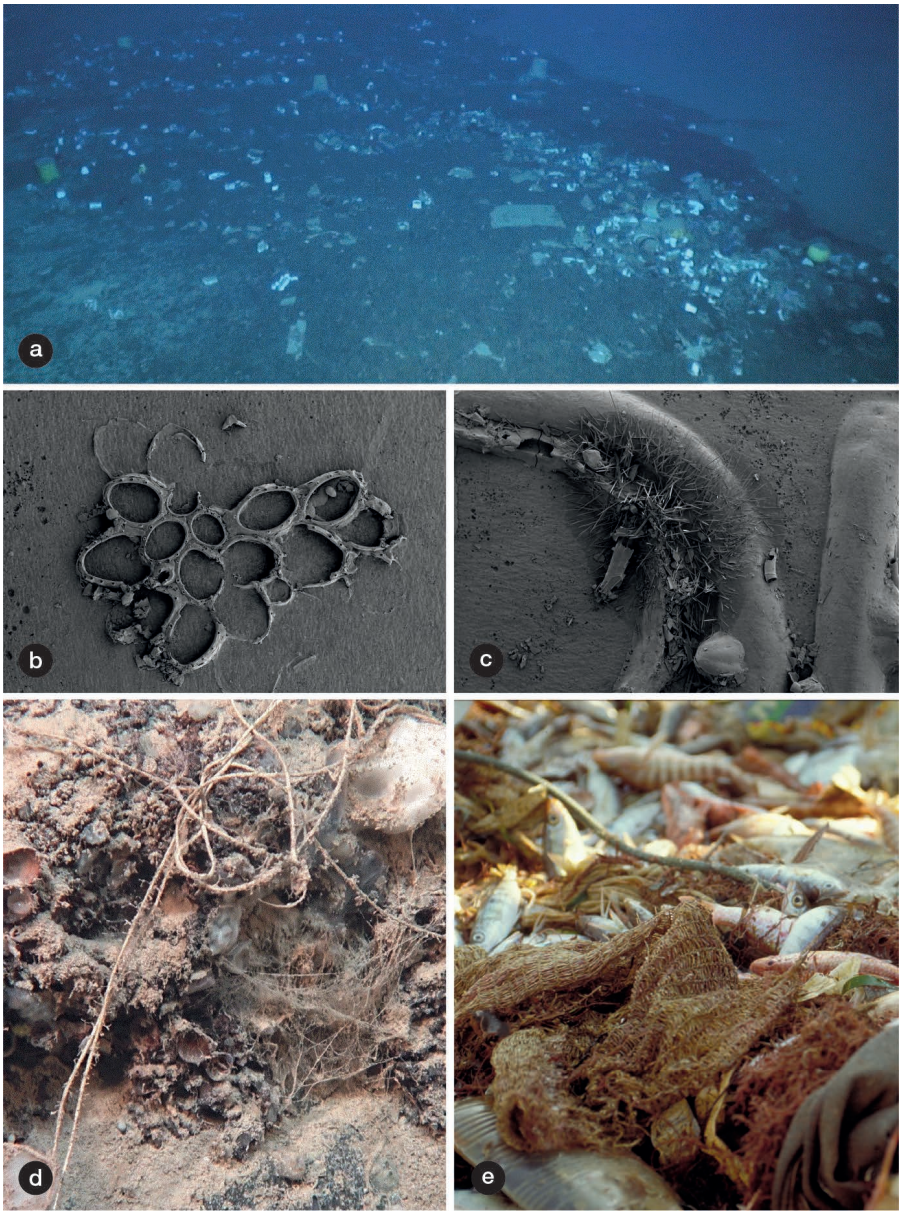


Figure 3.3.1. Accumulation of debris on the seafloor of the western Mediterranean Sea: **a)** Deep-sea accumulation zone observed by remotely operated underwater vehicle (Western Mediterranean canyon, 2,200 m, 2018) showing the large number of single-use plastics at the greatest depths of the ocean; **b)** Bryozoan shells (colonies of encrusting invertebrates) on a plastic bottle (northern shore of the western Mediterranean Sea, 700 m, 2018); **c)** Radiolarian (unicellular animal) attached to a PVC pipe (northern shore of the western Mediterranean Sea, 2018); **d)** Tangle of fishing lines on the seafloor of the western Mediterranean Sea (northern shore of the western Mediterranean Sea, 1,200 m, 2018); **e)** Debris collected by trawling on the seafloor of the western Mediterranean Sea (northern shore of the western Mediterranean Sea, 50 m, 2018).

of this waste, as well as the structure of the seafloor (e.g. the presence of canyons) and local hydrographic conditions. Waste that ends up on the seafloor originates from the land, such as runoff from rivers or urban and industrial areas, illegal dump sites and tourist activities. Although less common, large amounts of waste can also come from commercial and recreational shipping, fishing activities, aquaculture and offshore installations.

To a great extent, the quantities depend on the human modification of the coastline and catchment areas, whereas their transport to the seafloor is primarily controlled by oceanographic and geodynamic processes. As a result, certain heavily industrialized and densely populated coastal areas, such as the Mediterranean, have some of the highest concentrations of pollution in the world, with concentrations above one million objects per square kilometre (Pierdomenico *et al.*, 2023), in addition to high concentrations of microplastics measured in bottom sediments (Angiolillo *et al.*, 2021). Large amounts of waste may also be found along the main maritime routes and in areas where fishing-related debris may accumulate. Morales-Caselles *et al.* (2021) compared different regions around the world and found a broader range of waste categories and items on the seafloor than on the surface, as well as heavier waste items (glass, metal), large amounts of single-use plastics, especially plastic bags (12.1%), plastic packaging (11.8%), and plastic bottles (85%). Worldwide, fishing-related debris represents 8.5% of the debris found on the seafloor, particularly in Western countries and especially in Eastern Europe and Asia. Microplastics are also released by the maritime and fishing industries (accidental spillage of industrial resin pellets, paint particles, greywater, etc.).

Sea canyons, close to the coast, or other underwater structures such as seamounts or channels behave as the main transport vectors for plastic debris from the coast to the seafloor (Canals *et al.*, 2021), via submarine landslides, turbidity currents and downwelling currents. This channelling phenomenon creates accumulation "hotspots" for terrestrial and marine debris mixed with natural debris. Gravity-driven flows can be amplified by coastal flash flooding and salinity gradients, which also result in the sequestration of terrestrial debris—including large-scale vegetative matter—beneath the seafloor. Most of the observed debris seem to be concentrated in canyon thalwegs, with plastic (e.g. bottles) making up most of the waste and thereby confirming that it is mainly from the land. This litter is often deposited here because there are higher sedimentation rates near the seafloor (especially in canyons) and also because there are crevices, cliffs and shipwrecks.

By monitoring the abundance and composition of litter, we can then evaluate the impacts humans have on deep-sea environments, look at how the environmental status is changing, characterize specific waste or its sources and evaluate the effectiveness of the measures taken. Wide spatial variations are seen in plastic waste abundances on the seafloor, with average densities between 0 and more than 7,700 objects per square kilometre. Marine debris sites in the Mediterranean Sea have some of the highest densities of litter in the world. This is because there is a high population density along the coast, a high volume of maritime traffic (30% of global traffic passes through the Mediterranean), two major rivers that flow into this sea (Nile and Po) and intensive tourism activities around this enclosed basin. Extreme values were found off the coast of major cities, and the highest concentration was observed in a canyon adjacent to the Strait of Messina, Italy (1.3 million objects/km^2).

A significant percentage of waste on the seafloor is related to fishing activities. This percentage is higher than 50% in Italian fishing areas and, in extreme cases, is as high as 100% around the Azores (Galgani *et al.*, 2022).

Microplastics (which may include up to 90% fibres) are found all around the world, especially in shallow coastal environments, at concentrations several orders of magnitude higher than those found in surface waters, which supports the hypothesis that seafloor act as storage sites. Polar environments have lower concentrations of microplastics; however, a density of 13,600 particles/kg was observed south of Australia (Barrett *et al.*, 2020). Comparatively, the concentrations found in Mediterranean sediments have remained low, i.e. a few dozen to a few hundred particles per kilogram, and can go up to 2,000 to 4,000 particles/kg maximum. Contrary to macroplastics, microplastic concentrations do not have anything to do with local sources of contamination.

The timescales for observations need to be adjusted, over longer periods of several years, to be able to spot trends, especially as most trends draw from opportunistic evaluations while diving, trawling, and making video/photographic observations from submersibles during biodiversity studies. Typically, it is rare to come across evidence of increasing amounts of debris on seafloor over time, except in remote areas such as the Arctic, remote islands and in bottom sediments. It seems that, in general, plastic debris generated in densely populated (Western countries, Southeast Asia) or very exposed areas (large rivers, fishing grounds) are moved by currents toward the most distant parts of the ocean or toward the seafloor, and therefore this waste tends to be homogenous in terms of its distribution, degradation and microplastic accumulation (Galgani *et al.*, 2022).

⏩ Fishing gear

According to the FAO, global fish production was 171 million tonnes in 2016, with 53% from capture fisheries and 47% from aquaculture. This activity uses a wide variety of fishing gear such as nets, trawls, ropes, lines and traps, which usually contain polymers (polyamide/nylon, high-density polyethylene, polypropylene, PET). Lost gear often represents a significant proportion of the marine waste found on seafloor. This is a common occurrence throughout the world, but varies based on the geography, fisheries and type of gear, in addition to the operational context, how the gear is handled, the intensity of fishing pressure, type of aquatic habitat, and both environmental and meteorological conditions. Lost fishing gear often becomes trapped in rocky bottoms, reefs and areas with high biodiversity. Assessments of fishing effort can predict where these areas are located, but not for small-scale or recreational fishing activities because these types of fisheries are not bound by any regulatory monitoring systems. Richardson *et al.* (2019) reported that approximately 6% of all fishing nets, 8.5% of all traps and 29% of all lines are lost in the world's oceans each year, with an overall trend toward higher losses with time.

⏩ Significant impacts on ecosystems

Generally speaking, the sites most exposed to marine debris are found in coastal areas, enclosed bays, lagoons (especially those with coral reefs), fjords and at the heads and upper slopes of marine canyons.

One of the main impacts of marine debris on seafloor is the entanglement of marine fauna (see Part 2, Chapter 2). This concerns both benthic and demersal organisms, especially on seamounts and in canyons (Angiolillo *et al.*, 2021). A recent review at the world scale (Galgani *et al.*, 2018) reported that over 400 reef-associated species are likely to become entangled in plastic debris, with significant implications for species conservation and ecosystem balance. Gorgonians are particularly at risk due to their branching, arborescent morphology and sessile nature on the seafloor. These species form forests or reefs that are home to many species, thereby favouring biodiversity. Because these corals grow slowly and have long lifespans, they are heavily exposed to anthropogenic impacts and are especially vulnerable to the effects of lost or abandoned fishing gear. Certain vulnerable ecosystems (e.g. deep-water coral reefs, hydrothermal vents, canyon heads and seamounts) are home to higher numbers and a greater diversity of vulnerable sessile organisms, especially when with regard to lost fishing gear (Galgani *et al.*, 2018). For instance, the Mediterranean Sea has over 500 sea canyons, found along the continental margin, and over 242 seamounts. Although these areas are quite poorly studied, it is widely recognized that marine debris has a significant impact there.

Other benthic organisms such as crabs, cephalopods, echinoderms, fish and numerous small invertebrates can get caught in debris (usually from fishing activities) resulting in high mortalities (Galgani *et al.*, 2022). This kind of entanglement (called "ghost fishing") depends on the size and structure of the item, water turbidity, water depth and behavioural traits of the animals themselves. Given that this fishing gear is made to kill, lost gear will continue to catch organisms. In the end, there are not only repercussions for ecosystems but also for resources as this ghost gear has an impact on natural stocks. Mortalities in certain species can be higher than 5% in natural stocks and even as high as 20% in the case of Norwegian halibut, generating considerable losses.

Physical contact between fishing gear and sessile fauna can cause visible damage which, in the case of branching organisms, can lead to long-term skeletal abrasion, fractures, open wounds and epibiosis. On a seamount off the coast of the Azores, up to 31% of debris has been shown to have harmful effects on sessile organisms, mainly due to entanglement but also by covering the substrate (e.g. plastic bags) and thereby depriving organisms of light and oxygen. When large areas of sediment are covered with marine debris, this can ultimately hamper recolonization by large organisms and gas exchanges.

Plastic debris on seafloor create new substrates or habitats and thereby help increase local diversity or colonization. The effects of this are not well understood (Galgani *et al.*, 2022), however it should be noted that species-plastics interactions are usually considered to be neutral and sometimes even positive for certain artificial reefs. The introduction of new materials or materials with novel properties to a site increases the heterogeneity of habitats on a small scale, providing new substrates that are suited to certain species and favouring colonization by new species. This is a major risk for deep-sea ecosystems, about which not much is known. The kinds of species found on plastics include sea anemones, snails, hydras, brachiopods, tunicates and bryozoans—in other words, almost all the invertebrates in the animal kingdom. The percentage of the substrate covered varies significantly as it depends on different parameters such as the diversity of the waste items, the depth at which they are found, the type of habitat

and environmental factors. Nonetheless, substrates are often so heavily colonized that old debris may be completely covered by organisms, as seen for any other artificial substrate (e.g. shipwrecks). Nets stretched across soft-bottom habitats can provide attachment sites for unusual concentrations of filter feeders, such as the feather star *Leptometra* sp.; this appears to create an advantageous position for suspension feeding within bottom currents.

⏩ Future outlook

Entanglement of marine species in seafloor debris is the number one cause of mortality, necessitating urgent conservation measures. While it is planned to ban certain destructive fishing practices such as bottom trawling over the long term, there does not seem to be much interest in collecting abandoned, lost or discarded fishing gear accumulated in sites along coasts or in reusing, recycling or repairing gear. A lack of legal and financial support, and a lack of interest in the collected materials means that clean-up campaigns are usually not effective over the long-term. China's "Blue Circle" initiative is a marine debris collection system that involves hundreds of stakeholders (both individuals and businesses) and has successfully recovered thousands of tonnes of plastic. By implementing a recycling chain based on the individual characterization and digital traceability of each item, the system relies on polymer certification. This traceability has incentivized industrial interest, paving the way for the systematic recycling of marine waste. Despite this, collection strategies are still based on remedial actions instead of preventive ones and it is clear that the first and most important strategy to reduce the impact of plastic pollution on the seafloor is to significantly reduce the loss of fishing gear. Various solutions have been put forward for debris found on the seafloor, such as labelling fishing gear, using biodegradable materials that have already been tested in oceanic waters and encouraging the setting up of areas reserved exclusively for a specific type of gear so that they are not used in vulnerable habitats and areas. Last, a critical step in the prevention of waste is to inform and raise awareness among fishers, including recreational fishers and the fisheries sector in general.

The most critical objectives to be able to limit the impacts of marine debris on deep-sea ecosystems using the most appropriate management measures to gain a better understanding of how debris (especially fishing waste) is transferred to the seafloor, pinpoint accumulation areas and identify the sources of this waste.

Chapter 4

Plastics, vectors of harmful microorganisms and pollutants

Ika Paul-Pont, Gaëtan Burgaud, Jean-François Briand, Arnaud Huvet and Mélanie Ourgaud

Plastics: floating rafts acting as new ecological niches

Ika Paul-Pont, Gaëtan Burgaud, Jean-François Briand and Arnaud Huvet

As soon as plastic waste enters an aquatic environment, it is colonized by a large number of prokaryotes (mostly bacteria), microbial eukaryotes (fungi, microalgae, ciliates, flagellates, unicellular parasites), and even viruses. This microbial ecosystem forms on the surface of plastic debris and is called the "plastisphere", as defined by Zettler *et al.* in 2013, even though these microbial assemblages had already been observed in the 1970s. Estimates have shown that the plastisphere accounts for less than 0.2% of the microbial biomass in open oceans. This percentage is likely an underestimation, as recent studies have estimated that 171 trillion plastic particles are present at the ocean surface (Eriksen *et al.*, 2023), a figure far exceeding previous estimates of 5 trillion particles.

Some studies have suggested that when a microbial biofilm forms on the surface of plastic debris, marine fauna is more likely to ingest it, thereby further contaminating the marine food chain. Moreover, the presence of harmful and/or toxic species within the plastisphere (Bowley *et al.*, 2020), combined with the fact that plastic debris are ubiquitous and highly persistent in the environment, raises concerns about the ecological risks associated with species transport by such waste. Even though microorganisms also colonize other particles such as glass and wood, the plastisphere poses a higher risk because plastic debris persist much longer in the environment and, due to buoyancy, can be transported over long distances in aquatic systems.

It was already highlighted as early as 2011 that more research was needed on the interactions between plastic debris and microorganisms with the aim to better understand the formation, composition, diversity, dynamics and impacts of the plastisphere, especially the ecological consequences related to species transport. As a result, this field of research is still emerging, with most studies being conducted in marine environments compared with other environmental compartments, for example, freshwater, soil or atmosphere. Similarly, studies have primarily focused on bacterial communities within

the plastispheres, to the detriment of fungal, microalgal or viral components. Over the past decade, research has largely focused on the following three major questions:
– does "plastic specificity" exist? In other words, is there a specific microbial biofilm associated with plastic debris that differs from the surrounding environments and other marine substrates?;
– how do intrinsic factors (e.g. roughness, polymer type, chemical composition) and extrinsic factors (e.g. organic matter, temperature, salinity, pollution) influence plastisphere structure?;
– what are the ecological risks associated with the species transport on plastic debris for marine ecosystems, their organisms, and humans?

Below, we summarize current knowledge on these issues with the aim of highlighting the role of plastic debris as a vector of microorganisms in the oceans.

Formation of microbial communities within the plastisphere

In general, biofilm formation on any submerged surface follows three distinct steps: (1) an early colonization by opportunistic pioneer colonizers, followed by (2) a rapid turnover of diverse communities influenced by ecological interactions between species and environmental factors, before reaching (3) a dynamic equilibrium forming a mature biofilm (Wright *et al.*, 2021). Identifying the species involved in these three stages is essential to understand their specificity to plastic substrates compared with other marine substrates. Significant progress has been made through high-throughput sequencing approaches enabling the identification of species within complex samples (e.g. plastic debris surfaces) by sequencing universal genetic markers (e.g. specific regions of the 16S rRNA gene for prokaryotes and 18S rRNA gene for eukaryotes). Laboratory experiments have shown that several bacterial genera commonly found in aquatic environments and in the plastisphere are capable of degrading plastics (e.g. *Pseudomonas* spp., *Bacillus* spp., and *Achromobacter* spp., as well as fungi such as *Aspergillus* spp. or even *Zalerion maritima*). These findings pave the way for the identification, purification and/or synthesis of enzymes capable of breaking down polymers, with the long-term objective of improving chemical recycling processes for plastics without compromising material quality.

Plastic debris is a new ecological niche

Many studies have investigated the potential specificity of microbial communities associated with plastics compared with the communities in surrounding water or on other substrates (wood, sediment, algae). Depending on the study design, plastisphere communities have been compared with those surrounding water, suspended organic particles, and/or on non-plastic substrates (e.g. glass or wood) deployed in the environment near plastic samples. It is widely accepted that plastic debris are colonized by microorganisms found in the local water column. Over the past decade, meta-analyses of dozens of studies have shown that plastisphere bacterial communities differ significantly in structure from those found in the surrounding water or suspended particles. Biofilms on submerged plastic substrates appear to be enriched in taxa originating from the rare biosphere of the surrounding environment rather than dominant taxa. These rare taxa represent a minor fraction of the communities present in the surrounding water or in suspended particles, which likely limits their detection in the water due to current

sequencing technology limitations, thereby resulting in minimal overlap between the communities associated with plastic debris and those found in the surrounding water. These data therefore suggest that certain species are enriched and/or selected on the surface of plastic debris, making these materials a novel ecological niche. This well-documented phenomenon, widely observed for bacterial communities, has also been observed recently in microbial eukaryotic communities such as fungi.

Factors influencing the composition of plastispheres

The community composition and structure of plastispheres are continually influenced by stochastic processes (e.g. random encounters with microorganisms in the surrounding water), but especially by deterministic processes involving material properties (roughness, chemical formulation, surface energy) and environmental variables exerting selective pressure on plastisphere communities. The scientific literature has shown conflicting findings, especially regarding the influence of polymer type on plastisphere communities: some studies report significant differences between polymers, while others either conclude that this parameter has no effect or that differences can only be observed at given sampling times or in specific environmental conditions. These differences underscore the complexity of the processes by which microbial communities form on the surface of plastic debris but, for the most part, are related to variations in the colonization kinetics, which depend on both plastic properties and environmental conditions. The meta-analysis published in 2021 by Wright *et al.* analyzed data from more than 2,000 samples across 35 scientific publications and concluded that the incubation substrate (e.g. water versus sediment), environmental conditions (e.g. salinity, light, depth, temperature), geographic location (latitude, longitude) and incubation time all have greater effects on the community composition and structure of plastispheres than polymer type or chemical formulation. This emphasizes the key roles played by environmental conditions in structuring of microbial communities associated with plastic debris.

Is the health of ecosystems at risk?

Introduction of species

The colonization of plastic surfaces by organisms (both micro and macro) raises the issue of non-native and potentially invasive species being introduced into new ecosystems. It has long been known that species can be transported (dispersed) on natural debris (e.g. driftwood). The difference here is that plastic debris is ubiquitous and has a long lifespan in the ocean, which means that this waste is a powerful vector for dispersing species found in the plastispheres over large spatial (ocean basins) and temporal scales (decades). The study published by Carlton *et al.* (2017) reported that, following the 2011 tsunami, approximately 289 non-native species of marine invertebrates found on plastic debris were transported across the Pacific Ocean by ocean currents and introduced to the west coast of the United States. Non-native species have also been introduced to the island of Rapa Nui in the Pacific Ocean via floating plastic debris. These non-native species can then become established, competitive or even invasive, to the point where they pose a threat to endemic species and may disrupt the equilibrium within the communities and ecosystems (i.e. biological pollution).

Disease transmission

Some of the species found on marine plastic debris correspond to potentially pathogenic strains (e.g. bacteria, viruses) or toxin-producing organisms (e.g. toxic microalgae) that may be responsible for diseases in both aquatic and terrestrial organisms (Bowley *et al.*, 2020). For instance, species of the bacterial genus *Vibrio* (*V. anguillarum*, *V. harveyi*, *V. pectenicida*, *V. splendidus* and *V. xiamenensis*) may be responsible for diseases in certain fish and marine mollusc species. Other potential pathogens affecting fish (*Tenacibaculum* sp.) and invertebrates (*Vibrio splendidus*, *Phormidium* sp., and *Leptolyngbya* sp.) were also detected in over three-quarters of the samples analysed, accounting for up to 28% of the total bacterial flora. Finally, certain bacterial species (including some known to be pathogenic to humans) have been found on microplastics but not in the surrounding seawater (or only at low concentrations). Examples of this were found in studies conducted along the Belgian coast (*Escherichia coli*, *Bacillus cereus* and *Stenotrophomonas maltophilia*) and the Brazilian coast (*Vibrio cholerae*, *V. vulnificus* and *V. mimicus*). No parallel studies have been carried out to determine whether plastic debris plays a role in the dispersal of viruses, despite evidence that human enteric viruses, which are highly stable in marine environments (norovirus, rotavirus SA11, bacteriophage Phi6), and a virus affecting Pacific oyster populations (ostreid herpesvirus OsHV-1) can attach themselves to plastic polymers either deployed *in situ* or incubated in aqueous media under laboratory conditions. A recent study reported, for the first time, the presence of the White Spot Syndrome virus (WSSV) in the marine plastisphere. This virus can infect penaeid shrimps and result in large-scale outbreaks in shrimp farm populations along the coastlines of numerous countries (Lacerda *et al.*, 2024). Lastly, the identification of potentially pathogenic fungal taxa on plastic debris in terrestrial and lacustrine environments, together with the occurence of complex fungal communities in marine environments, suggests that pathogenic fungal microorganisms may also be present in the marine plastisphere. Although many studies have shown that potentially pathogenic microorganisms can be found on various microplastic samples in aquatic environments, few studies have investigated the factors promoting their attachment to plastic surfaces or to the mature biofilm of the plastisphere, as well as their potential persistence in a viable and infectious state. Yet this information is essential to evaluating the risk posed by microplastics as a vector for pathogens. In addition to simply determining whether these species are found on plastic debris, it is essential to understand what extent their transport contributes to the emergence and spread of diseases. This question has yet to be answered and is a major challenge for current research within the international scientific community.

Development of antibiotic resistance phenomena

Biofilm formation on the surface of plastics can provide physical protection against adverse environmental conditions (e.g. mechanical impacts, UV radiation, predation), allow access to the nutrients in the organic matter aggregated on the plastics, enable communication between species (quorum sensing), and facilitate the exchange of genetic material given the close physical proximity of the microorganisms. This was first discovered in a study on bacterial communities that had colonized a macroplastic item found washed up on a beach on King George Island in Antarctica (Laganà *et al.*, 2019). Many of the strains were found to be resistant to antibiotics. It has recently been suggested that horizontal gene transfers involved in virulence mechanisms

and/or antibiotic resistance mechanisms between bacterial communities within the plastisphere may occur in different aquatic compartments (freshwater, wastewater, seawater). Thus far, antibiotics and metals have been examined to determine their role in the co-selection and proliferation of antibiotic-resistant bacteria and antibiotic resistance genes (ARGs). The selection process for pathogens is not limited to metals or antibiotics; other chemicals that also bioaccumulate on plastics, such as PCBs and polycyclic aromatic hydrocarbons (PAHs), may also play a role. This means that because antibiotic-resistant strains coexist in close proximity on the surface of plastic debris, mostly smaller than 5 mm, ARGs can be readily transferred to species that were initially non-resistant; thereby contributing to the formation and spread of antibiotic resistance hotspots in the environment. The global rise in antibiotic resistance in many parts of the world has been described by the World Health Organization (WHO) as "one of the biggest threats to global health, food security and development today". It is therefore imperative to better understand these transfers occurring on the surface of plastic debris, both qualitatively and quantitatively, and to identify the factors facilitating them. This knowledge is critical for developing management and remediation solutions for most at-risk areas, such as densely populated coastal areas, landfill sites (via leachate discharge), and wastewater treatment plants (WWTPs), the latter being known sources of antibiotic release into the environment.

In summary, we can draw the following conclusions:
– plastic debris constitutes a new ecological niche for many microorganisms (bacteria, algae, fungi, viruses) collectively termed the "plastisphere";
– environmental parameters such as salinity, nutrients, light and temperature exert stronger selective pressures than polymer properties, which primarily influence plastisphere community composition and structure over time;
– as plastic debris is ubiquitous and long-lived in the environment, it can efficiently disperse species, including toxic and/or harmful species;
– bacterial, fungal and viral strains that are potentially pathogenic to marine organisms and humans have been found on the surface of floating plastic waste in aquatic environments (freshwater and seawater), which raises questions about the role of plastic debris in spreading diseases;
– similarly, the detection of reservoirs of antibiotic resistance within the plastisphere suggests that plastic debris may promote the emergence of multi-resistant traits, a phenomenon that the WHO already recognizes as a global threat.

⏩ Plastics as sources and vectors of contaminant cocktails

Mélanie Ourgaud

The weathering processes of plastic debris at sea result not only in their fragmentation into micro- or nanometric particles but also in a significant release of dissolved organic carbon (DOC), thereby disrupting the marine carbon cycle. Plastic-derived additives (including plasticizers, flame retardants, antioxidants, and UV stabilizers) represent a major class of persistent organic pollutants (POPs), specifically falling within the category of emerging contaminants. Indeed, 2015 estimates of the mass of additives reaching the oceans approached one million tonnes—a figure equivalent to the global annual atmospheric flux of Polycyclic Aromatic Hydrocarbons (PAHs). Thus, throughout their life cycle, all sizes of plastic debris will leach organic additives

into the environment (Paluselli *et al.*, 2018). In parallel, these plastics act as sea-borne "sponges" for a "cocktail" of diverse contaminants, including trace metallic elements and POPs. Much like multicellular organisms, viruses and bacteria, contaminants present in aquatic environments interact with plastic debris via sorption (Menéndez-Pedriza, Jaumot, 2020). Consequently, these contaminants can be transported by currents to areas often far removed from their initial point of entry, forming diffuse sources of chemicals. Macro-, micro-, and nanoplastics are therefore complex vectors of oceanic pollution, comprising (i) additives and polymer raw materials (e.g. monomers or oligomers) originating from the plastics themselves, and (ii) chemicals sorbed from the surrounding environment. The numerous chemicals contained within or on the surface of plastics influence the environment either through the ingestion of microplastics by biota or via their release into the marine environment, particularly during plastic degradation or leaching[26] (Paluselli *et al.*, 2018)

Plastics as diffuse sources of emerging organic contaminants

Chemically, plastic materials consist of a polymer matrix supplemented with approximately 1% to 20% additives (such as phthalates, phosphate esters, bisphenols, etc.) incorporated during manufacture (Figure 3.4.1). A small percentage of auxiliary components is also added to: (1) impart specific physical and chemical characteristics to the finished products; (2) facilitate processing during manufacture; and (3) reduce production costs and retail prices.

Several categories of additives and auxiliary components can be distinguished: (1) additives designed to inhibit the degradation of plastic materials (flame retardants, antioxidants, stabilizers, etc.), rendering them durable by design; (2) functional additives (antistatic agents, plasticizers, lubricants, slip agents, curing agents, foaming agents, etc.); (3) colourants (pigments, soluble dyes, biocides, etc.); (4) fillers (mica, talc, kaolin, clay, calcium carbonate, barium sulphate, etc.); and (5) reinforcements (glass fibres, carbon fibres, etc.). Trace metallic elements may also be used as plastic additives to serve as colourants, flame retardants, fillers, or stabilizers. Antimony oxide, aluminium oxide and zinc borate, for instance, are well-known flame retardants, as are chlorine and bromine.

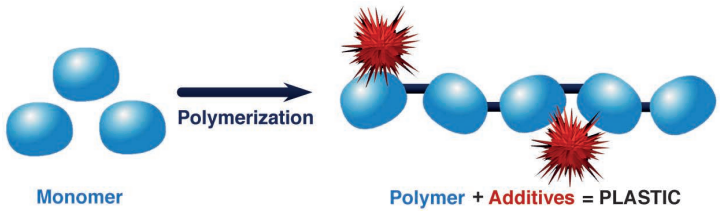


Figure 3.4.1. Plastic consists of a polymer (70-95%, derived from low- and high-density polyethylene, polyethylene terephthalate, PVC, polypropylene, or polystyrene, etc.), i.e. a repetition of simple molecular units called monomers, and 1 to 20% additives (PAE, BP, OPE, flame retardants, colourants, etc.), as well as a small percentage of fillers (polycondensate, resin, calcium carbonate, silica, clay, cellulose paste, etc.).

26. Leaching is a process that involves passing a solvent through a solid material. Leaching initially involves the extraction and solubilization of additives and synthetic residues from the polymer, possibly followed by the hydrolysis of the polymer.

Beyond additives, processing aids[27] or fillers plastics also contain a group collectively referred to as non-intentionally added substances (NIAS)[28] and, in certain instances, compounds with specific mechanical functions, such as carbon black in tyres. A recent inventory of chemicals associated with plastics identified a total of 16,325 chemical products (Wagner *et al.*, 2024). Paradoxically, when chemicals are categorized by function—noting that some may serve multiple purposes—over 3,000 are used as colourants, between 1,000 and 2,000 as processing intermediates, lubricants, or biocides, while only 959 are monomers.

These products constitute a broad range of chemicals of varying toxicity levels contained within the plastic matrix. Their respective proportions vary significantly depending on the nature of the auxiliary component and the polymer in question. In some materials, plasticisers may account for an equivalent or even greater mass than the polymer itself, in order to improve flexibility, impact resistance and performance at low temperatures.

Of the 16,325 identified chemicals, 4,219 are classified as hazardous based on existing toxicological data or their physicochemical properties. When combined with 1,191 less hazardous substances, one-third of all associated chemicals are of concern. To these identified products, one must add 10,726 chemicals for which no data are available. Ultimately, fewer than 1% of chemicals associated with plastics are considered safe. Consequently, a comprehensive toxicity assessment of these substances is complex—and at times insurmountable—though data do exist for a subset of them.

These products can be categorized by toxicity class, bearing in mind that many chemicals fall into multiple categories. Among chemicals identified as toxic, approximately 66% of identified chemicals are classified as toxic to the aquatic environment (likely because they were specifically evaluated in this context); 42% are toxic to specific organs (e.g. hepatotoxicity); 35% are CMR substances (carcinogenic, mutagenic, or reprotoxic); and finally, only 1% are formally evaluated as endocrine disruptors. Regarding the latter, it must be noted that the number of plastic-associated chemicals subject to regulatory testing for endocrine disruption is extremely low, with only 121 products tested. Of these, 47 (38%) exhibited endocrine-disrupting activity. It is therefore highly probable that the percentage of plastic-associated chemicals with such activity is significantly underestimated. According to Bergman *et al.* (2013), endocrine disruptors are "natural or artificial chemicals foreign to the body that can interfere with the functioning of the endocrine system (i.e., the hormonal system)." These pollutants are particularly concerning due to their well-documented health effects, even at low doses, their prolonged or delayed impacts, and their pronounced effects on developing organisms during embryonic stages across all invertebrates and vertebrates, including humans. Plastic-associated chemicals known for endocrine-disrupting activity include phthalates, perfluorinated or polybrominated flame retardants, and bisphenols (Table 3.4.1). These chemicals are generally not chemically bound to the polymer matrix, with the exception of constituent monomers, though unbonded residual monomers may remain, as is particularly the case

27. These chemicals are utilized during the manufacturing process but are not included in the list of ingredients; examples include catalysts, solvents and other processing aids such as foaming agents and flocculants.
28. These chemicals include impurities, reaction by-products and degradation products.

Table 3.4.1. Summary of the main endocrine disruptors. Adapted from Richard Sempéré's contribution to the National Assembly hearing report on endocrine disruptors in plastic containers, published in December 2019 (No. 2483).

	Characteristics	Uses	Toxicity	Environmental Distribution	Risk Assessment	Substitution Potential
Phthalates (PAEs)	Essentially hydrophobic molecules with a tendency to accumulate in organisms.	Plasticizers (packaging, bags, toys, cosmetics).	Eight phthalates identified as endocrine disruptors and carcinogens.	Present in major environmental compartments (air, water, sediment) as well as biota and humans (urine, saliva, breast milk, tissue).	Only the risks of DEHP are well-characterized.	Unknown.
Organophosphate Esters (OPEs)	Possess Persistent Organic Pollutants (POPs) properties; hydrophobic and lipophobic.	Plasticizers, flame retardants.	Environmental persistence and bioaccumulation; carcinogenic and neurotoxic properties.	Present in major environmental compartments.	Insufficient risk assessment.	Unknown.
Bisphenols (A, Z, S, F, ADGE)	Non-linear dose-response relationship: effects observed at low doses.	Antioxidants; polycarbonate monomers.	Oestrogen mimic; reprotoxic.	Low environmental persistence.	BPA has been prohibited in food containers since 2015.	BPA has been replaced by BPS, BPF and BADGE, of which BPS is more persistent than BPA and, according to several assessment parameters, even more harmful.
Perfluorinated Compounds (PFCs)	Possess POP properties; hydrophobic and lipophobic.	Waterproofing agents, flame retardants, surfactants in packaging, fire-fighting foams, textiles.	Highly toxic to marine organisms/ ecosystems	Highly persistent in the environment.	Risk assessment is well established for water (a major vector for dissemination).	PFBS, Novec 1230.

DEHP: di-2-ethylhexyl phthalate, also known as DEHP (DiEthylHexyl Phthalate) or DOP (dioctyl phthalate); BPS: bisphenol S; BPE: bisphenol E; BADGE: bisphenol A diglycidyl ether.

with styrene, the toxic monomer of polystyrene. Consequently, these substances risk migrating to the surface of the finished object, subsequently evaporating into the air or dissolving into water and other contact media, including food.

Plastics act as a diffuse pollution source, releasing numerous organic chemical molecules (including plasticizers, fillers, and additives) into the environment (Bolo, Préville, 2020). Laboratory experiments conducted by Paluselli *et al.* (2018) under controlled conditions of light and heterotrophic bacterial activity demonstrated a significant release of phthalates from polyethylene (PE) and polyvinyl chloride (PVC) debris during the first month of incubation in seawater. Specifically, the polyethylene debris primarily released di-isobutyl phthalate (DiBP) and di-n-butyl phthalate (DnBP), with peak values reaching 83.4±12.5 and 120.1±18.0 ng per gram of plastic, respectively. For the PVC debris, the principal compounds released were dimethyl phthalate (DMP) and diethyl phthalate (DEP), with mass fractions reaching 9.5±1.4 and 68.9±10.3 ng per gram of polymer, respectively. Furthermore, exposure to light and bacteria increased the total quantity of phthalates leached by the selected polymers by up to fivefold.

A major issue with endocrine disruptors lies in their ability to produce cumulative effects. These interactions between substances, known as "cocktail effects" or "combined effects", present significant difficulties for risk assessment. Depending on the scenario, "the combined effect may be additive (the sum of the two isolated effects), antagonistic (the combined effect is less than that of either substance alone), or, conversely, synergistic (the combined effect exceeds the sum of the two isolated effects); however, current regulations do not account for these cocktail effects" (Bolo, Préville, Report No. 217, 2020).

Plastics as vectors of environmental contaminants

The marine environment serves as the ultimate receptacle for a broad array of chemical contaminants arising from a diversity of humankind's activities: agricultural, urban, industrial, and tourism-related, among others. The transport of these contaminants to the marine environment occurs via runoff, discharge and fluvial input, and may also result from atmospheric transport and precipitation. Due to their high surface-area-to-volume ratio, certain organic or metallic contaminants can adsorb and accumulate on plastic debris in the environment. Trace metallic elements or highly hydrophobic contaminants—such as persistent organic pollutants (POPs), notably polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), dichlorodiphenyltrichloroethanes (DDT), hexachlorocyclohexanes (HCH), and polycyclic aromatic hydrocarbons (PAHs)—are examples of compounds sorbed onto the surface of micro- and nanoplastics. Research has demonstrated a substantial enrichment of POPs within polymers, in some cases exceeding their concentrations in solution by more than a hundredfold (Lohmann, 2017). Similarly, the potential interaction between plastic debris and emerging pollutants, such as active pharmaceutical ingredients (APIs), antibiotics, or UV filters, is the subject of intense scientific interest (Ho *et al.*, 2019). Owing to these adsorption processes, pieces of plastic debris may play a crucial role in aquatic ecotoxicology by acting as vectors for these pollutants. They represent a potential additional source of lipophilic chemicals in bioaccumulation and biomagnification phenomena, facilitating their entry into the food chain (Hartmann *et al.*, 2017). However, some scientists argue that the current volume of plastic debris in the

oceans is not yet sufficient to outweigh the distribution of POPs in the environment or dissolved organic matter (DOM) in the environment in general (Wang *et al.*, 2019). Furthermore, the specific details regarding how contaminant sorption onto microplastics enhances or mitigates their impacts remain unclear. Various factors influence the sorption of environmental pollutants onto plastic debris (Menéndez-Pedriza, Jaumot, 2020). The process of chemical transfer from a fluid phase (air or water) to a solid phase (plastic debris or DOM) defines the sorption of a compound. This term encompasses two types of processes: absorption and adsorption. Absorption refers to the chemical interaction between compounds and a sorbent via relatively weak van der Waals forces, in which molecules penetrate and integrate into the sorbent matrix. Adsorption involves molecules remaining at the interface between the fluid and the solid surface (governed by a variety of forces ranging from van der Waals to ionic, steric, or covalent interactions). In many instances, absorption and adsorption processes occur simultaneously, making it difficult to distinguish one interaction from the other. However, adsorption processes predominate in most common scenarios involving low environmental concentrations of organic chemicals due to stronger interactions with the surface of the solid phase. Sorption processes are fundamentally linked to the physicochemical properties of the sorbate and the sorbent, as well as the properties of the medium. Consequently, the mechanisms of sorption between pollutants and plastic debris depend on their mutual interactions, as well as various external factors (Figure 3.4.2).

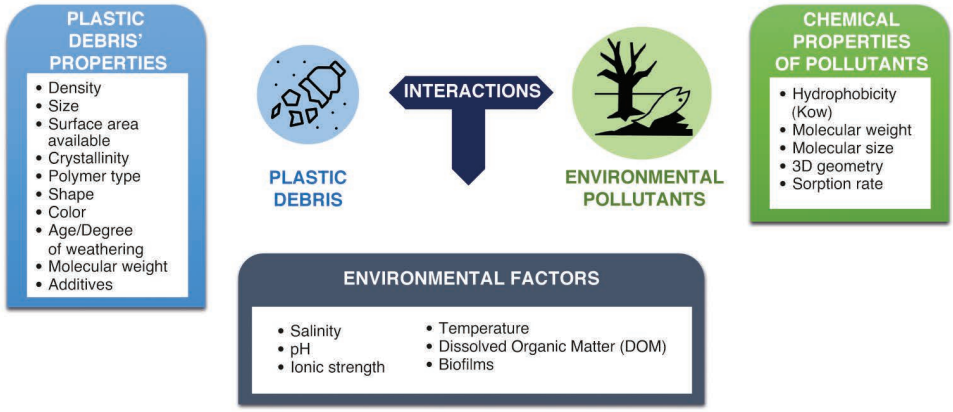


Figure 3.4.2. Summary of the main factors influencing the interaction between micro- and nanoplastics and chemical pollutants present in the environment.

A study has demonstrated that the absorption of PCBs onto polyethylene (PE) plastic films was significantly greater than onto polystyrene (PS) or PVC. Indeed, PE showed the highest absorption, diffusion and partition coefficients compared with other polymers (Pascall *et al.*, 2005). Particle size is another critical factor affecting sorption capacity. Consequently, nanoplastics possess an increased sorption capacity due to the higher surface-area-to-volume ratio resulting from the weathering process. Therefore, as plastic debris break down within the environment, the potential risk posed by microplastics becomes unpredictable. Similarly, PAHs, another family of hydrophobic pollutants found abundantly in the environment, show strong interactions with

micro- and nanoplastics in aquatic settings (Tan *et al.*, 2019). Experimental work on the sorption behaviour between PAHs and PS, PE and PP revealed that the order of partition coefficients between microplastics and seawater was significantly correlated with hydrophobicity, which appears to be the primary mechanism driving PAH sorption onto plastic debris (Lee *et al.*, 2014).

Much like organic pollutants, trace metallic elements have also been observed on plastic surfaces. Although trace metals occur naturally in the environment (e.g. in the atmosphere, lithosphere, hydrosphere, and biosphere), environmental contamination and human exposure are primarily due to diverse anthropic activities (Engwa *et al.*, 2019). An experimental study reveals that trace metal accumulation appears to be similar regardless of the type of microplastic. One hypothesis is that trace metal accumulation on plastics may be controlled by the presence of a biofilm (Johansen *et al.*, 2018). Furthermore, the distribution of biofilms appears similar across various polymer types. The accumulation of trace metals also seems to increase with exposure time, correlating with the greater development of biofilms on the plastic surface. Over time, plastic debris undergoes weathering, increasing its contact surface area and generating oxygen-containing functional groups; this can increase polarity, charge, surface roughness, and porosity, thereby influencing adsorption (Fotopoulou, Karapanagioti, 2012). The development of biofilms on the surface of plastic debris, by modifying surface polarity and the specific surface-area-to-volume ratio, increases the accumulation of various metals, such as Ga, Mn, Pb, Cu, Co, U, Fe, Ni, and Al[29] (Richard *et al.*, 2019). Similarly, Johansen *et al.* (2019) demonstrated that the enhanced sorption of trace metals (specifically Cs and Sr[30]) onto PE and PP was also linked to the increased surface area provided by biofilm activity.

While a consensus exists that plastic debris accumulate high concentrations of diverse pollutants, they remain secondary vectors compared to particulate organic matter (POM) (e.g. phytoplankton). Indeed, given the widespread contamination of the environment and biota by POPs and trace metals, the contribution of plastic debris may not play a significant role in the bioaccumulation and biomagnification of contaminants already present in the food chain. Nevertheless, plastic debris does contribute to the dispersal of a diversity of contaminants in the marine environment.

29. Gallium (Ga), manganese (Mn), lead (Pb), copper (Cu), cobalt (Co), uranium (U), iron (Fe), nickel (Ni), aluminium (Al).
30. Caesium (Cs) and strontium (Sr).

Conclusion

The first part of this book highlighted the ubiquitous presence of plastic debris across all size classes—from macro- to nanoplastics—and across all environmental compartments, including soils, freshwater, and marine systems, from surface waters to the deep sea. This presence is the result of continuous fluxes originating from both diffuse entry points (such as atmospheric deposition or inputs from agricultural and maritime activities) and point sources (such as fluvial inputs). This leads to a heterogeneous distribution across all ecosystems, exacerbated by the variability of human activities (e.g. localized landfilling) and hydrological or atmospheric drivers (currents and winds) that facilitate localized accumulation. The second part demonstrated the effects of exposure on biological organisms—observed across all studied species—with variations dictated by the relative dimensions of both the debris and the organisms. This third part, situated at the confluence of the preceding two, offers a synthesis dedicated to ecosystems; it considers organisms within interacting populations, their broader environment, and the overarching ecological equilibria that plastics may disrupt.

Soils, coastal and littoral marine ecosystems, and deep-sea ecosystems have been addressed in turn. Despite the differences inherent to each of these ecosystems, it is striking to repeatedly observe the association between the presence of plastic and biodiversity loss. This is also true for microbial populations, which appear to develop new equilibria on plastic surfaces to such an extent that it has led to the definition of a specific term: the plastisphere. Thus, the disruption of ecosystems can occur in various ways, through either subtraction or addition. This includes the loss of habitats via physical destruction—resulting from entanglement or the blanketing of a substrate that prevents light penetration—or, conversely, the creation of new habitats. Examples of the latter include vertical colonization or the facilitated transport of species (e.g. within the plastisphere), often over very long distances. In both cases, the upheaval of major biological equilibria can lead to alterations in ecosystem functioning.

In the case of the plastisphere, and its microbial component in particular, it must be noted that by providing a novel substrate, plastics allow the concentration of specific bacterial species and facilitate gene transfer between species. This natural phenomenon is amplified in the plastisphere by bacterial density which, by increasing the transfer of resistance genes, could promote the emergence of antimicrobial resistance (AMR), with consequences for both farmed and wild animal health.

In the context of ecosystem health, the role of plastics as a vector—for both pathogens and pollutants—has also been addressed. In connection with the plastisphere, it has indeed been observed that the abundance of pathogenic bacteria on plastic surfaces is higher than in the general environment.

Beyond sanitary consequences, this chapter indicates that an aspect of ecosystem health—or rather the consequences of its degradation—linked to plastic presence is the reduction in productivity. This decline has been correlated with the presence

of plastics in soils in parallel with structural modifications. In more dynamic environments, such as aquatic ecosystems, this link is less straightforward to establish; however, effects on the population levels of certain species have been demonstrated. These impacts on food resources may ultimately jeopardize global food security.

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Part 4

The plastic transition: regulatory obligations, material alternatives and their implications for biodiversity

Introduction

Since the first high-profile warnings regarding plastic pollution over 20 years ago[31], which was based on earlier scientific publications (Lecke-Mitchell and Mullin, 1992; Galgani *et al.*, 1995), extensive research has been conducted on the subject. This work has aimed not only to estimate the scale of the issue and its effects on living organisms but also to identify solutions and propose alternatives to contain it.

Over the last decade, the results of this research have informed numerous national, European and international reports, which serve to alert public authorities and inform both industry and consumers of the deleterious consequences of plastics across their entire value chain.

Despite these regular warnings, however, global plastic production continues to rise, highlighting the difficulty of reconciling human activity with environmental protection and the conflict between economic interests and the preservation of biodiversity.

Nevertheless, progress is evident in international instruments (agreements, conventions and action plans) and European directives, particularly regarding the preservation of marine environments and biodiversity and regarding waste treatment, where plastic pollution is addressed. Nonetheless, the latter still struggles to emerge as a distinct entity within the regulatory framework.

These regulatory aspects are the subject of the first chapter of this fourth part, which presents the current state of the legal framework against plastic pollution, with a focus on the specific case of the marine environment. We shall then examine why this framework remains insufficient in its current form and why the international treaty currently under negotiation holds so much promise.

While awaiting implementation of truly binding regulations, attention has turned towards improving plastic circularity to protect biodiversity. After presenting the origin of our plastic waste, the second chapter will examine its fate through various existing management methods and their degree of circularity.

Finally, innovation and the emergence of alternative solutions to plastics could contribute to limiting plastic pollution or its consequences. In the final chapter, we shall address the case of so-called "biodegradable"[32] plastics, presented as alternatives to

31. Discovery of the "7th continent" by oceanographer Charles Moore in 1997, a huge area of the Pacific Ocean consisting of plastic debris.

32. A plastic is defined as "biodegradable" if it can be broken down by living organisms, such as bacteria or fungi. This is distinct from the term "bio-based", which indicates that the carbon feedstock used for production is of biological origin (e.g. vegetable or bacterial) rather than petroleum-based. These properties are entirely independent: a biodegradable plastic may be petroleum-based (e.g. PBAT), while a bio-based plastic may be non-biodegradable (e.g. polyethylene derived from maize starch). The term bioplastic lacks a rigorous scientific definition and is frequently misused, often leading to confusion between bio-based and biodegradable properties.

conventional plastics for very specific applications. However, the primary and essential action required to combat plastic pollution and its threats to biodiversity and humanity is reduction as far upstream as possible—that is, the reduction of plastic production itself. Improvements in waste management systems, circularity and the development of alternative plastics are useful complementary approaches in certain circumstances, but on their own, they will not suffice to resolve this global problem.

Chapter 1

Regulatory aspects

Loïc Peyen and François Galgani

⏩ Existing regulations and requirements

Although it has long been deficient (Peyen, 2018), the legal framework for plastic has expanded considerably in recent years. It currently depends on several levels of action, involves various types of instruments, combines a multitude of approaches and pays great attention to the marine environment.

Multiple levels of action

Rules relating to plastics exist at several levels: international, regional, national and local.

At the international level, several conventions contain rules relating to plastic, such as the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter—commonly known as the London Convention or LC72—(London, Mexico City, Moscow and Washington, 29 Dec. 1972), the Convention on the Protection of the Marine Environment of the Baltic Sea Area—or Helsinki Convention—(Helsinki, 22 March 1974), the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Basel, 22 March 1989) or the Stockholm Convention on Persistent Organic Pollutants (Stockholm, 22 May 2001). Others, without focusing directly on the subject, have also addressed the subject, such as the Convention on Biological Diversity (Rio de Janeiro, 5 June 1992) and the Convention on the Law of the Sea (Montego Bay, 10 Dec. 1982). As these regulations only apply to specific sectors, the United Nations Environment Assembly on 2 March 2022 initiated a process aimed at developing an international legally binding instrument on plastic pollution, taking into account their entire lifecycle and all environments (Resolution 5/14, doc. Unep/EA.5/Res.14).

At the regional level, several actions are being undertaken to combat this scourge, as illustrated by the Association of Southeast Asian Nations (Asean), or indeed the Mediterranean coastal states bound by the Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona, 16 Feb. 1976). With greater authority, given that these acts are binding upon its Member States, the European Union possesses a multitude of instruments that address the issue: Directive 94/62/EC of the European Parliament and of the Council of 20 December 1994 on packaging and packaging waste; Directive (EU) 2015/720 of 29 April 2015 amending Directive 94/62/EC

regarding reduction in the consumption of lightweight plastic carrier bags, etc. More recently, it adopted a more transversal instrument to tackle the matter: Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.

At the French national level, and partly under European impetus, the number of texts focusing on the issue has grown steadily. Following the Energy Transition for Green Growth Law of 17 August 2015 (*Loi relative à la transition énergétique pour la croissance verte*), the Biodiversity, Nature, and Landscapes Recovery Law of 8 August 2016 (*Loi pour la reconquête de la biodiversité, de la nature et des paysages*), and Law No. 2018-938 of 30 October 2018 regarding balanced trade relations in the agricultural sector and healthy, sustainable food (*Loi pour l'équilibre des relations commerciales dans le secteur agricole et al.imentaire et une alimentation saine, durable et accessible à tous*), the pivotal Anti-Waste and Circular Economy Law of 10 February 2020 (*Loi relative à la lutte contre le gaspillage et à l'économie circulaire*) has further consolidated French law in this domain (Peyen, 2021). Most provisions relating to plastic are codified within the Environmental Code.

Finally, at the local level, local authorities and inter-municipal partnerships have significant scope for action. In addition to their mandatory waste management duties, they can launch local strategies and provide support for local initiatives to this end.

Diversity of instruments

The instruments addressing this issue are quite diverse: they may be authentic binding standards, established by conventions, European directives or regulations, laws or regulatory acts; however, they may also be instruments of more limited scope, such as declarations, action plans, guidelines or strategies. The nature of these instruments affects the reach and enforceability of their content.

Alongside these instruments, several voluntary tools are also deployed to address plastic pollution. The European Union, as well as several national stakeholders, frequently utilizes "calls for projects" to support local initiatives aimed at tackling this pollution, thereby employing a "bottom-up" approach. At the national level, conventions or commitment pacts, such as the National Pact on Plastic Packaging (*Pacte national sur les emballages plastiques*) of 21 February 2019 or the "Sushis Action Plan" (*Plan d'action-Sushis*) of March 2022, were signed between public authorities, companies and non-governmental organizations to foster action in this field. Following this logic, the law invites public authorities, for example to integrate clauses aimed at combating plastic pollution into public procurement contracts wherever feasible.

Multiple regulatory approaches

The legal treatment of plastic is fully integrated into the objective of attaining a circular economy and, for this reason, adopts its specific approaches. Indeed, two types of measures can be identified: on one hand, *ex ante* measures, which are anticipatory as they act before pollution occurs; and on the other, *ex post* measures, which are more curative as they intervene after pollution has taken place.

The *ex ante* approach reflects the application of the principles of prevention, precaution and "polluter pays". The measures within of this kind are diverse and of variable intensity.

Firstly, there are rules that apply to plastic without being specific to it. These include standards relating to waste and pollution in general, such as the prohibition of polluting and littering—notably of plastic—in the natural environment (e.g. *C. Pén.*[33], Art. R. 634-2), waste collection and recycling, and even the establishment of "extended producer responsibility" (EPR) schemes (*C. Env.*[34], Art. L. 541-10). More specifically, targeted solutions aim to reduce the use and consumption of plastic (through restrictions on marketing, regulation of packaging and over-packaging, consumer information and awareness) (see, for example, *C. Env.*, Art. L. 541-15-10), improve product design (use of bio-sourced and/or recycled materials), prevent plastic leakage into the environment (e.g. *C. Env.*, Art. L. 541-15-11) and, more generally, discourage the use of plastic or incentivize a better understanding of this material (see, for example, the tax introduced at the European level under Council Decision [EU, Euratom] 2020/2053 of 14 December 2020 on the system of own resources of the European Union) and repealing the decision 2014/335/UE, Euratom).

These measures, which are intended to concern any person, whether public or private, follow a principle of progressivity; that is, they are intended to multiply or become stricter over time. This applies to the objectives imposed on public authorities (notably *C. Env.*, Art. L. 541-1), as well as to the obligations imposed on economic operators (*C. Env.*, L. 541-15-10). This approach by "small steps" is open to criticism, particularly regarding deadlines and obligations that may appear distant or inconsistent. Nonetheless, it remains well-founded. Indeed, while the objective of environmental protection is in the general interest, the measures adopted must not disproportionately infringe upon rights, which include the freedom to conduct a business and the freedom of trade and industry. In other words, when measures are adopted to protect the environment and combat plastic pollution, they must—to avoid being struck down—allow economic operators time to adapt. At the national level, this is demonstrated by the regular petitioning of the case law of the *Conseil Constitutionnel* and the *Conseil d'État*, which are regularly petitioned to annul measures adopted to combat plastic pollution.

The *ex post* approach is the "poor relation" of regulatory action concerning plastic, and for good reason. While the preventive approach, though imperfect, is well-supported, the curative approach—which consists of dealing with plastic already present in the environment and the nuisances it causes—remains largely deficient. There is, in fact, no general objective or specific obligation regarding the collection of plastic from the environment, even if, under waste law and the preservation of public order, a few specific obligations are clearly identifiable. Regardless of the level of observation, standards in this area are quite rudimentary. In fact, even though several actors are competent in this field, they do not always have an obligation to act, which leaves them a somewhat questionable degree of latitude.

This is primarily due to practical considerations regarding the attribution of liability—specifically, determining which party should bear the burden, even when they may not be the primary source of the pollution—and the financing required to implement such measures. Furthermore, while the allocation of dedicated financial resources

33. Abbreviation of *Code pénal* (French Penal Code).
34. Abbreviation of *Code de l'environnement* (French Environmental Code).

may be a solution, there is a risk of absolving polluters of responsibility and placing the weight of their negligence on others.

In other words, *ex post* and *ex ante* interventions must be implemented in tandem.

Specific case of the marine environment

Oceans and seas have been the primary drivers in the development of international plastic pollution regulations. This is due, on one hand, to the significant body of knowledge acquired by the scientific community in recent years and, on the other, to the international and transboundary nature of the problem. According to Plan Bleu—the United Nations activity centre in the Mediterranean—the issue remains a complex challenge due to the diversity of actors, sources, materials and socio-economic aspects. Given that every citizen can be considered a potential source of waste, the capacity to implement solutions is constrained. The transition towards a circular economy is one of the fundamental principles of recent policies (Winterstetter *et al.*, 2023); however, existing policies focus on waste management rather than the reduction of single-use plastic consumption. Furthermore, government interventions appear fragmented, and the complexity of the plastic lifecycle complicates decision-making.

For the oceans, the transformation of economic sectors and production models is underway, notably through development strategies for fisheries and aquaculture that increasingly prevent the excessive use of plastic.

In addition to agreements of principle at the worldwide scale (Washington Declaration 1995; UN Resolution A/60/L 2005; Manila Declaration 2005; Honolulu Strategy 2011, UN Conference on Sustainable Development, Rio de Janeiro, 2012; UN Ocean Decade, launched in 2015), numerous global agreements and conventions exist for marine litter management (Table 4.1.1). These include the International Convention for the Prevention of Pollution from Ships (Marpol 73/78), the United Nations Convention on the Law of the Sea (Unclos 1982) and the Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Basel Convention, 1989, revised in 2019). Nevertheless, many of these conventions do not sufficiently account for land-based sources of debris, lack adequate facilities (including port reception facilities), fail to address waste movement via ocean currents and are sometimes difficult to enforce (Axelsson, van Sebille, 2017).

At the European level, the revised directives on waste (2008/98/EC, amended 2018/851) and packaging (94/62/EC, amended 2018/852) contribute to the prevention of plastic pollution. Since then, the Single-Use Plastics (SUP) Directive (2019/904)—transposed into French law via the 2020 Anti-waste for a Circular Economy Law (*loi anti-gaspillage pour une économie circulaire*)—restricts the consumption of the most common plastic items. This directive aims to ensure all plastic packaging will be reusable or recyclable by 2030. Related measures include (i) the prohibition of certain single-use plastic products where alternatives are available on the market (cutlery, straws, cups, etc.), (ii) measures to reduce the consumption of food containers and the introduction of specific labelling, and (iii) the establishment of a 90% separate collection target for plastic bottles by 2029, including 30% recycled plastic in PET bottles by 2030.

It is clear that the most relevant European Union directive dealing directly with the marine environment is the Marine Strategy Framework Directive (MSFD), the envi-

ronmental pillar of the EU Integrated Maritime Policy. This directive serves as a policy instrument that applies an ecosystem-based approach to manage human activities impacting the marine environment (Galgani *et al.*, 2013). It establishes a framework promoting the measures necessary to achieve Good Environmental Status (GES) in the marine environment. Among the 11 MSFD descriptors, Descriptor 10 concerns marine litter. EU Commission Decision 2017/848 specifies four criteria regarding

Table 4.1.1. Principal global conventions and european directives addressing marine plastic pollution.

Policy/Legislation	Objective	Year
INTERNATIONAL INSTRUMENTS		
London Convention	Land-based inputs of waste to the sea	1972
Marpol (Prevention of Pollution from Ships)	Annex V on the discharge of waste at sea	1973, revised 2017
UN Convention on the Law of the Sea (Unclos)	Prevention, reduction and control of ocean pollution	1982
Basel Convention	Transfer/transport of hazardous substances at sea; includes plastics since 2019	1989, revised 2019
FAO Code of Conduct for Responsible Fisheries	Management of fishing nets	1995
Global Partnership on Marine Litter (UN Environment)	Reduction of land-based and marine sources of waste	2012
G7 Marine Litter Action Plan	Global management of marine litter	2015
G20 Marine Litter Action Plan	Global management and monitoring of marine litter	2016
UN Environment Assembly (Unea)	Resolutions on plastic and microplastics (negotiations ongoing)	Since 2016; treaty planned for 2025
EUROPEAN DIRECTIVES AND ACTION PLANS		
EU Packaging Directives (94/62/EC, revised 2018/852/EU)	Management of the packaging plastic cycle	1994, revised 2018
EU Port Reception Facilities Directive	Collection of waste in ports	2000, revised
Marine Strategy Framework Directive (2008/56/EC)	Achievement of Good Environmental Status in European waters (Descriptor 10 on marine litter)	2008
Waste Framework Directive (2008/98/EC, revised 2018/851)	Sustainable waste management/measures to reuse, prevent, collect and recycle waste	2008, revised 2018
Plastics Strategy (2018) / Single-Use Plastics (SUP) Directive (2019/904/EU)	Prevent and reduce the impact of certain plastics on the environment; promote the transition to a circular economy	2019
Green Deal / "Zero Pollution" Action Plan	Reduction of waste and marine plastics by 50%, and microplastics by 30% by 2030	2021
EU Regulation 2023/2055 (SG 126/23)	Legislation on microplastics (Reach, Annex XVII)	2023

plastic pollution, including (i) the composition, quantity and distribution of litter on the coastline (Criterion D10C1), (ii) the composition, quantity and spatial distribution of microplastics at sea (coastline, surface, sediments; Criterion D10C2), (iii) the quantity of litter and microlitter ingested by marine animals (Criterion D10C3), and (iv) the number of individuals of each species negatively affected by entanglement, injury or health effects (Criterion D10C4).

The Landfill Directive (*Directive relative aux décharges*) and Urban Waste Water Treatment Directive (*Directive sur le traitement des eaux usées urbaines*) may have a direct, albeit perhaps limited, influence on marine litter by restricting the input of waste into the sea.

More recently, the European Commission set ambitious targets within its "Zero Pollution" action plan, notably the recycling of 55% of plastic packaging, a reduction in the quantities of waste produced and the halving of plastic litter at sea. To support these initiatives, several EU projects have been launched, some focusing specifically on microplastics (EU European Commission, 2023), notably the registration, evaluation, authorization and restriction of these materials within the European Reach regulation.

⏩ How should plastic be regulated in the future?

From a legal perspective, there is still a long way to go to fully combat plastic pollution.

Beyond the potential for improvement in existing mechanisms and notable deficiencies (for instance, the inadequacy of law relating to microplastics), the emerging pathways show real potential.

Currently, attention is primarily focused on the project for an international legally binding instrument on plastic pollution, for which the drafting process was launched by the United Nations Environmental Assembly (Unea) on 2 March 2022. To use its own terms, the goal is to better address this "serious global environmental problem" by the end of 2024 by establishing a framework for cooperation and defining measures to be implemented by all. The latest version of the draft made public at the time of writing dates from December 2024[35] and is extremely enlightening.

In terms of its formal status, the instrument should be legally binding upon States, provided that the standard formalities required under international law are duly completed and observed. This is significant, as it demonstrates a general agreement on the subject. Furthermore, in terms of its formal structure, it differs very little from other multilateral environmental agreements.

Nevertheless, because the instrument is intended to be binding, its content is not the subject of a consensus, and certain points are more delicate than others.

Among the points of convergence is the intent to combat the effects of this pollution and to eradicate it for the benefit of humanity and the environment by approximately 2040, by addressing the entire plastic lifecycle. Several principles are intended to structure this action, including traditional principles (including prevention, sovereignty

35. Draft Text (1st December 2024), https://wedocs.unep.org/bitstream/handle/20.500.11822/46710/Chairs_Text.pdf

and equity) and others that are much newer and more innovative (fair transition, circular economy, non-regression, etc.). *Ex ante* and *ex post* approaches found in certain existing regulations should also be combined. The marine environment constitutes a very clear anchor point for international action, and particular attention should be paid to substances and polymers of concern.

However, several notable points of divergence remain, fostering uncertainties for the future. The scope of the instrument is currently a subject of debate, particularly regarding exemptions for medical and sanitary purposes, as well as its potential impact on feedstocks, such as hydrocarbons and their derivatives. Furthermore, given the differing levels of development and responsibilities between States, it is probable that differentiated obligations will be defined—that is, firmer for some and more flexible for others. In the current draft it is notable that certain drafting options allow a degree of latitude for States that might not wish to be too strictly bound. Consequently, while some options are encouraging (imposing the adoption of firm, more or less precise measures and reporting), others are more timid (such as invitations to act): it goes without saying that refraining from authorising the production or sale of plastic products is not the same as reducing them; likewise, mandating the regulation of microplastics is not comparable to merely suggesting this; or indeed, requiring the use of recycled products or substitutes is not equivalent to simply permitting such actions at the discretion of national authorities.

Furthermore, the issue of plastic waste management should occupy a central place, and include the adoption of measures to improve collection, recycling and waste treatment. The most sensitive issue, here too, concerns plastics already present in the environment—most notably abandoned, lost or otherwise discarded fishing gear (ALDFG)—the collection of which is either mandated or encouraged, though the ultimate success of these operations remains inconsistent. In the same vein, the question of a possible financing mechanism or financial resources remains unresolved, although clearly of great importance.

In any event, the instrument is intended to encourage international cooperation and research in the field through work programmes.

In the current state of the text, it is not possible to be certain about its final content and scope, as some positions are, for example, quite hostile to the definition of binding targets. However, the range of pathways explored and explorable allows some optimism regarding global action across several scales, whether through prohibition, limitation or incentive measures (financial, fiscal, extended producer responsibility, etc.). It remains quite evident that, unless their action contradicts the text they have chosen to respect, States will be able to go further if they so wish and have the means to do so.

While this instrument will certainly have impacts at European and national levels, it is primarily the duty of vigilance developing within the framework of corporate social responsibility that is intended to consolidate action at these levels. This imposes an obligation on economic operators to inventory the risks associated with their activity and to act to reduce or even eliminate them. This tool, which appears between the lines of the draft international text, presents real potential by holding "private powers" accountable, as they bear considerable responsibility for plastic pollution; that said, its legal framework is far too recent and uncertain to measure its effectiveness.

Ultimately, the legal framework for plastic pollution suffers, as elsewhere, from a remarkable lack of political will, coupled with fierce opposition linked to the economic and social interests of the plastic industry. This is a genuine problem: while the fight against plastic pollution is in the general interest, the same is true, at an equal or even superior level depending on the individual, of economic and social considerations. In this respect, there is reason to wonder whether conservation and protection do not require more audacious and decisive positions in favour of the environment.

Chapter 2

Working towards circular plastic waste management to protect biodiversity

Emmanuelle Gastaldi

Plastic materials are primarily engineered to fulfil a specific function and maintain their properties throughout their intended lifespan of use (service life). However, this service life is generally far shorter than the time required for their degradation once thrown away into the environment. As waste, plastics continue to deteriorate under the influence of physical and chemical environmental stressors (UV radiation, temperature, frost, humidity, wind, etc.) as well as microbial activity. As shown in the preceding chapters, these weathering processes gradually release fragments into the environment ranging in size from macro- to micro- and nanometric scales. These fragments are susceptible to adsorbing and subsequently releasing various potentially toxic chemicals, while also hosting specific microbial communities. Plastic debris, its associated chemicals, and these microbial communities contribute in different ways to the toxicological effects of plastics on both the environment and human health.

Given the scale of plastic pollution and its devastating impacts on biodiversity, the search for strategies encompassing both upstream and downstream approaches for the implementation of circular plastic waste management has become a pressing necessity. The emission of particles and polluting substances throughout the life cycle of plastics, coupled with poor end-of-life management and a low degree of circularity, makes plastics a major environmental and climate issues.

Plastics, generally derived from fossil fuels by the petrochemical industries, are utilized across different sectors in various forms. Packaging is the primary sector for plastic consumption (45%), followed by construction and civil engineering (19%) and the automotive industry (10%) (Geyer, 2020).

⏩ The end-of-life of plastic packaging

Following decades characterized by a globalized, disposable consumption model, consumers have become increasingly aware of the urgency to protect the environment and preserve natural resources for future generations. In this context, food packaging is frequently identified as a significant source of pollution due to its very short service life and single-use nature (Geyer *et al.*, 2017). The mismanagement of post-consumer plastic packaging waste (i.e. that which is not reused, recycled, landfilled, or incinerated)

currently accounts for approximately 100 million tonnes per annum (Jambeck *et al.*, 2015; Kawecki *et al.*, 2018; Rochman *et al.*, 2020), with considerable ecological, social and economic consequences (Beaumont *et al.*, 2019). While the environmental impact of packaging poses genuine challenges regarding the depletion of fossil resources, global warming, and plastic pollution, it is often contrasted with its role in the fight against food waste. Indeed, packaging performs a vital protective function that ensures food safety from production through to consumption. To effectively reduce the environmental footprint of packaging while maintaining its crucial role in preventing food waste, a holistic approach is essential that considers the entire life cycle of the packaging material. Furthermore, the linear "take-make-dispose" model must be abandoned in favour of a sustainable system based on a genuine circular economy and the waste hierarchy (Lau *et al.*, 2020; Paul-Pont *et al.*, 2023). Consequently, efforts must focus simultaneously on reducing waste production by re-evaluating the food-packaging nexus to propose new "fit-for-purpose impact" solutions.

⏩ Plastic waste management and the circular economy

Plastic pollution cannot be attributed solely to failings in waste management; the primary and most effective lever for limiting plastic waste production remains the overall reduction of plastic manufacture. Nevertheless, the optimization of waste management constitutes a significant downstream lever. Plastic waste management methods are diverse and vary according to the nature of the material, its value, and the infrastructure available within a given territory. Their degree of circularity depends upon their position within the waste hierarchy.

Source reduction is the most environmentally favourable strategy, as it aims to limit the quantity of plastic waste generated from the point of manufacture. It is based on two main axes:

– the promotion of **reuse**, which refers to "any operation by which substances, materials, or products that are not waste are used again for the same purpose for which they were conceived" (*C. Env.*, Art. L. 541-1-1). In practice, a reused packaging item is "packaging subject to at least one second use (for a purpose of the same nature as that for which it was designed), and whose reuse is organized by or on behalf of the producer" following washing and decontamination (*C. Env.*, Art. L. 541-350). It is estimated that at least 20% of plastic packaging could be replaced by reusable systems (Ellen MacArthur Foundation, 2019). However, beyond the simple benefits associated with waste reduction and resource conservation, the environmental assessment of this mode of management must account for a multitude of factors. It must consider all externalities, both positive and negative, that may arise throughout the reuse life cycle (transport, logistics, cleaning, reconditioning, sanitary quality, disposal, equipment theft, etc.);

– the **elimination of plastic packaging**, which favours products sold in bulk or with reduced packaging. Although praised for its environmental and societal advantages, bulk sales encounter certain limits and constraints that hinder large-scale development. These include their restriction to dry products or those with low water activity, a lack of guaranteed quality and traceability, risks of microbial and allergen contamination, logistics, costs, and organizational challenges. Mention must also be made of replacing plastic packaging with other materials, such as glass or cardboard, which may only be suitable in certain cases. It is vital to precisely evaluate the entire life cycle of these

materials and their externalities so as to compare their impacts on biodiversity and the environment in general. In these two instances, it should be noted that collection and recycling streams are better structured than with plastic, and the environmental impact in the event of leakage into the environment is potentially less problematic.

Recycling is defined as "any recovery (i.e., material or energy valorization) operation by which waste, including organic waste, is reprocessed into substances, materials, or products for their original purpose or for other purposes" (*C. Env.*, Art. L. 541-1-1). There are three main types of recycling, differing by the methods employed: **mechanical recycling**, **chemical recycling**, and **organic recycling**. As chemical recycling remains exploratory and does not currently contribute to plastic recycling, only the other two types are addressed here:

– **mechanical recycling**, which accounts for 99% of recycled plastics. It is crucial to distinguish between "closed-loop" recycling, whereby recycled waste is repurposed for an identical application without significant loss of functional properties, and "open-loop" recycling or "downcycling" (i.e., loss of material quality leading to lower-value applications). The pivotal stage of closed-loop recycling involves the elimination of potentially toxic contaminants (decontamination) and the partial restoration of the degraded polymer (solid-state polycondensation). A prerequisite for plastic recycling is the existence of a functional recovery stream, integrating links such as collection, sorting, and conversion into recycled materials. Upon exiting sorting centres, only 30% of collected plastics are destined for recycling due to highly selective sorting that excludes numerous packaging types (e.g. undersized items, multi-layer materials, or those soiled by fats). While this material loop should theoretically allow most materials to begin a new life rather than being incinerated or landfilled, the reality in France is that only plastic packaging waste is recycled. Furthermore, transparent PET (primarily bottles) is the only material capable of being closed-loop recycled (Barthélémy *et al.*, 2014). In 2020, this represented approximately 17% by mass of bottles in Europe, with the remainder being downcycled into textiles and trays (Eunomia, Zero Waste Europe, 2022). Other plastic packaging (PE, PP, PS, etc.) can generally only be recycled once in an open loop to manufacture plastic objects that are eventually incinerated or landfilled, as they cannot be recycled (or downcycled) again. Despite recent technological advances, plastic waste remains generally under-recycled due to technical, sanitary and structural constraints. Consequently, of the 63.4 Mt of plastics used by industry across the EU-27 in 2019, only 7.2 Mt originated from recycled plastics, resulting in a recycling rate of 11.3% (OECD statistics). In countries where recycling is already widespread, research indicates that instead of reducing production, recycling ultimately leads to an increase in the production of single-use plastics, which is a prerequisite for achieving the required levels of recycled content. Although often presented as an ecological solution, recycling is merely a temporary delay rather than a preventive solution. Moreover, its economics remains largely linear, as plastic recycling often causes an inversion of the waste management hierarchy, which contradicts the principle of circularity. Environmentally, recycling can exert deleterious effects on ecosystems and living species, notably due to chemical pollution and the microplastics it generates during the washing and grinding stages. By infiltrating soil and water, these pollutants can impact biodiversity by contaminating trophic chains. A recent pilot study (Brown *et al.*, 2023) demonstrated that wastewater pollution from a mechanical recycling facility in the UK ranged between 6 and 112 million microplastics per cubic metre.

This represents an estimated 59 to 1,184 tonnes of microplastics potentially discharged annually into wastewater, as existing filtration systems prove ineffective for microparticles smaller than 5 microns. Thus, the recycling process itself may contribute significantly to environmental plastic pollution, despite its intended role in prevention;

– **organic recycling** applies to organically recoverable (i.e., suitable for organic valorization) or compostable waste, and by extension, to packaging certified as compostable under the ISO 18606[36] standard. Composting and anaerobic digestion are two biological processes capable of transforming organic waste into a standardized, stable product rich in organic matter for agricultural use. Industrial composting is conducted on open-air platforms, in bunkers, or in closed reactors under aerobic conditions. Aeration and moisture maintenance facilitate the decomposition of organic matter, leading to a temperature increase proportional to the microbial activity. According to Ademe, in 2023, 40% of the 15 million tonnes of household bio-waste produced in France was recovered through composting. The thermal inertia of these volumes allows temperatures of 70±10°C to be maintained for several weeks, which is essential for eliminating pathogens and inactivating weed seeds. It should be noted that domestic composting does not achieve these conditions, and consequently, the degradation of plastic is not effective in such environments. Methanization, in contrast, is an anaerobic digestion process carried out in dedicated digesters within a confined, oxygen-free environment at mesophilic (30-40°C) or thermophilic (45-60°C) temperatures. This process yields not only a solid digestate—potentially recoverable in agriculture depending on its level of plastic pollution—but also biogas, which can be converted into thermal or electrical energy.

The mandatory source separation of bio-waste, effective across France and Europe since 1 January 2024, aims to reduce the volume of organic matter sent to incineration or landfill while promoting its useful exploitation through composting or anaerobic digestion. In this context, compostable packaging meeting the specific requirements for biodegradation, disintegration, composition and ecotoxicity defined by the NF EN 13432[37] standard emerges as a viable alternative to conventional plastics, aligned with the circular economy strategy. Indeed, by separating bio-waste at the source and utilizing compostable materials, it is ensured that these organic fractions are directed towards controlled treatment streams. The use of genuinely compostable packaging also offers consumers the advantage of simplifying the source-separation process and reducing sorting errors, which most frequently involve packaging and cause plastic pollution of composts (Rodrigues *et al.*, 2019; Dronia *et al.*, 2024; Gastaldi *et al.*, 2024). Ultimately, these processes enable the conversion of bio-waste into useful products, such as compost and biogas, thereby reducing the environmental impacts associated with waste management. According to Ademe, in 2020, France possessed 300 composting platforms and 140 anaerobic digestion sites capable of processing household bio-waste. While access to this infrastructure

36. ISO 18606:2013. Packaging and the environment—Organic recycling, https://www.iso.org/fr/standard/55874.html

37. NF EN 13432:2000—Packaging—Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging, https://norminfo.afnor.org/norme/nf-en-13432/emballage-exigences-relatives-aux-emballages-valorisables-par-compostage-et-biodegradation-programme-dessai-et-criteres/89100

must be improved, particularly in rural areas, the current regional network makes it possible to manage waste locally, significantly reducing environmental emissions related to logistics and transport.

While the reconsideration of compostable plastic materials is encouraged by new European regulations on packaging and packaging waste[38], their performance under real-world composting conditions must still be scientifically validated to overcome barriers to large-scale adoption. A recent study (Gastaldi *et al.*, 2024) demonstrated that their incorporation into bio-waste treatment processes produced no negative effects on the final compost, which met the safety and agronomic quality requirements of the NF U44-051[39] standard (relating to compost and organic soil improvers), as well as organic farming criteria. Similarly, the presence of compostable materials in the bio-waste batch generated no acute ecotoxicity in higher plants (barley and cress), earthworms, or daphnia. These results are corroborated by another recent study (Mironov *et al.*, 2024) highlighting a positive effect on the microbial biodiversity of the compost, attributable to the diversification of carbon sources provided by the compostable materials in the decomposing bio-waste. Despite these promising advances, certain points require further clarification. Specifically, the transient or persistent nature of the microplastics generated by these materials during the composting process, their environmental fate, and their impact on ecosystems warrant in-depth investigation. Furthermore, the end-of-life management of compostable plastics via anaerobic digestion remains to be validated for many of these materials due to the lack of appropriate specification standards for this medium. Nevertheless, within the current energy context, their organic recovery through methanization in association with food waste has become a significant priority for biogas producers. Studies are currently being conducted to evaluate the anaerobic digestion biodegradation performance of commercial packaging materials and the fate of their residues under industrial composting and soil conditions.

Currently, biodegradable plastics represent approximately 0.25% of global annual plastic production.

Incineration of plastic waste with energy recovery is a solution that allows the recuperation of a portion of the energy required for plastic manufacture. This mode of treatment is generally employed as a default when materials cannot be integrated into a recycling circuit, thereby preventing their dissemination into the environment. It also offers the advantage of significantly reducing waste volume, which is particularly useful for geographically constrained areas. The process involves high-temperature combustion to generate energy in the form of heat and electricity, which can substitute for production from electricity and natural gas grids. Energy generation from waste depends on the carbon content and the calorific value of the material. Plastics have a high calorific value, ranging from 23 to 41 megajoules per kilogram (MJ/kg),

38. Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC (Text with EEA relevance), https://eur-lex.europa.eu/eli/reg/2025/40/oj?eliuri=eli%3Areg%3A2025%3A40%3Aoj&locale=fr

39. NF U44-051:2006—*Amendements organiques—Dénominations, spécifications et marquage.* (Organic amendments—Names, specifications and labelling), https://www.boutique.afnor.org/fr-fr/norme/nf-u44051/amendements-organiques-denominations-specifications-et-marquage/fa125064/754

compared with 43 MJ/kg for fuel oil, 28 MJ/kg for coal, and 16 MJ/kg for wood (Janakova *et al.*, 2024). In France, 43.4% of collected plastic waste was treated via incineration in 2018, aligning with the European average (Plastics Europe). In the countries with the most advanced waste management systems (Switzerland, Austria, Germany and the Netherlands), incineration serves as the primary alternative to open-air landfills.

However, plastic waste incineration is not a sustainable solution and generates significant environmental and health impacts. It produces harmful atmospheric pollutant emissions—nitrogen oxides (NOx), sulphur oxides (SOx)—fine particulate matter, and volatile organic compounds (VOCs), which impair human health by degrading air quality and causing respiratory issues. Incomplete combustion can also produce persistent organic pollutants (POPs) such as dioxins and furans, which are recognized carcinogens and endocrine disruptors. Finally, incineration releases CO_2 thereby contributing to global warming (Verma *et al.*, 2016; Azoulay *et al.*, 2019). Furthermore, the process generates incinerator bottom ash (IBA), solid residues that may contain toxic substances such as heavy metals and polycyclic aromatic hydrocarbons (PAHs), which can contaminate soil and groundwater through leaching. It should be noted that bottom ash is often utilized as a road sub-base or infill material following appropriate treatment. When they disperse into the environment, atmospheric pollutants and incineration residues can contaminate soil and water, affecting flora and fauna and potentially moving up trophic chains.

Landfilling or waste storage is considered the least virtuous treatment option (European Directive 2018/851). It should only be envisaged as a last resort, as it constitutes a loss of resources that escape recycling, penalizes the development of a circular economy, and, crucially, is deleterious to the environment. Plastic waste associated with household and similar waste (HSW) is stored in non-hazardous waste landfills dug in impermeable soils and sealed using plastic-based geotextile membranes. These confined, anaerobic conditions maintain the stability of plastic materials by limiting their photodegradation. In 2018, 32.5% of collected plastic waste was landfilled in France (Plastics Europe). Since then, this proportion has steadily increased due to rising sorting rejects (non-recycled) and the closure of Chinese borders (2017), which necessitated the domestic retention of waste previously destined for export[40]. In certain French departments, such as Guadeloupe or Corsica, landfilling remains the only available treatment mode. Nevertheless, aligning with the European objective (2018/850), the Anti-Waste and Circular Economy Law (*loi relative à la lutte contre le gaspillage et à l'économie circulaire*: AGEC, 2020) mandates a reduction in the quantities of household and similar waste admitted to landfills to 10% of produced quantities by 2035.

Landfilling plastic waste has environmental consequences affecting soil and groundwater quality, biodiversity, human health, land use and the climate. Despite the use of geotextiles, landfills do not remain watertight over the long term. This allows pollutants and microplastics to infiltrate and contaminate soils and aquifers, affecting drinking water quality and aquatic life. By occupying vast tracts of land, landfills

40. Environmental report for France published by the Ministries of Regional Planning and Ecological Transition, https://www.statistiques.developpement-durable.gouv.fr/bilan-environnemental-de-la-france-edition-2024-0

fragment natural habitats and disrupt existing ecosystems, resulting in biodiversity loss, declining animal and plant populations, and the disruption of trophic chains. The expansion of landfills also results in the loss of land that could be utilized for agriculture, forestry or nature conservation. Furthermore, biodiversity loss may be linked to the potential ingestion of plastic fragments by wildlife. Finally, there is a considerable impact on global warming resulting from methane emissions released by the anaerobic digestion of organic matter.

In conclusion, reducing plastic pollution to preserve ecosystems and biodiversity requires abandoning the linear "take-make-dispose" model in favour of a sustainable system based on the circular economy and waste hierarchy. To this end, it is essential to act simultaneously on two fronts: firstly, to drastically reduce plastic use by exploring all possible solutions for its elimination wherever feasible; and secondly, to optimize plastic waste management. This major challenge demands a profound transformation of lifestyles and the economic organization of our society, which must be driven by regulation and public policy. These changes should be initiated in industrialized nations without neglecting the developmental needs of emerging economies. In parallel, it is indispensable to continue producing rigorous scientific data on the impacts of this pollution to enable industrial and political stakeholders to make informed decisions based on robust evidence.

Chapter 3

Are biodegradable plastics a solution to plastic pollution?

Jean-François Ghiglione

Biodegradable materials have been proposed as a potential solution to stem the pollution linked to the excessive use of plastics, whose lifespans in the environment can attain several hundred years (Andrady, 2017). Recently, several scientific papers have tempered expectations regarding the potential of biodegradable plastics as a universal solution to global pollution, refocusing their application as an alternative for products whose collection cannot be ensured, or which is extremely difficult (Paul-Pont *et al.*, 2023).

As we have seen, the priority must remain the reduction of primary plastic production. In this chapter, we shall discuss the relevance of using biodegradable plastics to limit this pollution.

⏩ How do we define a biodegradable plastic?

A biodegradable plastic is a material that can be completely mineralized (converted into CO_2, methane, and mineral salts) through the action of micro-organisms, accompanied by the emergence or reorganization of new biomass (Paul-Pont *et al.*, 2023). This process depends on environmental conditions, which influence biodegradation kinetics. The biodegradation timeframe must therefore be evaluated for each specific environment (soil, air, water), accounting for the specificities of the planet's diverse ecosystems (forests, wetlands, deserts, mountains, marine and freshwater environments).

⏩ Are these plastics biodegradable in all environments?

The labelling "biodegradable" used by certain manufacturers has caused much confusion for both consumers and industry. Currently, this designation is still prohibited on objects in Europe. No biodegradable plastic exists that exhibits identical biodegradation kinetics across all environments (Bano *et al.*, 2017). Furthermore, the biodegradability of certain plastics may be proven in one environment but not in others, or only in the industrial systems mentioned above. For instance, plastics composed of the polymer polylactic acid (PLA) are biodegradable under industrial composting conditions but not at all in other environmental matrices, such as seawater (Cheng *et al.*, 2022) or soil (Fan *et al.*, 2022). This is also true for polybutylene adipate terephthalate (PBAT),

which shows signs of biodegradation in soil but not in aquatic media (Wierckx *et al.*, 2018). Currently, only certain compounds within the polyhydroxyalkanoate (PHA) family (notably short-chain varieties) demonstrate proven biodegradability in all tested environments (soil, freshwater, and seawater) (Meereboer *et al.*, 2020).

What should biodegradable plastics be used for?

Scientific consensus is increasingly converging on a limited use of biodegradable plastics. Their use is only logical if they fulfil an essential need and in cases where their end-of-life in the environment is unavoidable. This question arises, for example, for agricultural mulching films, fishing nets, meteorological buoys, or certain cosmetic products. There is a consensus that biodegradable plastics are not intended to become alternatives to all conventional plastics (Paul-Pont *et al.*, 2023).

The criterion of essentiality must be established as a prerequisite to the decision of whether to use plastics—including biodegradable ones—to evaluate whether their functions or applications are vital to health, safety and society. Adopting the concept of essential use as a decision-making tool will enable the implementation of feasible, efficient and effective reductions of hazardous and unsustainable items across all sectors, in accordance with the precautionary and prevention principles (Unep, 2018) and Article 5 of the Reach Regulation: "no data, no market" (Reach, 2020).

Products meeting the criterion of essentiality must also satisfy sustainability requirements. Biodegradable plastics must be produced without products hazardous for agricultural land (e.g. the use of plant protection products for the intensive exploitation of land used to produce raw materials for bio-based plastics, like maize or potatoes) and through production processes compliant with precautionary principles (Unep, 2018).

Can it be dangerous to use biodegradable plastics?

Biodegradable plastics potentially pose the same risks as conventional plastics, even though their environmental persistence is shorter. The disintegration of plastics into micro- and nanoplastics also occurs with biodegradable materials, often with faster kinetics. The toxicity of biodegradable microplastics appears comparable to that of non-biodegradable ones. So, while a general conclusion is difficult to draw, it is impossible to that biodegradable plastics are innocuous.

Moreover, the biodegradability of these plastics is due to the nature of their polymer but does not exclude the presence of additives incorporated to modify their physico-chemical characteristics. If these chemical additives are identical to those used in conventional plastics, their toxic effects on human and environmental health will be similar.

How is plastic biodegradability measured?

The measurement of biodegradability is primarily based on quantifying the transformation of carbonaceous matter within polymers into biomass (bioassimilation) and CO_2 (biomineralization). Biomass production is measurable via flow cytometry, microscopy, or molecular approaches such as quantitative PCR (culture-based techniques—colony-forming units—are not applicable to natural microbial

communities). CO_2 production (or O_2 consumption) is measured through respirometry tests (Jacquin *et al.*, 2019).

Physical or chemical transformations, mass loss measurements, and the production of oligomers are complementary metrics but do not constitute definitive proof of biodegradability.

⏩ What are the limitations of standard biodegradability tests?

Standard biodegradability tests have been widely criticized for their lack of representativeness regarding natural conditions (Harrison *et al.*, 2018). Research by Napper and Thompson (2019) showed that several plastics commercially labelled as "biodegradable" showed no signs of biodegradation under natural conditions across various environments (soil, air, water, compost).

Biodegradability results depend on numerous factors specific to the plastic and the particular environmental conditions. Proving environmental biodegradability is complex due to factors rarely accounted for in standard tests:
– **presence of additives**: as previously established, plastics—including biodegradable ones—are composed of polymers and chemical additives. Generally, the biodegradability of a plastic was tested on its constituent polymer(s); it much more seldom accounted for the presence of chemical additives, such as stabilizers or substances potentially toxic to microorganisms, which may inhibit the biodegradation of commercial products (Noopur *et al.*, 2015). The use of a biodegradable polymer does not guarantee that the final product, following the inclusion of additives, will remain biodegradable under the same conditions as the base polymer. Testing protocols must, therefore, account for the biodegradability of the chemical additives themselves, or ideally, the final end-product after assembly—a factor that is very rarely considered;
– **physico-chemical properties of plastic**: these properties can be extensively modified by environmental parameters, and their response may vary significantly depending on the presence of additives. In the case of polyethylene (PE), for instance, biodegradability can be accelerated by ultraviolet (UV) radiation, which contributes to an increase in its oxidation state—a critical parameter during the initial stages of PE biodegradation. Certain additives specifically possess the capacity to enhance or inhibit this oxidation process, thereby exerting a major influence on the material's overall biodegradability (Eyheraguibel *et al.*, 2017);
– **plastic size and thickness**: biodegradability tests are typically conducted using plastics in powder form, with particle diameters measuring only a few micrometres. While this simplification allows for the standardization of experimental protocols regardless of the original dimensions or morphology of the plastics, it fails to account for the actual mechanisms of biodegradation. These are essentially surface-mediated processes that can depend on the available exchange surface area (Cheng *et al.*, 2021);
– **microbial inoculum**: the biodegradation of plastics is carried out by the microorganisms that colonize them. These organisms accumulate on the plastic surface, forming a biofilm whose characteristics are contingent upon environmental conditions (Amaral-Zettler *et al.*, 2020). The biofilms that develop on plastics are so distinct that they have been termed the "plastisphere", highlighting that these microorganisms differ from those inhabiting the immediate surrounding environment (soil, water, air). The plastisphere comprises a vast diversity of microorganisms, including

bacteria, micro-eukaryotes (such as diatoms and fungi), and viruses. Certain species have developed the capacity to adhere to the surface, while others proliferate by utilizing it as a food source; each species subsequently yields to predatory species, which must themselves compete with specialized species adapted to local environmental shifts. Plastics harbour such complex ecological successions, shaping the diversity of the species inhabiting their surfaces, that they are now considered a new ecological niche for microorganisms. Biodegradability studies must account for the diversity of these microbial biofilms, which vary according to natural conditions. Furthermore, the evolution of biofilm diversity and its functional capacity must be assessed during testing to ensure that biodiversity is maintained throughout the experimental period, thereby guaranteeing its representativeness of real-world environmental conditions;
– **test conditions**: these must align as closely as possible with actual environmental conditions. Specifically, the maintenance of parameters such as temperature, salinity, pH, and nutrient availability—notably the nitrogen-to-phosphorus (N:P) ratio—must be ensured throughout the duration of the test. Furthermore, these conditions must be sufficiently representative of the specific environments under consideration (soil, air, or water); such factors are seldom accounted for in standard testing protocols (Jacquin *et al.*, 2019);
– **measurement of biodegradation**: biodegradability tests for plastics in the environment typically only account for the final stage of mineralization (production of CO_2). However, research into plastisphere activity has revealed the presence of numerous microorganisms with both autotrophic CO_2-consuming) and heterotrophic CO_2-producing) metabolisms. The interplay between these activities can significantly distort biodegradation test results (Conan *et al.*, 2022). To correct for this methodological artefact, negative controls utilizing established biofilms—rather than surrounding water, which fails to reflect the microbial diversity of biofilms—can be employed, primarily for readily biodegradable plastics. Furthermore, standard tests do not account for the incorporation of the polymer into biomass, a process that remains difficult to monitor using conventional analytical tools (such as microscopy or quantitative PCR);
– **potential biodegradability**: it is currently impossible to test the biodegradability of plastics directly in situ within the environment. Measurements of mineralization (via CO_2 production) require incubation in a confined medium (closed system), which restricts the interpretation of the results to the potential activity of the tested inoculum, rather than a definitive measurement of real-world degradation. The representativeness of the laboratory inoculum relative to natural biofilms, as well as its evolution throughout the duration of the test, must be evaluated. This assessment should ideally include analyses of microbial abundance and diversity—utilizing techniques such as quantitative PCR (qPCR) and 16S rRNA sequencing, respectively (Azeredo *et al.*, 2017; Jacquin *et al.*, 2019).

This section highlights the inherent complexity of evaluating plastic biodegradability in the environment (including industrial composting). Scientific studies that account for the aforementioned constraints remain in the minority. These limitations can only be addressed through a sustained effort by the scientific community to expand research in this field. The study of environmental biodegradability remains an emerging field of investigation that must be developed to address the numerous questions raised by the commercialization of these materials.

In conclusion, biodegradable plastics have been presented as viable alternatives to conventional polymers, offering a potential solution to the current plastic pollution crisis. However, the standards defining the biodegradability of plastic products lack representativeness regarding environmental conditions and fail to account for chemical additives that may impact human and environmental health. Current research into biodegradability remains insufficient to support the stated aims of these materials to be a potential solution to plastic pollution.

Finally, from a regulatory perspective, the use of these plastics raises concerns regarding the difficulty of enforcement and the observed risks of counterfeit products. Distinguishing between biodegradable and non-biodegradable plastics is not straightforward and requires at least some staff training and the purchase of analytical equipment (e.g. for infrared spectroscopy) to confirm the polymer composition. This ambiguity can lead to confusion among retailers and consumers, and the dissemination of non-compliant contraband plastics is currently difficult to contain.

Conclusion

At the time of writing, negotiations are underway to develop a legally binding international instrument to end plastic pollution, pursuant to Resolution 5/14 supported by 175 countries in 2022 during the fifth United Nations Environment Assembly (Unea). These negotiations are a theatre of conflict between proponents of a restricted treaty—who argue that plastic pollution results solely from waste mismanagement without questioning production levels—and advocates of an ambitious treaty. The latter accounts for scientific knowledge and considers all forms of pollution and negative externalities associated with the entire life cycle of plastic products, beginning with raw material extraction (recalling that 99% originates from petroleum).

Besides the production reduction recommended by the scientific community, improving plastic circularity is also cited as a potential course of action within these negotiations. This involves promoting the development of products with enhanced recyclability (e.g. limiting multi-material use and simplifying formulations). While the low rate of mechanical recycling (averaging 11% in Europe) could potentially be increased, it must be noted that not all plastics are recyclable. Furthermore, almost all products manufactured from recycled plastic are of lower quality and are no longer recyclable themselves (downcycling). Consequently, this represents neither a sustainable nor an ecologically-friendly solution.

The development of alternatives in the form of biodegradable plastics is also part of the proposed suite of solutions. However, it must be remembered that all the issues associated with plastics discussed in previous chapters—notably the toxicity of certain additives—apply equally to biodegradable plastics. Moreover, biodegradation is a complex phenomenon; the polymers used in plastic production are generally not degradable under natural conditions and require industrial systems (composting or anaerobic digestion). This necessitates specific recovery streams to avoid further mismanagement. Currently, only PHAs are biodegradable in marine environments. These plastics, therefore, cannot be a universal substitution solution.

Thus, there is no single alternative, but rather several pathways, each with its own limitations. These can only be effective if implemented following reduction at source to eliminate non-essential plastics.

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General conclusion

⏩ Containing plastic pollution: a new paradigm for research

Let's try a quick exercise: from the moment you wake up until you go to sleep at night, how many plastic items do you actually use? Think about your alarm clock, a coffee cup, food packaging, the clothes you're wearing, your hairbrush or toothbrush. Then there are your children's toys, parts of your car or bike, the TV remote—the list goes on. Plastic is in every part of our daily lives, and global production shows no sign of slowing down.

Having become ubiquitous in our lifestyle, plastic constitutes a source of pollution throughout its life cycle, from the extraction of raw materials to its management once it has become waste. Because the pollutants emitted by plastics—whether particles or chemical molecules—cannot integrate into biogeochemical cycles, they accumulate and contaminate every environmental compartment for hundreds, if not thousands, of years. This plastic pollution, resulting from waste lost accidentally or discarded deliberately, represents a major threat to the biodiversity of terrestrial and aquatic ecosystems. It affects a multitude of species through various processes extensively documented in this book. The ingestion of plastic fragments by animals can cause significant internal and physiological damage, or even death. This threat concerns marine and terrestrial animals alike, from invertebrates to birds and fish. As the exposure is constant, it is repeated day after day throughout the organisms' lifespans. This results in chronic exposure, which can lead to long-term effects likely to alter population maintenance and, ultimately, ecosystem balances. Entanglement in plastic debris constitutes another major hazard, with dramatic consequences particularly for already endangered species. Animals may become trapped in fishing nets, plastic bags, or other waste, leading to injury, restricted movement, drowning, or malnutrition. Furthermore, plastic waste causes the disruption of natural habitats; it can smother soils, modify the composition of the seabed, and thus disturb ecological equilibria. This results in significant biodiversity loss, affecting both flora and fauna. Finally, plastic pollution can exert indirect effects on biodiversity by facilitating the transport of pollutants and the dispersal of invasive species.

As we have seen, the assessment of the impacts of plastic pollution on ecosystem biodiversity is currently the subject of extensive scientific research. It is also foreseeable that climate change will exacerbate the effects of plastic pollution on biodiversity loss, with severe consequences for global ecosystem processes. Indeed, recent studies suggest that threatened species and ecosystems are vulnerable to both plastic pollution and climate-related stressors (Chowdhury *et al.*, 2022). The ubiquitous nature of plastics and the vast diversity of the pollutants released throughout their life cycle complicate the precise assessment of these impacts. Ingestion, entanglement, habitat

disruption, and chemical contamination are just a few examples of the damage caused. More subtle, as-yet-unknown effects could have serious consequences for organism health and long-term ecosystem functioning. As plastics fragment, they are more likely to be inhaled or ingested, but they also become increasingly difficult to detect using current scientific methods. Nonetheless, recent technologies allow for the detection of particles measuring only a few microns; the polymer type (PET, PVC, etc.) can be confirmed via infrared spectroscopy, for example. Such methods have revealed that the smallest particles can translocate through tissues. Recent research has shown that humans are not exempt, with plastic found in various organs. As with any other living organism, the plastics we inhale—such as fibres from synthetic clothing (Gasperi *et al.*, 2018)—or ingest via our food (Zao, You, 2024) can have health repercussions in the short or long term (Chartres *et al.*, 2024; Saha, Saha, 2024). These studies confirm that plastic pollution constitutes a genuine public health challenge.

Already a significant concern, the ecological pressure of plastic pollution will intensify exponentially in coming years given the uncontrolled rise in global plastic production and vast accumulation of legacy plastic (Figure C.1). Studying microplastic effects, especially when compounded by factors like food insecurity or pathogen spread, are therefore a research priority to address challenges of environmental conservation and public health.

⏩ Widespread awareness but a response that still falls short

The alarming assessment of impacts on biodiversity detailed in this book corroborates the urgency of rapidly implementing more effective solutions. These must be supported by investment across multiple scales, from the individual to political commitment. While we have become dependent on plastics, we must now achieve a transition away from it.

As we have seen, the most effective way to combat plastic pollution is reduction of its use—which, in turn, automatically reduces production (Figure C.1). Alongside this shift, there are many individual and collective steps we can take to lessen our impact. Changing our own individual behaviour is powerful means for change. We can start by: modifying our consumption habits, especially by cutting out single-use plastics that are used for mere minutes before being discarded; managing our daily waste more mindfully; swapping plastics for alternative materials and choosing reusable options whenever possible; participating in waste collection within our environment, whether during daily walks or via participatory clean-ups organized by associations or enterprises. Alternative solutions may also be pursued, such as the development of a biodegradable plastic recovery stream or the potential orientation towards the recycling of specific materials. However, these innovations still require rigorous scientific backing and will likely only ever be suitable for very specific, niche applications.

While these individual behaviour changes are necessary, informing one's social or professional circles and engaging local elected officials on the issue of plastic pollution constitutes a more effective lever. Indeed, without genuine political will accompanied by more stringent regulation at the international, European, and national levels, individual or local actions exert little effect against the scale of the pollution. Like various private or public institutions, local authorities can implement curative or preventive solutions. Global and systemic measures at each of these scales are essential.

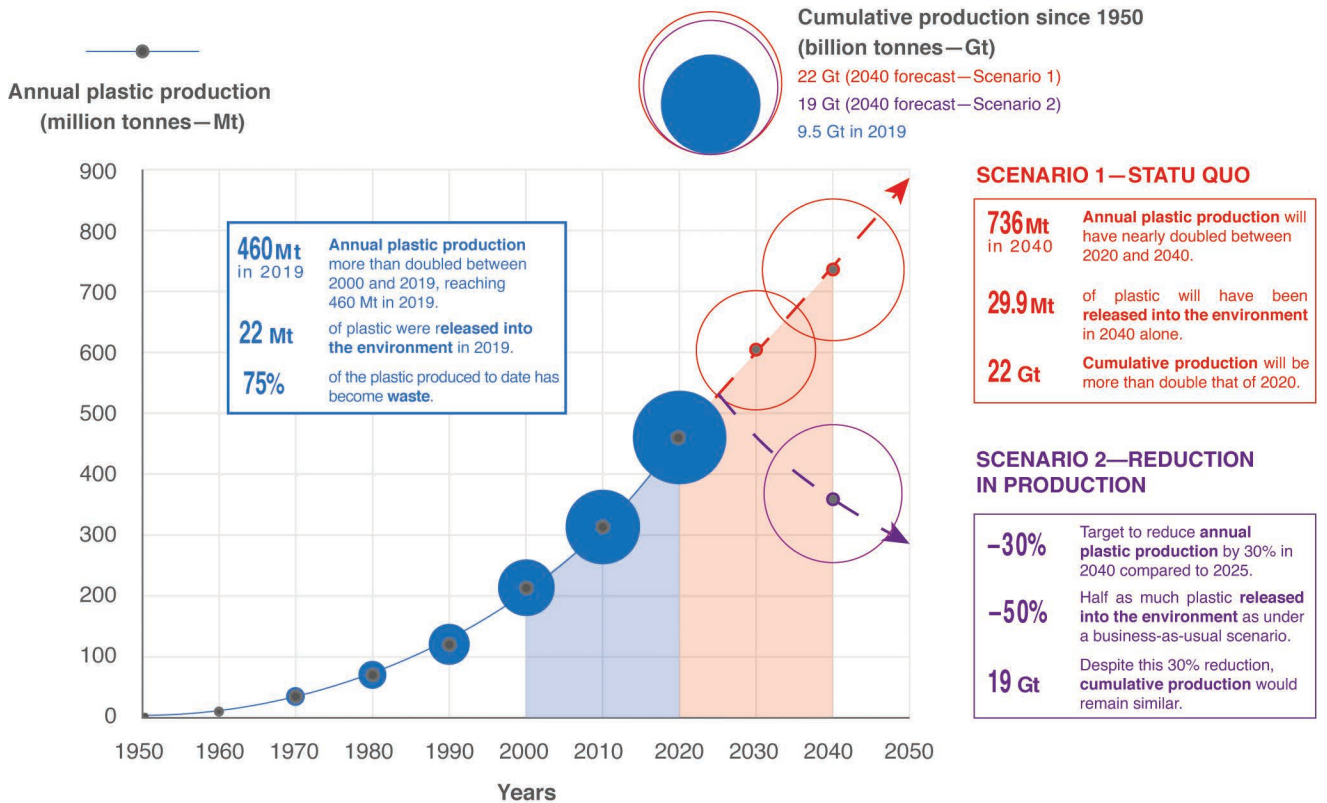


Figure C.1. Change in annual and cumulative plastic production between 1950 and 2020, and projections until 2040 based on a business-as-usual scenario and a scenario involving a reduction in annual production from 2025 onwards, with a target of –30% by 2040.

A 30% reduction in production by 2040 would halve the amount of plastics released into the environment, but cumulative production since 1950 would not change significantly. Some of these plastics that have already dispersed in the environment cannot be recovered, but changing our practices could limit further plastic release into the environment.

These must begin, in particular, by setting objectives for the reduction of primary plastic polymer production, ensuring total transparency regarding their composition, and simplifying their formulations. Furthermore, standards need to be established that account for the full life cycle of plastics (composition, additives, life span, reuse, and recycling) and to introduce Extended Producer Responsibility (EPR) and the "polluter pays" principle into legal frameworks.

In 2022, United Nations Member States adopted a resolution for the development of a legally binding instrument. The Scientists' Coalition for an Effective Plastics Treaty[41], formed within this framework, has issued numerous recommendations to prevent environmental leakage of plastics (Figure C.2)[42].

Regulatory change is all the more necessary as, as we have seen, existing alternatives—such as improved circularity and recycling, or the development of biodegradable plastics—are generally unsatisfactory and applicable only to specific situations. The substantial financial resources allocated to the "recycling" of these materials address less than 10% of global waste; such waste management remains ineffective in addressing the life cycle impacts of plastics. Furthermore, biodegradable plastics account for only 0.25% of annual plastic production.

Measures focused very far downstream in the plastic life cycle, such as the recovery of waste already present in the environment, have not been detailed here. Although these are locally beneficial, they cannot be considered a systematic solution. Technologies designed to remove plastics from the environment (e.g. beach cleaning, trapping of floating debris) may also pose a threat to biodiversity. There is a notable absence of environmental impact assessments for these non-selective tools, which can alter habitats and inadvertently capture flora or fauna. Only manual collection allows the selective removal of plastic, yet its efficiency is very limited. Ultimately, it is municipalities and local communities that bear the burden of plastic removal.

Given this reality, there is an urgent necessity to "turn off the tap" (Figure C.3). The objective of reducing primary plastic polymer production has become a self-evident requirement, as has the ban of single-use plastics, which account for nearly 60% of plastic consumption (Unep[43]).

A reduction of at least 12% per annum starting from 2024 (equivalent to a global reduction of nearly 80% by 2050) in primary plastic polymer production would be necessary to ensure carbon budgets remain compatible with a 1.5°C global trajectory by 2050 (Karali *et al.*, 2024). This figure, notably, does not account for the additional reductions required to address the environmental and human health challenges linked to biodiversity loss and pollution. During INC-4 in Ottawa, Rwanda and Peru proposed a target of a 40% reduction in production by 2040 relative to 2025 levels. This objective, which would merely return production to 2015 levels, is insufficiently ambitious.

41. The Scientists' Coalition for an Effective Plastics Treaty is an international network of independent scientists and technical experts. Their goal is to advance negotiations by providing summaries and analyses of the state of science to policymakers and stakeholders involved in negotiations for an international agreement to end plastic pollution.

42. See all of the recommendations of the Scientists' coalition at https://ikhapp.org/library/

43. United Nations Environment Programme (Unep), https://www.unep.org/fr/actualites-et-recits/recit/tout-ce-quil-faut-savoir-sur-la-pollution-plastique

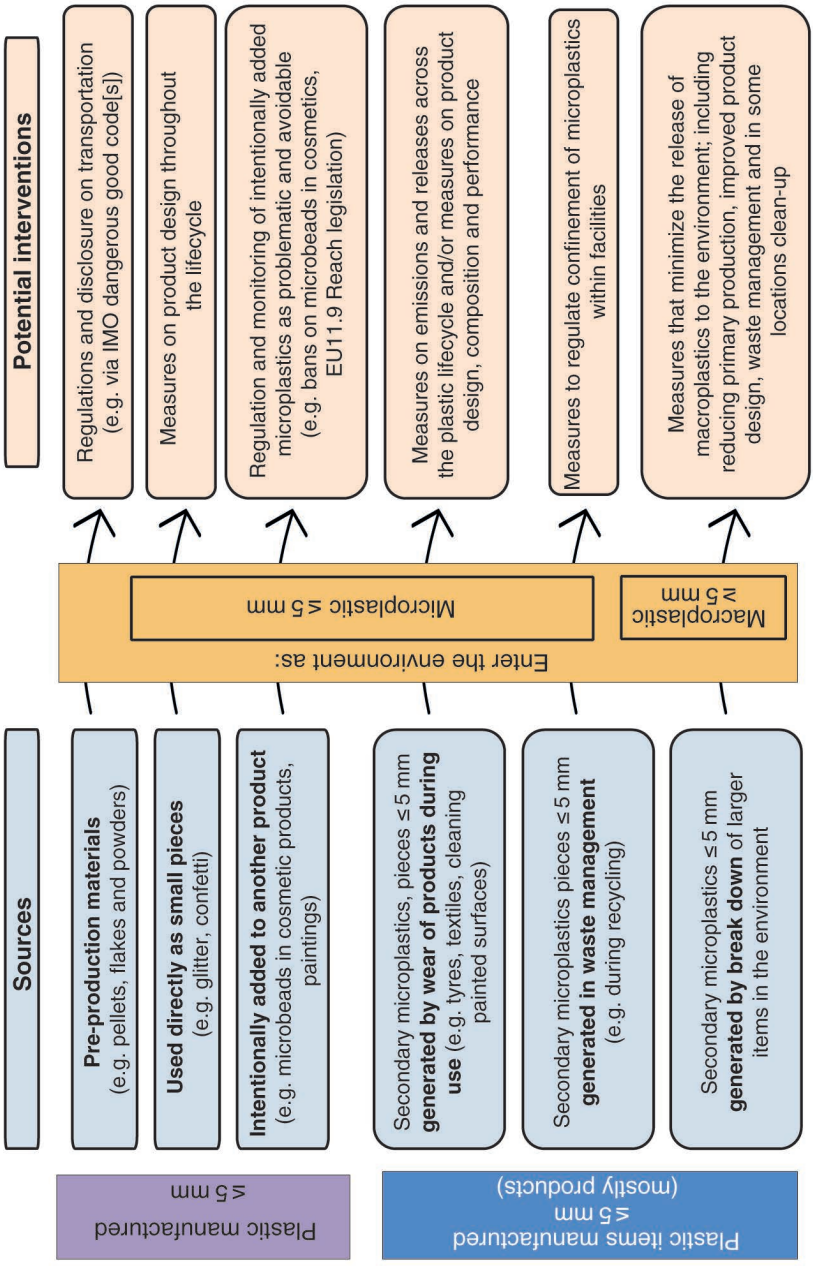


Figure C.2. Categorization of microplastic sources according to size at time of manufacture/mode of generation together with examples of potential policy interventions.

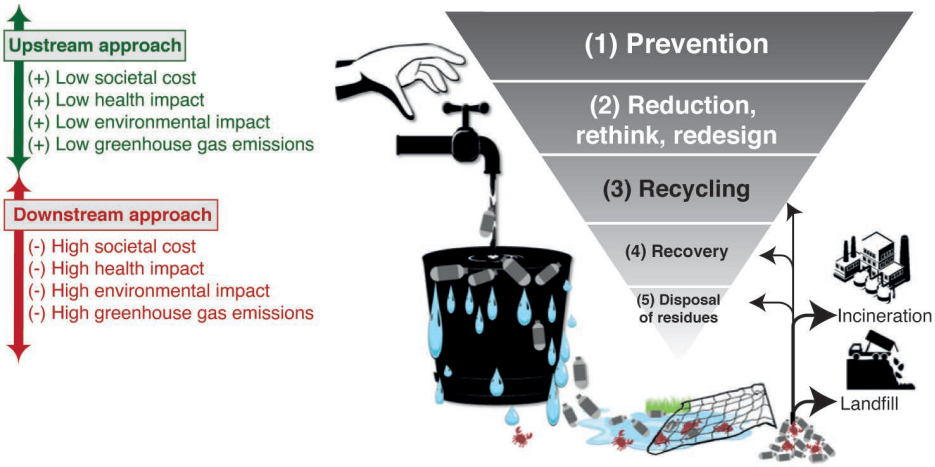


Figure C.3. Benefits of an upstream approach to the plastic life cycle.

The most effective and least costly interventions are based on prevention and reduction of plastic production. Technologies for eliminating plastic pollution are at the bottom of the "zero waste" hierarchy.

The priority must be to "turn off the tap"—or at the very least significantly reduce its flow—rather than attempting to "mop up" a perpetual overflow. The problem must be resolved at the source, prioritising the concepts of essentiality and sustainability. These paradigms are based on scientific principles derived from a deeper understanding of the complete plastic life cycle. Such knowledge is indispensable for informing and sensitising the entire decision-making chain—from political actors and industrial stakeholders to individual citizens—each of whom has a role to play in stemming the tide of this global pollution.

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At every stage of their life cycle, plastics release debris, particles and molecules that contaminate terrestrial, aquatic and marine ecosystems. They thus contribute to the three major environmental crises: pollution, biodiversity loss and climate change.

No species is spared: from sea turtles to phytoplankton, from wheat to the European hedgehog, and including pike and grey herons, all are affected by this pollution, which is largely invisible as it consists mainly of micro- and nanoplastics, now present in every part of the environment.

The result of a collaborative effort involving several research organizations and universities, this book explores various aspects of this problem, which has now taken on a global dimension. It draws on the latest scientific advances, which have made it possible to better quantify and characterize this pollution and to study its impacts on biodiversity and the functioning of ecosystems—through biomonitoring, the study of sentinel species, research in ecotoxicology and other innovative approaches.

The authors also propose a regulatory framework, as well as solutions and alternatives for public policy-makers to address the challenges posed by this threat.

This book is aimed at decision-makers, researchers, and students of ecology, biology or environmental sciences, as well as members of the public keen to better understand the many forms that plastic pollution takes today and the challenges it raises.

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