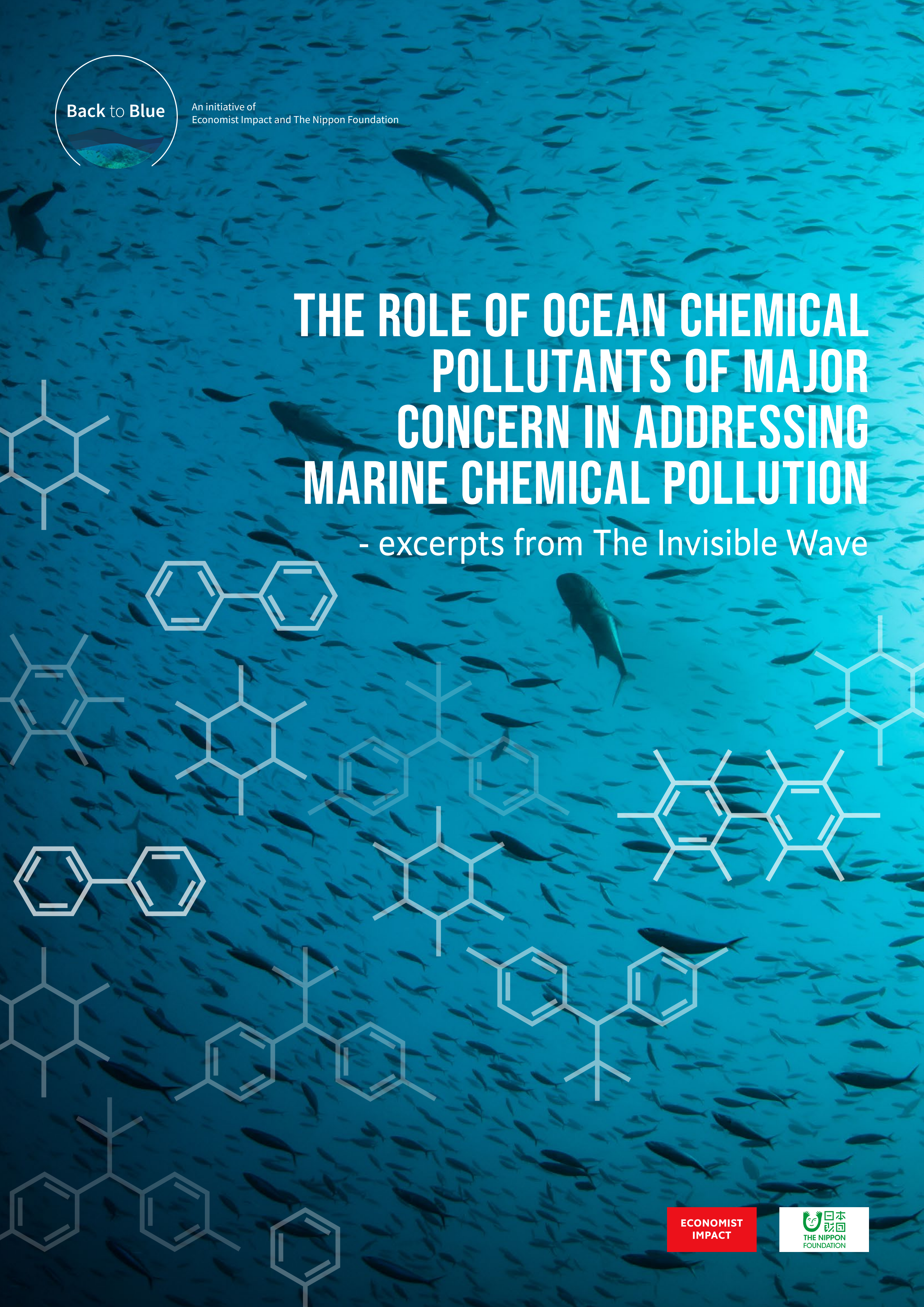

Back to Blue

An initiative of
Economist Impact and The Nippon Foundation

THE ROLE OF OCEAN CHEMICAL POLLUTANTS OF MAJOR CONCERN IN ADDRESSING MARINE CHEMICAL POLLUTION

- excerpts from The Invisible Wave

ECONOMIST IMPACT

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About The Invisible Wave

Chemical pollution—of land, air, rivers, watersheds—has been a festering issue for decades, occasionally prompting resolute action. But only recently has the scale of chemical pollution become more apparent. Chemicals in the form of nutrients, heavy metals, persistent organic pollutants, sewage and many others are being uncovered almost everywhere—in soils, aquifers, food chains, remote ecosystems such as the Antarctic, in the highest and lowest places on Earth, and in humans. As evidence accumulates of its impact on nature and human health, there is a gathering consensus that chemical pollution is a first-order global threat, alongside climate change and biodiversity loss, and often compounding the impacts of these other issues.

This awakening to the systemic nature of chemical pollution understandably focuses on where humans live, on land. This report seeks to raise awareness of marine chemical pollution, as its scale and potential impact—and thus urgency—are not widely appreciated, and to focus minds on delivering solutions that prevent, reduce and minimise chemical pollution in the marine environment. An aspiration towards zero pollution is gaining currency. The hope is not so much that the ocean can be free of pollution, which may be impossible, but rather that more will be accomplished if the goal is seen to be ambitious. Back to Blue shares this aspiration.

The Back to Blue initiative grew out of the findings of our 2021 global survey, which showed that plastic and chemical pollution are the two greatest concerns that people have about ocean health, with climate change ranked third. As this report will show, the three are profoundly connected.

The ocean is fundamentally important to all life on Earth. It covers 70% of the planet's surface and comprises 99% of its habitable space.[1] It is therefore remarkable that there has not yet been a serious scientific assessment at scale of marine chemical pollution and its impact on life in the ocean, marine biodiversity and how ocean ecosystems function, and ultimately on the ocean's overall health. The Invisible Wave seeks to set out clearly what is known about its impact and where our knowledge gaps sit, prompting the urgent need for more research.

This urgency is underscored by a further point that this report seeks to demonstrate: that despite lacking a complete picture of the dangers posed by marine chemical pollution, failing to act now is a risk too far. The report therefore suggests solutions for various groups of stakeholders that, if taken, would ameliorate chemical pollution in the marine environment. It is a starting point: mapping out the paths to those solutions is the function and aim of a research and engagement programme

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that the Back to Blue initiative will undertake following the launch of the report.

Despite lacking a complete picture of the dangers posed by marine chemical pollution, failing to act now is a risk too far

The marine environment

This report concerns itself with the impact of chemicals on the marine environment. In other words, we are looking at the saltwater part of the hydrosphere: from the deep ocean to coastal seas, bays and estuaries, and including the array of ecosystems found there, including coral reefs, seagrass beds, mangroves, mudflats, sediments and water columns. The freshwater part of the hydrosphere—rivers, land run-off and groundwater—is a key transport mechanism for chemical pollution reaching the ocean and coastal areas, but otherwise is not a focus of this report.

The importance of the saltwater hydrosphere to life on Earth is greatly underestimated. Not only is the ocean a crucial food source for billions of people, but it also provides more than half the planet's atmospheric oxygen, acts as a massive carbon sink (without which global warming would be far worse), regulates the weather and climate, and provides countless formal and informal jobs in economically crucial activities that include fishing, shipping, tourism, recreation and offshore hydrocarbon exploration. The ocean provides services estimated to be worth trillions of dollars—services that are at risk from marine chemical pollution.

Despite the ocean's centrality to all life on Earth, humanity's view has been that the seas have an infinite capacity to absorb waste. That is wrong. While there is patently a need for more research on the harm that chemicals inflict on the marine environment, the existing evidence is clear: chemical pollution has damaged marine biota, from polar bears to plankton to large-scale ecosystems such as the seas and beyond. As the production and use of chemicals rises, so inevitably will their impact escalate too.

There are many reasons why this matters. Science has already shown that climate change is in large part due to human activities, and this anthropogenic cause is true too for marine chemical pollution. Importantly, the two are linked: science is learning that synthetic chemicals in the seas can increase climate change's negative effects, while the effects of climate change (including warming water temperatures, increased acidification due to higher carbon levels, and greater salinity) can heighten the negative effects that chemicals have in the marine environment. In other words, climate change and marine chemical pollution are deeply interlinked. Consequently, it is crucial to tackle both.

Failing to do so will lead to accelerated damage to marine life and biodiversity—"the variety of life ... and the natural patterns it forms"[2] —and would come even as the number of species on Earth is declining at perhaps its most rapid rate due to factors like climate change, pollution and activities like overfishing. And while biodiversity loss is common to the terrestrial environment and ocean, one key difference is that we know very little about countless marine creatures. Consequently, when it comes to the ocean, we often do not even know what we are losing.[3]

This damage to marine biodiversity, and the complex interactions that underpin it, has important knock-on effects on the functioning and resilience of ocean ecosystems. Exactly how such ecosystems are affected by complex and multiple stresses such as warming waters, acidification, chemical pollution and the growing industrialisation of the seas, including overfishing, is still not well understood. The science is in its infancy. Yet rising levels of marine chemical pollution are an important factor in

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undermining, even potentially imperilling, the capacity of marine ecosystems to provide the services on which all of humanity relies, and that are crucial to the stability of wider systems, including climate and the carbon cycle.

Why marine chemical pollution?

Marine pollution as a broad topic has deservedly gained greater attention in recent years, with plastic taking centre stage. As many of our interviewees pointed out, this is because plastic pollution is highly visible and emotive: who can forget the video of a turtle with a plastic straw in its nostril, or media coverage of whales and seabirds found dead with plastic waste in their stomachs?

Plastic is a challenge of epic proportions and complexity, and is also important to the chemicals story. Marine chemical pollution, however, is of a different order:

- For a start, it is invisible and, in a world where awareness-raising is often most effective when it is visual, as the turtle video shows, this hinders understanding its scope and significance.
- Second, synthetic chemicals production is increasing rapidly and set to grow fastest in the coming years and decades, with many new chemicals being created and circulated. The green transition is an important driver of these trends.
- Third, production is shifting to middle- and lower-income countries where regulations to manage chemicals and combat chemical pollution are typically limited and less effective. At the same time, higher-income countries that have addressed conventional chemical contaminants to some degree face new challenges with the relentless pace of chemicals' innovation and associated pollution risks.
- Fourth, scientists are open about the need for more research to better determine how marine chemical pollution will damage the ocean, which is not surprising given that there are tens of thousands of chemicals with, in most cases, completely unknown effects on human health and the environment.
- And fifth, while marine chemical pollution continues to be a threat in wealthier countries, much of the new and incremental damage taking place globally is in poorer countries where people and ecosystems are at a great remove from the markets ultimately driving the increased use of chemicals. This further decreases its visibility.

For these reasons and more, as we explore in detail in this report, marine chemical pollution is an under-appreciated and underestimated danger. It must not be.

Key chemicals and their sources

A recent study found that there are at least 350,000 synthetic chemicals and mixtures of chemicals, with thousands being added each year.[4] Yet, worryingly, we know almost nothing about most of their health and environmental consequences. Additionally, even when chemicals are deemed so harmful that they must be replaced, their replacements are also often found to be toxic (known as regrettable substitution).

In recent years, hundreds of chemicals have been placed on lists for banning, restriction or substitution. Of particular concern are persistent organic pollutants (POPs), which, as the name indicates, linger in the environment, can travel long distances, and have serious effects on the environment and biota. Although hundreds of chemicals have been recognised as POPs, some researchers believe thousands of other unrestricted chemicals meet the requirements to be classified that way.

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The sheer volume of chemicals makes drafting a list of the worst of them a significant challenge, and inevitably this report does not provide a comprehensive list of all chemicals of concern. For that reason, our expert panelists have suggested a list of classes or groups of chemicals that they feel are the most severe or that could have the greatest impact in terms of:

- Environmental health, particularly the health of the ocean.
- Human health.
- Economics (quantifying this is a long-term goal of the Back to Blue initiative).

Given their effects, POPs are an obvious category for inclusion, and feature heavily in this report. The others include heavy metals, nutrients, pesticides, plastics, pharmaceuticals, radioactive materials, oil products, household chemicals and pseudo-persistent chemicals. While some of these chemicals are banned or restricted, most are not.

By default, these are the chemicals or chemical groups that we know most about. However, future research will surely identify others that constitute a greater threat or that inflict increased harm to marine ecosystems. It is entirely possible, then, that the potential impact of marine chemical pollution will prove to be wider and more serious than currently estimated.

That raises two important questions:

- What effects do these chemicals have in the marine environment?
- How do they enter the marine environment?

Answering the first with accuracy requires more research, particularly when it comes to determining how chemicals react individually and collectively in the real world. The answer to the second question begins by identifying the various parties involved in the chemicals value chain: the chemicals industry (which to date has externalised its costs), its clients (more than 95% of manufactured goods contain chemicals) and financiers. It also includes regulators and governments (with public sector sources of pollution including dredging and defence), end-of-life operators and civil society.

Consumers are also of note. Sources of marine chemical pollution here include pesticides, fertilisers and plastics, with pharmaceuticals and personal care products—sometimes referred to as chemicals of emerging concern—becoming increasingly important due in part to the growth in the number and size of coastal cities and towns in recent decades, and with the background rise in population numbers and incomes globally.

Our efforts to map accountability across the value chain of the chemicals' lifecycle also includes the pre-production phase: extracting and processing the fossil fuels, minerals and metals used to manufacture chemicals, with oil and gas majors like ExxonMobil, Shell and BP involved in both extraction and chemicals manufacturing. Given the projected growth of the chemicals industry and its role at the heart of marine chemical pollution, as well as often-lax industry oversight, accountability will become more important going forward.

The end-of-life phase of the chemicals value chain is another important source of marine chemical pollution, with municipal waste, e-waste and untreated sewage growing in importance. Plastics, for instance, are laced not only with chemicals from the manufacturing process, but they also break down into micro- and nano-sized particles that can adsorb chemicals in the water and transport them vast distances.

Overseeing, in theory at least, this vast value chain from extraction to disposal are regulators.

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The success of any strategy to combat marine chemical pollution hinges on regulators enacting and enforcing stricter rules on pollution, and working in concert with peers elsewhere to combat regulatory arbitrage, where firms move to jurisdictions with less oversight. Encouragingly, research by the European Commission shows that regulations bring numerous benefits, cutting the costs of marine chemical pollution on the environment and human health, and lowering water pollution levels.

The success of any strategy to combat marine chemical pollution hinges on regulators enacting and enforcing stricter rules

Regulations, properly enforced, also require that producers adhere to common standards, and should be employed to ensure that product designers factor in end-of-life aspects, particularly impacts on the marine environment.

The dangers of inaction

Most marine chemical pollution is caused by humans, and most of that has taken place in the past 100 years. Given that the pace of chemical production and innovation is predicted to rise rapidly in the coming years and decades, and that much of the production growth will happen in countries with less regulation, it is likely that marine chemical pollution will get significantly worse unless action is taken.

Assessing the scope, extent and impact of marine chemical pollution, now and in the future, is a pressing task for scientists and environmentalists, as is evaluating the cost of such pollution. Armed with a clearer picture, action is more likely to succeed. And while inaction remains a possible response, it is no longer necessarily the likely response. The past few years have seen a broad awakening to the problem of pollution. The UN Environment Programme (UNEP) has elevated pollution (chemicals, plastics and waste) alongside climate change and biodiversity loss as one of three interconnected anthropogenic crises. Pollution is one of the key stresses that led the UN to state that ocean sustainability is "under severe threat", and that addressing pollution was vital to achieve the UN Sustainable Development Goals (SDGs). Meanwhile, *New Scientist* rang the alarm in mid-2021 with the headline: "Why chemical pollution is turning into a third great planetary crisis".[5] The Stockholm Resilience Center has, for the past decade, included pollution as one of several planetary boundaries within which humans need to operate to ensure stable Earth systems.

The language of crisis and emergency is nothing if not a call to action. While more research (and funding) is needed to close some significant knowledge gaps, it makes no sense to refrain from acting until every gap is filled. After all, it will be decades before we understand the effects that the tens of thousands of synthetic chemicals might have on health and the environment, whether individually or collectively, and the world does not have that much time. Additionally, intervening is in line with the precautionary principle, which demands that we act now on the grounds that we know enough about the effects of marine chemical pollution to be concerned about its potential effects.

A large part of this burden to act must fall on the chemicals industry and on its clients in the broader business world. In part, this will require that the business community factor in its impact on marine chemical pollution in the way that it has started to do on climate change.

If the world does not act, it is reasonable to assume that the problem of marine chemical pollution will worsen. Rising production volumes is one reason, but there are others like weak regulation and enforcement, poor product design, the lack of domestic and industrial wastewater treatment in much of the world, and insufficient waste management.

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Yet perhaps the biggest problem, our experts said, is assuming that we can keep dumping waste into the ocean because it is vast enough to absorb and dilute the array of toxic substances that we produce. As this report shows, we cannot.

A global problem that lacks local research

The transboundary nature of marine chemical pollution means it affects everyone, no matter how far they are from its production. Toxins have been found in islanders in the Pacific and the Faroes, as well as in people living in the Arctic Circle—and, notably, in women and children in poorer countries who rely on seafood.

Marine chemical pollution, in other words, is a global problem. That said, much of our understanding of its economic costs is derived from a few high-income countries, which means that research is lacking that would be most relevant to billions of people for whom the seas are crucial to lives and livelihoods. This needs to be remedied. Funding should be targeted at the chemicals with the greatest potential to harm ocean biota and, in turn, human health and local economies.

It is also clear that much more research is needed on chemicals and their impact—particularly in conjunction with other chemicals in the marine environment. This needs to factor in climate change variables like temperature, acidity and salinity, as each can affect how chemicals react.

One result of the research bias favouring wealthier nations is that the studies cited often examine marine chemical pollution in the rich world. While this is an unavoidable consequence, we have kept this imbalance in our minds and endeavoured where possible to incorporate research that covers poorer nations. Clearly, a key task for the future is tipping the scales back.

A final point on research is that what is known needs to be brought to the wider community. As UNEP notes, this includes improving the flow of communication between researchers and policymakers. This could help to motivate change by quantifying the costs of inaction and the rewards of intervention. Our bespoke case study on marine chemical pollution in the US Gulf of Mexico, for instance, found that dead zones worsening—where the sea has been starved of oxygen owing to pollution—would cost the US about US$838m a year in fisheries revenue. Taking measures to reduce dead zones, on the other hand, would boost marine biodiversity and therefore increase revenue by more than US$117m.

Industry

As the ultimate source of chemical pollution, the chemicals industry has the primary responsibility to act. It could hugely influence resolving the issue. However, if it fails to act, it could face an existential crisis for two reasons. First, this industry is dependent on fossil fuels to manufacture feedstocks, with the likely regulatory and financial pressures this carbon-heavy operational base will bring. Second, owing to the growing understanding of the impacts of chemical pollution on environmental and human health, there is increasing consumer and investor pressure on this issue, which could ultimately prove as critical as climate change.

Additional pressure on laggards in the sector will come as more innovative firms step up in areas like green chemistry, which could hold the key to sustainable change for the sector, even as clients come under pressure from customers to better manage the chemicals in their product portfolios, and as public awareness compels governments to enforce stricter regulations.

Surprisingly, though, industry efforts have been piecemeal at best, even though the momentum for a circular economy is growing—as with plastics. Accelerating change will require a shift at the corporate culture and systems levels.

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Conclusion

Although marine chemical pollution remains a largely invisible problem, this is starting to change. There is now enough evidence to show that the problem is extensive and worsening. Moreover, given the crucial role that the ocean plays in regulating climate and weather, generating oxygen, absorbing carbon, and providing food for billions of people, we also know that inflicting further harm risks too much.

Action, then, is vital. It requires that all stakeholders play their part. Although marine chemical pollution is a huge challenge to solve, it is not impossible. In mapping the sources of marine chemical pollution, the consequences (as we know them) and a series of paths that can resolve one of the defining issues of our times, this report and the Back to Blue initiative aim to raise awareness and galvanise action from all of those involved.

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1: Ocean chemical pollutants of major concern

This excerpt of The Invisible Wave outlines the key chemicals and chemical groups of greatest concern when it comes to marine chemical pollution, looking at the known causes and impacts of each group.

1.1 Principal findings and recommendations

- **There are huge numbers of chemicals, but there is limited knowledge of the potential impact of most. Regrettable substitution is often the result.**
  There are tens of thousands of synthetic chemicals, yet in most cases we know nothing about their potential impact on the ocean environment—or on humans. In some cases, however, the toxic effects are understood. In recent years, scores of chemicals have been put on lists for banning, restriction or substitution. Yet a lack of knowledge has led to regrettable substitution, in which replacement chemicals are not properly tested and then later found to be toxic.

- **The list of chemicals of concern for the marine environment is long.**
  The list of the chemicals of greatest concern, some of which overlap, includes the following: persistent organic pollutants (POPs); heavy metals; nutrients; pesticides; plastics; pharmaceuticals; radioactive materials; oil products; household and consumer chemicals; and pseudo-persistent chemicals. While some of these are banned or restricted, most are not. And even where some are banned, there are still large stockpiles that require disposal or treatment. POPs are of particular concern: although a few dozen chemicals are listed in the Stockholm Convention and other international regulations for banning, restriction or substitution, thousands more chemicals likely meet the definition of POPs (and of other chemicals of concern). Acting on these is essential.

- **More research is needed to overcome knowledge gaps ...**
  Much more research is needed to determine the damage that many chemicals inflict on the marine environment, including how their interactions increase or lessen that harm. This will require far greater levels of funding, which should be targeted towards the chemicals of greatest concern in terms of their harm to ocean ecosystems and biota and, via those, to human health and local economies. This will also require focusing more on the effects of marine chemical pollution on poorer nations. To date, research has centred on wealthier nations,

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despite the fact that marine chemical pollution disproportionately affects poor and marginalised populations.

- **… but this must not hamper taking steps to combat marine chemical pollution.** The fact that there is a lack of sufficient research to fully quantify the damage done by chemicals to the marine environment must not preclude action. It is already clear that certain chemicals inflict significant harm; additionally, a large number of chemicals still need to be assessed and managed. For these reasons and more, the need to act is urgent.

A comprehensive 2020 study found more than 350,000 chemicals and mixtures of chemicals have been registered for production and use —threefold a previous estimate—and that the identities of about 120,000 of these are publicly unknown because industry claims they are confidential or they are described ambiguously.

We know so little, and in many cases nothing whatsoever, about the vast majority of chemicals, very few of which have been tested for their potential to do harm on humans or the environment

Consequently, there is significant concern among experts that the toll that chemicals exact on the marine environment and its wildlife is far higher than currently known, to say nothing of the impact on humans—either directly through the seafood we eat or indirectly through accelerating climate change, for instance, or damaging ecosystem services like fisheries and reducing the protection from storm surges provided by mangroves and coral reefs.[6]

The need to fill the array of global knowledge gaps is one that UNEP highlighted in its 2019 Global Chemicals Outlook report—one of ten key areas it identified as important for the world to tackle in order to minimise the adverse effects of chemicals and waste. Success requires "taking steps to harmonise research protocols, considering health or environmental impact information and harm caused to set and address priorities (eg, emerging issues), and strengthening the science-policy interface through enhanced collaboration of, scientists and decision-makers".[7] Linked to that, UNEP noted that more attention is needed to determine how mixtures of chemicals affect the environment—including the marine environment.

"The cumulative exposure of ecosystems to the mixture of chemicals entering the environment has been identified [by the Secretariat of the Convention on Biological Diversity 2010] as one of the five main pressures negatively affecting biodiversity," UNEP's report notes. "How this chemical 'cocktail' interferes with human health, and how it interacts with organisms and the environment, is still largely unknown."[8]

This makes drafting a list of the ocean chemical pollutants of greatest concern a significant challenge. We know so little (and in many cases nothing whatsoever) about the vast majority of chemicals, very few of which have been tested for their potential to do harm on humans, to say nothing of the damage they do to the environment.[9] Consider this: a recent 20-year study that examined more than 3,500 chemicals in 130,000 scientific papers found that just 65 chemicals constituted half of all occurrences, and that "for some chemicals the scientific knowledge is dominated by publications associated with the industry".[10] In short, only a limited number of chemicals have been tested for their ecotoxicity, with the objectivity of at least some of that research questionable.

Much of what we do know is based around chemicals' impact on human health, and that alone is worrying enough: the WHO calculated that exposure to a limited range of chemicals

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contributed to 2 million premature deaths in 2019, with lead alone responsible for nearly half of these.[11] And, the global health body warned, the data covered only "a small number of chemical exposures, and people are exposed to many more chemicals every day".[12]

1.2 Defining the problem: A work in progress

For reasons we will examine in more detail shortly, our knowledge about the impacts that the majority of chemicals might have on the marine environment remains woefully inadequate. While this makes it impossible to draft a list that is both comprehensive and definitive, some national and supranational bodies have made a start. The EU's European Chemicals Agency (ECHA), for instance, has several. One is its Candidate List of 223 chemicals or groups of chemicals that it describes as "substances of very high concern [that are manufactured in Europe or imported to it] that may have serious effects on our health or the environment".[13]

Another, the ECHA's Authorisation List, has the names of 54 chemicals or groups of chemicals that have already been or will be phased out in the EU,[14] while its Restricted List contains 69 substances or groups of substances for which the manufacture or use in the EU is limited or banned.[15]

Logically enough, these lists are a work-in-progress. EU nations can propose that the ECHA consider adding other worrisome chemicals. Eight of the chemicals on the ECHA's Candidate List, for example, were added in July 2021, with the ECHA noting that they have been included because "they are hazardous to human health as they are toxic for reproduction, carcinogenic, respiratory sensitisers or endocrine disruptors".[16]

Inclusion on the Candidate List, though, does not mean that companies are barred from using these chemicals. Under the bloc's REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals, which entered into force on June 1st, 2007), it simply means that a supplier of products that contain a Candidate List substance with concentration above 0.1% weight-by-weight "has to give sufficient information to their customers and consumers to allow safe use".[17]

Other national and supranational bodies have their own lists of chemicals of concern, as do interested parties like ChemSec, a Europe-based non-profit. It has created the SIN List (in which SIN stands for Substitute It Now) of 1,027 hazardous chemicals and groups of chemicals that it wants to see replaced by businesses with safer alternatives—far more than those listed in the three ECHA lists, for instance.

That raises a further key point: how best to determine whether a particular chemical is so dangerous that it should be banned or restricted. Establishing the knowledge base for a clear, swift and globally applicable process for this is one of the core aims of the ongoing Back to Blue programme. In part this means identifying the chemicals that are doing the most harm to marine environments (or that are likely to), and in that way are also harming people and local economies. This process will also point the way to where research is most urgently needed.

As mentioned, determining which chemicals are of concern is far from easy. At the heart of this is deciding which characteristics should be considered. Some assess a chemical's persistence, bioaccumulation and toxicity (known as its PBT). For its part, the Stockholm Convention on Persistent Organic Pollutants—a global treaty designed to prevent harm to human health and the environment from a range of chemicals known collectively as POPs—also incorporates the ability of a chemical to travel long distances (which is one reason no individual country can successfully deal with POPs' toxic impacts).[18] On top of this, assessment bodies often vary in terms of the threshold values used to measure a chemical's impact, and sometimes use different data sources—all of which can result in different outcomes.[19]

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Not surprisingly, the lists of chemicals of concern (including whether they qualify as POPs) differ depending on the body concerned. To some experts, existing lists of chemicals of concern fall far short of what is needed. Independent assessments have concluded that the number of chemicals that should be considered as POPs, for instance, is far higher than the 29 currently listed in the Stockholm Convention. One study of 95,000 industrial chemicals identified as many as 5,000 as potential POPs.[20]

Regrettable substitution

A sensible solution for chemicals that are known to be toxic is to phase them out. However, this does not necessarily solve the problem; the replacement itself is also crucial. Take polybrominated diphenyl ethers, or PBDEs. This class of chemicals replaced another synthetic fire-retardant class of chemicals devised about a century ago called polychlorinated biphenyls, better known as PCBs. This latter class was found to have hugely toxic effects on humans and animals, leach into the environment and build up in sediment in seas, rivers and on land, and thereby enter the food chain.

Although using PBDEs in products like furniture, mattresses, carpets and plastic cabinets is meant to make them less likely to catch fire (a questionable conclusion, some scientists say, although one that has for years been promoted by US manufacturers of fire retardant chemicals)[21] it subsequently transpired that PBDEs, which are structurally similar to PCBs,[22] are also extremely toxic and disrupt the delicate hormone systems (the endocrine systems) of humans and animals.[23] This consequence, in which a substitute for a banned chemical has not been sufficiently tested and is later found to be as dangerous or even worse, is known as regrettable substitution.

While there are restrictions on using the three types of commercially available PBDEs (pentaBDE, octaBDE and decaBDE—the last of which was brought to market as a substitute for pentaBDE and octaBDE, and which is therefore another example of regrettable substitution), they are still present in countless products around the world, including in the EU, for example, where their use is subject to certain limits.

PBDEs are only one of the five main classes of so-called brominated fire retardants,[24] and—as with PCBs—their regrettable substitution is not the end of the matter. One of the replacements for PBDEs is a class of fire-retardant chemicals called organophosphate esters (OPEs),[25] which at least one study has associated with hyperthyroidism in household cats.[26] Concerns about OPEs are on the rise: they are listed as Chemicals of Emerging Arctic Concern by the Arctic Monitoring & Assessment Programme,[27] a working group of the Arctic Council, an intergovernmental forum;[28] and a 2019 study concluded that OPEs "are now often found at higher levels compared to PBDE peak exposure levels", with data suggesting health concerns for humans at current exposure levels.[29]

As it turns out, regrettable substitution is not unusual, with its effects seen more recently in the shipping sector. In January 2020 the International Maritime Organization (IMO) made it mandatory for ships to start using a new type of marine fuel called Very Low Sulphur Fuel Oil, replacing the standard heavy fuel that was rich in sulphurs and that emitted sulphur oxide , which contributes to ocean acidification and harms aquatic species.[30]

In July 2020 the *MV Wakashio*—a bulk carrier—ran aground near Mauritius and eventually broke up. Although most of the fuel was pumped out, about 1,000 tonnes leaked into the ocean. The good news was that researchers found that the version of this new class of fuel oil that was

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used in the *MV Wakashio* had lower quantities of components known to be toxic to marine life than those found in typical heavy fuel oils.[31]

However, they also found that other Low Sulphur Fuel Oils that they tested "contained higher concentrations of toxic components than the oil discharged in the Mauritius spill," said Dr Alan Scarlett of the Australia's WA Organic and Isotope Geochemistry Centre in Curtin's School of Earth and Planetary Sciences, and lead author of the study.

"So, more research will be needed before we can conclude that all the oil types within this new class pose less of a threat to marine ecosystems than heavy fuel oils," he said.[32]

Combinatory effects

How to replace pollutants, therefore, is one challenge in drafting a list of chemicals of greatest concern, because we simply do not know enough about the chemicals that are already in use.

It gets more complicated still. Chemicals in the ocean do not exist in isolation and are not immune to what is happening around them. Consequently, some have additive toxicological effects (the damage accumulates as other chemicals are added to the mix) while others have synergistic effects (the damage is multiplied). Some chemicals worsen the impact of other chemicals, or even inflict greater or lesser damage on organisms depending on the order in which those chemicals are encountered.

All of this is without considering other factors that seem to affect chemicals' mobility and toxicity like sea temperature, acidity levels and deoxygenation, all of which the report examines in more detail in Chapter 3. Some experts fear these factors could mean that the ways that chemicals interact in the future might change—which means that the relative importance of different contaminants might also alter (an issue that Chapter 3 also looks at). In short, there is much that we do not know.

Toxic mix: Spoiled for choice

For the purposes of this report, determining the most worrisome chemicals starts by drafting the following list. And although this must be prefaced with an acknowledgement that it will by definition be incomplete, it is important to have such a list as a baseline.

As noted in the Summary, our expert panel believes these categories constitute the most significant risk to the marine environment (to the best of our current knowledge). They also believe that tackling these will be crucial to efforts to reverse the damage to the ocean and restore ocean health.

To that end, this report categorises marine chemical pollutants as follows (though many chemicals fall into more than one category):

- **POPs:** these chemicals include the PCBs and PBDEs outlined earlier, as well as organochlorine pesticides, dioxins, furans and certain fluorinated chemicals in the PFAS group like perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA).

- **Heavy metals:** mercury, lead and cadmium are among the key constituents in this group.

- **Nutrients:** this includes fertilisers as well as organic matter, including human and animal waste, that leads to eutrophication[33]—when algal blooms consume so much oxygen from the water that other sea life dies off en masse.

- **Pesticides:** an important category given that, for example, more than half of the chemicals targeted for elimination under the Stockholm Convention are pesticides.

- **Plastics:** this covers macro-, micro- and nanoplastics, all of which are themselves pollutants, and which can pick up and transport POPs and other chemicals long distances.

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CHEMICAL POLLUTION AND THE OCEAN: PATHWAYS AND POLLUTANTS

Over 350,000 chemicals have been registered for production and use, and they play a fundamental role in many of the technologies and products of our everyday life, from smartphones to food preservation. Most marine chemical pollution, then, begins on land—about 80%, according to a commonly cited statistic, versus 20% that is thought to originate in the seas. Here, we illustrate some chemicals of key concern to ocean health.

HEAVY METALS

Hg

Mercury

Enters the environment through channels including artisanal gold mining, burning coal, and non-ferrous metal and cement production

Cd

Cadmium

A grade 1 human carcinogen used in products such as batteries, solar panels and plastics, with major effluent sources including marble, steel and metal-plating industries

Pb

Lead

Produced by industries including mining, oil and gas exploration, construction and dredging, and electronics. Lead accumulation is linked to heart disease, strokes and cancer

MANUFACTURED CHEMICALS

POPs

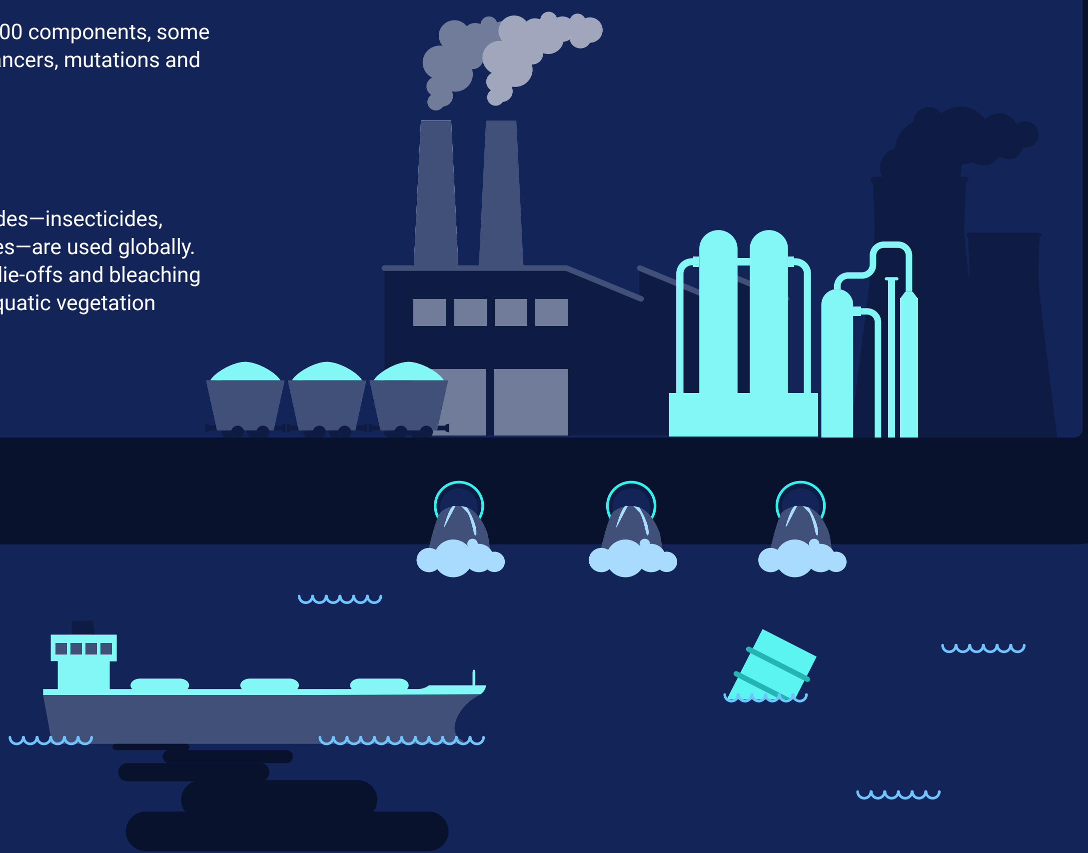
Carbon-based chemicals found in everyday products like furniture and electronics that can harm human health

Hydrocarbons

Oil includes around 10,000 components, some of which are linked to cancers, mutations and birth defects

Pesticides

More than 1,000 pesticides—insecticides, herbicides and fungicides—are used globally. They are causing coral die-offs and bleaching events and damaging aquatic vegetation



- **Pharmaceuticals:** this covers medication for humans and animals, with antibiotics a central concern given that their overuse or misuse can give rise to antibiotic resistance.

- **Radioactivity:** this covers recent contamination (for example, the 2011 Fukushima disaster in Japan), the historical dumping of radioactive waste, as well radiation emanating from natural sources.

- **Oil:** this also includes the toxic chemicals that are used to clean up spills.

- **Household and consumer chemicals:** many cleaning products contain toxic chemicals, as do numerous cosmetics, shower gels and sunscreens.

- **Pseudo-persistent chemicals:** these are chemicals that would dissipate relatively quickly in the aquatic environment, but that have concentrations that keep rising because they are so prevalent in products —for example, some pharmaceuticals.

- **Other chemicals:** this includes a wide variety of the approximately 300,000 chemicals in use, most of which have unknown effects.

1.3 Persistent organic pollutants (POPs)

POPs is the collective name for a range of carbon-based chemical substances with properties that make them toxic to humans and animals, ensure that they can be widely distributed via soil, water and the air—including to the Arctic, far from any sources of POPs—and remain in the environment for years (or, in the case of PFOA, potentially forever). POPs enter the food chain and often accumulate in fatty tissue, where their concentrations build up over time—as high as 70,000 times the background levels for those high up the food chain like humans, fish, predatory birds and mammals.[34]

Many POPs present in the environment were used in agriculture and manufacturing, including in consumer products like furniture, electronics and toys; others, like dioxins and furans, spew into the environment from incineration or are the by-products of industrial processes.[35] Although there is less production today of some of the 29 POPs listed in the Stockholm Convention, large stockpiles exist and need to be disposed of or treated properly to avoid further contaminating the environment. Additionally, it is likely that far more chemicals than those 29 meet the criteria for classification as POPs.

POPs are problematic because they can trigger a wide array of ailments in humans and animals, including cancers, allergies, reproductive disorders, birth defects and developmental disorders. Many are endocrine disruptors, while others damage the immune system or the nervous system. Most of the 29 POPs listed in the Stockholm Convention are targeted for elimination,[36] with a further six being considered for inclusion as of early 2022.[37]

Perhaps the best-known POPs are the dioxins associated with Agent Orange, which was a defoliant used in the Vietnam war that has had appalling health consequences, and DDT, an insecticide that disrupts the endocrine system. The latter is still used in some countries for mosquito control, but is banned from use in agriculture.

PCBs

Less well known, but described as "one of the world's worst toxic legacies",[38] are a group of synthetic chemicals known as polychlorinated biphenyls, or PCBs, with an estimated 680,000 tonnes manufactured in the US alone until production was banned in 1979.[39] With 1.3 million tonnes thought to have been produced worldwide,[40] PCBs were used in electrical transformers, as flame retardants, in paint,

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in electronic items and in plastics—and even sprayed on roads to keep down dust. About a third of the total produced is believed to be in coastal sediments and the ocean, with the rest in landfill or still in use, and so will likely continue to contaminate the ocean for decades.[41]

POPs, many of them endocrine disruptors, can trigger a wide array of ailments in humans and animals, including cancers, reproductive disorders and birth defects, and can damage the immune and nervous systems

There are 209 PCB congeners, or unique chemical compounds, in the PCB category. All are listed for elimination under the Stockholm Convention, and have a range of toxic effects in humans and animals. In humans, transmission is often through food, and causes developmental delays and behavioural problems as well as harming short-term memory. PCBs suppress the immune system in humans and some animals, such as seals, and are likely carcinogenic.[42] They are also toxic to fish: high doses kill them, while lower doses result in failure to spawn.

A major study of PCBs in the 1980s found that atmospheric deposition was central to contamination of the ocean; subsequent research indicates that PCB concentrations are higher in the marine environment of the northern hemisphere, particularly the Mediterranean and the Baltic.[43]

There are indications that PCB levels in at least some parts of the ocean are dropping. Although a study by the OSPAR Commission, a regional body that works to protect the marine environment of the North-East Atlantic, showed no appreciable decline up to 2015 in PCB concentrations in sediment in the Irish and Scottish West Coast and in the Irish Sea, it did reveal significant statistical declines in the other three areas surveyed (the northern North Sea, southern North Sea and the Gulf of Cádiz).[44]

That said, a 2017 study found extremely high levels of numerous types of PCBs (along with PBDEs) in crustaceans in two of the deepest parts of the ocean, far higher than surface levels, and with the most contaminated crustaceans exhibiting levels 50-fold those found in crabs in a highly polluted river in China.[45] And a study from 2016 found that concentrations of PCBs and other POPs in fish in the remote Antarctic Ocean in the southern hemisphere had risen over the past two decades.[46]

In addition, countries may continue to use PCBs in certain equipment until 2025, with the obligation by 2028 to dispose of and destroy all such waste. In some countries, though, it is clear the 2025 deadline will be missed, which means PCBs will continue to contaminate the ocean despite the decades-old ban on production.

Other POPs

Largely unknown to the public yet also included for elimination under the Stockholm Convention's Annex A are a further two dozen or so POPs. These include chlordane, dieldrin and lindane (all of which are insecticides), dicofol (a pesticide), endosulfan (an insecticide that is still used in many countries, including on coffee and rice) and mirex (an insecticide and fire-retardant in plastics, rubber and electrical goods). Others are decabromodiphenyl ether (known as decaBDE, a bromine-based flame retardant still widely used in, for instance, electrical goods, vehicles, airplanes and carpets) and hexabromobiphenyl (another bromine-based flame retardant).

However, as noted earlier, there are likely far more chemicals that should be categorised as POPs than the Stockholm Convention

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recognises. A 2012 study reckoned that between 190 and 1,200 chemicals of about 93,000 that it assessed could exceed the criteria for inclusion as POPs—with those criteria being persistence, bioaccumulation, toxicity and long-range transport.[47] Ten of those, the authors wrote, are "high-production volume chemicals".[48]

One group that has for now been dealt with only minimally under the Stockholm Convention are the perfluoroalkyl and polyfluoroalkyl substances, known as PFAS, with the US Environmental Protection Agency (EPA) calculating there are more than 9,200 of these synthetic compounds.[49] Within the PFAS group, only PFOS and PFOA are currently listed as POPs under the Stockholm Convention, although the convention's expert committee has recommended that PFHxS be listed as a POP. Other PFAS chemicals are also in line for inclusion. In mid-2021 Canada nominated long-chain PFCAs, their salts and related compounds for addition to the Stockholm Convention,[50] with the convention's POPs Review Committee agreeing in early 2022 that they met the criteria for POPs. This should move them forward to the second stage in the three-stage listing process that in several years might see them banned globally.[51] (The committee also agreed action was needed on toxic plastic additives UV-328 and Dechlorane Plus, as well as on medium-chain chlorinated paraffins [MCCPs], which are produced in huge quantities and used as flame retardants in plastics and numerous industrial applications.)[52]

The resistance of many PFAS to heat, oil, water stains and grease have seen them used for decades in an array of household and industrial products, including firefighting foam, waterproofing for clothing, and grease- and water-resistant food packaging, as well as in non-stick cookware, cosmetics, sunscreens, artificial grass (for properties like low-friction) and electronics (for properties like flame retardance).

The two most notorious PFAS are PFOA (once used to make Teflon non-stick cookware coatings) and PFOS (precursors of which were used in 3M's Scotchgard coatings, and which is now used mostly in industrial processes like metal-plating), both of which have been phased out for domestic manufacture in the US.[53] In the body, many PFAS bind to proteins; many are carcinogenic, harmful to the immune system and damaging to the hormone systems of humans and animals. Both PFOS and PFOA are among the PFAS that have been found in measurable levels in ocean-based plankton[54] and ocean waters.[55] A study, for instance, of 30 surface seawater samples taken from the North Pacific to the Arctic Ocean found PFCAs (which are a subset of PFAS that includes PFOA[56]) in more than 80% of them.[57]

"If that doesn't ring an alarm bell, then I don't know what will—because we know that the PFAS are endocrine disruptors, we know they are reproductive toxins and, most importantly, we know they are immune toxins," says Dr Mariann Lloyd-Smith, senior adviser to the International Pollutants Elimination Network (IPEN), a global network of non-profits. "If you have something that adversely affects the immune system of living things, then that inevitably impacts all health issues."

Some PFAS dissolve in water, and many of those that end up in the ocean stay in a layer 50-200 metres deep.[58] Studies have also shown high concentrations of PFAS at the sea's surface, which is a microlayer (which is less than 50 µm, or 0.005 cm, thick) "where exchange happens between the atmosphere and the ocean, [and which] provides [a] vital habitat for biota, including the fish eggs and larvae of many commercial fishery species and their phytoplankton food resources".[59]

Some PFAS are consumed, some sink to the sediment and others in the depths rise to the

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surface and then enter the atmosphere as tiny droplets that can be carried vast distances. These sea-spray aerosols are reckoned to be the largest secondary source of many atmospheric PFAS, with effects, too, on climate.[60] While much research is still needed on their prevalence and impact on the ocean, studies show PFAS levels in the rainfall of the Great Lakes region of North America are 10-1,000 times higher than those of traditional legacy chemicals like mercury, PCBs and pesticides.[61]

In the meantime, PFAS continue to pollute the ocean, with firefighting foams an important source. Many defence sites, which regularly practise firefighting exercises, are known to be contaminated by PFAS. The US Defense Department, for example, is investigating nearly 700 military sites for potential PFAS contamination,[62] with the Environmental Working Group, a US NGO, stating that "tests have confirmed that PFAS chemicals have contaminated drinking water or groundwater on or near" 385 bases to date. Similar contamination of defence bases in other countries, including Australia, is also evident.[63]

With half-lives measured in years or even decades, not for nothing are PFAS known as "forever chemicals"

Many PFAS are not only ubiquitous; they are also nearly impossible for water treatment plants to remove.[64] Additionally, their carbon-fluorine bonds ("the strongest chemical bond in nature"[65]) ensure they are extremely stable, making many of them highly resistant to degradation once they are in the environment. Even those PFAS that do degrade often culminate in end-products that are still highly persistent PFAS. Many of the PFAS that have been studied—and most have not been tested for their potentially harmful effects—are known to stay in human tissue for years, with half-lives measured in years or even decades.[66] Not for nothing are PFAS known as "forever chemicals".

Despite this litany of toxic effects, most PFAS are legal to use—though that could start to change. In the US, the EPA has created a body that will work "to better understand and ultimately reduce the potential risks caused by these chemicals".[67] That work included removing and updating a "politically compromised" assessment of the toxicity of one type of PFAS—an indication that improper influence of chemical toxicity can be found even in the world's richest nation.[68]

In mid-2021 five European countries announced a proposal to restrict the "manufacture, placing on the market and use of PFAS" in the EU. The countries stated that failure to act would see the concentration of PFAS in the environment continue to rise, making their harmful effects hard to reverse.[69]

"Due to their water solubility and mobility, contamination of surface, ground-, and drinking water and soil has occurred in the EU as well as globally and will continue," Germany, Denmark, Netherlands, Norway and Sweden wrote. "It has been proven very difficult and extremely costly to remove PFAS when released to the environment. In addition, some PFAS have been documented as toxic and/or bioaccumulative substances, both with respect to human health as well as the environment."[70]

1.4 Heavy metals

Although the world has seen regulatory action at country and international levels in recent years to counter the damage done by some heavy metals, "the market for most heavy metals (including lead and mercury) is stable or increasing", UNEP notes in its Global Chemicals Outlook II report.[71]

In the public consciousness, lead and mercury rank far higher than many chemicals that pollute the ocean, including their metal peers like cadmium (used, for instance, in batteries and solar panels, as well as in plastics as a stabiliser and pigment), copper, chromium and manganese.

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For lead, 2021 was a landmark of a sort, as it saw this contaminant phased out of petrol for trucks and cars when Algeria announced that it had used up its stock of leaded petrol.[72] In the century in which lead was added to petrol, UNEP said, it had "contaminated air, dust, soil, drinking water and food crops" and caused heart disease, strokes and cancer, damaged human development and cut IQ by 5-10 points.[73] Banning leaded petrol, UNEP said, had prevented an estimated 1.2 million premature deaths annually, and saved the global economy nearly US$2.5 trn.[74]

Lead, however, still enters the ocean each year, along with other heavy metals like arsenic, cadmium and mercury. Deep-sea mining is one source of heavy metal contamination in the ocean, as the next chapter will show, and one that will become more critical as companies and governments look to exploit underwater reserves as land-based mineral deposits decrease.

Another source is the dredging of harbours and near-shore areas, which can release heavy metals trapped in sediments.[75] Untreated sewage is a third—the proportion of untreated sewage that enters the ocean from many lower-income countries, for example, is 80-90%, and it "often contains heavy metals such as lead, cadmium and mercury".[76] Industrial sectors, including land-based mining as well as oil and gas, are also key sources of heavy metals contamination, as is the burning of fossil fuels.

One key pathway for mercury exposure is from eating fish and shellfish that accumulate the metal through their diet, with studies showing that as many as 1.7% of children from subsistence fishing populations in Brazil, Canada, China and Columbia suffered cognitive impairment this way.[77]

Mercury has highly toxic effects on the nervous system, the immune system, the lungs and kidneys, and is especially dangerous for babies in utero and young children.[78] Mercury's effects are so devastating that the WHO classes it as one of its ten chemicals of major public health concern.[79]

1.5 Nutrients

This category includes fertiliser nutrients—nitrogen, phosphorus and potassium—as well as human waste and animal waste. When these nutrients contaminate the sea, it causes eutrophication, the rise of algal blooms that bring so-called red tides and the smothering of seagrasses by algae. The algae pull the oxygen out of the water, causing marine life, including fish, to die en masse, and resulting in deoxygenated dead zones.

This brings an environmental cost as well as an economic one, as there are fewer fish and other marine stocks (like oysters and crabs) available to catch. While eutrophication can occur naturally, most is caused by human activity—in part from wastewater treatment plants but also from the runoff from agricultural and urban land after rainfall.[80]

One of the most affected marine areas is the Baltic Sea, where a recent study found that "at least 97 percent of the region was assessed as eutrophied in 2011-2016"—mainly from the agricultural run-off of nitrogen and phosphorus fertilisers. While inputs of nitrogen and phosphorus have decreased in recent decades, large amounts of both still enter the Baltic Sea (in 2014 alone, 825,825 tonnes and 30,949 tonnes respectively). Most flowed in from the region's rivers (see chart), with the economic cost estimated at €3.8bn-4.4bn annually.[81]

We examine the broader cost of dead zones, as a case study in quantifying the economic impact of ocean chemical pollution, in Chapter 4.

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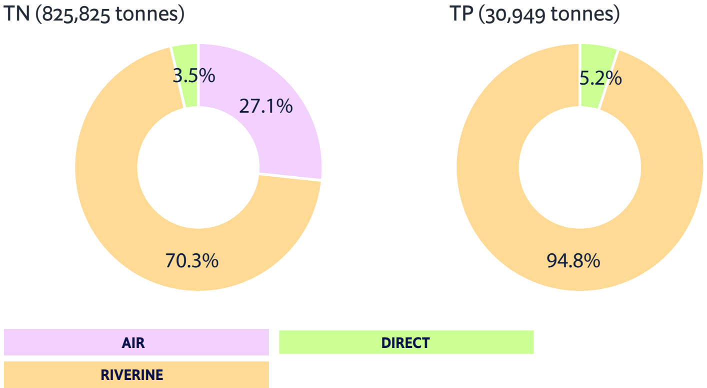
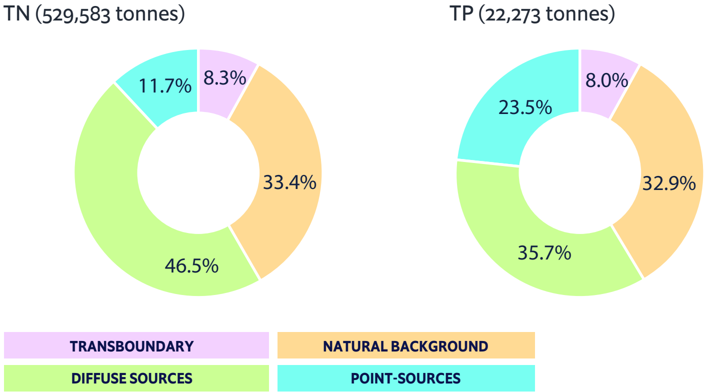
Baltic Sea—nitrogen and phosphorus flows

The sources for the Baltic Sea's nitrogen and phosphorus loads in 2014

Total load in 2014 to the Baltic Sea



Riverine load in 2014 to the Baltic Sea



Source: State of the Baltic Sea—Second HELCOM holistic assessment 2011-2016

1.6 Pesticides

The rise of industrial farming has seen demand for problem-solving chemicals—insecticides, herbicides and fungicides—climb fast. More than 1,000 pesticides are used globally,[82] helping to grow sufficient food for the planet's increasing population. Without pesticides, it has been estimated that the number of people at risk of malnutrition or starvation would rise from 800 million to 3 billion[83]—although, as the UN's Food and Agriculture Organization (FAO) points out, the use of organic methods for food production in non-industrialised nations has the potential to increase yields or at least to ensure that yields do not drop.[84]

The need for pesticides, then, is something that experts debate. What is not in question is that their very function as toxins means many are also highly damaging to human and animal health and the environment. The fact that more than half of the chemicals scheduled for elimination as POPs under the Stockholm Convention are pesticides shows that at least some of this harm is understood.

While much of that harm takes place on land, run-off and atmospheric deposition mean pesticides affect the marine environment too. In the Caribbean, for example, their use has resulted in fish die-offs, coral mortality and thinning eggshells, according to UNEP.[85] In Jamaica, UNEP noted that "an increase in fish mortality in coastal areas coincides with the period of the year when pesticides are applied on coffee plantations". Herbicides, in particular, damage seagrass beds and other aquatic vegetation.[86]

A healthier marine environment requires better managing pesticides, and eliminating the worst of them. Progress is slow. The Stockholm Convention lists fewer than 20 pesticides for elimination; the Pesticides Action Network lists 338 as highly hazardous

Australia's Great Barrier Reef, the world's largest coral reef system and one of its most important sanctuaries, is arguably the best-known example of a marine environment that has been damaged in recent years with large-scale coral die-offs and bleaching events. While pesticides and agricultural run-off are by no means only to blame (climate change is a key reason), some experts fear that large-scale pesticide run-off from sugarcane plantations and other crops are damaging the reefs, with studies showing pesticides and their associated degradation products are present in the river sources that flow into the sea,[87] and in the sea itself.[88]

What is clear is that a healthier marine environment requires better management and use of pesticides, and eliminating the worst of them. But progress is slow. While the Stockholm Convention lists fewer than 20 pesticides for elimination, the latest report from the Pesticides Action Network (PAN), a global network of more than 600 NGOs in 90 countries, lists 338 pesticides that it has concluded are highly hazardous (based on information from, for instance, the WHO, the EU and national agencies in the US and Japan).[89]

And, as PAN points out, the list is incomplete—in part because so little is known about the potential endocrine-disrupting properties of many pesticides. That holds true for their effects on ocean ecosystems too: a 2021 study that assessed the use of nearly 400 pesticides over the past 25 years, for instance, concluded that "despite decreasing total amounts applied and decreased impacts on vertebrates, toxicity—in particular to insects and aquatic invertebrates—has increased substantially". The authors added that their findings challenged claims that pesticide use was having decreased impacts on the environment.[90]

Meanwhile, pesticide use continues to climb in both absolute terms and in the amount used per hectare. In the three decades to 2019, according to the FAO, the world used 4.2 million tonnes of pesticides for agriculture in 2019—an increase of about 50%. By then, the amount used equated to 0.6kg for every person on the planet.[91] Herbicides account for just over half of the total used, while fungicides and insecticides account for most of the rest.

For its part, PAN, which is supported by hundreds of environmental health NGOs, wants the use of the 338 highly hazardous pesticides phased out globally by 2030.[92] Pesticides, PAN says, should be used only as a last resort, with studies from around the world showing that an agroecological approach—like using leguminous

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cover crops, compost, integrating livestock into cropping farms, and better timing of planting and weeding—are better for human health, yields and the environment.[93] They would also be far better for ocean health.

1.7 Plastics

The amount of plastic the world has manufactured since mass production started around 1950 is staggering: by 2015, that number was estimated at 8.3 billion tonnes, of which 2 billion tonnes was still in use.[94] The remainder was waste, with nearly 80% of that sent to landfills or polluting the environment, including the ocean, where it will take centuries to degrade. Even there, though, it will not disappear, but break down into smaller and smaller particles, with unknown effects on the environment.

It is perhaps not surprising, then, that public concern about plastics is high. In a recent survey about ocean health, 60% of people said that tackling plastic pollution was the top priority for restoring ocean health, ahead of dealing with chemical pollution and addressing climate change.[95] This concern is timely: in 2020 the world manufactured 367 million tonnes[96]—most of which was used in packaging and construction[97]—and production is forecast to double again by 2040.[98]

With such volumes, vast quantities of plastic have ended up in the environment. Between 1950 and 2015 an estimated 80% of the 8.3 billion tonnes manufactured went to landfills or was dumped, with some going into the ocean.[99] In 2016 the marine environment was estimated to hold about 150 million tonnes of all types of plastics, with eight million tonnes being added to that sink annually. That equates to a garbage truck of plastic being dumped in the marine environment every minute; unless action is taken, that volume is likely to triple by 2050.[100]

One reason plastics are such a problem is because most of what is made has zero value (or close to it). Added to this, plastics are cheap to make, and therefore disposable, and too few countries have sufficient ability to recycle or reuse what is generated.

However, the issue runs deeper. While the public perception of the damage that ocean-based plastics do often revolves around seals entangled in plastic fishing nets, whales choked with plastic debris, or turtles dying from ingesting plastic bags, much of the harm is done out of sight.

This is because people typically consider the problem to involve bags, containers, fishing gear, straws, cup lids and single-use packaging. However, these visible plastics—known as macroplastics—are just one element. Microplastics, which measure between 5mm and 1 micrometre (one thousandth of a millimetre), and nanoplastics, which are less than 1 micrometre, comprise the third group.

Some of these micro- and nanoplastics are added to products during manufacture (think microbeads for cosmetics, for example), while others come from the wear and tear of car tyres or clothing that is made from synthetic materials, with all of these known as primary microplastics. The other category is secondary microplastics, which have broken down in the natural environment from abrasion, wave action or sunlight.

Crucially for ocean health, though, this process is not the same as the decomposition that happens with, say, an apple. Instead, plastics become smaller and smaller particles, with the resultant microplastics and nanoplastics ending up in the food chain. The fish and crustaceans that eat these microplastics become malnourished, and the plastics and the chemicals attached to them then accumulate up the food chain as those animals are eaten by other predators.[101]

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Another challenge to ocean health is the fact that plastics pick up pollutants, including POPs, and transport them vast distances on ocean currents. That is one reason POPs have been found in the deepest parts of the ocean and at the polar extremes, far from any POP sources.

But perhaps the biggest concern is that plastics—which are largely derived from oil—contain not only those oil compounds that break down, but in almost every case have added chemicals (like BPA, phthalates or colourants) that leach into the environment. And these do not only have toxic effects of their own, but also have impacts that can worsen when, for example, the ambient temperature changes, or when they encounter other chemicals. More work needs to be done to understand many of these interactions—with the working assumption that our overuse of plastics is likely to have become highly dangerous for the ocean.

There is evidence that certain pharmaceutical products adversely affect marine organisms, and growing evidence that these chemicals are entering the food chain

1.8 Pharmaceuticals

A growing global population with more money to spend on healthcare means more pharmaceuticals being sold. At the same time, the growing demand for meat, including farmed seafood, means more pharmaceutical products are used on animals too.

While this is good news for pharmaceutical companies, it is clearly not the case for ocean health. There is evidence that certain pharmaceutical products in marine ecosystems adversely affect organisms, not least algae, which could have knock-on effects further up the food chain.[102] According to UNEP, evidence is also growing that these chemicals are entering the food chain, and even changing the sex functions of fish.[103] And at least one study has found that antidepressants affect how fish interact and hunt for food.[104] Beyond that, however, much about these effects is not known.

What we do know are the main routes by which pharmaceuticals enter the environment: during the manufacturing process; when used and excreted by humans or animals; and through the improper disposal of unused products that have, say, expired.

Wastewater treatment plants are central to the first two routes, but are largely unable to cope. As UNEP notes, these plants "mostly reduce solids and bacteria by oxidizing the water. They were not designed to deal with complex chemical compounds."[105] And because wastewater treatment plants cannot filter out the chemical compounds used for pharmaceuticals, "these chemicals seep into freshwater systems and into the ocean".[106]

Those consequences have been seen in studies across the world. A 2017 study of pharmaceutical levels in the Baltic Sea, for example, concluded that most entered the marine environment from municipal wastewater treatment plants.[107] It determined that the removal rate for most of the 188 pharmaceutical compounds it assessed was low: nearly half saw removal rates below 50%, with 16 of those compounds increasing in concentration.

Beyond the effects on marine life, many of which remain unclear, there are significant concerns that leakage of antibiotics into the environment—including the ocean—will lead to greater rates of antimicrobial resistance (AMR), which the WHO has identified as one of the ten key threats to global health.[108]

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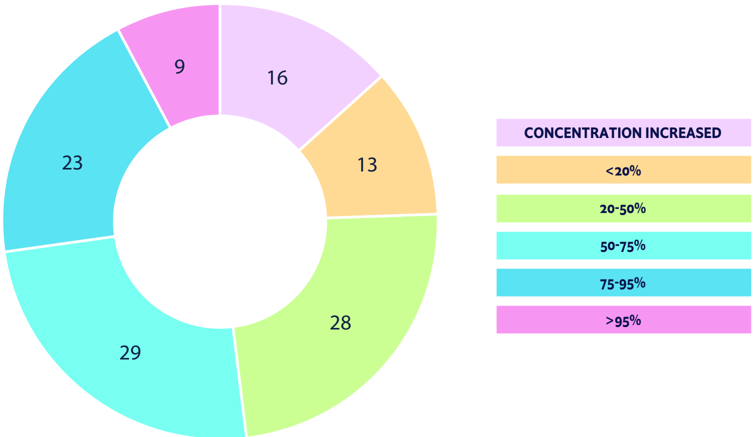
Proportion of pharmaceutical products removed in MWWTPs

Of the 118 pharmaceutical products assessed, just nine recorded removal rates greater than 95%, while 16 were more concentrated after treatment—an outcome that the researchers could not conclusively explain



Source: Pharmaceuticals in the aquatic environment of the Black Sea region: A status report, UNESCO and HELCOM

Triclosan, for example, is an antimicrobial agent with antibacterial, antifungal and antiviral properties that is used in hand sanitisers and a range of other personal consumer products. Evidence is growing that it and other biocides (along with heavy metals like cadmium and mercury) "contribute to the spread of AMR because they increase the selection for antibiotic resistance genes among bacteria".[109] In short, killing off weaker bacteria leaves room for more dangerous bacteria to flourish.

That could have catastrophic effects. A 2014 UK government report, for instance, forecast that superbugs would kill 10 million people worldwide annually by 2050, with an economic cost by that date of US$60-100trn.

1.9 Radioactivity

According to the International Atomic Energy Agency (IAEA), the first dumping of radioactive waste at sea took place in 1946 some 80 km off the Californian coast.[110] Since then, radioactive waste has entered the marine environment in a range of forms—encased within nuclear reactor pressure vessels, as solid radioactive waste and liquid radioactive waste, with 14 countries dumping it into more than 80 sites. It last took place in 1993.

In addition, accidents and losses at sea—including military vessels, nuclear weapons and cargoes of nuclear materials in transit—have added to the burden. On top of that are releases from accidents on land, the fallout from nuclear tests (both above ground and underwater), and the discharge of radioactive liquid effluent from nuclear power stations.

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According to the IAEA, most radioactive waste dumped at sea was either low-level solid waste (54%) or reactors with spent nuclear fuel (43%), with nearly 95% of the 8.5 x 10^4 terabecquerel (TBq) of deliberately dumped radioactive waste ending up in either the north-east Atlantic or the Arctic Sea off northern Russia (in roughly equal volumes). The remainder was dumped in the northwest Atlantic or the Pacific.

Activities of different types of waste dumped in the Atlantic and Pacific oceans and the Arctic Sea

The data covers from 1946, when the first dumping took place, to 1993, when this activity ceased. The unit of measurement is a terabecquerel.

Waste type	Atlantic	Pacific	Arctic	Totals	Percent of total activity
Reactors with spent nuclear fuel	0	0	3.7 x 10^4	3.7 x 10^4	43
Reactors without spent nuclear fuel	1.2 x 10^3	1.7 x 10^2	1.4 x 10^2	1.5 x 10^3	2
Low level solid waste	4.4 x 10^4	8.2 x 10^2	5.9 x 10^2	4.6 x 10^4	54
Low level liquid waste	<1 x 10^{-3}	4.6 x 10^2	7.6 x 10^2	1.2 x 10^3	1
Total	4.5 x 10^4	1.4 x 10^3	3.8 x 10^4	8.5 x 10^4	-
Percent of total activity	**53**	**2**	**45**	**-**	**100**

Source: Inventory of Radioactive Material Resulting from Historical Dumping, Accidents and Losses at Sea, IAEA (2015)

Radioactive decay means the inventory of radioactive material dumped at sea declined to about 2 x 10^4 TBq, and will further halve by 2050.

Aside from the deliberate dumping of radioactive waste, the marine environment is also contaminated by enhanced naturally occurring radionuclides (NORM), like uranium, radium and radon. These can also stem from offshore oil and gas processes and from discharges during phosphate processing, as well as accidental releases—like the Fukushima disaster in 2011, when thousands of tons of contaminated water entered the ocean (see box).

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Fukushima—an ongoing challenge for the marine environment

Apart from the terrible human toll, the catastrophic events of 2011 when a tsunami hit the Fukushima Dai-ichi nuclear power plant on Japan's east coast had a significant impact on the nearby sea. Radiation reached levels millions of times higher than before,[111] with iodine-131, caesium-134 and caesium-137 the most abundant radionuclides.[112]

The first two, however, have relatively short half-lives, and radiation levels dropped rapidly after a matter of weeks. Most of the iodine-131 decayed in a few weeks, and by 2021 scientists reckoned that 97% of the caesium-134 had decayed. Caesium-137, however, with a half-life of 30 years, will take far longer.[113] The high levels of caesium-137 and caesium-134 found in fish saw the government close local fisheries.[114]

In terms of the marine environment, there have been some positive developments since then. First, after 2015 only two fish out of thousands tested had levels higher than Japan's strict limits.[110] Second, although the facility still leaks radioactive materials into the sea, the current release rate "would take 5,000 years to equal the amount of caesium that entered the ocean in the first month of the accident". And third, radioactivity in the sea off Fukushima remains well within safe limits—since 2016, those levels have measured around 100 Becquerels per cubic metre. Although that is well above the pre-disaster level of 2 Becquerels per cubic metre, it is a vast improvement on the 50 million level seen in the days after the disaster.[116]

However, that looks set to change. In 2021 the government said it would release over 1 million tonnes of radioactive water that has been stored in about 1,000 tanks on the facility's site into the sea by 2023, angering China and South Korea. Filtering the water would in theory see the release of only tritium—a radioactive isotope of hydrogen considered relatively low risk.[117]

However, the tanks still contain high amounts of other isotopes. Dr Ken Buesseler, a senior scientist and marine radiochemist at the Woods Hole Oceanographic Institution, was reported as saying these were a concern, as they "are all of [a] greater health risk than tritium and accumulate more readily in seafood and sea floor sediments".[118]

Among the known contaminants are cobalt-60 and strontium-90, "which are much more likely to end up on the seafloor or be incorporated into sea life". And, Dr Buesseler said, the lack of information provided to experts like himself by TEPCO, the plant's operator, and the government of Japan mean other contaminants could be present too, including plutonium.[119]

The government and TEPCO, he says, must be open about what is in the water, and "demonstrate that they have cleaned up the non-tritium contaminants before they propose to release the water into the ocean".[120]

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Oil and gas activities discharge NORMs from so-called produced water. That is the water emitted from the oil and gas reservoir, which has low levels of radionuclides like lead-210, polonium-210 and radium.[121] However, there are limited data available outside the northeast Atlantic, making it impossible to determine trends.[122]

The risks to marine life of radioactive materials are significant, whether those elements are short-lived (like iodine-131, which has a half-life of eight days) or longer-lived, like caesium-137, with a half-life of 30 years. In either case, phytoplankton, zooplankton, kelp and other marine life can absorb radioactive elements, with those elements passing up the food chain, including to humans.[123]

Studies in the UK, for example, have shown that seals and porpoises in the Irish Sea, into which a UK nuclear power plant released radioactive material for decades, had significant concentrations of caesium and plutonium—with the former concentrated "by a factor of 300 relative to its concentration in seawater, and a factor of three to four compared to the fish they ate".[124]

The bulk of marine oil contamination is from land-based sources such as untreated waste disposal from industry; accidents involving oil tankers or oil rigs are also a prominent source

The accumulation of radiation depends on several factors, including the dose received, the duration for which it is received and the half-life of the element concerned. The consequences can range from genetic damage to cancers or death.

1.10 Oil

Much of the oil and gas extracted annually comes from marine sources, and the processes that are tied to exploration and production are one of the contributors to this category of marine chemical pollution. More prominent, though, are accidents involving oil tankers or oil rigs, with the 2010 Deepwater Horizon explosion in the Gulf of Mexico a prominent example.

The bulk of marine oil contamination, however, comes from land-based sources: more than half of the estimated 2.7 billion litres of waste oil entering the ocean each year is from land drainage and untreated waste disposal from industry.[125]

Regardless of their source, oil spills not only kill wildlife and destroy habitats, but they can also wreak a high economic cost for years through their impact on tourism and fishing, for example.[126]

Oil has about 10,000 components. Within these, a group of substances called polycyclic aromatic hydrocarbons (PAHs) are key polluters—in particular, so-called petrogenic PAHs. (A second type, known as pyrogenic PAHs, is generated from the incomplete burning of organic matter—for example, forest fires, volcanic eruptions, vehicle emissions and when burning waste.)

More than 100 PAHs have been found in the environment,[127] with many able to cause cancers, mutations and birth defects in animals. Adding to the problem is that PAHs are relatively stable: they do not dissolve easily and accumulate in sediment, often for decades.[128]

The chemicals used to clean up after oil spills are another contributor to marine pollution. After the 2010 Deepwater Horizon disaster, which saw about five million barrels of oil spilled, some 47,000 barrels of dispersants Corexit 9500 and 9527.203 were used to tackle the oil. These dispersants break down the oil into microdroplets that are more easily diluted; however, this also increases their bioavailability. Additionally, the chemicals that comprise the dispersal agent have been shown to be toxic to animals in laboratory tests, with effects on their immune, neurological, cardiovascular and pulmonary systems.[129]

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1.11 Household and consumer chemicals

The list of chemicals in the average home is long, featuring items like solvents and household cleaners, mould removers, laundry products, detergents, bleach, furniture polish, air fresheners, paints and varnishes, poisons (insecticides, for example) and batteries.

The list of household chemicals is long—solvents and cleaners, mould removers, detergents, bleaches, paints and varnishes, poisons and batteries. All contain harmful substances that can leach into the ocean

All contain substances that are harmful and that can leach into the ocean if improperly disposed of. However, this also occurs when these products are used as directed: windscreen-washer fluid, for example, ends up on the road and is washed by rain into drains, where it heads to rivers and the ocean; and laundry products and detergents go down the sink to wastewater treatment plants, where those exist, from where treated effluent is often pumped into the ocean.

Most homes contain other chemicals too. Many cosmetics, shower gels, deodorants, shampoo and sunscreens, for example, contain benzophenone or its derivatives oxybenzone[130] and dioxybenzone,[131] which are used for their ability to absorb UV-A and UV-B light. Oxybenzone is toxic to aquatic life and has long-lasting effects,[132] as are other substances added to some sunscreens such as octinoxate, 4-methylbenzylidene camphor and butylparaben.

Some countries have responded. In mid-2021, for instance, Thailand said it would ban the use of sunscreens containing these ingredients from its marine national parks due to their damaging effects on coral.[133] Hawaii and Palau have enacted similar bans.

Triclosan, a antimicrobial agent mentioned earlier, is used as a preservative in cosmetics,[134] is present in some toothpastes and is used in hand-sanitising products.[135] (The US FDA banned the use of triclosan in antibacterial hand soaps in 2016, though it is still used in many other consumer products.)[136]

Indeed, triclosan is so common that, according to the CDC, three-quarters of Americans have detectable levels of it in their urine. And because it can survive treatment in wastewater plants, triclosan can flow into the seas where it kills bacteria. In the Mediterranean, for instance, where water scarcity means dilution is less pronounced, one study concluded that "the potential environmental risk of triclosan is high".[137] Beyond its direct effect on bacteria in the ocean, triclosan has also been shown to impair the thyroid function in fish.[138]

1.12 Pseudo-persistent chemicals

Some chemicals dissipate relatively quickly in the aquatic environment, which should mean they have no long-lasting negative effects. Others, like POPs, for example, last far longer.

As seen earlier, the persistence of chemicals is a key parameter for assessing candidates for inclusion in the Stockholm Convention. How long is too long? For UNEP, a half-life longer than 60 days in water falls into the persistent category.[139]

Pseudo-persistent chemicals are an intriguing category. While their half-life is relatively short, the concentration of these substances keeps rising in the environment. That is because they are prevalent in products that are constantly in use. Pharmaceuticals are one example.

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Determining half-lives, though, can be tricky. The results found under laboratory conditions can vary significantly from those measured in the field, where conditions like temperature and sunlight can make a major difference, as found by an assessment of three pharmaceuticals (including carbamazepine, an anti-epileptic drug, and ibuprofen, a pain-reliever and anti-inflammatory drug).

One laboratory result for carbamazepine, for instance, calculated a half-life of just 3.5 days, while two field studies calculated that the half-life was 63 days and 1,200 days. Results for ibuprofen, on the other hand, found that the compound seems to break down faster in the environment than the laboratory results had indicated.[140]

If nothing else, the results show that much more research is needed to see how long chemicals persist in the environment versus their supposed persistence in a laboratory setting, not least as persistence is one of the key criteria for inclusion in the Stockholm Convention and other regulatory lists of hazardous chemicals.

1.13 Other chemical pollutants of concern

While the above categories incorporate some of the approximately 300,000 chemicals in use, they do not cover a range of others that pollute the ocean daily. One example is from the shipping of bulk hazardous cargoes, where sources for ocean contamination can vary. Shipwreck is one risk, while others include illegally dumping chemicals or washing tanks at sea after unloading cargo.

Another is dyes for clothing, with the garment industry a major polluter. Take blue jeans: these use synthetic indigo, which requires using large amounts of water (up to 100 litres per pair of jeans) and chemicals to dye clothing—some 40,000 tonnes of synthetic indigo, 75,000 tonnes of sodium hydrosulphite and 48,000 tonnes of lye annually.[141] Much of that ends up down the drain and then into the ocean, particularly in developing countries where many dyeing processes take place.

But, in a rare piece of good news, researchers in the US have developed a method that uses nanotechnology to dye jeans, cuts the amount of water required and eliminates the need for toxic chemicals. While the process has not yet been commercialised, researchers said it marks a positive step for an industry that manufactures billions of pairs of jeans annually.[142]

Regardless of the sources of ocean chemical pollution—and often these sources overlap—resolving this colossal challenge requires first understanding how the chain of accountability works. In a globalised world it has become increasingly hard to connect the links in the chain that sees chemicals end up in the ocean. As the next section will show, that chain starts with extracting the raw material.

Please see Notes for references

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Chemical pollution and marine biodiversity: What do we know?

There is no shortage of scientific gaps that need closing. At the broadest level, this requires improving our understanding of ocean ecosystems, the biodiversity of Earth's saltwater hydrosphere (from coastal zones to the deep ocean), the complex gradation zones that constitute the marine environment, as well as the crucial link between ocean and freshwater aquatic systems.

There is also a pressing need to monitor and study the ecological, biogeochemical, climate and other processes that are at the heart of all ocean functions.

When it comes to marine chemical pollution specifically, significant gaps remain in terms of how this affects biota, biodiversity and ecosystem functions, as well as the impact of different sources of marine chemical pollution (whether these enter the marine environment via, for example, atmospheric deposition or rivers).

And, as noted earlier in this chapter, there is an near-wholesale lack of knowledge of the effects that the hundreds of thousands of synthetic chemical contaminants might have on the marine environment—whether individually, in concert with other chemicals, and when factoring in the effects of climate change-related consequences like shifts in water temperature and salt concentrations.

In short, although the world's knowledge of marine chemical pollution in all its complexity has grown in recent years, it remains far short of what is needed. Such research would help to build a more complete understanding of how the ocean functions and how chemical pollutants are likely to affect those functions in the short and long term.

While much research is either under way or being planned, far more is needed. Gratifyingly, this has been recognised by the UN, which in 2021 launched its Decade of Ocean Science for Sustainable Development. The programme ("the science we need for the ocean we want") runs until 2030, and has as one of its seven goals "a clean ocean where sources of pollution are identified and reduced or removed".[143]

The programme identifies ten challenges, the first of which is to understand marine pollution and end it. This includes not only determining sources of contaminants and removing them or mitigating their impact, but also understanding "their potential impacts on human health and ocean ecosystems".[144] To that end, the UN is involving scientists, governments, businesses and others to map pollution, ensuring that it is eliminated at its source.

This push to understand the ocean better will doubtless pay dividends, and help to build upon the knowledge that has been gained in recent decades—and from which we can already conclude that chemical pollution constitutes a large-scale risk to ocean health, marine organisms, biodiversity and ecosystems.

Here, for instance, is what science can tell us about five key marine contaminants.

1. Microplastics and nano-plastics

Microplastics are an important conduit for marine chemical pollution. Along with nanoplastics, the impact that these small plastic particles have on marine biodiversity is a growing concern, not least because they can be transported vast distances while adsorbing chemicals and microbes.

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Plastics and microplastics can be ingested by fish, seabirds and marine mammals that mistake them for food, where they can get trapped in their digestive systems, causing malnutrition, reproductive impairment and death.[145] Microplastics can also damage cells and cause inflammation,[146] while nanoparticles can cross the gut lining and accumulate in animal tissues.[147]

Another concern is that the toxic chemical additives found in plastics can leach into the water and enter the tissues of marine organisms,[148] while microplastics and microfibres in the marine environment can transport and shelter hazardous microorganisms, including vectors for both human and non-human diseases such as E.coli.[149] Lastly, the species involved in harmful algal blooms that can destroy coastal ecosystems are able to colonise microplastics, thereby hitching a ride to expand their geographical range.[150]

2. Major chemical pollutants

These fall into three broad categories: toxic metals like mercury, cadmium and lead; manufactured chemicals including persistent organic pollutants (POPs), hydrocarbons, pesticides and organometals (including tributyltin, or TBT, an antifouling treatment for the hulls of vessels); and radioactive substances like nuclear waste. Some are long-term persistent polluters, while others are short term with a high impact.

Much chemical pollution affects marine biodiversity and ecosystems over a time scale of years, and often has a bio-accumulative effect in which chemicals become more concentrated further up the food chain. As such, they can cause the irreversible breakdown of local ecosystems.

Short-term events release high levels of pollutants that can have a lasting impact on marine organisms, biodiversity and ecosystem services, directly and indirectly affecting individual species through, for instance, local population die-off, genetic mutations or introducing new diseases.[151]

Research has shown some chemicals disrupt key functions of marine animals—their hormones, immune systems, ability to reproduce and behaviour—with contamination often starting in biota at the base of the food chain. UV filters in sunscreens, for example, have been shown to harm coral reefs and other aquatic ecosystems.[152] Other pollutants are taken up by phytoplankton, which are eaten by krill, which are in turn consumed by small fish and whales. Small fish are eaten by larger fish, which then provide food for seals, which are themselves eaten by polar bears or sharks.

POPs, for instance, damage the immune systems of polar bears and their ability to reproduce; they can also cause cancers.[153] And PCBs are so prevalent in some orca populations around the world that they can no longer breed.[154] No less importantly, chemical pollutants can kill off marine plant life, undermining and even destroying local ecosystems.

3. Harmful algal blooms

Life in the seas and ocean is founded on algae—the invaluable primary producers of oxygen and of fixed carbon, a vital nutrient that supports aquatic ecosystems. Free-living planktonic algal species dominate the ocean, with a small number accounting for the majority of global algal biomass. In coastal ecosystems, many algae emerge seasonally and are vital ecosystem components.

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Floating tropical beds of brown macroalgae, for instance, serve as habitats and nurseries for many marine species, fostering and maintaining tropical marine biodiversity. They also absorb CO_2, helping to mitigate global warming and acidification, buffering marine pH levels and maintaining optimal conditions for a wide range of shell-making marine organisms under a warming climate.[155,156]

Some marine algal species, however, produce powerful toxins and, under certain conditions, accumulate in high densities to form harmful algal blooms, or red tides. Although this can occur naturally, their frequency and scale have increased sharply in recent decades due to higher levels of pollutants (from wastewater as well as nitrogen and phosphorus from fertilisers), sea-surface warming and acidification. These harmful algal blooms disrupt food sources and alter marine chemistry, including by lowering dissolved oxygen levels to an extent that causes mass die-offs of plants, fish and crabs.

4. Introduced pathogens

This refers to a range of bacteria and viruses that are normally land-based but enter the marine environment through, for example, sewage effluent or agricultural run-off.

Horizontal gene transfer can see these pathogens introduce harmful new genetic traits into indigenous marine microorganisms, thus increasing their virulence and capacity for antimicrobial resistance.[157] Studies have shown that the more polluted the seawater, the more likely it is that these pathogens can survive.[158]

5. Less-studied technology-critical elements

The final group covers chemicals and elements used in new technologies in electronics, defence and related industries. These include trace metal elements such as niobium, tantalum, gallium, indium and germanium, as well as rare earth elements like neodymium, gadolinium and ytterbium.

Although some studies have been carried out (or are being carried out) on some elements, much about their effects on the marine environment remains unknown. A 2019 study, for example, noted that, while the geochemical behaviour of elements like gallium, indium and germanium was well constrained, there was very little understanding on the chemistry of these elements in coastal waters. That makes assessing their status in environmentally impacted coastal areas extremely challenging.

In addition, although concentrations of some elements have been reported in several organisms, there is little information on how they might harm certain types of marine organisms, their potential to be bio-accumulated through the food web (as mercury is, for instance) or their safety threshold in the marine environment.

Conclusion

The UN Decade of Ocean Science for Sustainable Development should give a significant boost to our knowledge of numerous facets of the marine environment, not least in terms of the effects that marine chemical pollution has and the steps needed to remedy it. While the programme will surely advance scientific knowledge of the ocean, its existence is a clear reminder that there is much that we still do not know—and that far more work is needed before we have a full understanding of the complex and vital role that the ocean plays.

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