OCEAN POLLUTANTS GUIDE
TOXIC THREATS TO HUMAN HEALTH AND MARINE LIFE

PREPARED BY
Mariann Lloyd-Smith, PhD
Joanna Immig B.App.Sc

October 2018

NTN NATIONAL TOXICS NETWORK

IPEN a toxics-free future

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ACKNOWLEDGMENTS

Thank you to all those who commented and edited. Thank you to John Wickens for providing many of the photos in this guide.

IPEN is a network of non-governmental organizations working in more than 100 countries to reduce and eliminate the harm to human health and the environment from toxic chemicals.

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The National Toxics Network (NTN) is a community based network working to ensure a toxic-free future for all. NTN was formed in 1993 and has grown as a regional network giving a voice to community and environmental organisations across Australia, New Zealand and the Asia Pacific region.

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IPEN gratefully acknowledges the financial support provided by the:

- Government of Germany;
- Government of Sweden;
- Government of Switzerland; and
- Other donors that made the production of this document possible.

The expressed views and interpretations herein shall not necessarily be taken to reflect the official opinion of any of the institutions providing financial support. Responsibility for the content lies entirely with IPEN.

This guide is an educational tool of the IPEN Toxics-Free Sustainable Development Goals Campaign.

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EXECUTIVE SUMMARY

Marine pollutants are impacting the health of our oceans, their inhabitants and those dependent on oceans for food, culture and their very survival. Everyday an ever-increasing cocktail of intentional and unintentional chemical releases, as well as an unrelenting tidal wave of wastes, particularly plastic waste, enters our waterways and the marine environment.

Ocean pollutants include persistent organic pollutants (POPs), endocrine disrupting chemicals (EDCs), mercury and heavy metal compounds, pesticides, pharmaceuticals, oil, plastic wastes and their related chemicals (e.g., BPA, phthalates), personal care products and other industrial and agricultural emissions. We are only just becoming aware of the identity, volume and scope of many ocean pollutants. Their hazards and complex ecological interactions are still unknown.

Many ocean pollutants do not have human health data or environmental fate information, and our understanding of the long-term impacts of endocrine disrupting chemicals on the reproduction and behaviour of fish and other marine organisms is still in its infancy.

Chemicals enter the marine environment via atmospheric transport, runoff into waterways or by direct disposal into the ocean. It is estimated that 80% of marine chemical pollution originates on land. The vast majority of the global land surface is connected to the marine environment via river systems, so chemical and plastics pollution of rivers is inextricably linked with ocean pollution.

Since the 1950s, de-oxygenated or "dead zones" in the ocean have quadrupled as a direct result of climate change, pollution and warming waters. Dead zones now occupy an area the size of the European Union. Coastal sites with low oxygen, as a direct result of nutrient (nitrogen and phosphorous), organic matter and sewage runoff, have multiplied tenfold. Coastal ecosystems have changed drastically from human activities in a short period of time and the ecological impacts are immense.

The notion of a vast ocean with endless food supplies and a limitless capacity to absorb and "dilute" pollution is a deeply embedded cultural myth in industrialised cultures. It is also the cornerstone of regulatory systems that permit discharges of "safe" levels of individual pollutants into the environment. In reality though, the marine environment is exposed to a cocktail of toxic chemicals that interact with each other in unknown ways.

The "safe" level approach to pollution management also fails to protect oceans because there is a finite quantity of water on the planet and only so much pollution it can dilute, particularly if those pollutants are persistent, bioaccumulative and toxic substances.

Much of the world's waste, around 20 billion tonnes per year, ends up in the sea, often without any preliminary processing. With the world population projected to reach 9.7 billion by 2050, it is clear that the current levels of resource consumption and creation of waste and pollution cannot be sustained. Even some recycling is inadvertently recycling pollutants.

Chemical production is also growing steadily, at around 4% per year. Some 5,000 of these substances are produced in volumes exceeding over one million tonnes a year. The fossil fuel industry also has its sights set on a massive increase in production of chemicals and plastic into the future.

While there has been knowledge for decades about some persistent ocean pollutants such as PCBs, DDT and tributyl tin, more recently there has been a growing awareness of so many more pollutants, including the perfluorinated "forever chemicals" and others, that challenge the accepted idea of what persistent toxic chemicals are and how we should address them.

As the extent and impacts of the marine plastic pollution crisis continues to unfold, the role that microplastic pollution (pieces of plastic less than 5 millimeters in diameter) plays as a source of pollution itself, as well as a vector for concentrating other chemical ocean pollutants, is becoming clearer.

Plastic pollution is now documented in all marine environments, from coastlines to the open ocean, from the sea surface to the sea floor, deep-sea sediments and even Arctic sea ice. Microplastics are also found inside marine life such as krill, fish, molluscs, seabirds, sea turtles and marine mammals.

Recent investigation of the Great Pacific Garbage Patch (GPGP) found evidence that plastic pollution is increasing exponentially compared to surrounding waters and the GPGP is now estimated to cover an area of 1.6 million square kilometers.

The worsening impacts of climate change add another complex layer of urgency to addressing the growing problem of ocean pollutants. Climate change has already altered salinity levels, increased ocean acidification and eutrophication, changed water oxygen levels, and affected the adaptability of species.

Polar regions, once considered environmental sinks for many of the most persistent, bioaccumulative and toxic substances (PBTs), are fast becoming new sources of re-contamination to the world's oceans as the ice melts.

Climate change is influencing the rate at which toxic chemicals are released from materials and stockpiles, as well as altering the distribution of chemical contaminants in air and water through increased extreme weather events and other factors, such as partitioning. Climate change impacts are also affecting chemical degradation, bioavailability and toxicity, while changes in water acidity are devastating some marine organisms, corroding their skeletons and shells.

For healthy oceans, there needs to be a healthy food web, including bacteria, protozoa, phytoplankton, microalgae, seagrass, coral, zooplankton, shellfish, prawns, squids and fish. Today marine organisms from the largest to the smallest show signs of stress, disruption and damage from ocean pollutants.

Marine sentinel species such as the California sea lion, Atlantic Bottlenose dolphin, polar bear and the endangered West Indian manatee are already providing early warnings of the negative impacts from ocean pollutants.

Marine organisms exposed to chemical pollutants are impacted in multiple ways, including at the cellular, organism, population and community levels. Humans are also impacted by the exposure to seafood contaminated with chemicals such as POPs and PBTs as well as with mercury and microplastics.

Addressing ocean pollution requires deep changes to the way we live and consume. It is a vast and complex problem that will not be solved by business as usual and reliance on existing management practices and policies. Current regulatory systems are fragmented and do not address resource extraction, product design, manufacture, use, reuse and recycling within the framework of a true circular economy. The much-needed changes require political will and leadership.

The United Nations Sustainable Development Goal 14, Life Below Water, sets a target to prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution, by 2025.

For this to occur, multi-sectorial and multi-stakeholder approaches based on principles of good chemical management, that is: right-to-know, polluter pays, precaution and substitution, are required.

Policy responses must also adhere to the principles of social, environmental and intergenerational equity.

Actions that must occur as a minimum response include adoption and full implementation of current international ocean, climate and chemical conventions and programs; harmonized global standards for water quality; biomonitoring programs to inform governance; expanding and implementing extended producer responsibility programs; creating and implementing zero waste policies; pollution prevention while avoiding creating new problems; remediation and clean up; and, community awareness-raising, capacity building and empowerment.

The fossil fuel origins of plastic and chemical production pose complex and difficult challenges for all countries. The entire life cycle of current petrochemical-based production from raw materials extraction through to consumption and final disposal represents threats to the marine environment. Any solutions to address ocean pollution must tackle this.

We are all citizens of the sea and negatively impacted by the pollution of the oceans. All surface life depends on the health of the ocean. It produces much of the oxygen we breathe, stores the carbon dioxide we produce and regulates the weather we experience. While remote and subsistence communities, such as Arctic and Pacific Island peoples, already experience disproportionate impacts, due to their high dependence upon the ocean for their sustenance, health, culture and human rights, ultimately, the health of the ocean and the pollutants that degrade it affect us all.

CHAPTER 1
INTRODUCTION TO OCEAN POLLUTANTS

Marine pollutants are threatening the health of our oceans. Everyday an ever-increasing cocktail of intentional and unintentional chemical releases, as well as the unrelenting tidal wave of wastes, particularly plastic waste, enters our waterways and marine environment.

Ocean pollutants include persistent organic pollutants (POPs), endocrine disrupting chemicals (EDCs), mercury compounds, pesticides, pharmaceuticals, oil, and plastic wastes and their related chemical compounds (e.g., BPA, phthalates), as well as other industrial and agricultural emissions. We are only just becoming aware of the identity and volume of certain ocean pollutants.

Ocean pollution is disproportionately impacting remote Arctic and Pacific Island communities who are highly dependent upon food from the ocean for their sustenance. It also poses a serious threat to their environment, food security, health, culture and human rights. Ultimately however, ocean pollutants affect us all.

THE GLOBAL OCEAN

The word "ocean" is derived from the Greek *Ōkeanos*, which means "the great stream encircling the earth's disc." The global ocean covers 71% of the earth's surface and contains 97% of the earth's water. The remaining 3% is found as water vapour in the atmosphere and water in rivers, lakes, glaciers and ice caps. Since the source of the majority of ocean pollution is land-based, it is critical to consider this part of the hydrogeological cycle and the role it plays in delivering pollutants to the ocean.

According to the first Census on Marine Life[1] , a culmination of ten years of research published in 2010, the global ocean is home to an estimated one million species, the majority of which are yet to be named and described. This baseline study discovered a rich and connected global ocean, but also found an ocean more altered by human impacts, such as climate change and oil spills, than previously realised.

We are all citizens of the ocean and not isolated from these impacts. All surface life depends on the health of the ocean, since half of the world's oxygen is produced by sea life. The global ocean stores fifty times more carbon dioxide than our atmosphere, and transports heat from the equator to the poles, regulating our climate and weather patterns.

OCEAN POLLUTION

The United Nations Joint Group of Experts on the Scientific Aspects of Marine Pollution defines marine pollution as the: "*Introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of sea water and reduction of amenities*."

The notion of a vast ocean with a continuous capacity to absorb and "dilute" pollution is directly challenged by the pervasiveness and impacts of the ocean pollution crisis we face today. There is the dawning realisation that in the blink of an eye, since the industrial revolution, the ocean as the "away" place where our industrial and domestic wastes can be disposed of and absorbed, has reached its limits.

The ocean is now throwing pollution back on our doorstep in the form of contaminated fish and seafood, entangled marine life, extensive plastic pollution, and expanding oceanic "dead zones."

De-oxygenated or dead zones in the ocean have quadrupled since 1950 as a direct result of climate change, pollution and warming waters. Dead zones now occupy an area the size of the European Union. Coastal sites with low oxygen, as a direct result of nutrient (nitrogen and phosphorous), organic matter and sewage runoff, have multiplied tenfold. Coastal ecosystems have changed drastically in a short period of time from human activities and the ecological impacts are immense.[2]

Land-based atmospheric transport of toxic chemicals such as persistent organic pollutants (POPs) and heavy metals has contaminated the globe, including the world's ocean. Pesticide and fertiliser run-off from agricultural land, industrial releases, pharmaceuticals in sewage, leachate from landfills, mining activities, burning of fossil fuel and waste, oil spills and runoff from roads have contaminated streams and rivers, which eventually release their toxic load into the oceans of the world.

Added to this is the growing tsunami of plastic wastes entering our oceans every day. While plastics may take hundreds of years to break down, once in the marine environment, they undergo weathering and degradation into smaller and smaller pieces of plastic, which aids the sorption of other contaminants from seawater. These chemical contaminants can concentrate in or on the surface of microplastic fragments at several orders of magnitude higher than background levels in seawater.

OCEAN POLLUTION OUTLOOK

No consideration of ocean pollutants would be complete without casting forward and anticipating what the problem might look like in the future if business as usual continues.

The world population is projected to reach 9.7 billion by 2050.[3] With population growth comes increased consumption of resources, waste production and further environmental degradation. Indicators of severe environmental stress are already evident and the risk of irreversible changes with far-reaching consequences, such as biodiversity loss and rising greenhouse gas emissions, is increasing.

Most of the world's megacities with more than 2.5 million inhabitants are in coastal areas. Much of the world's waste - around 20 billion tons per year- ends up in the sea, often without any preliminary processing.[4] As industrialisation and urbanisation intensifies, and plastic production and use escalates, without intervention we should expect even more serious pollution and deterioration of marine ecosystems.[5]

Both developed and developing economies face a great dilemma in reorienting growth and development in the direction of a more harmonious interaction with nature. The challenge is intensified by the uneven stages of development around the world. The rate of natural resource use and fossil fuel consumption characteristic of developed economies, and that expected of developing economies, cannot be sustained.

While the spotlight has been on reducing fossil fuels in the energy production space, the fossil fuel industry also has its sights set on a massive increase in production of chemicals and plastic into the future.

An estimated 100,000 chemical substances are commercially available and this number is rapidly expanding. Almost 5,000 of these substances are produced in volumes exceeding one million tonnes a year. While OECD countries are still the biggest producers of chemicals, output is increasing more than twice as fast in India, China, Brazil, South Africa and Indonesia.[6] Chemical production is growing steadily, at around 4% per year.[7]

The shale gas boom in the United States has made plastic feedstock very cheap, driving investment and increased production. U.S. industry alone is planning to invest over $164 billion by 2023, with many new ethane "crackers" designed specifically to produce ethylene from fracked ethane.[8] Ethylene is the critical feedstock for polyethylene, polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polystyrene. Additionally, propane from natural gas is used to make propylene and ultimately, polypropylene. Plastic production is expected to double over the next 20 years to 600 million tons per year.

Against this backdrop, community awareness of marine plastic pollution has been growing, driven by images of once pristine, remote beaches now seen strewn with plastic pollution. Images of dead wildlife with their stomachs full of plastic debris and entangled sea creatures have proliferated in the media and shown us first-hand the damage plastic pollution is causing.

There is however, far less awareness about the impacts of marine chemical pollutants and their nexus with plastic pollution. This is partly because chemical pollutants are largely "invisible" to the naked eye and their health and ecological consequences are complex and long-term.

OCEAN POLLUTION SOURCES

It is estimated that 80% of marine chemical pollution originates on land.[9] The vast majority of the global land surface is connected to the marine environment via river systems, hence the chemical pollution of rivers is inextricably interlinked with ocean pollution.

More than 100,000 chemicals are used commercially. Many enter the marine environment via atmospheric transport, runoff into waterways, or direct disposal into the ocean.[10]

Industries such as manufacturing, waste incineration, coal fired power stations and fossil fuel production release tonnes of hazardous emissions into the atmosphere every year.[11] Combustion of fuels in automobiles, factories and smelters introduces hydrocarbons and metals into the environment.

Many of these pollutants eventually end up in our oceans through atmospheric deposition. Atmospheric deposition occurs when contaminants, once airborne (either as vapour or attached to dust particles), are washed out by rain or snow, or fall back to earth in the colder climates.

Industrial facilities, pulp and paper mills, sewerage outfalls and mining activities contribute toxic chemical runoff directly into the aquatic environment, while toxic chemicals, such as spilled oils and fuels, are washed off streets, down storm drains, and into water bodies. Inadequate waste management also results in significant releases of hazardous chemicals to air, land and water.

Oil pollution, which can degrade or destroy marine ecosystems, results from oil tanker disasters, urban-based runoff, spills and operational discharge of fuel from boating traffic and port operations. Discharge associated with boats constitutes 24% of the total amount of oil in the ocean, with 8% of overall oil ocean pollution a result of spills during transportation or production.[12]

River networks facilitate the transport of terrestrial sediments, organic carbon, nitrogen, heavy metals, oil, pesticides, sewage, plastic wastes and various other industrial waste and contaminants into the oceans.

Similarly, the terrestrial environment contributes between 64% and 90% of the microplastic debris in the oceans.[13] An assessment of river catchments in northwest England found catchment-wide patterns of microplastics in channel bed sediments at 40 sites across urban, suburban and rural river catchments. After severe flooding, resampling found that up to 70% of the microplastics were flushed from the river.[14]

Larger rivers export disproportionally more plastic from their catchments than smaller rivers, and plastic concentrations in rivers vary over seven orders of magnitude. Plastic loads and concentrations in rivers vary depending on the characteristics of the catchment, such as urban land use and population density, both of which are indicators of plastic concentrations.[15]

The top ten rivers with the highest loads contribute approximately 90% of the total river-driven plastic inputs into the ocean. In order of their plastic concentration loads, the rivers are: Yangtze; Indus; Yellow River; Hai River; Nile; Meghna; Pearl River; Amur; Niger; Mekong.

Plastic pollution is now found in every marine habitat, including estuaries, the breeding grounds of many species of fish and marine organisms. It is one of the most serious threats to ocean ecosystems.[16] Research confirms that marine fauna, ranging from zooplankton to cetaceans, seabirds and marine reptiles, are all impacted by plastic pollution through ingestion and entanglement.[17] The chemicals found in and on plastic represent further risks to marine life, as may the biofilm communities growing on the plastic, which may include pathogenic, toxic and /or invasive species.[18]

One of the most shocking predictions is that "plastic rubbish would outweigh fish in the ocean by 2050 unless the world takes drastic action".[19] Exactly how much plastic is entering the ocean is still uncertain; however, recent estimates suggest between 4 -12 million metric tons of plastic washed offshore in 2010 alone. If nothing changes, this amount is predicted to increase by an order of magnitude by 2025.[20]

Plastic debris is now documented in all marine environments, from coastlines to the open ocean, from the sea surface to the sea floor, deep-sea sediments and even Arctic sea ice.[21] The deepest plastic was found at 10,898 meters in the Mariana Trench.[22]

OCEAN GYRES AND "GARBAGE PATCHES"

Ocean gyres are places where large systems of circulating ocean currents occur and the wastes collected in their currents are called "garbage patches." There are numerous garbage patches in the ocean, big and small, and of varying composition.

The most well-known is the "great Pacific garbage patch" (GPGP) in the North Pacific gyre, in a region between Hawaii and California. Recent investigation[23] of the GPGP found evidence that the plastic pollution is increasing exponentially compared to surrounding waters.

The size of the GPGP is now estimated at 1.6 million square kilometers. While garbage patches contain visible debris, much of the plastic is actually smaller pieces of microplastics and nanoplastics in the upper layers of the water column not immediately visible to the naked eye or satellites.

MICROPLASTIC POLLUTION

All of the world's oceans are contaminated with microplastics.[24] A current estimate for the number of plastics in the ocean, the majority of which are microplastics, is five trillion, weighing more than 250,000 tons.[25]

As the marine plastic pollution crisis continues to unfold, the role that microplastic pollution (pieces of plastic less than 5 millimeters in diameter[26]) plays as a source of pollution itself, as well as a vector for other ocean chemical pollutants, is becoming more apparent.

Microplastics can include resin pellets, microbeads, polystyrene, plastic debris and cigarette butts, tiny threads and fibres from ropes, nets and synthetic clothing. Engineered plastic nanoparticles derived from post-consumer waste, as well as from nanoplastics via degradation, pose a specific challenge to the marine ecosystem.

Plastics become microplastics become nanoplastics, but they are all plastics. They are just of increasingly smaller size, allowing them to be more easily ingested and, in some cases, cross the gastrointestinal tract to be transported throughout a living organism.[27]

Nanoplastics and microplastics are also generated through industrial abrasion processes (e.g., air blasting), synthetic paints and car tires.[28] Wind and surface water run-off transports these particles to aquatic ecosystems. A further source is synthetic textiles, which release large amounts of microplastic fibres into waste-water during washing.[29]

Once in the marine environment, plastic polymers undergo weathering and degradation via UV solar radiation, chemical degradation and biodegradation. This weakens the plastic, causing it to become brittle and break apart when subjected to sea motion.

Similarly, when ingested, larger pieces of plastic can be broken down into smaller pieces in the gut of seabirds and other wildlife. For example, fulmars (*Fulmarus glacialis*), a type of seabird, are estimated to reshape and redistribute about 6 tonnes of microplastics annually.[30]

The degradation process aids in the sorption of toxic contaminants from the seawater, as nano- and microplastics fragments have a larger surface-area-to-volume ratio, and they can concentrate POPs and persistent bioaccumulative toxins (PBTs) at several orders of magnitude higher than in seawater.

Different coloured plastics and different types of polymers will sorb POPs from the environment differently. When ingested, the contaminated plastics may provide another pathway by which persistent chemicals can enter the marine food web.[31]

In order to understand and manage ocean pollutants, one must consider the role that river catchments are playing, not only in terms of delivering microplastics into the marine environment, but also in delivering pulses of toxic chemicals.

FRACKING AND PLASTICS

Hydraulic fracturing (fracking) and the U.S. shale gas boom has made plastic feedstocks very cheap, driving investment and increasing production. By 2023, the U.S. industry plans to invest over $164 billion to produce ethylene from ethane,[32] a fracking byproduct used to manufacture plastics like polyethylene, polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polystyrene. Propane from natural gas is used to make propylene and ultimately, polypropylene. Plastic production is expected to double over the next 20 years to 600 million tons per year. The conversion of natural gas into the petrochemicals that form the basis of plastic emits large amounts of carbon dioxide (CO2) and nitrogen oxide, exacerbating ocean acidification,[33] while the emissions from both the fracking and the production of plastic are toxic to human health and the environment.

CLIMATE CHANGE AND OCEAN POLLUTANTS

The impact of ever-increasing climate change has added another layer of urgency to the growing problem of ocean pollutants. Areas once considered environmental sinks for many of our most persistent bioaccumulative and toxic substances (PBTs) are fast becoming new sources of contaminants to the world's oceans.[34]

The semi-volatile nature of many POPs means that part of the global POPs burden generated at more temperate latitudes is transported to polar regions via atmospheric and oceanic processes. Global warming is altering the polar climate and increased temperatures are re-mobilising historical contaminants from "polar sinks" such as ice, snow, water, soils and sediments. These are fast becoming secondary sources of POPs to the atmosphere; a process already observed in re-emissions of hexachlorocyclohexanes (HCHs) from Arctic soil and ocean.[35]

Climate change is influencing the rate at which toxic chemicals are released from materials, stockpiles and contaminated sites. Higher temperatures increase the release of persistent toxic substances to air by changing their rate of partitioning between air and soil, and between air, water and sediments. It is also altering the distribution of chemical contaminants in air and water through increased wind, storm, flooding and extreme weather events.

In oceans, climate change has altered salinity levels, increased ocean acidification and eutrophication, changed water oxygen levels, and affected the nutritional status [36] of species and their adaptability. These changes, either alone or in combination, can enhance the toxic effects of chemicals on wildlife, increasing disease risks and species vulnerability.

Ocean acidification is one of the most pervasive impacts. As carbon dioxide concentration in the atmosphere rises due to the use of fossil fuels and other activities such as forest clearing, more of the gas is absorbed by the oceans, gradually making the water more acidic.

This increasing acidification directly affects fish, corroding their gills and attacking the calcium content of the skeleton.[37] It also affects their ability to spawn,[38] with hatchlings or small fry unable to withstand acidity. Other studies suggest more acidic waters interfere with their neurotransmitters, affecting fish behaviour.[39] Acidification also adversely affects a range of other sea life, including polyps, which form the basis of many coral reefs, tiny molluscs such as pteropods,[40] and krill,[41] on which so many fish, whales and bird species rely.

Climate change impacts are also affecting chemical degradation, bioavailability and toxicity.[42] For example, increasing water temperatures have been shown to increase the toxicity of commonly used pesticides to aquatic species.[43] Climate induced changes in water acidity have also been shown to affect the bioaccumulation of toxic substances in marine organisms.[44]

While the global community grapples with the problem of ever-increasing ocean pollution, it must, at the same time, address both the causes of climate change and its impacts on the fate and toxicity of chemicals.

CHAPTER 2

IDENTIFYING OCEAN POLLUTANTS

The marine environment is exposed to the combined impacts of a cocktail of toxic chemicals and wastes entering our waterways and oceans everyday. While environmental assessments are often carried out on individual pollutants, in reality marine life is exposed to multiple chemicals and other stressors, such as rising sea temperatures, sea acidity and deoxygenation, all at once.

There has been knowledge about some persistent ocean pollutants for decades. For example, in 1974, a paper describing PCB and DDT contamination of sea turtle eggs in the South Atlantic Ocean was published.[45] In more recent times, we have become aware of so many more pollutants, including chemicals that challenge our idea of what a persistent toxic chemical is and how we should view its impacts.

A chemical's ability to bioaccumulate in living things was once seen only in terms of how lipophilic or "fat loving" it was, allowing it to accumulate in the fatty tissue of organisms. However, fluorinated chemicals, which are fast becoming some of the most widespread ocean pollutants, have given us a new understanding of persistency. Instead of accumulating in fatty tissues, they bind to proteins in the blood and the liver. The terminal breakdown products of the perfluorinated compounds, due to their strong carbon fluorine bond, resist further breakdown in the environment and are sometimes known as the "*forever chemicals*".

Due to their incorporation in plastic polymers, chemicals that would not normally fulfil the criteria of persistency, e.g., phthalates, may remain in the marine environment, travelling to remote parts of the globe.

For many of the new ocean pollutants there is little, if any, information on their ecotoxicity or their impacts on human health. For some, even basic chemical information is lacking. Where there is information on toxicity, the chemical has usually been assessed individually. This singular pollutant approach to risk assessment inevitably results in an underestimation of both hazards and risk to the marine ecosystem.

The toxicological impact of chemical mixtures such as those we see in ocean pollution can have effects that are either additive, meaning individual chemical toxicities are added together, or synergistic, meaning chemicals multiply each other's toxicities.[46] Some persistent ocean pollutants have been shown to exacerbate the adverse effects of certain pesticides as well as other POPs.[47]

Even the sequence in which organisms are exposed to toxic substances can affect their toxicity.[48] For instance, in freshwater crustacean, researchers found different toxicity when the exposure order of two toxic chemicals was reversed, while maintaining the same dose.

There are significant data gaps in the knowledge about the identity and impacts of the complex mixtures of pollutants to which our oceans and marine organisms are exposed.

ENDOCRINE DISRUPTING CHEMICALS

Complex chemical mixtures in the ocean include many endocrine (hormone) disrupting chemicals (EDCs). As EDCs can mimic, compete with or disrupt the synthesis, transport and natural turnover of the hormones in living organisms, low-level, non-linear exposures to EDCs can lead to both transient and permanent changes to endocrine systems.

Evidence now points to exposure to EDCs playing a significant role in the worldwide loss of species and reduced population numbers of amphibians, mammals, birds, reptiles, freshwater and marine fishes and invertebrates.[49]

EDCs affect the reproduction, metabolism, development and immune function of wildlife. This can lead to increased susceptibility to infectious diseases, notably in marine mammals, or the development of hormone sensitive cancers.[50]

EDCs frequently have unconventional dose-response relationships called non-monotonic dose-response (NMDR).[51] This means that the effects of low-dose exposure cannot be predicted from high-dose exposures and in some cases low doses may actually cause greater impact than high doses for a specific response. Chemicals that demonstrate NMDR include plastic additives; detergents and surfactants; polycyclic aromatic hydrocarbons; heavy metals; pesticides; flame retardants; PCBs and dioxins; and dioxin-like chemicals.

The developing organism is particularly vulnerable to EDCs. At critical and sensitive developmental stages, any disruption to natural processes can change the structure and/or the function of a physiological system, sometimes irreversibly. This applies as much to marine mammals, fish and other species, as it does to humans.

In humans, endocrine-associated disorders include male reproductive impacts; cryptorchidism, hypospadias, testicular cancer as well as early female puberty; leukemia; brain cancer and neurobehavioral disorders; obesity, type 2 diabetes and cardiovascular disease.[52]

Current body burdens of EDCs such as PCBs, organochlorine pesticides and methylmercury in some fish-eating birds and marine mammal populations are at levels known to impact on breeding and the immune system. Higher rates of reproductive problems are found in animals with higher exposure to EDCs.[53]

TRIBUTYL TIN AND IMPOSEX

The most infamous story of EDCs in the marine environment is the impact on marine molluscs from exposure to tributyl tin (TBT) used in antifouling paint. TBT containing anti-fouling paints were applied to many vessels, often moored in estuaries and marinas, close to commercial shellfish beds.

TBT at very low concentrations damages the reproduction functions in a number of mollusc species, with some female marine snails developing male sex characteristics termed "imposex". The female whelks become sterile when the superficial excretory duct finally blocks the release of eggs.[54] In 1995, a survey of marine gastropods from the South Australian coast revealed 100% demonstrated `imposex'.[55] The sensitivity of marine molluscs has made it an important indicator species of endocrine disruption in the marine ecosystem.[56]

TBT can also activate a hormone receptor linked to the development of fat. Mice exposed during prenatal life grow fatter; a trait that could be transmitted to future generations.[57] While TBT antifouling paint has been withdrawn in most countries, the use of tin-containing plastic stabilisers continues, and they have also been shown to elicit immunological disorders in fish and induce imposex in gastropods.[58] Dibutyltin, a chemical used in the manufacture of polyvinyl chloride, or PVC, can alter glucose metabolism and increase fat storage in mice.[59]

MERCURY – AN UBIQUITOUS MARINE POLLUTANT

Mercury is a ubiquitous endocrine disrupting contaminant in the marine environment.[60] Thousands of tonnes of mercury are emitted and re-emitted each year to the atmosphere, with much of it finding its way into our oceans.

Sources of mercury pollution include atmospheric emissions from coal fired power generation, industries such as mercury-cell chloralkali plants and vinyl chloride monomer production, waste incineration, dentistry and small-scale gold mining (ASGM). In ASGM, mercury is used to separate the gold from unrefined ore, resulting in widespread contamination of waterways and communities.

Mercurial fungicides have been widely used in sugarcane farming in countries like Australia, contaminating the soil and adjacent waterways. Mercury-based skin whitening cosmetics are still available in Asia and African countries, and on the internet.

Poor waste management of discarded products containing mercury in developing countries, especially small island developing states (SIDS), has also resulted in mercury leaching into the soils and waterways, after the products have been landfilled.

The United Nations Environment Programme (UNEP) and the Arctic Monitoring and Assessment Program (AMAP) estimate total global mercury emissions to air from human-generated sources were approximately

2,063 metric tons for 2010. Fossil fuel combustion and small-scale gold mining accounted for more than two-thirds.[61]

In aquatic environments, inorganic metallic mercury is converted by bacterial organisms to the highly toxic methylmercury. Methylmercury has similar characteristics to POPs in terms of toxicity, persistence and bioaccumulation, and capacity for long-range transport. It is lipophilic and bioaccumulates in aquatic organisms, biomagnifying and reaching high concentrations in top order predators such as sharks, tuna and swordfish. Methylmercury levels in some fish species can be up to a million times greater than the levels present in the surrounding water.[62]

Mercury is toxic to birds at 4 parts per million (ppm), but has been reported in the Flesh-Footed Shearwater (a sea bird species) at 30,000 ppm,[63] indicating serious contamination of the marine food chain.

HIGH MERCURY LEVELS IN ASIA PACIFIC COMMUNITIES

Mercury monitoring in women of child-bearing age in Asia and the Pacific Region was jointly conducted by UN Environment, Biodiversity Research Institute (BRI), and IPEN.[64] Women from six countries participated in the study, providing a total of 234 samples for analysis at the BRI laboratories. The countries included Cook Islands, Kiribati, Marshall Islands, Nepal, Tajikistan, and Tuvalu. Women from small island developing states (SIDS) in the Pacific had very high levels of mercury in their bodies compared to other locations. Most Pacific Islanders' diet is rich in seafood and the large predatory fish they eat have high methylmercury concentrations in their flesh. Of the 150 Pacific Island participants in the study, 96% exceeded the reference level of 1ppm total mercury in hair,[65] compared to 21.4% of participants living elsewhere.

Human consumption of contaminated fish can lead to accumulation of mercury in the body, particularly in myelin, the fatty layers that coat and protect nerve fibres, and in the brain and spinal cord. Sampling for methylmercury has shown that in some developing countries, populations have been exposed to methylmercury through their fish-rich diet, even in countries where industrial pollution is uncommon.

Human exposure at high levels can harm the brain, heart, kidneys, lungs, and immune system of people of all ages. High levels of methylmercury in the bloodstream of unborn babies and young children can damage the developing nervous system and impact on their development, potentially reducing IQ. Communities dependent on seafood for their protein suffer a chronic, disproportionate and more dangerous dose of toxic mercury.

GLOBAL TOXIC POLLUTANTS: PERSISTENT ORGANIC POLLUTANTS

Persistent organic pollutants (POPs) are toxic carbon-based compounds that have contaminated the global environment, including the oceans and marine ecosystems. They persist in the environment for long periods and are capable of long-range transport. POPs bioaccumulate in human and animal tissue and can biomagnify in food chains, including the marine food chain.

The public first became aware of the impacts of POPs in 1962, when biologist Rachel Carson published Silent Spring. In her now world famous book, she highlighted the death of birds resulting from the aerial spraying of DDT to kill mosquitoes. Less than a decade later, the public became aware of another POP, dioxin, and its contamination of Agent Orange. The devastating impacts of Agent Orange used as a defoliant in the Vietnam War quickly became apparent among service personnel, the Vietnamese people and the global community. The impact of the dioxin contamination still continues decades later.[66]

POPs have been used extensively over the decades and large quantities have been released into the environment from agriculture, manufacturing, waste stockpiles and consumer products. Some POPs, like dioxins and furans, are also formed as by-products of industrial processes and incineration.

There are 28 chemicals, or groups of chemicals, destined for eventual elimination that are listed in the *Stockholm Convention on Persistent Organic Pollutants*. More chemicals are currently undergoing assessment by the POPs Review Committee, a United Nations technical group, for inclusion in the Convention. However, there may be upwards of 500 chemicals that exceed all four POPs criteria (persistence, bioaccumulation, toxicity and long range transport) and should also be considered as potential POPs. Approximately ten of these are high-production volume chemicals.[67]

Most POPs are semi-volatile in nature and after intentional or accidental release, travel the globe via water or air currents, sometimes hitching a ride on air born particles to reach even the most remote areas. POPs generated at the more temperate latitudes are transported to polar regions where the prevailing cold conditions diminish their volatility.[68] This results in their deposition in cold climate environmental sinks, such as snow, ice/sea-ice, soil, sediments, fresh water and oceans. This long-range environmental transport of POPs has resulted in the contamination of the global marine environment.

At coastal sites in northeast Greenland and eastern Antarctica, air, snow, sea ice, and seawater were tested for a range of POPs pesticides at the early stages of spring sea ice melting. Concentrations in seawater, sea ice and snow were generally greater at the Arctic site than the Antarctic. Under current climatic conditions, the Southern Ocean in the Indian Pacific sector still serves as an environmental sink for POPs.[69]

POPs have a high potential to bioaccumulate in aquatic biota, and particularly in Antarctic species, which generally possess lower elimination rates for these chemicals compared to temperate fish.[70]

CONTAMINATION OF THE ARCTIC FOOD WEB

The cold northern environment and fat-based food web of the Arctic favours the retention and accumulation of persistent organic pollutants (POPs). In a process known as global distillation, prevailing ocean and wind currents bring contaminants to the Arctic where they are subsequently trapped by the cold climate. Migratory animals are thought to offload their body burdens into Arctic ecosystems through excretion of wastes and during decomposition. The large rivers that empty into Arctic waters contribute as well. The Arctic appears to have a greater capacity for storage of POPs as compared to other regions; therefore, once POPs enter the Arctic, they are readily incorporated within biological systems and the Arctic food web. Arctic communities, and Indigenous peoples who rely on traditional foods (e.g., greens, berries, fish, and land and marine mammals comprising 80% of the diet of some Alaska Native peoples) often bear the greatest burden of chemical contamination. Even in minute quantities, POPs in our bodies can cause cancers, neurological and learning disabilities, hormonal (endocrine) disruption, and subtle changes to reproductive and immune systems. Children are especially vulnerable to exposures to these persistent chemicals. Exposures can occur before birth *in utero*, from breast milk, and during a child's early years of rapid growth and development.

Adapted from Alaska Community Action on Toxics
https://www.akaction.org/tackling_toxics/world/global_transport_toxics_arctic/

The effect of POPs on wildlife and the marine environment may vary considerably, but generally, POPs exposure in humans and marine organisms can cause serious health problems including certain cancers, birth defects, dysfunctional immune and reproductive systems, greater susceptibility to disease, and even diminished intelligence.

POPS IN THE MARINE ENVIRONMENT

Many POPs are found in the marine environment, including the following examples:

Polychlorinated biphenyls (PCBs) are a large group of highly toxic, endocrine disrupting industrial chemicals. From the 1930s until the 1970s when PCB production ceased, the total global production was approximately 1.3 million tonnes. Around 65% is thought to be in landfills or still in electrical equipment, but the other 35% is likely to be found in coastal sediments and open oceans.[71]

PCBs have been used extensively in electrical transformers, which often end up in landfill at the end of their life. They have been used as flame retardants in cables and other polymers, including in PVC (polyvinyl chloride) coatings. These coatings are sometimes removed from bridges and water infrastructure by abrasive blasting. This has resulted in large quantities of fine contaminated particles ending up in rivers and the sea.[72] Natural weathering, renovation, and volatilization of PCB-contaminated paint has led to increased levels of PCBs in harbour sediments, where high concentrations have resulted in government advice against consumption of certain seafood.[73]

PCBs pollute the wider marine environment, including in Antarctica and the Arctic. Concentrations of PCBs in certain fish from Antarctica are still rising,[74] while some of the highest PCB contamination occurs in Chinese coastal areas and estuaries.[75] PCBs have been measured in many marine creatures, even in the remote depths of the Mariana Trench. High PCBs concentrations were found in the bodies of shrimp-like crustaceans called amphipods living almost 10 kilometers beneath the ocean's surface.[76]

PCBs are potent toxic substances with adverse effects such as body weight loss, immunosuppression, hepatotoxcity, reproductive and developmen-

tal toxicity, and endocrine disruption. In aquatic species, PCBs can affect growth and reproduction. PCBs are also carcinogens.[77]

PCBs represent one of the world's worst toxic legacies. In 2001, the Stockholm Convention prohibited all Parties from intentionally producing PCBs but allowed the continued use of PCB-containing equipment such as transformers or capacitors through to the year 2025. Countries are not obliged to finally dispose of and destroy all PCB-containing waste until the year 2028. Unfortunately, even these targets are unlikely to be met. The contamination caused by PCBs has lasted for decades and is likely to last for decades to come. It has driven the initiation of scores of legal cases against the manufacturer, Monsanto, for the cost of clean-up and remediation.[78]

Dichlorodiphenyltrichloroethane (DDT) is an organochlorine insecticide banned from use in agriculture due to serious health effects in animals. DDT is an EDC. An estimated 1.5 million tonnes of DDT were used worldwide between the 1940s and 1970s, and it is still used by some countries to control malaria-carrying mosquitoes.[79] DDT is toxic to a wide range of aquatic life. Marine organisms concentrate DDT and its degradation product, DDE, by factors of millions as the contaminants move up the food chain, reaching toxic levels in fish or in the animals that eat them.

Although the remaining DDT use tends to be in the southern hemisphere, DDT concentrations are increasing in the northern hemisphere. While some eventually settles into the deep ocean where it is buried in sediments, research suggests substantial quantities of DDT are being released from the world's oceans. DDT is continually re-entering the atmosphere from the ocean, evaporating more rapidly from warmer, southern waters before being dissolved again in cooler seas in a recurring cycle.[80]

Hexachlorocyclohexane (HCH) is used as an organochlorine insecticide, e.g., lindane, which is an EDC. HCH has two isomers; beta-HCH and alpha-HCH.[81] They are neurotoxic (damaging nerve tissue), hepatotoxic (damaging liver cells), and cause immunosuppressive effects and cancer in laboratory animals.[82, 83]

Lindane is relatively volatile and hundreds of tonnes have entered the atmosphere every year;[84] much of which has then been deposited in the oceans. HCH isomers are the most abundant organochlorines in the Arctic Ocean, resulting in elevated residues of HCH isomers in marine mammals.[85]

Rivers flowing through areas where the pesticide lindane has been applied are important sources of HCH to the marine environment. Lindane is more water-soluble than most other organochlorine compounds, and is very stable in water with a half-life in sea-water of up to 200 days. It is mainly removed by adsorption to sediments and uptake by marine biota.[86]

HCH isomers are acutely toxic to aquatic organisms,[87] and water concentrations between 0.5 µg/l - 2.5 µg/l have proved lethal for fish, shrimp and crabs.[88] Beta-HCH was identified in nine kinds of molluscs from ten coastal cities along the Chinese Bohai Sea.[89]

Although lindane is less lipophilic than other organochlorine compounds, it does bioaccumulate and has a potential to biomagnify through the food chain. Sampling of the subsistence foods in Alaskan communities from 1990 to 2001 found total HCH concentrations were the highest in whale and seals, while high concentrations were also found in other marine species, e.g., walrus, whitefish and salmon.[90]

Hexachlorobenzene (HCB) was a widely used agricultural fungicide and industrial chemical. Significant stockpiles still exist. HCB is both a carcinogen and an EDC.[91] Small amounts of HCB are emitted during combustion processes. Once released, HCB is very resistant to biodegradation and is very persistent in water. HCB has a half-life from 2.7 to 6 years in water and in the atmosphere.[92]

In water, much of the HCB is adsorbed to particulate matter and sediments, which may help prolong its persistence in the marine environment. High levels of HCB were found in sediments offshore from one of Sydney's sewage outfalls in Australia.[93]

HCB has been detected in air, water and marine organisms in the Arctic region and poses a threat to seabirds and mammals through secondary poisoning and its strong potential for biomagnification.

Hexachlorobutadiene (HCBD) is primarily the by-product from the manufacture of the dry-cleaning fluids carbon tetrachloride and tetrachloroethene. HCBD is a persistent, bioaccumulative EDC. It is very toxic to aquatic organisms and has been found in marine waters and sediment. HCBD bioaccumulates in aquatic species and is found in Arctic marine invertebrates, fish, seabirds and mammals, including polar bears.[94] HCBD is classified as a possible human carcinogen by the U.S. EPA.[95]

Pentachlorobenzene (PeCB) is an industrial chemical, a flame retardant, a chemical intermediate and a fungicide. PeCB is also produced unintentionally during combustion and industrial processes, and is found as an impurity in some solvents and pesticides. It is a persistent EDC in the environment, highly bioaccumulative, and has been found in water samples collected in the North Pacific Ocean, and the Bering and Chukchi Straits.[96]

PeCB is very toxic to aquatic organisms and may cause long-term adverse effects in the aquatic environment. PeCB has been measured in many marine species in the Arctic and Antarctic regions, including fish, penguin eggs, seals, beluga whale blubber, polar bears, Arctic fox and predatory mammals.[97] When assessed using freshwater and marine amphipods, PeCB demonstrated the additive toxicity with other organic chemicals such as pyrene, an aromatic hydrocarbon present in coal tar.[98]

Pentachlorophenol (PCP) has been used as a herbicide, insecticide, fungicide, algaecide, disinfectant, a wood preservative and an ingredient in antifouling paint. PCP can break down or transform into pentachloroanisole (PCA). Both are hepatotoxic, carcinogenic, immunotoxic, neurotoxic and toxic to reproduction, and both are endocrine disruptors.

PCA is semi-volatile and one of the most abundant contaminants in the remote marine troposphere. The troposphere is lowest layer of Earth's atmosphere, and where nearly all weather conditions take place. Studies suggest that oceans may be a major continuous source to air.[99] PCP and PCA are found in air, water, soil and biota throughout the world, including in the marine environment and in remote regions. Both are highly toxic to aquatic organisms.

PCA contaminates marine species such as polar bears, ringed seals, Arctic char, landlocked char, lake trout and burbot in the Canadian Arctic. Residues have also been reported in aquatic invertebrates, fish, birds and mammals in Greenland. PCP has been found in the North Sea, coastal waters and estuaries of Germany, Netherlands and the U.K.[100]

Hexabromocyclododecane (HBCDD) is a flame retardant used mainly in expanded polystyrene (EPS) and extruded polystyrene (XPS) foam insulation, as well as in some textiles and electronic appliances.

HBCD is widespread in the global environment and has been detected in both freshwater and marine biota. Deposited in sediments at the beginning of the 1970s/1980s, HBCD is still present in significant amounts in marine sediments in Asia and in Europe.[101]

HBCD is very toxic to aquatic organisms [102] and has been found in fish in some European waters.[103] HBCD is ubiquitous in the Arctic environment and contaminates the Arctic food webs, including marine mammals such as beluga whales, fish, polar bears and seabirds. Some of the highest HBCD concentrations in marine mammals were measured in porpoises stranded on the Irish and Scottish coasts of the Irish Sea.[104]

HBCDD was also found in oysters from aquaculture farms where polystyrene buoys containing HBCDD were used.[105]

In mammals, exposure to HBCD can have potentially severe effects on the neuroendocrine system [106] and can affect offspring during early phases of development. HBCD can cause reproductive and developmental effects. Some effects are trans-generational and affect both parents and offspring.[107]

HBCD is listed in the Stockholm Convention for global elimination, with a five-year specific exemption for use in building insulation that should expire for most Parties in 2019.

Polybrominated diphenyl ethers (PBDEs) have been used as flame retardants and can be physically combined with materials such as plastics. The brominated flame retardants are neurotoxins; that is, substances that alter the structure or function of the nervous system. PBDEs also demonstrate developmental toxicity.

The main components of commercial octabromodiphenyl ether (OctaBDE) are hexabromodiphenyl ether and heptabromodiphenyl ether.[108] Tetrabromodiphenyl ether and pentabromodiphenyl ether make up the commercial product, pentabromodiphenyl ether (PentaBDE).[109]

Decabromodiphenyl ether (DecaBDE) is primarily used as a flame retardant chemical in the plastic housings of computers and TVs, making it a key toxic component of electronic-waste (e-waste). Both e-waste and recycled contaminated plastics provide ongoing sources of DecaBDE to the environment, particularly in their waste phase. Emissions of DecaBDE

during use are also substantial, making it one of the most prevalent flame retardant chemicals in the global environment.[110]

PBDEs are highly persistent in the environment. PentaBDE was still evident in marine sediments after 30 years.[111] PBDEs bioaccumulate in both aquatic and terrestrial species and have been measured in a variety of marine mammals, in seabirds, and in fish, including those from remote Arctic regions.[112] DecaBDE has been found in high concentrations in top predators.[113] The St. Lawrence Estuary beluga whales doubled their blubber concentration of PBDE congeners in less than three years,[114] while in the Antarctic, testing of krill and phytoplankton suggest PBDE concentrations are increasing over time.[115]

In aquatic organisms and mammals, PentaBDE has demonstrated reproductive and neurodevelopmental toxicity and effects on thyroid hormones.[116] OctaBDE has caused neurotoxicity and effects on the immune system in laboratory animals,[117] while DecaBDE has demonstrated reproductive and developmental toxicity, as well as neurotoxic effects. DecaBDE and its degradation products may also act as endocrine disruptors.[118]

PBDEs can act in combination and induce developmental neurotoxicity in both humans and wildlife at environmentally relevant concentrations.[119, 120]

Although highly persistent, some PBDEs can break down through a process of debromination. Higher bromodiphenyl ether congeners may be converted to lower, and possibly more toxic, congeners. For example, DecaBDE is shown to degrade to components of PentaBDE and OctaBDE.[121]

Per- and poly-fluoroalkyl substances (PFAS), also referred to as perfluorochemicals (PFCs), are a large group of industrial and consumer chemicals; many of which are endocrine disruptors, carcinogens and toxic to the immune system. PFAS have been widely used since the 1950s in household and industrial products due to their resistance to heat, oil, stains, grease and water. They are also used extensively in fire-fighting foams, which results in direct releases to the environment.

PFAS contamination has resulted in many lawsuits against the manufacturers over contamination of drinking water supplies and human health impacts. The manufacturer 3M settled a lawsuit with Minnesota's Attorney General Lori Swanson for $USD 850 million over PFAS contamination of the state's drinking water.[122] DuPont and Chemours Co paid $USD 671 million to settle about 3,550 personal injury claims arising from the leak of perfluorooctanoic acid PFOA (also known as C-8) from its plant in Parkersburg, West Virginia, U.S.[123]

In 2009, PFOS (perfluorooctane sulfonic acid) and its salts perfluorooctane sulfonyl fluoride) were listed in the Stockholm Convention. As of 2018, two others, perfluorooctanoic acid (PFOA) and perfluorohexane-1-sulfonic acid (PFHxS), are undergoing assessment by the POPs Review Committee.

However, there are between 3,000 [124] and 4,730 PFAS compounds,[125] many of which have been measured in marine environments. It is estimated that a "*single PFAS precursor compound can create 10 to 20 intermediate transformation compounds with functional groups quite unlike the initial compound.*" [126]

PFAS have wide usage in both industrial processes and consumer products. PFOS is still used in electronic parts, photo imaging, hydraulic fluids and fire-fighting foams. It is also the unintended degradation product of the pesticide sulfuramid.[127] PFOA and PFOA-related compounds are used to produce fluoropolymers for the production of non-stick kitchenware and food processing equipment. PFOA-related compounds are also used as surfactants and stain resistant treatments in textiles, paper and paints. PFOA can be formed from inadequate incineration of fluoropolymer plastics. PFHxS is used in consumer goods such as carpets, leather, apparel, textiles, papermaking, printing inks, sealants, non-stick cookware and in fire-fighting foams.[128]

PFOS, PFOA and PFHxS are all highly stable and, due to their strong carbon-fluorine bonds, very resistant to degradation. They are released from manufacturing processes and product use. Waste disposal also re-

sults in releases from wastewater treatment plants and outfalls as well as from landfills and contaminated soil.

PFOA residues have been found in industrial waste, carpet cleaning liquids, stain resistant carpets, house dust, microwave popcorn bags, water, food, and Teflon.[129]

PFOS use in fire-fighting foams has led to widespread contamination of ground and surface water, particularly around airports and defence bases. It is found in coastal and open ocean waters and biota in the Canadian Arctic, Sweden, the U.S. and the Netherlands. In a study of cities across China, PFOS was detected in all water samples, including surface and seawater, groundwater, municipal and industrial effluents and tap water.[130]

Once released, PFAS travel the globe via air, water and wildlife. They enter the environment as a direct release to surface waters or as air-borne dust particles. These releases then undergo long-range transport through a cycle of atmospheric deposition and volatilisation from marine waters.

Perfluoroalkyl carboxylic acids (PFCAs) were found in more than 80% of 30 surface seawater samples from the North Pacific to Arctic Ocean.[131] Another PFAS, perfluorobutanoic acid (PFBA), was the most prevalent compound found in the samples and perfluorooctanoic acid (PFOA) was the second most abundant. The concentration of individual PFAS in the surface seawater of East China Sea was much higher than other sampling seas.

Novel perfluorinated chemicals introduced as substitutes for PFOS and PFOA have been identified as potential global surface water contaminants. Perfluoroalkyl ether carboxylic and sulfonic acids (PFECAs and PFESAs) have been found in surface waters in China, U.S., U.K., Sweden, Germany, Netherlands and Korea, indicating ubiquitous dispersal and distribution in global surface waters. It is estimated that over 12 tonnes have been discharged to five of the major river systems in China.[132] China is a major producer of PFAS chemicals.

Eighteen PFAS were measured in beach sediment from Greek coastal areas with PFOA being found at the highest concentrations.[133] PFOA is found in water, air, sediment and biota from remote locations. PFOA-related compounds, once released, can degrade to PFOA either in the environment or in organisms. PFHxS is also globally distributed and has been detected in the Arctic and Antarctic air, snow, seawater, freshwater lakes and sediment, as well as in fish, seabirds, marine and terrestrial mammals.

While PFAS have substantial bioaccumulation and biomagnifying properties, they do not follow the classic pattern of other POPs by partitioning to fatty tissues. Instead, they bind to proteins in the blood and the liver.[134]

PFOS has been found in the wildlife of Alaska and the Arctic Circle,[135] particularly in high order species such as polar bears [136] and marine mammals such as seals.[137] PFCAs are also widespread in Arctic wildlife, accumulating in the blood, liver and kidneys of wildlife such as dolphins and polar bears,[138] birds [139], fish,[140] and other marine wildlife,[141] including turtles.[142] There is also evidence that for some PFCAs (C9 and C10), the concentrations found in the highly vulnerable polar bears have been doubling every 5 to 8 years.[143]

Fish from the Yangtze River and Tangxun Lake were analysed for PFAS. In addition to traditional PFASs (e.g., PFOS, PFOA, PFHxS, PFBS), over 330 other fluorinated chemicals were detected in fish livers.[144]

PFAS chemicals are toxic to aquatic organisms. Declines in survival rates of zebra fish (*Danio rerio*), following PFOS-exposure, were evident over generations.[145] Fish excrete some PFOA through the gills, leading to reduced uptake and bioaccumulation, but PFOA biomagnifies in marine mammals and can affect immune function in dolphins and sea turtles.[146] Aquatic organisms such as freshwater male tilapia, marine mussels and Baikal seals have demonstrated PFOA-induced oestrogenic effects, hepatotoxicity, inflammation, and chemosensitivity.[147]

PFOA can also exacerbate the adverse effects of certain pesticides,[148] with the toxicity of the herbicide paraquat doubled with PFOA pre-exposure. In mixtures, PFOS and PFOA showed complex interactive effects that changed from "*an additive to a synergistic effect, then to antagonistic effect, and back to a synergic effect again.*" [149]

Ecotoxicity data for PFHxS are limited, but neurotoxic and neurodevelopmental effects as well as endocrine impacts have been observed.[150] Polar bears from East Greenland have PFAS concentrations (including PFHxS) that exceed the threshold limit for neurochemical alterations.

In humans, PFOS is associated with thyroid disease, immunotoxicity, and reduced fertility. PFOA has been linked to kidney and testicular cancer and shown to cause thyroid disease, pregnancy-induced hypertension and high cholesterol. The effects of PFHxS in humans are found to influence the nervous system, brain development, endocrine system and thyroid hormone.

Examples of other PFAS chemicals that contaminate aquatic and marine environments include:

Perfluorononanoic acid (PFNA) is used as surfactant for the production of the fluoropolymer polyvinylidene fluoride. PFNA is also the breakdown product of precursor compounds such as fluorotelomer alcohols (FTOH), used industrially and in consumer products. PFNA is toxic to the developmental and immune systems. It has been measured in biota, including in marine mammals e.g., seals, dolphins and pilot whales in remote Arctic and Antarctic regions. High residues in Delaware Bay dolphins in the U.S. have been attributed to local industrial discharges.[151]

Perfluorobutane sulfonate (PFBS) is used widely in outdoor consumer products such as ski waxes, jackets, trousers, and boots. PFBS is highly resistant to microbial degradation and contaminates drinking water, sediment, rivers and marine biota e.g., humpback whales, dolphins and finless porpoises. PFBS is not well characterised toxicologically,[152] but has been shown to affect immune response in vitro, inhibit aromatase in human placental cells,[153] and alter heart rates and behaviour in zebra fish.[154]

Perfluorobutanoic acid (PFBA) is found in ski waxes, leather samples, and outdoor consumer products such as jackets, trousers, and boots. PFBA contaminates oceans, lakes, marine fish, rivers, and lakes, including in the Arctic. PFBA is found in wastewater effluent of sewage treatment plants.[155]

Short-chain chlorinated paraffins (SCCPs) are a group of widely-used industrial chemicals, including as a lubricant in metal cutting and as a flame retardant in some plastics, rubber, and carpets. They have also been used as plasticisers in paints, adhesives and sealants. SCCPs can have adverse effects on the kidney, liver and thyroid. They are toxic to aquatic organisms at low concentrations, disrupt endocrine function, and are suspected to cause cancer in humans. SCCPs have been found in children's products, such as toys and sports gear.[156]

Once in the marine environment, SCCPs are persistent and can remain in sediments for longer than a year. They have been measured in water, fish, birds, terrestrial and marine mammals in remote Arctic and Antarctic regions, indicating widespread contamination. High concentrations of SCCPs have been found in beluga whales and ringed seals, as well as in aquatic freshwater biota and various fish. Freshwater and marine invertebrates appear particularly sensitive to SCCPs.[157]

Endosulfan is an organochlorine POPs insecticide, which is genotoxic, neurotoxic and an endocrine disruptor. Endosulfan has been used on a variety of crops including coffee, macadamias, cotton, rice, sorghum and soy, and for the control of tsetse flies and ectoparasites of cattle, and as a wood preservative. Endosulfan occurs as two isomers: alpha- and beta-endosulfan, and both are highly toxic to aquatic invertebrates and fish. Endosulfan sulfate, a breakdown product, is more persistent and toxic than endosulfan isomers.[158]

Endosulfan persists in the atmosphere, sediments and water and has been detected in air, fog, sediments, fresh water and seawater, ice, snow and in wildlife, including in remote Arctic areas. Alpha-endosulfan was also found in 40% of samples of Antarctic krill.[159] In Greenland, endosulfan was measured in freshwater fish, seabirds, marine organisms like shrimp and crabs, and in marine mammals such as ringed and harp seals, minke whales, beluga and narwhal. Endosulfan has been undergoing net deposition to surface waters across all the regions of the Arctic Ocean since the 1990s. This air-water transfer appears to be its dominant pathway into the Arctic Ocean.

CURRENT USE PESTICIDES AS MARINE POLLUTANTS

Many ingredients in pesticide formulations still used today are potentially toxic to marine organisms, including the active constituents; the formulating chemicals like surfactants; and the impurities and metabolites. Pesticides enter the marine environment through sewage and storm water systems, rivers and streams, and as direct runoff, vapour and spray drift from agriculture, forestry, aquaculture, golf courses, parks and gardens, sports fields, utilities, roadside vegetation maintenance and residential properties.

Different classes of pesticides have different effects on aquatic life. Pesticides are known to cause death, cancers, tumours and lesions, reproduc-

tive inhibition and failure, suppression of the immune system, disruption of the endocrine system, and cellular and DNA damage. Pesticides also induce behavioral changes that can alter animal survivability, and changes in population dynamics and/or ecosystem imbalance. In a comparison of the toxicities of organophosate and pyrethroid insecticides to aquatic macroarthropods (crayfish and water bugs), pyrethroid insecticides were consistently more toxic than organophosphates.[160]

Other stressors in the marine environment such as temperature, carbon dioxide and oxygen levels, pH/acidification, pathogens and nutrient levels, all influence the effects pesticide exposures can have on the marine environment. Research has shown that chronic exposure to some chemicals (e.g., endosulfan, phenol, chlorpyrifos) can reduce a species tolerance to increased temperatures,[161] which is of concern in a world affected by climate change and global warming.

A study of crustaceans from agricultural streams showed increased toxicological sensitivity to sequential pesticide contaminants as a result of the synergistic interactions between pesticide and temperature stress. Individuals were 2.7-fold more sensitive to pesticide exposure than individuals from reference streams.[162]

Neonicotinoids were developed to replace organophosphate and carbamate insecticides. They are structurally similar to nicotine. Globally, neonicotinoids have been detected in a variety of water bodies, typically at concentrations in the low μg/L range.[163] Leaching into surface waters is one of the major concerns surrounding the extensive global use of neonicotinoids, especially in close proximity to water bodies.

A survey of surface waters was conducted in Ontario, Canada to assess neonicotinoids across fifteen sites consisting of nine streams near agricultural areas (drainage area <100 km2), and six larger streams/rivers (drainage area >100 km2).[164] The most widely used neonicotinoid insecticides, imidacloprid, thiamethoxam and clothianidin, were detected in over 90% of samples from over half of the sites surveyed during the three years of the study between 2012 and 2014.

Aquatic insects are particularly vulnerable to neonicotinoids and chronic toxicity has been observed at concentrations of imidacloprid below 1 µg/L. Acute toxicity has been reported at concentrations below 20 µg/L for the most sensitive aquatic species. Imidacloprid disturbs feeding of a freshwater amphipod crustacean (*Gammarus pulex*) at environmentally relevant concentrations. The effects on feeding rates were observed at concentrations two orders of magnitude lower than those causing mortality.[165] The growth of marine Mysid shrimp (*Americamysis bahia*) was impaired at 0.163 µg/L imidacloprid.[166]

Australian research investigated the impacts of pyrethroid and neonicotinoid insecticides on shrimp (prawn) aquaculture in northeast Australia.[167] Previous studies have shown that crustaceans, including commercially important species, can be extremely sensitive to these pesticides. Most shrimp farms are located adjacent to estuaries for access to saline water. Multiple land-uses upstream, such as sugar cane farming, banana farming, beef cattle and urbanisation, all impact water quality.

The study found that shrimp have sensitivities to imidacloprid, bifenthrin and fipronil at concentrations that are comparable to other crustaceans, and they are susceptible to imidacloprid and bifenthrin-induced feeding inhibition. The analysis of pesticide concentrations in shrimp farm intake waters suggests that at some locations, concentrations of all of these insecticides was high enough to cause negative impacts on growth and survival.

Organophosphates/Carbamates are used in both the urban and agricultural environments. They are toxic and block the enzyme acetylcholinesterase (AChE), which is essential to the functioning of neurotransmitters, the body's chemical messengers. Mixtures of carbamate and organophosphate pesticides have the same mode of action so their effects can be additive or sometimes synergistic.

Chlorpyrifos is a widely-used organophosphate and, as an EDC,[168] poses risks to aquatic organisms and ecosystems.[169] Exposures are mostly via direct uptake from water, although dietary exposure to chlorpyrifos can result from residues adsorbed to food items such as algae, macrophytes, and invertebrates, or from ingested sediment particles.


Chlorpyrifos is very toxic to crustaceans and sea urchins.[170] Several studies have reported effects of chlorpyrifos on behaviour of arthropods and fish. Sub-lethal effects on fish have measured changes in olfactory perception and behaviour. Most of the reported behavioural responses of fish to chlorpyrifos were related to its inhibition of AChE.

Chlorpyrifos bioaccumulates in aquatic organisms and its residues have been measured in the blood of free-ranging sea otters in Alaska and California.[171]

Glyphosate is one of the most widely-used herbicides in the world. Glyphosate residues are found in soil, air, surface water and groundwater,[172] and in marine sediments in several countries.[173, 174] Research into the persistence of glyphosate in seawater[175] found that it was moderately persistent in marine water under low light condition (half-life of 47 days at 25 degrees) and is highly persistent in the dark (half-life of 267 days at 25 degrees). AMPA, the major microbial metabolite of glyphosate, was detected under all conditions.

Glyphosate-based herbicides have demonstrated endocrine disruption.[176, 177] Glyphosate can alter microbial diversity and community composition,[178] and promote algal blooms.[179, 180] It has been reported that surfactants and wetting agents in commercial glyphosate formulations are themselves more toxic and /or increase the bioavailability and toxicity of glyphosate to non-target species.[181]

PESTICIDES AND THE GREAT BARRIER REEF

The Great Barrier Reef (GBR) is Australia's most well-documented case of contamination of a marine ecosystem by pesticides. Agricultural runoff into the GBR contains nutrients, sediments and pesticides that reach the marine environment via rivers, and is a significant stressor in the decline of coral cover across large parts of the GBR.[182] Agricultural runoff is an important stressor for other estuarine and marine ecosystems within the GBR world heritage area, including seagrass meadows and mangrove systems.

Pesticide residues detected in GBR rivers and creeks during flood events include the herbicides diuron, atrazine (and associated degradation products desethyl and desisopropyl atrazine), hexazinone, ametryn, tebuthiuron, simazine, metolachlor, bromacil, 2,4-D and MCPA, and the insecticides imidacloprid, endosulfan and malathion. Diuron, atrazine, hexazinone and ametryn were frequently detected at the highest concentrations at sites draining sugar cane. Diuron was also found in urban sampling since it is used to control annual and perennial broadleaf and grassy weeds on roads, garden paths and railway tracks.[183]

Research also found there is little potential for herbicide degradation in flood plumes that typically occur over a few weeks of the year.[184] Coastal fish in and near rivers discharging into the GBR lagoon are exposed to oestrogenic compounds associated with the pesticide run-off from sugar cane land use in the GBR catchment.[185]

Persistent herbicides are believed to pose one of the greatest risk to ecosystems and organisms in the GBR World Heritage Area.[186]

WASTE WATER AND PHARMACEUTICAL POLLUTION

There are major threats to water quality from inadequate treatment of both municipal and industrial wastewater. Many contaminants are not captured or destroyed in waste-water treatment plants and are found in the sewerage sludge and effluent, e.g., PBDEs[187, 188] and PFAS.[189]

Municipal waste water also releases pharmaceutical pollution to the aquatic and marine environments. Wastewater treatment systems are not designed to remove pharmaceutical residues and many of these compounds are released in wastewater effluent and consequently into the aquatic and marine environment.

Pharmaceuticals are highly active compounds that target specific biologic systems and can have adverse impacts on the physiology and behaviour of a variety of organisms even at low concentrations. These impacts can be exacerbated by chronic, long-term exposure to complex mixtures of pharmaceuticals in the environment.

Pharmaceutical residues have been detected in marine waters and sediments[190, 191] including in sea ice and coastal seawater. Data from over 71 countries identified 631 different pharmaceutical agents (or their metabo-

SUNSCREEN CHEMICALS AND CORAL REEFS

Some sunscreen lotions and personal-care products contain the ingredient benzophenone-3 (BP-3; oxybenzone), which protects against the damaging effects of ultraviolet light. Oxybenzone is an emerging contaminant of concern in marine environments, dispersed by swimmers and discharged in municipal, residential, and boat/ship wastewater. Between 6,000 and 14,000 tons of sunscreen lotion make its way onto coral reefs every year. While not all coral reefs are located near tourist areas, approximately 10% of global reefs are at high risk of exposure to sunscreen damage.[197]

Exposure of corals to oxybenzone can promote viral infections,[198] cause deformities in baby coral and can damage their DNA. It is also a skeletal endocrine disrupter. The endocrine disrupting effect makes baby coral encase itself in its own skeleton, leading to death.[199] The harmful effects of oxybenzone were observed even when it was highly diluted.

Hawaii has become the first state in the U.S. to pass legislation banning sunscreens containing oxybenzone and octinoxate, due to their significant harmful impacts on ecosystems.

lites and transformation products) in the environment, including antibiotics, nonsteroidal anti-inflammatory drugs (NSAIDs), analgesics, lipid-lowering drugs, oestrogens, and drugs from other therapeutic groups.[192]

The 61 most frequently encountered pharmaceutical compounds in river systems around the word have been detected at median concentrations ranging from 6.2 nanogram per liter (ng/l) to 163,673 ng/l.[193] As pharmaceutically active compounds are designed to be active at low concentrations, the presence of pharmaceutical residues in the environment even at low levels may adversely impact a variety of biological systems and have broader negative effects on ecosystems. Clams have been affected by the sewage effluent at two Antarctic research stations.[194]

One study found that chronic exposure of fathead minnow to low concentrations (5–6 ng/l) of the synthetic oestrogen 17α-ethinylestradiol (EE2, used as a contraceptive) in a freshwater lake produced reproductive failure. This resulted in the complete collapse of the fish population in that lake.[195] The direct effect of EE2 on the fathead minnow population and other small fish species in the lake was found to have corresponding indirect effects on the whole lake ecosystem due to disruption of the food web. The loss of these small fish resulted in a reduction in food supply for larger predator fish such as trout, leading to a corresponding loss of condition in these predator species.[196]

OIL POLLUTION

Oil pollution is one of the most conspicuous forms of marine pollution. While oil tanker or oil-rig disasters are often the most visible, oil pollution originates predominantly from diffuse sources. Oil enters the ocean via storm water drainage from cities and farms, untreated waste disposal from factories and industrial facilities, and unregulated recreational boating. It is estimated that approximately 706 million gallons (approx. 2673 megaliters) of waste oil enter the ocean every year,[200] with over half coming from land drainage and waste disposal.

Oil wastes also result from offshore drilling operations, such as the disposal of oil-based drilling fluid and produced water, pipeline leaks, well failures and blowouts. Some vessels sunk in World War II still contain large quantities of oil. In 2003, the U.S. government pumped 10 million liters of fuel from the hull of a U.S. tanker sunk in 1944 in the Western Pacific.[201] Small Pacific nations whose islands have many WWll wrecks cannot afford to address this source of oil pollution. Oil can also enter the environment through oil seeps from natural oil reservoirs.

Major oil spills cause enormous harm to marine biota and coastal fisheries. The immediate effects may be mass mortality and contamination of fish and wildlife, but long-term ecological effects can include disruption of the marine food chain and species population decline. Fish, marine mammals, sea turtles, amphibians, and seabirds are all affected by oil spills.

The hazards for wildlife include injuries such as smothering, deterioration of their insulating ability, for instance, in sea otter fur, and damage to the water-repelling abilities of bird feathers. Birds and marine animals swallow oil and are poisoned when they try to clean themselves or when eating oiled prey.

The toxic effects of exposure and ingestion can result in damage to reproductive systems and altered behaviours. Fish and shellfish can digest oil, but this can cause changes in reproduction, growth rates or even death.[202] Commercially important species such as oysters, shrimp, mahi-mahi, grouper, swordfish and tuna can suffer population decline and become too contaminated to be caught and safely eaten.

The Deepwater Horizon oil spill of 2010 resulted in the release of 5 million barrels of oil and approximately 47 thousand barrels of the dispersants Corexit 9500 and 9527.[203] The dispersant - based on the hydrocarbon solvent, ethylene glycol monobutyl ether, plus non-ionic and anionic surfactants[204] - has demonstrated toxicity in lab animals affecting the immune, neurological, cardiovascular, and pulmonary systems.[205] The Deepwater Horizon spill resulted in the die-off of tiny foraminifera (single

celled organisms with shells) in the path of the underwater plume, but these did show some recovery in the following years.[206] There was also evidence of abnormal skin lesions in fish[207] and apparent drop in population of some fish species.

POLYCYCLIC AROMATIC HYDROCARBONS (PAHS)

Crude oil consists of over 10,000 individual substances, predominantly hydrocarbons. The precise composition varies according to the place of origin, but will often contain contaminants like heavy metals.

An important constituent of crude oil is a group of substances called polycyclic aromatic hydrocarbons (PAHs). In the marine environment, PAHs are divided into two groups; pyrogenic and petrogenic. Pyrogenic PAHs are formed by incomplete combustion of organic material while the petrogenic PAHs are present in oil and some oil products. PAHs have been measured in mussels caged in the vicinity of Norwegian oil platforms.[208] Large-scale oil spills, pipeline leaks, and tanker accidents release PAHs direct into the marine environment.[209] PAHs emissions are also associated with unconventional gas production and incomplete combustion processes e.g., in engines. Mining of tar sands in northern Alberta, Canada released PAHs into the Athabasca River.[210]

PAHs do not dissolve easily in water and tend to accumulate or attach to sediment particles. This is a serious concern in lake and river sediment where many fish lay their eggs and where their embryos develop. PAHs can be slowly degraded by various bacteria and microbes in water and soil, but many microbes are affected by the toxicity of PAHs. This means that PAHs remain in the environment for long periods of time. In 1989, the Exxon Valdez tanker ran aground off the coast of Alaska, with up to 119 million liters of crude oil released into the coastal ecosystem. PAHs persisted in the coastal sediments for over 20 years.[211]

Some PAHs and/or their degradation products are highly toxic and can cause cancers, mutations and birth defects in fish and other animals.[212] Acute exposures to complex PAH mixtures in developing fish embryo caused cardiac malformations and oedema (build-up of fluid). Exposure of fish embryos to PAH-contaminated sediment resulted in long-term locomotor and behavioural alterations. Alterations in locomotion were also observed in the early larval stages.[213] Researchers have also expressed concerns about reptilian exposure to PAHs, citing deformities and developmental abnormalities, tumours, reproductive toxicity, hatching success, and survival.[214]

Seafood samples from the Mississippi Gulf Coast affected by the Deepwater Horizon oil spill were collected about one month after the first leak. Higher levels of total PAHs were detected in all four types of seafood samples.[215]

DREDGING AND OCEAN POLLUTANTS

Dredging involves the removal or relocation of sediment to improve marine access in harbours and ports, to remediate contaminated sediment, or for land reclamation activities.

Dredging inevitably re-suspends sediments in the water column, increasing turbidity. Turbid waters directly impact fish species when their larvae confuse sediment particles for food, resulting in less food eaten and far less larval survival.[216] The disturbed sediment smothers seagrass and shellfish beds, and also remobilises legacy contaminants.[217]

In ports and harbours adjacent to urbanised or industrialised areas, sediments can contain high levels of organic and inorganic contaminants. Dredge wastes can be contaminated with POPs, pesticides, petroleum hydrocarbons and PAHs, as well as a wide range of heavy metals, including copper, lead, chromium, cadmium, mercury and arsenic.[218]

The dredging and resultant turbidity spread the legacy sediment contaminants into the water-body. Suspended materials originating from land reclamation activities and dredging of shipping lanes is reported to be Singapore's biggest marine pollution issue.[219]

In 2010, Australia's largest dredging operation commenced in Gladstone Harbour within the Great Barrier Reef World Heritage area. The rapidly growing industrialised harbour is host to a wide range of industries. Heavy metals including copper, arsenic, nickel, chromium, aluminium, manganese and zinc, as well as PAHs and TBT, have been measured in the aquatic environment and biota of Gladstone Harbour.[220]

Over a three-year period between 2010 – 2013, more than 23 million cubic meters of seabed was removed from Gladstone Harbour, resulting in the destruction of large areas of inner harbour seagrass. This dredging coincided with a multi-species marine finfish and crustacean disease event.

Disease and mortality were observed in the harbour's aquatic species, including teleosts, elasmobranchs, crustaceans, molluscs, turtles, cetaceans, and sirenia (e.g., dugongs).[221] Significantly higher prevalence of ulcerative skin disease and parasitism were found in a range of species, while mud crabs demonstrated a much higher prevalence of shell lesions. High levels of parasitism were found in moribund and deceased green sea turtles from the Gladstone coastline.[222] In 2011, the mortality rates for dolphins, dugongs, and turtles around Gladstone were well above long-term averages.

MINING WASTES AND OCEAN MINING

The mining industry is one of the world's largest waste producers.[223] Most industrial-size mines dispose of their tailings (the by-products of hard rock mining operations)[224] on land. However, attention has recently shifted to other methods of tailings disposal, including submarine tailings placement (STP) and deep-sea tailings placement (DSTP). Marine disposal of mine wastes can have significant environmental impacts across a range of ecosystems.[225]

The composition of the tailings depends largely on the composition of the ore being mined and the process used to extract it. Generally, tailings consist of silt particulates, metals (including zinc, copper, arsenic, cadmium, mercury and lead), process chemicals (e.g., flotation agents), and high quantities of sulphides. The tailings water left after the filtering process of the mineral ores contains even higher concentrations of heavy metals.[226]

One of the main problems of mining is acid mine drainage,[227] which occurs when mine wastes containing sulphides are exposed to the atmosphere and water, as happens in mine tailings dams and storage areas. The resultant metal-contaminated water can disrupt growth and reproduction of aquatic plants and animals.

The difficulty and costs involved in managing mine wastes has driven interest in deep-sea disposal of tailings. The process usually involves discharging the waste as a finely ground rock slurry via an outfall to depths below 1000 meters.[228] Deep-sea tailings placement from terrestrial mines is a large-scale industrial activity taking place in the deep sea, yet the scale and persistence of its impacts on seabed biota are unknown.[229] However, research indicates that the dissolved heavy metals from tailings are likely to have a long-lasting influence on the deep-sea environment for up to 60 to 70 years.[230]

At sites sampled around Papua New Guinea, tailings deposition has had severe impacts on the deep-sea communities of benthic animals that live in the substrate of a body of water, especially in a soft sea bottom.[231] The abundance of these sediment dwellers (e.g., clams, tubeworms, and burrowing crabs) are substantially reduced across the sampled depth range (800–2020 m).[232]

While submarine tailings placement is still not practical for many land mines, the disposal method would be an integral part of deep-sea mining, which is gaining interest due to the decrease of land-based mineral reserves. Large quantities of mineral deposits are found on the sea floor (“sea floor massive sulfides” / SMS).

Modelling studies of the potential impacts of this form of mining suggest wide dispersal of sediment discharge with increased sedimentation thickness within 1 kilometer of the discharge site. Some particulate material could extend up to 10 kilometers from the site, settling at lower than natural rates. This may smother organisms and release toxic metals and other contaminants into the ocean. Toxic effects of plumes discharged at depth from dewatering are also possible, as is spillage of ore or hazardous material from the mining surface vessel or from hydraulic leaks.[233]

SMS mining is still at the prospecting phase yet exploitation of SMS deposits may occur in the foreseeable future in the western Pacific Ocean.[234]

MARINE PLASTICS CONTAMINANTS

The chemical toxicity associated with plastics found in the marine environment can be attributed to one or more of the following:

- Residual monomers[235] from manufacture present in the plastic or toxic additives used in the plastic that can leach out of the ingested plastic, e.g., bisphenol A (BPA), phthalate plasticizers, heavy metals;
- Toxicity of intermediate products from partial degradation of plastics, e.g., PAHs and styrene from polystyrene. Styrene is both a monomer and degradation product;
- Hydrophobic chemicals e.g., POPs present in seawater, which are absorbed or adsorbed, concentrating in the microplastic fragments.

The Norwegian Institute for Water Research released a comprehensive review of contaminants measured in plastic collected from the marine environment.[236] They include:

- Pesticides: DDT and related compounds, HCHs, Chlordanes, Cyclodienes, Mirex, Hexachlorobenzene
- Industrial chemicals and plastic additives: PCBs, PBDEs, Nonylphenols, Octylphenols, Bisphenol A, PFAS
- Byproducts: PAHs, aliphatic hydrocarbons

PLASTIC TYPES AND ADDITIVES

Plastics are typically complex cocktails of polymers, residual monomers and chemical additives. There are several broad classes of plastics, including polyethyelene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyvinyl chloride (PVC). Fluoropolymers like polytetrafluoroethylene (PTFE) and perfluoroalkoxy polymer (PFA) are used in many nonstick plastics and medical products.

Once released in the ocean, the environmental fate of plastics primarily depends on the polymer density. Polymers denser than seawater, like PVC, will likely sink, while those with lower density, such as PE and PP, will tend to float in the water column. Processes like biofouling (the colonisation of organisms) on the plastic surface increase the weight of particles.

Degradation, fragmentation and the leaching of additives can change the density of objects and their distribution along the water column.[237]

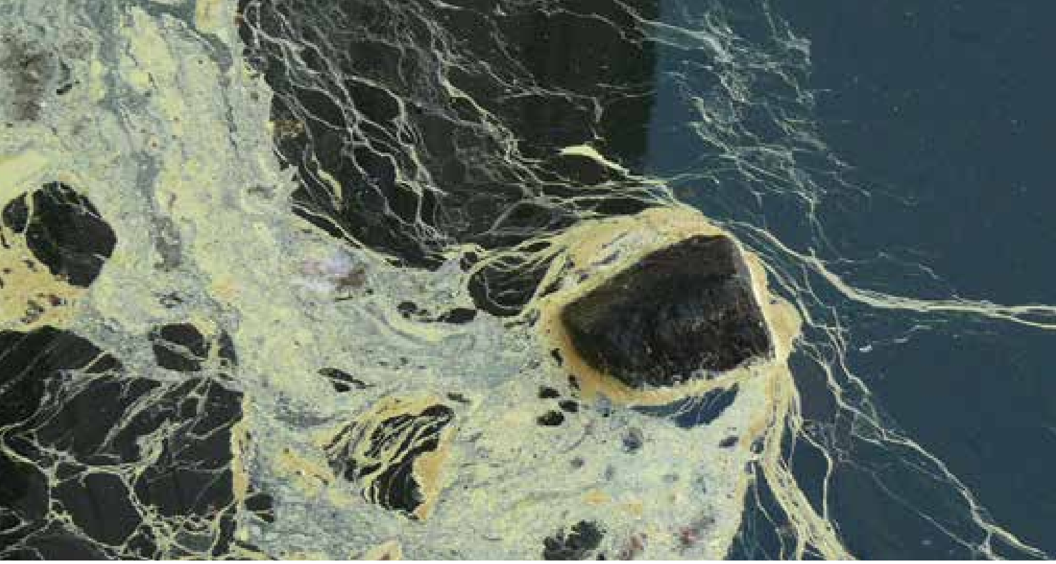
Plastic additives are incorporated into polymers during manufacturing processes to improve their properties; for example, to extend their resistance to heat by adding flame retardants, to reduce oxidative damage with nonylphenol, or to control microbial degradation by adding triclosan. The type of plastic and its intended use influences the type of plastic additives that are used.

- Plasticizers improve flexibility and durability, and are added at 10-80% w/w e.g., phthalates;
- Flame retardants (10-20%) to reduce the risk of fire, e.g., organophosphorus compounds, halogenated esters, heavily brominated or chlorinated organic compounds, e.g., hexabromocyclododecane (HBCDD), PBDE/ brominated flame retardants, tetrabromobisphenol A (TBBPA), anthed Tris(2-chloroethyl) phosphate;
- Stabilisers (0.1-10.09%), e.g., arsenic / organic tin compounds, triclosan, bisphenol A (BPA), cadmium and lead compounds, and nonylphenol compounds/ octylphenol;
- Curing agents, e.g., formaldehyde;
- Colourants, e.g., titanium dioxide, cadmium/chromium/lead compounds; and
- Fillers to increase stiffness and hardness and reduce costs, e.g., calcium carbonate, talc and barium sulphate.

Plastic additives have been found in marine ecosystems, including in biota.

Phthalates are commonly used as plasticisers and are found in children's toys, personal care products and food containers. Some are known EDCs.[238] Phthalates have been measured in marine plastic pellets.[239] In one study, over half of surface plankton samples analysed contained micro-plastic particles with high concentrations of phthalates (DEHP and MEHP).[240] The study warned that concentrations of mono- (2-ethylhexyl) phthalate (MEHP) found in the blubber of stranded fin whales may indicate an emerging threat of micro-plastics and their contaminants to baleen whales.

Bisphenol A (BPA) is a high volume chemical produced worldwide. As a monomer of polycarbonate plastic and epoxy resin, it is used in food containers and the epoxy-based linings of canned foods. BPA is released to the marine environment from plastic wastes and via sewage effluents, rivers and coastal waters.



BPA is a known endocrine disruptor.[241] Tetrabromobisphenol A (TBBPA), used as a flame retardant in some plastics, degrades to BPA. Relatively high concentrations of BPA have been detected in plastic fragment samples from remote beaches and from the open ocean. Sand and seawater analysed from more than 20 countries (mainly in Southeast Asia and North America) found significant amounts of BPA (0.01 - 50 ppm). Polycarbonates and epoxy resin coatings and paints were seen as the main source.[242]

PBDEs are used as flame retardant chemicals in the plastic housings of computers and TVs, making them key toxic components of electronic-waste (e-waste). The burning of e-waste is an important source of PBDEs to the aquatic and marine environment.

Nonylphenols (NP), used as stabilisers in plastics, have been found in polypropylene resin pellets collected from Japanese coasts and were two orders of magnitude higher than levels found in sediment.[243] NPs are also formed from the environmental degradation of surfactants based on nonylphenol ethoxylates (NPEs).

Heavy Metals are used as colourings. In a study of beached microplastics, cadmium and lead were detected in all samples, with higher concentrations found in red and yellow pellets or fragments. The maximum bioaccessible concentrations of cadmium and lead were evaluated as exceeding those estimated for the diet of local seabirds by factors of about 50 and 4, respectively.[244]

ENDOCRINE DISRUPTING CHEMICALS IN MARINE PLASTIC

In 2011, researchers found that most plastic products released estrogenic chemicals, stating that "*Almost all commercially available plastic products sampled, independent of the type of resin, product, or retail source, leached chemicals having reliably detectable endocrine activity (EA), including those advertised as BPA free. In some cases, BPA-free products released chemicals having more EA than did BPA-containing products*."[245]

The commonly used plastic additives, such as phthalates, BPA, alkylphenols and PBDEs, are EDCs. Both phthalates and BPA have been shown to affect the development and reproduction in molluscs, crustaceans and amphibians, which can occur at very low environmental concentrations.[246]

Some plastic additives with endocrine disrupting properties, such as PBDEs, can be present in the plastics at very high levels; that is, 1000–500,000 milligrams /kilogram (mg/kg). These have been used extensively as flame retardants in plastics and polyurethane foams. HBCDD is still used in polystyrene foam (EPS/XPS).[247] Tetrabromobisphenol A (TBBPA), used as a flame retardant in epoxy, vinyl esters and polycarbonate resins, has also demonstrated endocrine activity.[248]

Alkylphenol polyethoxylates are also EDCs.[249] Nonylphenols (NP) can cause feminisation of aquatic species and/or demasculinization of male fish. This decreases male fertility and the survival of young fish.[250] Laboratory studies demonstrate the reproductive effects that NP can induce in aquatic life. These include:

- changes in male and female hormone levels in turbot;
- decreased gamete production and fertilization in medaka and zebrafish;
- reduced hatching of rainbow trout embryos;
- altered sex ratios in offspring of NP-exposed oysters; and
- development of intersex trout, bream, and frogs, i.e. offspring with characteristics of both sexes.[251]

Nonylphenols can also induce a variety of non-reproductive effects, such as the inability to maintain fluid and electrolyte balance in sea bream and Atlantic salmon, which may prevent their migration from fresh water to sea-water. Clams and sea urchins exposed to NP have exhibited decreased respiration and increased malformations, respectively.[252]

INTERNATIONAL PELLET WATCH

International Pellet Watch (IPW) is a volunteer-based global monitoring program designed to monitor the pollution status of the oceans. Launched in 2005, it focuses on the monitoring of POPs using beached plastic resin pellets. IPW has presented data on the chemical concentrations in pellets collected from 30 beaches from 17 different countries. The results reflected past and present usage of particular POPs in that country. PCB concentrations in pellets were highest on U.S. coasts, followed by western Europe and Japan, and were lower in tropical Asia, southern Africa and Australia. DDTs were at high concentrations on the U.S. west coast and in Vietnam. High concentrations of HCHs were detected in the pellets from southern Africa.[268] Pellets from remote islands in the Pacific, the Atlantic, Indian Ocean and the Caribbean Sea returned levels of PCBs, DDTs and HCHs one to three orders of magnitude smaller than pellets from industrialized coastal shores, although there were sporadic large concentrations of POPs in the pellets.[269]

PLASTIC DEGRADATION PRODUCTS

Unreacted monomers in plastics and resins, as well as degradation products, can leach from the polymers into the environment, e.g., chemical intermediates from the partial degradation of polystyrene.

Expanded polystyrene foam (EPS) is pervasive in the marine environment. EPS was the second most abundant form of beach debris at 43 sites along the U.S. Orange County coast.[253] Styrene monomers and degradation by-products have been detected in seawater and sand from coastal regions, likely originating from polystyrene litter.[254] Styrene by-products have been shown to migrate from polystyrene products, e.g., from instant noodle polystyrene cups.[255] Styrene is an animal carcinogen, a possible human carcinogen and a neurotoxin.

EPS may also contain the POPs flame retardant HBCD (or HBCDD). Elevated HBCD levels were found in oysters from aquaculture farms where EPS/XPS buoys containing HBCD were used. High levels of HBCDD have been found in fish in some European waters.[256]

SORPTION OF TOXIC CONTAMINANTS

Biodegradation of marine plastic also aids in the adsorption and absorption of toxic contaminants from the seawater. The combined impact of environmental conditions and exposure time can modify the plastics' properties. Photo-weathering can cause bond breakages in the polymer, forming cracks and increasing the surface area and pore size, resulting in more contamination of POPs and other PBTs. Microplastics in the aquatic environment are also prone to biofouling and the biomaterials can act as additional sorbents.[257] POPs and other ocean pollutants can concentrate in and on microplastic fragments at several orders of magnitude higher than in the surrounding seawater.

Different types of polymers appear to attract POPs from the environment differently. For example, adsorption occurs more readily onto LDPE and PP plastic debris than for PET and PVC fragments.[258]

In plastic fragments (<10 millimeter / mm) from the open ocean, and from remote and urban beaches, PCBs, PAHs, DDT and metabolites, PBDEs, alkylphenols and bisphenol A were measured at concentrations from 1 to 10,000 ng/g.[259] While the highest concentrations of PCBs and PAHs were observed in plastic fragments from urban beaches, high concentrations were found in marine plastics from both remote and urban beaches and from the open ocean.

PLASTIC NURDLES

Plastic resin pellets, or nurdles, are the raw material for plastic manufacture and are widespread throughout the world's oceans, along with other plastic wastes.[260] The concentrations of POPs and other contaminants of pellets can depend on how long they have spent in the ocean or circulating in heavily polluted areas before eventually being beached. The colour of the resin pellet may influence the concentrations of contaminants.[261] Based on the testing of pellets collected on Portuguese beaches, black pellets had the highest concentrations of POPs (PCBs, DDT), but not PAHs.

PCBs and DDE readily adsorb to polypropylene (PP) resin pellets, increasing concentration over time and accumulating in concentrations of up to 106 times higher than surrounding seawater. Significant amounts of PCBs, DDE, and nonylphenols (NP) in PP resin pellets were collected from four

Japanese coasts. Concentrations of PCBs (4-117 ng/g, parts per billion), DDE (0.16-3.1 ng/g), and NP (0.13-16 μg/g, parts per million) varied among the sampling sites. The NP contents in the PP resin pellets were two orders of magnitude higher than those found in Tokyo Bay sediment (0.1-0.6 μg/g).[262]

In 2007, pellets comprised mainly of PP and PE polymers were collected from the North Pacific Gyre and selected sites in California, Hawaii, and Guadalupe Island, Mexico. PAHs and DDT and its metabolites were found in all the plastic samples.[263] Total concentration of PCBs ranged from 27 to 980 ng/g; DDTs from 22 to 7100 ng/g, PAHs from 39 to 1200 ng/g and aliphatic hydrocarbons from 1.1 to 8600 ug/g. Pellets collected from the southwestern shores of England contained metal concentrations with maximum values of 3390 μg/g for Cd and 5330 μg/g for Pb.[264]

TOXIC RECYCLING: A SOURCE OF CONTAMINANTS IN MARINE PLASTIC

Recycling plastic products containing persistent organic pollutants (POPs) contaminates new products and is especially damaging to a true circular economy. It also provides a further pathway for POPs into the marine environment if contaminated products become wastes and are not appropriately managed. IPEN studies on children's products have shown evidence of toxic recycled plastics in toys. A study by IPEN tested Rubik's Cube-like toys from 26 countries, including European countries, and found that 90% of the samples contained OctaBDE and DecaBDE.[270] Nearly half (43%) also contained HBCD. Other studies of toys made of recycled plastic have also found commercial PentaBDE, OctaBDE, and DecaBDE,[271] while electronic waste has also been recycled into kitchen utensils and thermos cups.[272] A further IPEN study [273] tested SCCPs in children's products from 10 countries and found SCCPs in 45% of the samples at concentrations ranging from 8.4 to 19,808 parts per million (ppm).

Eighteen PFAS were measured in plastic pellets and beach sediment around Greek coastal areas. The concentrations in plastic pellets were higher than those in the sediments and the researchers propose that the origin of PFASs on the pellet surface was adsorption from surrounding water.[265]

Plastic pellets can be produced with either virgin plastic or by using recycled plastics that may already contain POPs and other toxic substances.[266] Bromine was found in over 10% of pellets collected from the shores of southwest England. The high concentrations (13,000 μg/g) suggested the presence of brominated flame retardants arising from the recycling of plastics originally used in casings for heat-generating electrical equipment.[267]

CHAPTER 3.
IMPACTS OF OCEAN POLLUTANTS

The notion of a vast ocean with an infinite capacity to absorb and "dilute" pollution is deeply embedded in our psyche. Despite mounting evidence of widespread ecological harm from chemical exposures, and increasing levels of persistent pollutants in the commons, regulators continue to rely on the out-dated approach, "*dilution is the solution to pollution*."

Environmental regulators continue to permit supposedly "safe" levels of chemical releases to air, soil and water, assuming that when diluted, the pollutants cause minimal or no harm. These decisions are made despite significant data gaps about complex ecological interactions and cumulative impacts of pollutants, as well as a disregard for the bigger picture.

In terms of ocean pollution, the dilution approach is fundamentally flawed, since the planet's water resource has a finite volume and is constantly cycling, moving downhill into the oceans, which act as a "sump". It is also a flawed approach because there can be no "safe" levels of persistent pollutants that travel around the globe and bioaccumulate up the food chain.

For healthy oceans, there needs to be a healthy food web. Prior to industrialisation, fish sat close to the top of the aquatic food web, supported at the bottom by bacteria and protozoa, with healthy populations of phytoplankton, microalgae, seagrass, coral, zooplankton, shellfish, prawns and squid in between. The aquatic food web today looks very different. Fish numbers have significantly diminished along with other aquatic organisms, causing a proliferation of bacteria and accompanying disease. Microalgae, phytoplankton and seagrass, which constitute the "ocean's lungs" and make two thirds of global oxygen, are all diminishing under the strain of excess sediment, nutrients and pesticides.

Nutrient pollution in the form of fertilisers and human and animal wastes leads to deoxygenated dead zones in the ocean. It drives freshwater blue-green algae outbreaks, and in marine habitats, algal blooms cause red tide and algal smothering of seagrass. Dredging results in sediment pollution, which smothers seagrasses and other marine environments while mobilising legacy contaminant loads into the water column. Herbicides can cause dieback in mangroves and impact corals.[274]

Marine animals exposed to toxic substances can suffer a loss of resilience and immunosuppression. Pesticide exposures cause abnormal larvae development in fish and other reproductive and developmental dysfunction. Sub-lethal exposure to many chemical pollutants makes fish more susceptible to heat stress and alters their behaviours.[275] Pesticides kill off invertebrates that fish depend on for food. This picture adds up to death by a thousand cuts for ocean ecosystems.

ECOLOGICAL IMPACTS

Coupled with other stressors such as habitat loss and climate change, marine species are already impacted by ever-increasing levels of ocean pollutants. While short-term exposure to high concentrations of pollutants have resulted in acute effects such as mass mortality, even at very low concentrations, toxic pollutants can have detrimental impacts on marine organisms' physiology, reproduction and immunology, particularly if they are EDCs or the exposure is chronic. This has led to an increase in the number and extent of disease outbreaks in marine species.

The response of marine organisms exposed to chemical contaminants can occur at many levels: [276]

- Biochemical and cellular, e.g., toxication[277] , metabolic impairment, cellular damage, detoxication;
- Organisms e.g., physiological changes, reduced growth due to energy spent on detoxification and tissue repair, behavioural changes, susceptibility to disease, reproductive impacts, larval viability, immune responses;

- Population e.g., age/size structure, recruitment, mortality, reproductive output and other demographic characteristics; and
- Community e.g., species abundance and distribution, impacts on food chains, ecosystem adaptation.

POPs exposure in fish and aquatic invertebrates can affect reproduction, growth and development, as well as the immune and endocrine systems. POPs have been associated with disrupted reproductive function in male fish and can impair maternal transfer of nutrients or hormones.[278]

Two fish species inhabiting a shallow lake located in an agricultural area from Argentina showed lesions in the gills and liver, with high levels of endosulfan in these organs. Male fish also demonstrated possible exposure to EDCs, with vitellogenin (precursor protein of egg yolk) found in the plasma of male fish.[279]

Developmental abnormalities in fish embryos and larvae due to parental exposure and maternal transfer of PBDEs can occur at very low exposure concentrations. In the offspring of exposed parents, decreased hatching, altered thyroid hormone levels, and inhibition of growth can occur.[280]

As early as the 1970s, research was showing that the incidence of DDT and PCBs in the bodies of seals was reducing the individual's chance to reproduce. Either the seals failed to conceive or they aborted or resorbed the foetus.[281] Female Baltic Ringed seals, when exposed to organochlorine pollution, suffered a narrowing or closure of the uterine passage and hormonally induced softening of the bone.[282] Additionally, by 1987, Dall's porpoises from the northwest Pacific demonstrated that as concentrations of PCBs and DDT increased, the level of male hormone testosterone decreased.[283] In 2003, similar reductions in testosterone levels were reported in polar bears in Svalbard with high PCB concentration.[284]

Eggs and early developmental stages of fish and other marine organisms are also highly vulnerable to the toxic effects of genotoxic ocean pollutants. Genotoxic substances can damage the genetic information within a cell, causing mutations that may lead to cancer. Genotoxic pollutants like DDT, certain PCBs and HCH can induce DNA damage, and studies have reported multigenerational effects of POP exposure in fish. Fish exposed to heavy metals, tributyltin, and synthetic and natural oestrogens, have also shown changes in DNA methylation,[285] which can play an important role in gene regulation and development.

Both cancers and precancerous conditions can be initiated and promoted by pollutant exposure. The occurrence of neoplasia (a cancer-like condition) in flatfish livers has been reported as direct evidence of contaminant exposure, indicating exposure to carcinogenic chemicals that initiate and promote cancer-like diseases.[286] Neoplastic (tumour growth) conditions have been reported worldwide in 15 species of marine bivalves, including four species of oysters, six species of clams and five species of mussels.[287]

Elevated levels of pollutants have also been linked to a high prevalence of tumours in marine mammal populations from the Canadian St. Lawrence Estuary.[288] A variety of cancer-like conditions have been reported in marine organisms from urban coastal sites across the globe and in many cases, linkages between the pollutant exposure and neoplastic changes have been made.

By the mid 1990s, POPs were also associated with immune impacts and the growing numbers of seals suffering a disease complex; "*primary lesions of the adrenals with secondary reactions*."[289] Researchers linked the disease to immuno-suppression and hormonal imbalances resulting from contamination, particularly PCBs.

In 2005, a comprehensive review [290] of POPs impacts on Arctic biota reported associations between concentrations of some POPs and several biomarkers that measure changes at the cellular or individual level. Of particular significance were those biomarkers relating to the effects on resistance to infection, reproduction and behaviour.

The review concluded that the impacts on hormones were correlated with increased levels of PCBs, dioxin-like compounds, DDE, HCB and HCH. Negative effects on reproduction and development were correlated to increased levels of DDE, PCBs and dioxin-like compounds in a range of species, including Alaskan peregrine falcons, bald eagles from the Aleutian Islands, glaucous gulls, and polar bears in Svalbard and Hudson Bay

The researchers reported measures of normal immune function were negatively correlated to increasing PCB levels in northern fur seal and Steller sea lion pups.[291] In polar bears, there was a significant decrease in antibodies with increased PCB levels, and in glaucous gulls, the intensity of nematodes was positively correlated with concentrations of DDT, mirex and PCBs. Similar correlations were seen between high PCB levels and increased cytochrome P450 activity in Arctic species.[292] Cytochrome P450 enzymes are primarily found in liver cells and are essential for metabolizing potentially toxic compounds.

Environmentally relevant concentrations of mercury, PCBs, and 4,4′-DDE (dichloro diphenyl-dichloroethylene) have also been shown to affect the immune function and health of loggerhead sea turtles.[293] Field studies found a negative correlation between mercury in the blood of loggerhead

sea turtles and lymphocyte numbers and immune responses. This indicates the negative impacts of mercury on the immune function of sea turtles are possible at concentrations observed in the wild.[294] Correlative observations in free-ranging loggerhead sea turtles also suggest that current, chronic exposure to DDE, PCBs and chlordane suppress their immunity. This is further supported by *in vitro* experiments, indicating that OC exposure modulates immunity in loggerhead turtles.[295]

Green turtle (*Chelonia mydas*) eggs were analyzed for POPs and heavy metals. OCPs, PCBs, chlordanes, and HCHs were found in all 55 of the eggs analysed.[296] OCPs and PCBs were the most highly concentrated POP compounds, while arsenic was the most common element with the highest concentrations, detected in 65% of the eggs sampled. The concentrations of arsenic suggested a relatively high risk of embryonic mortality and reduced hatching success.

Researchers suggested that the large number of POP compounds observed in the eggs could be important in terms of combined effects, e.g., the effect of multiple PCB compounds on sex reversal. They concluded that the concentrations of POPs and heavy metals reported in eggs posed considerable risks to sea turtle conservation.

Even the platypus, an egg laying aquatic monotreme in Australia, have demonstrated widespread POPs contamination.[297] Samples of tail fat detected PCBs (average of 0.5 mg/kg), DDT (0.6 to 0.8 mg/kg) and HCH. The contaminants were implicated in the failure of the incubation of clutches of eggs and the immunotoxicity of PCBs contributing to their increased susceptibility to infections.

MARINE SENTINEL SPECIES

Marine animals serve as sentinel species, providing early warnings of the negative impacts from ocean pollutants. Marine mammals in aquatic and coastal environments are often long-lived, feed at a high trophic level and store fat, which serves as deposits for POPs and PBTs, similar to humans.

The U.S. National Oceanic and Atmospheric Administration (NOAA) has identified a range of sentinel species, including the Californian sea lion, Atlantic bottlenose dolphin, southern sea otter, bowhead whale, polar bear and the endangered West Indian manatee.[298]

California sea lions live in close proximity to human communities. Approximately 20% of sexually mature stranded sea lions have a high incidence of a newly identified urogenital cancer. The cancer is linked to a novel herpes virus and exposure to POPs contaminants such as PCBs and DDTs, which contaminate the sea lions and their feeding grounds. Animals with the carcinoma had higher mean concentrations in blubber (based on wet weight) of PCBs and DDTs (more than 85% and 30% higher, respectively).[299] Genetically inbred sea lions were more likely to develop the cancer, suggesting interactions between genes, toxins, and viruses.

Similarly, dolphins live in ocean, coastal, and estuarine environments also inhabited by human communities. Studies of dolphins and manatees show an emergence, or resurgence, of infectious and neoplastic diseases, reflecting environmental pressures.[300] This may have direct or indirect relevance to human health.

The biomagnification of POPs, PBTs and heavy metals among polar bears and bowhead whales also tells us much about the health of the Arctic Ocean and the threats to those human communities dependant on it for native foods. Both humans and polar bears feed on similar prey.[301]

IMPACTS OF MICROPLASTIC CONTAMINATION

Microplastics contaminate every marine habitat, including estuaries, the breeding habitats for many fish species.[302] Microplastic pollution present in the water column and sediment provides a direct exposure route for aquatic and marine organisms. Microplastics can also contaminate prey and expose predators via transfer through the marine food chain. This represents an indirect but potentially major pathway of microplastic ingestion for any species whose feeding ecology involves the consumption of whole prey, including humans.[303]

The trophic[304] transfer of microplastics in the marine environment has been observed e.g., green algae (*Scenedesmus spp.*) eaten by the planktonic water flea (*Daphnia magna*), which in turn is eaten by several species of fish, including Northern pike (*Esox lucius*) and Atlantic salmon (*Salmo salar*).[305]

A study of trophic transfer of fluorescent nano-sized polystyrene plastics (nanoplastics) through a freshwater ecosystem containing alga, water flea and consumer fish confirmed that nanoplastics are easily transferred through aquatic food chains.[306]

Daphnia water fleas exposed to nano-sized polystyrene plastics showed reduced body size and severe alterations in reproduction. The numbers and body size of neonates were lower, and malformations among neonates rose to 68% of the individuals.[307]

Direct consumption of microplastic is prevalent in many suspension feeders such as oysters and mussels, as well as in deposit feeders, such as sea cucumbers, crabs and lobsters. These organisms cannot differentiate between microplastics and food. The situation is further complicated by microplastics in marine environments acquiring a "*dimethyl sulphide signature*",[308] which emits a scent that attracts some aquatic and marine wildlife.[309] Phytoplankton release dimethyl sulphoniopropionate in the seawater, which breaks down to dimethyl sulphide (DMS) and is emitted to the air. This molecule is used by predators (e.g., seabirds, penguins) for locating foraging areas.

Studies have shown plastic debris can perforate the gut and/or obstruct the passage of food, which can lead to sub-lethal (e.g., reduced growth) and even lethal effects. Yet, it has been argued in the framework of ecotoxicity[310] that it cannot be shown that these deaths cause identifiable ecological impacts such as altered population.[311]

In laboratory studies, exposure of aquatic organisms to microplastics has been associated with negative health effects such as increased immune response, decreased food consumption, weight loss and energy depletion, decreased growth rate, decreased fertility and impacts on subsequent generations.[312]

BIVALVES AND CRUSTACEANS

Bivalves such as molluscs are the most commonly used organisms in microplastic ecotoxicity and exposure studies. Adverse effects include alterations of immunological responses, neurotoxic effects and the onset of genotoxicity. Microplastics have been shown to affect the reproduction and subsequent population growth of the Pacific cupped oysters.[313] Mussel survival also declined with increasing PVC abundance, probably due to prolonged periods of valve closure as a reaction to particle presence.[314]

Impacts of microplastics on crustaceans include a reduction in feeding and, when chronically exposed over successive generations, increased mortality rates. Green crabs can take up microplastics through the gills, reducing food consumption and growth, while long-term exposure in Norway lobsters reduced their nutritional health and energy stores.[315]

In a study of a commercially important crustacean (*Crangon crangon* (L.)) from shallow water habitats of the Channel area and southern part of the North Sea, synthetic fibres ranging from 200 micrometers (µm) up to 1000µm were found in 63% of the shrimp samples. The results suggested that microplastics greater than 20µm are not able to translocate into the tissues.[316] Microplastics were found in the exoskeleton and muscle of tiger prawns from the Persian Gulf.[317]

In laboratory tests, polystyrene microplastics demonstrated short-term toxicity for mysid shrimps, resulting in 30% mortality at high concentration (1000 µg/L).[318] The size of the microplastic influenced their toxicity. Exposing the small aquatic crustacean copepod (*Tigriopus japonicas*) to 0.05- and 0.5-µm sized polystyrene microbeads led to significant retardation of developmental time and decreased survival rate. Slightly larger polystyrene microbeads (6-µm) did not lead to significant growth retardation.[319]

FISH

Microplastic ingestion by commercial (benthic and pelagic) fish species was evident in the English Channel, the North Sea, the Baltic Sea, the Indo-Pacific Ocean, the Mediterranean Sea, the Adriatic Sea and the

North Eastern Atlantic.[320] Generally, the quantities of microplastics in fish were low.

Microplastics have been found in the digestive tract of wild fish larvae from the English Channel. **Ten species of fish from the English Channel were found to have microplastic fibres, with polymide accounting for 35.6% of the microfibers and rayon 57.8%.**[321] Fish from the Persian Gulf had microplastics in their gastrointestinal tracts, skin, muscle, gills and liver.[322]

Microplastics have also been found in the gills, liver and digestive tract of the zebrafish, resulting in inflammation, oxidative stress and disrupted energy metabolism.[323] In Flathead grey mullet, small particles (< 600 µm / 0.6mm) moved from the digestive tract to liver tissue, albeit in small numbers.[324]

Exposure to nano-sized polystyrene plastics affected fish activity, measured by distance and area covered. Nanoplastics were also shown to penetrate the embryo walls and were present in the yolk sac of hatched juveniles.[325]

SEABIRDS AND MARINE MAMMALS

The occurrence of microplastics in seabirds and marine mammals has been well documented and almost all seabird species studied have shown evidence of microplastics ingestion.[326] Those with high levels of ingested plastic exhibited reduced body condition and increased contaminant load.[327] The majority (95%) of Northern fulmar (*Fulmarus glacialis*) in the North Sea had plastic in their stomach, averaging 35 pieces weighing 0.31 grams. The critical level of 0.1 grams of plastic was exceeded by 58% of birds.[328]

Microplastics are also ingested by marine mammals and have been found in the stomachs of harbour seals, beaked whales and baleen whales. In post-mortem examinations of 528 stranded and by-caught marine mammals, 45 (8.5%) had marine debris in their digestive tracts.[329] Marine debris (e.g., soft plastic, ropes, Styrofoam and monofilament lines) was found in 35.2% of 54 loggerhead sea turtles (*Caretta caretta*) found stranded or dead by fisheries in the Adriatic Sea.[330]

TRANSFER OF CONTAMINANTS VIA MICROPLASTICS

Microplastics have the potential to increase the availability of chemical contaminants from seawater. Feeding experiments have shown PCBs can transfer from contaminated plastics to Streaked Shearwater chicks.[331]

Studies of wild seabirds have shown that their contaminant loads can be positively correlated with the amount of plastic ingested.[332, 333]

In an assessment of the relationship between plastic load and trace element concentrations in Flesh-footed Shearwater fledglings, measurable concentrations of 17 trace elements were found in their breast feathers. High concentrations of chromium and silver were positively related to the mass of ingested plastic. Chromium bioaccumulates in avian tissues, and levels exceeding 2.8 mg/g in feathers are thought to be associated with adverse neurotoxic effects. Silver nanoparticles have well documented toxicological effects at the cellular and subcellular level.[334]

When mussels (*Mytilus galloprovincialis*) were exposed to PAH-contaminated microplastics, the plastics were found in the haemolymph, gills and, especially, digestive tissues, and were accompanied by marked accumulation of the PAH, pyrene. Adverse cellular effects were seen, including alterations of immunological responses and neurotoxic effects.[335] Increased PCB loads due to microplastics were also demonstrated in lugworms[336] and in Myctophid fish from the South Atlantic Ocean; greater plastic densities were associated with significantly higher concentrations of PBDEs.[337]

Microplastics are ingested by baleen whale species through consumption of planktonic prey. In a study of the Mediterranean fin whale (*Balaenoptera physalus*), surface plankton was shown to contain microplastic particles with high concentrations of phthalates. Concentrations of Mono-(2-ethylhexyl) phthalate (MEHP) were also found in the blubber of stranded fin whales.[338]

In green turtles,[339] concentrations of PCBs were positively correlated with the number of plastic pieces ingested; however, the findings were confounded by their body condition index (BCI). Green turtles with a higher BCI had eaten more plastic and also had higher POPs. Taken together, the researchers suggest that sea turtles still accumulate most POPs through their prey rather than from marine debris.[340]

The UN Food and Agriculture Organization FAO[341] also concluded that, based on current research, the "*overall amount of PBTs bioaccumulated from natural prey overwhelms the amount from ingested microplastics*."

The increased sorption of ocean pollutants to nanoplastics could plausibly increase the significance of marine plastics as contributors to overall chemical exposure. PCB sorption to multi-walled carbon nanotubes and fullerenes (e.g., carbon spheres or "buckyballs") was shown to be three to four orders of magnitude stronger than to organic sediment matter or micro-sized polyethylene.[342] Sorption to nano-polystyrene was one to two orders of magnitude greater than to micro-sized polyethylene. This was thought to be due to the higher aromaticity (from biofouling) and surface-volume ratio of nano-polystyrene. Salinity also increased sorption for the polymers, nano-polystyrene and micro-sized polyethylene.[343]

While impacts from ocean pollutants and marine plastic debris have been demonstrated, the frequencies and nature of ecological impacts are yet to be quantified and fully understood. For some marine mammals and sea-birds, there is ample information to show adverse impacts from exposure to marine pollutants and microplastic ingestion, but despite this, there is little information on the full impacts on aquatic and marine ecosystems to the ever-increasing problem of ocean pollutants.

CHEMICAL CONTAMINATION OF THE MARINE FOOD THAT HUMANS EAT

The combined impacts of toxic chemicals, plastic pollution and climate change in the marine environment are catastrophic to marine ecosystems and to those communities dependent on them. This is especially so for indigenous peoples in remote Arctic and Pacific Island communities and in the Asia Pacific region where communities rely heavily on the marine environment for their food, culture and livelihoods.

Fish provides at least 40% of protein for two-thirds of the world's population, including most of the world's poor.[344] Yet, many commercial and recreational fisheries across the world are contaminated with POPs and mercury. As marine food species are increasingly exposed to toxic chemicals, this inevitably results in increased human exposure. While the young and vulnerable are at most risk, all those who depend on seafood are adversely affected.

MERCURY IN FISH

Mercury contamination of the atmosphere, oceans, lakes and rivers has led to widespread contamination of fisheries. Those highly dependent on seafood for their protein suffer a far greater and more dangerous chronic dose of mercury than those with more options to choose from for their protein needs.

It is predicted that mercury concentrations will double in the North Pacific Ocean by 2050.[345] This is likely to result in significant mercury increases in pelagic marine fish, such as the Pacific bluefin tuna swordfish, and other large pelagic fishes. These fish are the top of the marine food web and are important species for global marine fisheries and human

consumption. In 2013, swordfish from the Southern Atlantic Ocean had the highest average mercury level, followed by Pacific Bluefin tuna from the Northern Pacific Ocean.[346]

The evidence of the role fish consumption plays in human exposure to mercury is evident in human hair testing of populations with high seafood diets. The Cook Islands, a tiny Pacific nation highly dependent on a seafood diet, returned hair samples with average mercury levels 3.3 times higher than the U.S. EPA reference dose. Tokyo residents with high seafood intake had average mercury levels 2.7 times higher than the U.S. EPA reference dose. Overall, 95% of the hair samples from Japan and 89% of the samples from the Cook Islands exceeded the U.S. EPA reference dose for mercury.[347]

The Swedish National Food Administration takes the risk seriously and has recommended that women trying to conceive a baby, or who are pregnant or breastfeeding, not eat Swedish fish such as pike or perch more than 2 to 3 times a year, due to possible mercury contamination.

POPS IN INDIGENOUS PEOPLES' DIETS

The main exposure path for POPs is through contaminated foods. POPs chemicals and other PBTs contaminate seafood to varying degrees across the globe. This exposure can lead to a greater risk of adverse health effects, including reproductive, endocrine, developmental, behavioural, neurological and immunological health effects.

People whose diets include large amounts of fish, shellfish, or wild foods that are high in fat are at risk of POPs exposure. This is particularly relevant for many indigenous peoples dependent on traditional foods, as well as local subsistence fishers and island peoples. For example, contaminated green turtle eggs sold for human consumption had POPs and heavy metals at concentrations that posed considerable risks to human health.[348]

In Inuit peoples living predominately on a traditional marine diet, concentrations of POPs are high. The adverse effects of POPs, such as disruption of the immune system and cardiovascular diseases, are evident in Greenland Inuit peoples. POPs are associated with inflammation and may promote chronic diseases common to populations in Greenland.[349] A link has also been made between POPs and high cholesterol levels among Inuit. The study followed earlier work that found a similar link between POPs and some kinds of diabetes.[350]

In a study of Alaskan native communities who rely on a traditional marine diet, researchers concluded that elevated concentrations of long chain PFASs (perfluorononanoic acid (PFNA) and perfluoroundecanoic acid (PFUnDA)) in their blood was likely due to exposure from traditional foods. Both PFASs and PBDEs were found in sentinel fish consumed by these communities.[351]

POPs, mercury and cadmium also contaminate the native foods (e.g., seals, whale and fish) of Chukotka coastal communities in the Russian Arctic. In response to the high contaminant levels and the likely transfer of these to humans, researchers called for urgent consumption restrictions for a range of marine and freshwater fish, some wild meats (waterfowl and seal), fats (whale and seal), liver (most animals) and kidney (reindeer, walrus and seal).[352]

Yet, it is not only communities reliant on native foods that are impacted. HCB, DDE and PCBs have been measured in the edible tissues of commercial fish species such as Bluefin tuna, swordfish and Atlantic mackerel. Researchers suggest consumers eating 400 grams of these fish per week would exceed the established tolerable weekly intake (TWI).[353] Importantly, the TWI is normally calculated for an average adult male and does not take into consideration vulnerable subpopulations such as children. PBDEs also contaminate seafood,[354] and in China, dietary intakes of PBDEs were dominated by fish (45%) and molluscs (45%).[355]

A study of African American Gullah people from South Carolina linked their high local seafood diet with high body loads of POPs and PBTs and adverse oestrogenic impacts on women. This study showed higher levels of DDT and its metabolites, HCHs, fluoranthene, pyrene, benzo(a)pyrene, PCBs, and BDE-99 in patients with non-cancerous uterine growths, a condition linked to endocrine effects.[356]

In Australia, elevated levels of dioxins were detected in some seafood (fish, crustaceans and molluscs) from Sydney Harbour and the Parramatta River. As a result, all commercial fishing in Sydney Harbour was prohibited. While recreational fishing was not banned, health advice was provided to limit intake for seafood caught east of the Sydney Harbour Bridge and to not eat seafood caught west of the Sydney Harbour Bridge.[357]

PFAS contamination of groundwater and surface water resulting from PFAS production or the use of certain firefighting foams has also resulted in Fish Advisories being announced in Australia [358] and the U.S. These warn communities that their fish are PFAS-contaminated and eating them represents a risk to human health.

POPs, PBTs and mercury represent some of the worst contaminants of the human food chain, particularly marine foods. While some cancers and endocrine impacts have been associated with high seafood diets, there is limited understanding of the full impacts of this exposure, including possible epigenetic or intergenerational impacts of toxic exposure on human health.[359]

MICROPLASTIC POLLUTION OF THE HUMAN FOOD CHAIN

Many studies now show the presence of microplastics in seafood intended for human consumption.[360, 361, 362, 363] For example, in Sweden, microplastics have been found in Swedish blue mussels, Norway lobster, cod, haddock and prawns.[364] Twenty-seven fish species collected from Shanghai fish markets had varying degrees of microplastic contamination (from 1.1 to 7.2 items per individual).[365]

Microplastics and other marine debris have mainly been observed in the gastro-intestinal tracts of fish, but, as most fish species are gutted before consumption by humans, direct human exposure to microplastics from fish in most cases may be negligible.[366] However, diets rich in oysters and other bivalve may provide a more direct connection between microplastics and food targeted for human consumption. Bivalves and several species of small fish are consumed whole, which can lead to microplastic exposure.

The presence of microplastics in seafood inevitably raises concerns regarding human health. As marine plastics ingestion has led to inflammation in the gastrointestinal tract, there could be the potential to cause physical harm to humans when ingested via whole seafood, e.g., whole sardines, mussels and oysters. Concern over cellular toxicity in human liver cells has been raised based on analyses of the liver of exposed mice. Biochemical biomarkers suggested that microplastic exposure can induce oxidative stress (the imbalance between free radicals and antioxidants in the body) and energy and lipid metabolism, as well as neurotoxic effects.[367]

The chemicals transported by microplastics may transfer to fish after ingestion and in turn, into humans.[368] This transfer of chemicals into organisms at lower trophic levels raises the possibility of biomagnification in predators, including humans.[369] The potential migration of polymer constituents and additives into food and drinks has been considered by some as a major route of exposure to the human population.[370] Yet, others have argued that while plastics can be hazardous to human health via the toxicity of associated chemicals or particle toxicity, the "*…extent to which microplastics in individual food products and beverages contribute to this is debatable.*" [371] Compared to the enormous use of plastic materials in everyday lives, they stress that microplastics from food products and beverages are likely to only be a minor exposure pathway for plastic particles and associated chemicals to humans.[372]

The World Health Organisation is conducting a review on whether a lifetime of eating and drinking plastic particles could have an effect on health.[373]

Adverse effects on human health from nano- and microplastics may result from a combination of the plastic's intrinsic toxicity (e.g., physical damage); chemical composition (leaching of additives); and its ability to adsorb, concentrate and release environmental pollutants into organisms. The role of microplastics as a source of contamination to humans is still being investigated, but, as the incidence of marine microplastics grow at an alarming rate, with a corresponding increase in seafood contamination, this exposure pathway can only increase in importance.

MICROPLASTIC CONTAMINATION OF DRINKING WATER

Microplastic contamination has been found in 83% of tap water samples tested around the world. The U.S. has the highest contamination rate at 94%, while European nations had the lowest contamination rate, but this was still 72%.[374] Bottled water is also contaminated with microplastic pollution.[375] Tests on 27 different samples of bottled water from 11 different brands purchased in 19 locations across 9 countries found that 93% had microplastics present, with polypropylene the most common plastic found. Microplastics have also been found in commercial salts.[376]

CHAPTER 4. OPPORTUNITIES AND CHALLENGES IN ADDRESSING OCEAN POLLUTANTS

Addressing ocean pollutants requires deep change.

Ocean pollutants, including marine debris and microplastic pollution, are now globally recognised as a pervasive and shared threat to humanity and to the ecosystems on which all species depend.[377]

Unsustainable population growth and ever-increasing consumerism means more and more chemical products continue to be produced and used, eventually ending up in the waste stream. Some of the waste stream will find its way into the marine environment.

The problem of ocean pollutants is vast and reliance on existing management practices and policies is no longer an option. Governments and industry have failed to implement effective life cycle approaches. Many chemicals do not have adequate toxicological data or environmental fate information. Regulatory systems are fragmented and do not address resource extraction, product design, manufacture, use, reuse and recycling within the framework of a circular economy.

Governments remain steadfast in their rejection of the concept of "frivolous use" and wasteful products, instead arguing for industries' right to manufacture products no matter how wasteful of the earth's finite resources. These factors have resulted in the toxic legacy of chemical releases and plastic wastes we experience in our oceans today.

The fossil fuel origins of plastic and chemical production pose complex and difficult challenges for all countries. The entire life cycle of current petrochemical-based production, from raw materials extraction through to consumption and final disposal, represents a threat to the marine environment. Any solutions to address ocean pollution needs to acknowledge this. While many countries have committed to the Paris Climate Agreement and to reducing consumption of fossil fuels for energy production, in

contrast, chemical and plastics production based on fossil fuels is continuing on a rapidly increasing trajectory.[378]

There are policy options to address ocean pollutants, but a commitment to genuine change is essential. Actions to stop further pollution and to remediate the existing impacts are well overdue and the implementation of the urgent actions needed requires leadership, financial support and involvement by all aspects of society. The problem is great and the solutions require deep changes in policy and in the way most of us live our lives.

POLITICAL WILL TO ADDRESS OCEAN POLLUTANTS

Over the past five decades, awareness of ocean pollutants has grown, as have the expressions of political will to address the issue. Many global and regional programs and instruments have been developed and initiated, yet they have been demonstrably unsuccessful in achieving their goals of a clean and safe ocean environment.

GLOBAL PROGRAMME OF ACTION FOR THE PROTECTION OF THE MARINE ENVIRONMENT FROM LAND-BASED ACTIVITIES

In 1995, international concern over marine pollution prompted the establishment of the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA).[379] Over 108 governments declared "*their commitment to protect and preserve the marine environment from the impacts of land-based activities*."

As a global intergovernmental mechanism, the GPA aimed to address the connectivity between terrestrial, freshwater, coastal and marine ecosystems. It aimed to provide practical guidance for national and/or regional authorities to help prevent, reduce, control and/or eliminate marine degradation from land-based activities.

The program focused on the impacts from sewage, POPs, radioactive substances, heavy metals, oils (hydrocarbons), nutrients, sediment mobilisation and litter, as well as physical alteration and destruction of habitat. Nutrients management, marine litter and wastewater were highlighted as the priority source categories.

UNEP hosts the GPA Coordinating Unit and coordinates program activities. Intergovernmental Review Meetings are organized every 5 years to review the progress made by countries in the implementation of the GPA through their respective National Action Plans.

The GPA also established three global multi-stakeholder partnerships - the Global Partnership on Nutrient Management, the Global Partnership on Marine Litter and the Global Wastewater Initiative. The Global Partnership on Marine Litter [380] was finally established in June 2012 at the United Nations Conference on Sustainable Development (Rio+20).[381] It aims to bring together international agencies, governments, academia, the private sector, civil society and individuals to address marine litter.

While the GPA has focused attention on the land-based pollution transported by rivers, estuaries and storm drains, its voluntary and non-binding framework has limited its effectiveness.

UN SUSTAINABLE DEVELOPMENT GOALS

In October 2015, governments adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs). The Preamble notes a determination to take "*bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path.*" [382]

The 2030 Agenda for Sustainable Development reaffirms all the principles of the Rio Declaration on Environment and Development and the commitments regarding "*the human right to safe drinking water and sanitation*" and a world "*where food is sufficient, safe, affordable and nutritious.*"

A report prepared through a multi-stakeholder process proposes 100 Global Monitoring Indicators, accompanied by suggestions for Complementary National Indicators, which together track the full range of SDGs and targets in an integrated, clear and effective manner.[383]

UN Sustainable Development Goals (SDGs) are relevant to ocean pollutants and marine plastic debris, with actions related to chemical safety and toxic chemicals either referenced or implied in many of the SDGs.

SUSTAINABLE DEVELOPMENT GOAL 14, LIFE BELOW WATER

The SDG 14 aims to "*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*." To achieve this, Target 14.1 requires: "*By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land based activities, including marine debris and nutrient pollution*."

For this to occur, multi-sectorial and multi-stakeholder approaches based on principles of good chemical management, i.e., right-to-know, polluter pays, precaution and substitution, are required. Policy responses must also adhere to the principles of social, environmental and intergenerational equity.

Activities need to incorporate, at a minimum:

- current international conventions and programs to address chemicals and wastes with a new international instrument for plastics;
- review of water quality standards, resulting in harmonized global standards for marine water;
- biomonitoring programmes to inform such governance, for national quality coastal zones and in global oceans and seas;
- expanding and implementing extended producer responsibility programs;
- zero waste policies;
- pollution prevention while avoiding regrettable substitution;
- remediation and clean-up;
- fishing and ocean certification systems; and
- community awareness-raising, capacity building and empowerment.

To help achieve SDG 14, the UN Environment administers the Regional Seas Programme (RSP),[384] which has programs for the protection of marine and coastal environments in West Africa, Caribbean, Mediterranean, Northwest Pacific, East Asian Seas, Caspian Sea, and East Africa, as well as several other regions of the world. A notable omission from the Regional Seas Programme appears to be the south-east Pacific sub-region, where many Pacific Small Island Developing States (SIDS) rely on fisheries as a significant source of national revenue.

COMMUNITY OF OCEAN ACTION

In February 2017, the UN Environment launched #CleanSeas[385] with the aim of engaging governments, the general public, civil society and the private sector in the fight against marine plastic litter. They aim to address the root-cause of marine litter by targeting the production and consumption of non-recoverable and single-use plastic, and give a platform to the many local organisations already doing important work on marine litter.

The UN Ocean Conference in June 2017 brought together more than 4,000 participants from governments, the UN system and other intergovernmental organisations, NGOs, academia, the scientific community and the private sector. The Conference resulted in the adoption of the "Our Ocean, Our Future: Call for Action" declaration and the appointment of the UN Secretary-General's Special Envoy for the Ocean.

The Community of Ocean Action is a registry of voluntary commitments by stakeholders to help achieve SDG 14. More than 1,400 voluntary commitments have been registered, of which over 540 relate to the reduction of marine pollution.[386] Most commonly, they address marine plastic pollution and include bans on some plastic products, as well as recycling and coastal clean-ups. There were also commitments relating to nutrient management and controlling some sources of pollution. This Community of Ocean Action supports its members by exchanging progress reports, experiences, lessons learned and examples of best practices.

HIGH LEVEL POLITICAL WILL – G7 AND THE G20

More recently the political will to address at least some aspects of the ocean pollutants has been evident in the stated commitments of the G20 and the G7.

In 2015, the G7 (Canada, France, Germany, Italy, Japan, U.K. and U.S.) adopted the G7 Action Plan to Combat Marine Litter.[387] The countries committed to prevent, reduce and remove marine litter, by supporting development and implementation of national or regional action plans to reduce waste entering inland and coastal waters and ultimately becoming marine litter, as well as removing existing waste. The G7 supported the use of existing platforms and tools such as GPA and Regional Seas Conventions and Action Plans.

In 2017, the G20 also adopted the Action Plan on Marine Litter,[388] which promoted waste prevention, resource efficiency, sustainable waste management, effective waste water treatment and storm water management, as well as awareness raising and capacity building. The G20 action plan is linked to the UNEP Global Partnership on Marine Litter.

INTERNATIONAL INSTRUMENTS ADDRESSING MARINE POLLUTION

There are international instruments with objectives to address marine pollution. These include:[389]

- International Convention for the Prevention of Pollution from Ships (MARPOL),[390] which addresses pollution and dumping from ships due to operational losses or accident.
    - MARPOL Annex V[391] focuses on plastics disposed at sea and at port reception facilities.
- UN Convention on the Law of the Sea (UNCLOS)[392], which focuses on the prevention of pollution from ships and land-based sources of pollution, as well as dumping and pollution transfer from one nation to another.
- London Dumping Convention,[393] which addresses deliberate at-sea disposal of land-based waste, with each member regulating discharges of waste on its own ships.

- Barcelona Convention[394] addresses land and ocean-based waste from dumping, runoff, and discharges (including plastics) in the Mediterranean Sea region.
- Cartagena Convention[395] addresses pollution from ships, dumping at sea and land-based sources of pollution in the Wider Caribbean Region.
- European Marine Strategy Framework Directive[396] addresses all litter in European Union seas based on where it is found (e.g., washed ashore, in water column, ingested by marine animals) and type (e.g., microplastics).
- Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR)[397] addresses European ship discharges, lost and discarded fisheries materials from vessels, land-based wastes from coastal or riverine disposal and recreational littering.
- Helsinki Convention[398] addresses marine pollution from all sources (e.g., point-source or diffuse inputs from land-based sources). Members must establish legislation for prevention and abatement of marine pollution.

While some instruments such as the Helsinki Convention have significantly improved sub-regional marine water quality, collectively these instruments have so far largely failed to address the wide diversity of land-based sources of ocean pollutants[399] estimated to be responsible for the majority of chemical and plastic pollution in the marine environment.

THE CIRCULAR ECONOMY

The concept of a circular economy is based on a sustainable system of resource input, "closed loop" production, use and re-use/recycling. The notion of a waste is rejected and negative impacts minimised.[406] This is achieved through appropriate product design and ingredient choice, allowing the product to be reused, refurbished and recycled without toxic emissions or residues. Turning waste into energy is often touted as one key to a circular economy, enabling the value of products, materials, and resources to be maintained on the market for as long as possible, minimising waste and resource use. However, incinerating materials even for the generation of energy does not fulfil the criteria of a circular sustainable system, as the resource is destroyed. Instead, "waste to energy" incineration continues the linear model of raw materials extraction, production, use and disposal.

UN FRAMEWORK CONVENTION ON CLIMATE CHANGE

Climate change affects chemical releases and their toxic impacts, as well as causing dangerous acidification of our oceans. The objective of the **UN Framework Convention on Climate Change** is to "*stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*." The Convention sets non-binding limits on greenhouse gas emissions for individual countries depending on whether they are a developed country, an economy in transition, or a least developed country.

Addressing climate change is essential to protect the marine environment; however, effective and sustainable chemical management is also paramount.

STRATEGIC APPROACH TO INTERNATIONAL CHEMICALS MANAGEMENT (SAICM)

In 2002, the World Summit on Sustainable Development established the Strategic Approach to International Chemicals Management (SAICM), a multi-stakeholder, multi-sectorial process committed to a goal to ensure "*chemicals are produced and used in ways that minimize harms*." [400]

SAICM has a key role in promoting safer chemicals policy through toxics reduction. It calls for elimination and substitution to avoid and ultimately eliminate the adverse toxic impacts embedded in the life cycle of products and packaging from raw materials extraction, use and final disposal.

SAICM recognises 11 basic elements critical at the national and regional levels to achieve sound chemicals and waste management, which are crucial to address ocean pollution:

- Legal frameworks to address the life cycle of chemicals and waste
- Relevant enforcement and compliance mechanisms
- Implementation of chemicals and waste-related multilateral environmental agreements, as well as health, labour and other relevant conventions and voluntary mechanisms
- Strong institutional frameworks and coordination mechanisms among relevant stakeholders
- Collection and systems for the transparent sharing of relevant data and information among all relevant stakeholders using a life cycle approach, including the implementation of the Globally Harmonized System of Classification and Labelling of Chemicals

- Industry participation and defined responsibility across the life cycle, including cost recovery policies and systems as well as the incorporation of sound chemicals management into corporate policies and practices
- Inclusion of the sound management of chemicals and waste in national health, labour, social, environment and economic budgeting processes and development plans
- Chemicals risk assessment and risk reduction through the use of best practices
- Strengthened capacity to deal with chemicals accidents, including institutional strengthening for poison centres
- Monitoring and assessing the impacts of chemicals on health and the environment
- Development and promotion of environmentally sound and safer alternatives

IPEN prepared a NGO Guide to SAICM,[401] which presents ways that NGOs and civil society can make use of SAICM to protect human health and ecosystems from the harms caused by exposure to toxic chemical substances.

CHEMICAL AND WASTE CONVENTIONS

There is a range of international and regional chemical and waste conventions that can contribute to limiting chemicals releases. To fulfil their aims and objectives, all countries need to ratify and fully implement their obligations.

Stockholm Convention on Persistent Organic Pollutants 2001

The Stockholm Convention on POPs is a global, legally-binding treaty adopted in 2001 with the objective to protect human health and the environment from the impacts of POPs.[402] There are 182 parties to the Convention.

To be listed in the Convention, chemicals must be nominated by a Party to the Convention, fulfil the POPs criteria of toxicity, persistence and bioaccumulation and capacity for long-range transport, and be shown to warrant global action. The POPs Review Committee undertakes the assessment of new POPs, including known ocean pollutants. Some, like PBDEs, are associated with plastics and polymer production. Once a chemical is listed, Parties to the convention must eliminate production, use and trade unless exemptions apply.

POPS CHEMICALS

ANNEX A (ELIMINATION)

Parties must take measures to eliminate the production and use of the chemicals listed under Annex A. Specific exemptions for use or production are listed in the Annex and apply only to Parties that register for them.

- Aldrin *
- Chlordane *
- Chlordecone
- Decabromodiphenyl ether (commercial mixture, c-decaBDE)
- Dieldrin *
- Endrin *
- Heptachlor *
- Hexabromobiphenyl
- Hexabromocyclododecane (HBCDD)
- Hexabromodiphenyl ether and heptabromodiphenyl ether
- Hexachlorobenzene (HCB) *
- Hexachlorobutadiene
- Alpha hexachlorocyclohexane
- Beta hexachlorocyclohexane
- Lindane
- Mirex *
- Pentachlorobenzene
- Pentachlorophenol and its salts and esters
- Polychlorinated biphenyls (PCB) *
- Polychlorinated naphthalenes
- Short-chain chlorinated paraffins (SCCPs)
- Technical endosulfan and its related isomers
- Tetrabromodiphenyl ether and pentabromodiphenyl ether
- Toxaphene *

ANNEX B (RESTRICTION)

Parties must take measures to restrict the production and use of the chemicals listed under Annex B in light of any applicable acceptable purposes and/or specific exemptions listed in the Annex.

- DDT *
- Perfluorooctane sulfonic acid, its salts and perfluorooctane sulfonyl fluoride

ANNEX C (UNINTENTIONAL PRODUCTION)

Parties must take measures to reduce the unintentional releases of chemicals listed under Annex C with the goal of continuing minimization and, where feasible, ultimate elimination.

- Hexachlorobenzene (HCB) *
- Hexachlorobutadiene (HCBD)
- Pentachlorobenzene
- Polychlorinated biphenyls (PCBs) *
- Polychlorinated dibenzo-p-dioxins (PCDD) *
- Polychlorinated dibenzofurans (PCDF) *
- Polychlorinated naphthalenes

Note: Those marked with * are the original listed POPs chemicals.

Parties are also required to develop and implement strategies to identify existing POPs stockpiles, and to develop strategies for identifying products in use that contain or are contaminated with POPs and POPs-containing wastes. POPs-containing wastes must be disposed of in such a way that the POPs content of the waste is destroyed or irreversibly transformed and no longer exhibits POPs characteristics. Article 6 of the Convention prohibits recycling or reuse of the POPs content of the waste.

Nevertheless, when the flame retardants PentaBDE and OctaBDE were listed, Parties agreed to an exemption that permits recycling of materials such as foam and plastics that contain these substances until 2030. In response, the POPs Review Committee developed recommendations to address this toxic recycling,[403] including the elimination of PBDEs from the recycling streams as swiftly as possible. They acknowledged that failure to do so would result in wider human and environmental contamination and the dispersal of PBDEs. Recycling materials that contain POPs contaminates the final products and continues the legacy of hazardous emissions and exposures.

Due to the persistency, toxicity, bioaccumulation and long-range transport of micro and nano-plastics, it has been suggested that these could be considered as a new class of POPs under the Stockholm Convention.[404] Consideration of the role that marine plastics play in the distribution of POPs chemicals should also be included in the assessment of new POP nominations, while measures to reduce marine plastics should be included in the National Implementation Plans for the Stockholm Convention.[405]

Since its inception, the Stockholm Convention has been successful in helping rid the world of some of the worst ocean pollutants, but it has its limitations. For example, listing requires nomination by a Party to the Convention and there is considerable reluctance by many countries to undertake this task. In some cases, the banning of one POP has been quickly replaced by another of a similar calibre, referred to as "regrettable substitution." This practice, and the sheer number of POPs chemicals requiring assessment, has highlighted the urgent need to introduce group assessments with resultant bans or restrictions on groups of chemicals such as the highly persistent perfluorinated chemicals, which are ubiquitous contaminants of the marine environment.

Industry pressure is also increasing and exemptions to continue using some of the worst POPs pollutants have been incorporated in recent Stockholm Convention listings. Those industries that have already eliminated potential POPs from their production cycles are often not represented in the meetings, allowing "dirty" industry to lobby to continue their polluting activities. Improved participation by environmental NGOs,

health advocacy groups and worker organisations could serve to improve outcomes.

Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal 1989

The Basel Convention[407] aims to protect human health and the environment against the adverse effects of wastes. It covers wastes defined as "hazardous wastes," based on their origin and/or composition and their characteristics, as well as two types of wastes defined as "other wastes" - household waste and incinerator ash. There are 186 Parties to the Convention.

The Convention is responsible for developing the technical guidelines for POPs and for plastic waste. The guidance includes incineration of hazardous waste as a suitable destruction technology, despite the Stockholm Convention statement that the process generates hazardous by-products such as dioxin air emissions and contaminated ash.

In December 2002, the Convention adopted the "*Technical guidelines for the identification and environmentally sound management (ESM) of plastic wastes and for their disposal*",[408] which focuses on the management and recycling of plastic wastes. However, to be effective in addressing marine plastics, the plastic waste guidelines need to be amended to specifically address plastic throughout its life cycle. This includes its toxic additives, its use, and, plastic's role as an ocean pollutant.

The Convention's guidance on the prevention and minimisation of the generation of hazardous and other wastes highlights plastic waste as a key waste stream. Yet, the Convention does not address the export of plastic-containing waste to countries where there is no environmentally sound recycling, recovery or final disposal.

The Basel Convention has developed some guidance on marine plastic issues,[409] including guidance on how to improve the sea-land interface to ensure that wastes falling within the scope of MARPOL, once offloaded from a ship, are managed in an environmentally sound manner. The regional and coordinating centres of the Basel and Stockholm Conventions have been encouraged to work on the impact of plastic waste, marine plastic litter and microplastics, and on measures to prevent them.

In 2017, the Basel Convention Conference of Parties decided that its subsidiary body, the Open-ended Working Group, should consider relevant options available under the Convention to further address marine plastic litter and microplastics.

An amendment to the Convention has been proposed that would reclassify scrap plastic under the category of "*wastes requiring special consideration*." This would mean shipments of plastic waste between Parties would require prior notification and consent by the competent authorities of the exporting, transit and importing countries.

The Basel Convention also established the Household Waste Partnership to promote environmentally sustainable management (ESM) of household waste.[410] It is a forum for information sharing, awareness raising, outreach and coordination in relation to activities on ESM of household waste.

The Basel Convention could be instrumental in developing efficient strategies and ways to help prevent and minimise marine plastic and other ocean pollutants classified as hazardous wastes.[411] This would need not only changes to Basel guidance documents, expanding their reach to effectively address marine plastics, but it would also depend on the full implementation of the Convention by all Parties, including ratification and implementation of the Basel Ban amendment, which provides for the prohibition of all transboundary movements by developed countries to developing countries of hazardous wastes destined for reuse, recycling or recovery operations.

Minamata Convention on Mercury 2013

The Minamata Convention aims to protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds. The Minamata Convention recognises "*that mercury is a chemical of global concern owing to its long-range atmospheric transport, its persistence in the environment once anthropogenically introduced, its ability to bioaccumulate in ecosystems and its significant negative effects on human health and the environment*." [412] There are 95 Parties to the Convention.

The Convention requires the phase-out of many products containing mercury, implements restrictions on trade and supply of mercury and establishes a framework to reduce or eliminate emissions and releases of mercury from industrial processes and mining. The Convention requires national management plans for a major source of mercury such as artisanal and small-scale gold mining. IPEN has prepared a guide to the mercury treaty to assist NGOs active in the mercury-free campaign.[413]

VOLUNTARY AGREEMENTS

There are voluntary efforts aimed at addressing marine litter, including the Honolulu Strategy,[414] a framework for a comprehensive and global collaborative effort to reduce the ecological, human health, and economic impacts of marine debris worldwide. It was developed with the support and assistance of scientists, practitioners, managers, and the private sector from around the world with UNEP and NOAA's Marine Debris Program providing technical and financial support.

Intended for use as a planning and monitoring tool for marine debris programs, the strategy provides a frame of reference for collaboration and sharing of best practices.

The strategy has three goals:

- Reduce the amount and impact of land-based sources of marine debris introduced into the sea;
- Reduce the amount and impact of sea-based sources of marine debris, including solid waste; lost cargo; abandoned, lost, or otherwise discarded fishing gear (ALDFG); and abandoned vessels, introduced into the sea; and
- Reduce the amount and impact of accumulated marine debris on shorelines, in benthic habitats, and in pelagic waters.

In January 2012, the Honolulu Strategy was endorsed by representatives of 65 governments and the European Commission at the 5th International Marine Debris Conference.

UN ENVIRONMENT ASSEMBLY

The United Nations Environment Assembly (UNEA)[415] is the world's highest-level decision-making body on the environment. It was established to address the critical environmental challenges facing the world and to implement the 2030 Agenda for Sustainable Development.

At its second session, UNEA adopted a resolution on marine plastic litter and microplastics,[416] and in December 2017, UNEA established an Open-Ended Ad Hoc Working Group on marine litter and microplastics to assess potential strategies to address the problem, including consideration of a legally binding instrument. Their recommendations will be presented at the next UN Environment Assembly in 2019.

To be effective, a legally binding instrument would need to:

- Address sustainable management of plastics throughout their life cycle, including design, production, use, recycling and disposal of plastics;
- Phase out EDCs and other toxic ingredients in plastic to facilitate their recycling;
- Incorporate strong monitoring, reporting and enforcement mechanisms;
- Assist in building effective national collection and audited recycling systems;

- Develop and implement extended producer responsibility schemes;
- Ban the most common or damaging types of plastic marine litter (e.g., microbeads and fish-egg-sized nurdles);
- Support the development of and transition to sustainable product substitutes;
- Develop criteria for product and material substitutes that incorporate and emphasize potential marine impacts, e.g., design products and materials to be benign by design for the ocean (using green chemistry, renewable / regenerative feedstocks, etc.) ;
- Specify necessary steps to achieve agreed goals and review system(s);
- Develop model template legislation;
- Research and provide funding to recover marine plastic debris;
- Identify and provide support for non-combustion treatment / destruction of contaminated plastics / unrecyclable plastics;
- Include multi-stakeholder partnerships with a multi-sectoral scope;
- Create an adequate funding mechanism; and
- Include an effective monitoring and feedback system to assess outcomes.

A new instrument would need to be compatible with existing multilateral agreements and, to achieve its aims, would also need to focus on reduction in production and consumption levels as well as ensuring industry responsibility for their products from cradle to cradle. It would need to address issues of unnecessary or frivolous use, foster product reuse wherever possible, and promote non-toxic recycling, not down-cycling. The instrument must raise community and industry awareness and be based on an acceptance that "business as usual" is not an option.

NON-GOVERNMENTAL ORGANIZATIONS

There are a range of international non-governmental organizations (NGOs) and networks working in the area of toxic reductions, wastes management, and chemical and plastic pollution. These include, but are not limited to, the following:

IPEN
https://ipen.org/

IPEN brings together leading public interest groups working on environmental and public health issues in over 100 countries to take action internationally to minimize and, whenever possible, eliminate hazardous, toxic chemicals. IPEN's mission of a toxics-free future for all is captured in its Stockholm, Dubai, and Minamata Declarations.

Break Free From Plastic
https://www.breakfreefromplastic.org/

BFFP aims to bring systemic change through a holistic approach, tackling plastic pollution across the whole plastics value chain, focusing on prevention rather than cure, and providing effective solutions.

Basel Action Network (BAN)
https://www.ban.org/

BAN's mission is to champion global environmental health and justice by ending toxic trade, catalyzing a toxics-free future, and campaigning for everyone's right to a clean environment.

Center for International Environmental Law (CIEL) https://www.ciel.org/

CIEL uses the power of law to protect the environment, promote human rights, and ensure a just and sustainable society. It works to achieve a toxics-free future through negotiating new international treaties and changing public policy and private practices.

Friends of the Earth (FOE)
https://foe.org/issues/oceans/

Friends of the Earth strives for a more healthy and just world. Its oceans campaign focuses on air, water and oil pollution from ships, oil tankers and recreational boats.

Global Alliance for Incinerator Alternatives (GAIA) http://www.no-burn.org/

GAIA is a worldwide alliance of grassroots groups, NGOs and individuals in over 90 countries whose ultimate vision is a just, toxic-free world without incineration.

Greenpeace International
https://www.greenpeace.org/international/

Greenpeace's goal is to ensure the ability of the earth to nurture life by protecting biodiversity, preventing pollution and abuse of the earth's ocean, land, air and fresh water, and ending all nuclear threats.

IPEN OCEAN POLLUTANTS PLATFORM

In response to the increasing threat of marine pollutants in our oceans, IPEN developed a platform incorporating current and future commitments to address ocean pollutants. IPEN's research [417] demonstrated the impact of mercury pollution in the Asia Pacific region, and, through its work on new POPs and the Stockholm Convention's POPs Review Committee, has highlighted the increasing detection of POPs such as PBDEs and PFAS in the marine environment.

IPEN participates in the assessment process for nominated POPs and has also highlighted the failures of countries to manage their wastes, demonstrating the generation of POPs pollution from the combustion of waste. IPEN campaigns for the adoption of non-combustion destruction technologies. IPEN Participating Organisations pursue efforts to ensure effective implementation of the Stockholm and Minamata Conventions, including participation in National Implementation Plans (NIPs) and National Action Plans (NAPs), respectively.

To raise global awareness about EDCs, IPEN worked with the Endocrine Society to develop an "Introduction to Endocrine Disrupting Chemicals (EDCs): A Guide for Public Interest Organizations and Policy-Makers."

CONCLUSION

"... we are accustomed to thinking of the ocean as limitless, it is not. We have pushed many of its inhabitants to the brink of extinction and beyond. We have choked its waters with plastics and other pollutants, leaching poisons into the bodies of fish and other animals as well as ourselves. We have already irreversibly altered its ecology, its biology, even its very chemistry." [418]

The Earth's oceans have been eroded by humanity, with only 13.2% of the world's oceans now classified as marine wilderness.[419] Even these wilderness regions are impacted by chemical contamination and plastic litter. Ocean pollutants are contributing to the destruction of marine ecosystems and food supplies, while the impacts of climate change on the marine environment and our life support systems are devastating.

Despite a myriad of national and regional programs and global instruments, ocean pollution is out of control and worsening, with the continued reliance of fossil fuels, an ever-increasing population and rampant consumerism.

The global industrial environment remains one largely of self-regulation, driven by profit and greed, with little regard for the finite resources of the global environment or for future generations.

Many ocean pollutants, including marine plastics, will take centuries to break down, if at all. Terminal products such as PFOS and PFOA are likely to be with us until the end of time. Still, more and more chemicals and single use plastic products are created and released to the marine environment either intentionally or inadvertently.

National governments are failing to adequately regulate polluting industries and failing to protect their citizens and future generations. Global programs and instruments, while diverse and extensive, have not been fully implemented and are not achieving their objectives. At the same time, there is increasing corporate capture of organisations like UN Environment and an ongoing uncoupling of science and policy.

While the work of NGOs, committed individuals and sustainable industries grows in scope and impact, the broader community struggles with incomplete knowledge of the extent of the problems and its capacity to effect change beyond the individual and community level.

The way forward is challenging and the changes required to protect and restore oceans are nothing short of revolutionary. But face them we must, because we and countless other species are totally dependent on healthy ocean ecosystems for food, regulation of the climate, and life itself.

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