# AQUATIC POLLUTANTS IN OCEANS AND FISHERIES

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NTN NATIONAL TOXICS NETWORK

IPEN for a toxics-free future

# AQUATIC POLLUTANTS IN OCEANS AND FISHERIES

*Lead Authors*
***Matt Landos**, BVSc (HonsI) MANZCVS (Aquatic Animal Health Chapter)*
***Mariann Lloyd Smith**, PhD, Senior Advisor, NTN*
***Joanna Immig**, B.App.SC National Coordinator, NTN*

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**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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**National Toxics Network** (NTN) is a not for profit civil society network striving for pollution reduction, protection of environmental health and environmental justice for all. NTN is committed to a toxics free future.

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## KEY FINDINGS

- **Overfishing is not the sole cause of fishery declines.** Poorly managed fisheries and catchments have wrought destruction on water quality and critical nursery habitat as well as the reduction and removal of aquatic food resources. Exposures to environmental pollutants are adversely impacting fertility, behavior, and resilience, and negatively influencing the recruitment and survival capacity of aquatic species. There will never be sustainable fisheries until all factors contributing to fishery declines are addressed.
- **Chemical pollutants have been impacting oceanic and aquatic food webs for decades and the impacts are worsening.** The scientific literature documents man-made pollution in aquatic ecosystems since the 1970s. Estimates indicate up to 80% of marine chemical pollution originates on land and the situation is worsening. Point source management of pollutants has failed to protect aquatic ecosystems from diffuse sources everywhere. Aquaculture is also reaching limits due to pollutant impacts with intensification already driving deterioration in some areas, and contaminants in aquaculture feeds affecting fish health.
- **Pollutants including industrial chemicals, pesticides, pharmaceuticals, heavy metals, plastics and microplastics have deleterious impacts to aquatic ecosystems at all trophic levels from plankton to whales.** Endocrine disrupting chemicals, which are biologically active at extremely low concentrations, pose a particular long-term threat to fisheries. Persistent pollutants such as mercury, brominated compounds, and plastics biomagnify in the aquatic food web and ultimately reach humans.
- **Aquatic ecosystems that sustain fisheries are undergoing fundamental shifts as a result of climate change.** Oceans are warming and becoming more acidic with increasing carbon dioxide deposition. Melting sea ice, glaciers and permafrost are increasing sea levels and altering ocean currents, salinity and oxygen levels. Increases in both de-oxygenated 'dead zones' and coastal algal blooms are being observed. Furthermore, climate change is re-mobilizing historical contaminants from their 'polar sinks'.
- **Climate change and chronic exposures to pesticides all can amplify the impacts of pollution by increasing exposures, toxicity and bioaccumulation of pollutants in the food web.** Methyl mercury (MeHg) and PCBs are among the most prevalent and toxic contaminants in the marine food web.
- **We are at the precipice of disaster, but have an opportunity for recovery.** Progress requires fundamental shifts in industry, economy and governance, the cessation of deep-sea mining and other destructive industries, and environmentally sound chemical management, and true circular economies. Regenerative approaches to agriculture and aquaculture are urgently required to lower carbon, stop further pollution, and begin the restoration process.

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# FOREWORD

Health experts have long promoted the benefits of incorporating fish in a heart-healthy diet, yet at the same time it is now well established that much of the seafood we eat is dangerously polluted. Contamination coupled with the fact that nearly 90% of our global fisheries are fully exploited, overexploited or depleted, leads us to limit our fish consumption to avoid species more ladened with harmful toxins as well those at risk of collapse. However, some of us do not have the luxury of selecting less contaminated or more sustainable seafood options. Over 3 billion people rely on fish as a significant source of animal protein, especially those in the world's poorest countries.

Despite the global importance of seafood, this report demonstrates how scientists are now discovering serious disruptions in entire aquatic food chains throughout the world due to the growing use of hazardous chemicals, climate change, plastic pollution, and other manmade factors. Healthy marine environments are essential not only for the survival of all aquatic organisms, but for all life on land as well, including humans. Unfortunately, by the time the damage caused by these so-called "invisible" threats become "visible", it is too late – the damage is already done.

Chemical production and use have been growing rapidly since the 1970s, and today there are 100,000 to 350,000 commercially available chemicals. Shockingly, only about 1% of the chemicals on the market have been tested to assess their impact on human health and the environment. At the same time, the climate is warming at an unprecedented rate, and plastic is piling up all over the world and at every depth of our oceans.

We are still learning the total impact of these developments on marine environments, but we do know that marine life is damaged, endangered and dying off rapidly. Pesticides not only kill the invertebrates fish depend on for food, pesticide run-off also poisons the waterways where fish breed and spawn. Pharmaceuticals travel from our water treatment plants into aquatic environments where they inhibit fertility and damage the hormonal systems of marine animals. Fish, crabs, mussels, and lobsters mistaking microplastics for food become malnourished, and microplastics and the chemicals attached to them accumulate up the food chain. Climate change compounds these threats by creating warmer, more acidic oceans, which destroys essential habitats and fisheries. And when all of these processes mix, their results can be unpredictable and magnified.

The most insidious impact is on the food web itself. The diverse world we live in is a complex ecosystem of interrelationships that have developed over millions of years. Plankton and seagrass, microbes and bacteria, insects and birds, fish larvae and predator fish, polar bears, and humans: all play a role in the food chain and all are dependent on a healthy marine environment for their survival.

Fortunately, there is still time to reverse these trends. Most importantly we must:

- Require and enforce strict industrial chemical pollution controls
- Limit new plastic production and innovate into new materials and systems free of plastics and the harmful chemical additives
- Transform away from the reliance on the heavy use of pesticide and fertilizers to produce the world's food
- Invest in artisanal farmers and fishers engaged in regenerative agriculture and aquaculture

This report is the first to begin to detail the numerous ways and places in which chemical pollution and climate change is destabilizing this marine infrastructure and the world's fisheries. We still have time to stop the destruction, but as this report indicates, we will need to go beyond thinking only about how to control overfishing or manage pollutants in the fish we consume. Our survival, along with that of all other species, will depend on ensuring the health of the entire ocean, an objective we all must work on together to achieve.

Kristian Parker

*Kristian Parker,*
*Oak Foundation*

Sara Lowell

*Sara Lowell,*
*Marisla Foundation*

OAK FOUNDATION

Marisla foundation

# 1. SUMMARY

It is thanks to an abundance of seafood from the once bountiful oceans that human brains apparently grew larger, contributing to our evolution as Homo sapiens.[30]

Indeed, we've become so successful as a species that our rapid growth in numbers, coupled with our consumptive and polluting impact on the planet, now threatens the entire marine and aquatic ecosystems that have nourished humanity.

According to the UN Food and Agriculture Organization[70], a third of commercial fish stocks are harvested at biologically unsustainable levels and 90% of fisheries are exploited to their maximum capacity.

The population of Pacific bluefin tuna for instance has plunged 97% from historic levels due to overfishing of one of the ocean's top predators. The persistence of overfished stocks is a significant concern in terms of meeting the United Nations Sustainable Development Goals for regulating harvesting, ending overfishing, and restoring fisheries.

In considering why fish stocks are diminishing, it is a common belief that they have simply been overfished. If that were the case then the shift to aquaculture, which now accounts for nearly 50% of fish consumption, as well as better management of "sustainable" wild fisheries would fix the problem.

**WHERE DID ALL THE FISH GO?**

- Did we catch too many?
- Did we manage fisheries poorly?
- Did we remove their habitats?
- Did we take away their food resources?
- Did we drain their nursery areas?
- Have we made them less fertile?
- Have we changed their behavior?
- Are we making them less resilient?

**All of the above.**

However, this is not the case and the reasons for continued fishery declines are far more complex.

Regulation of fisheries is not always underpinned with biologically or scientifically relevant data on all contributors to the health of fish stocks. This has led to a narrow view on why fish numbers are declining focused largely on quota catch rates and effort. Attempts to manage fisheries without considering their interface with the land, and the impacts of pollution on fish wellbeing, will inevitably lead to poor outcomes. If the fundamentals of water quality and habitat are wrong, sustainability—or sustained high productivity which fisheries are capable of—will not be achieved. Regulators have yet to grasp the impact of pollution.

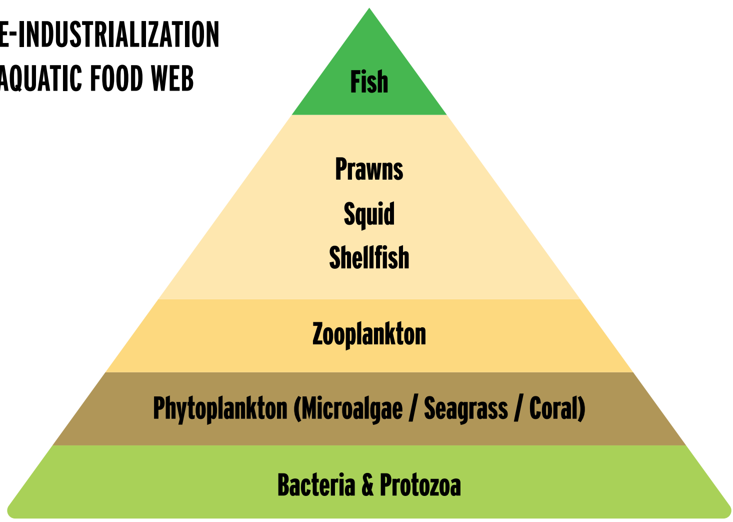
Pollution is having deleterious effects on all parts of aquatic food webs. It causes declines in populations of fish and other aquatic organisms by affecting their survival and ability to reproduce. Fishery declines are occurring amid the perfect storm of habitat destruction, loss of healthy food resources within aquatic food webs, draining and damage to nursery areas, as well as the impacts on water quality caused by pollution and climate change. While mass fish kills are obvious and often garner media coverage, slow invisible killers like persistent organic pollutants and excessive nutrients impact aquatic life in far more insidious ways. There is a wealth of scientific research now pointing to serious impacts on aquatic animal immunity, fertility, development, and survivability.

WHILE MASS FISH KILLS ARE OBVIOUS AND OFTEN GARNER MEDIA COVERAGE, SLOW INVISIBLE KILLERS LIKE PERSISTENT ORGANIC POLLUTANTS AND EXCESSIVE NUTRIENTS IMPACT AQUATIC LIFE IN FAR MORE INSIDIOUS WAYS. THERE IS A WEALTH OF SCIENTIFIC RESEARCH NOW POINTING TO SERIOUS IMPACTS ON AQUATIC ANIMAL IMMUNITY, FERTILITY, DEVELOPMENT, AND SURVIVABILITY.

Prior to industrialization, the aquatic food web had a healthy abundance of fish, prawns, squid, and shellfish built off a broad base of zooplankton, phytoplankton, bacteria, and protozoa. The integrity of the post-industrial aquatic food web has been seriously compromised, with fewer and fewer fish at the top, losses of invertebrates in the sediments and water column, losses of marine algae, coral, and other primary producers, as well as the proliferation of bacteria and toxic algae.

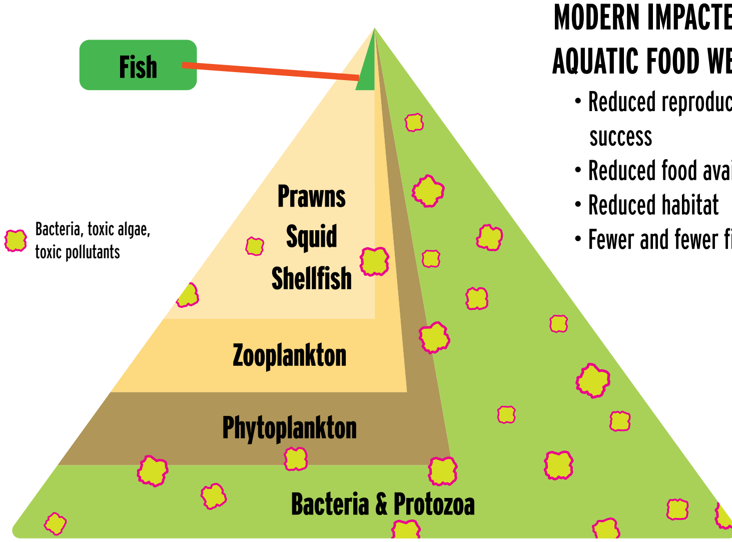
**Prior to industrialization, populations of fish helped keep the aquatic food web in balance. Now, however, the food web is disrupted leading to the proliferation of bacteria and toxic algae that further threaten all levels of the food chain.**

## PRE-INDUSTRIALIZATION AQUATIC FOOD WEB




## MODERN IMPACTED AQUATIC FOOD WEB

- Reduced reproductive success
- Reduced food availability
- Reduced habitat
- Fewer and fewer fish



**Persistent Organic Pollutants, such as pesticides, find their way into waterways, lakes, and ocean, impacting wildlife in unexpected ways.**

The marine ecosystem is under threat from increasing levels of chemical and plastic pollution as a result of industrial and urban runoff, mining and agriculture. The impacts on fisheries are significant, with contamination now evident in marine and aquatic ecosystems and food webs. Pollution affects fish health and the quality and quantity of available wild seafood for human consumption. It also now compromises the suitability of some inshore waters for aquaculture production.

Persistent organochlorine contaminants, like polychlorinated biphenyls (PCBs) and DDT (dichlorodiphenyltrichloroethane), have been measured in waterways, oceans, and marine and aquatic life since the 1970s. But now, many more highly persistent and toxic chemicals—including pesticides, metals such as mercury, pharmaceuticals, and industrial chemicals—are found in marine and aquatic environments and their inhabitants. Often these pollutants impact aquatic ecosystems in totally unexpected ways.

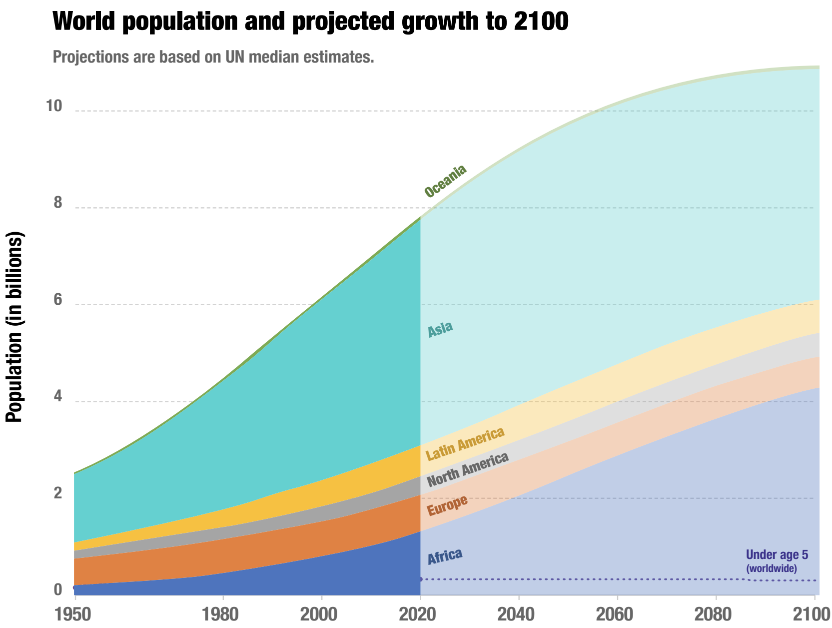
The solution to pollution was once seen as "dilution"—dumping our wastes into rivers and oceans, diluting and washing them away. In many places however, we've fundamentally run out of "diluent" to keep pollutant levels under "safe" levels. Due to urbanization and intensification of industry, localized plumes of pollution are so intense they often overwhelm the freshwater river and coastal marine ecosystems capacity to dilute it.

Pollution is already a limitation for aquaculture production and ongoing wild fishery productivity. There are many localities that have such poor water quality from pollutants that farmed fish raised in those waters have very poor health and survival outcomes. The difficulties the Asian aquaculture shrimp industry faces are a case in point.

We tend to think of forests as the lungs of the earth, but in fact it is the plankton which comprise the "oceanic lungs" that make two-thirds of global oxygen. Oceans also provide a substantial amount of nature's carbon sequestration.

Climate change is already threatening sustainable growth in both aquaculture and wild fishery production worldwide. Hotter temperatures are remobilizing historic contamination while increased ocean temperatures are altering essential currents, and contributing to increased bacterial diseases, bleaching coral reefs, damaging intertidal zones, killing kelp forests, and impacting the entire marine ecosystem through increased acidification.[203]

Set against the backdrop of the climate emergency and worsening pollution levels, world population continues to grow, and as wealth increases, so too does the demand for seafood. Yet, wild capture fisheries are stagnating and falling increasingly short of a growing world demand for seafood. The global seafood industry, and the livelihoods of millions of family and small-scale fishers and communities who depend on seafood, is at a crossroads.




**Human populations continue to increase at a rapid rate, putting additional pressure on food webs and increasing pollution sources.**

The fossil fuel based petrochemical industry, currently near $5.7 trillion in global sales, is expected to double in size by 2030, substantially increasing dangerous emissions, climate change impacts, and plastic pollution in our oceans.

# 2. IMPACTS OF AQUATIC AND MARINE POLLUTANTS

The often-invisible releases of industrial chemicals, pesticides, pharmaceuticals, and nutrients entering our waterways are contaminating aquatic and marine ecosystems and contributing to the demise of fisheries and aquatic biodiversity.

Chemical pollutants enter our waterways and oceans through industrial emissions, agricultural and stormwater runoff, waste dumping, domestic sewerage, agricultural spray drift, and mining. Coupled with increasing ocean temperatures, acidification, and deoxygenation, exposure to toxic pollution adds another significant stressor for aquatic and marine life.

Contaminants such as PCBs and DDT have been measured in rivers and ocean waters and aquatic life since the 1970s[214], but now many more highly persistent and toxic chemicals, including currently used pesticides, pharmaceuticals, and industrial chemicals such as per- and polyfluoroalkyl substances (PFAS)[142] and polybrominated diphenyl ethers (PBDEs)[91] contaminate many, if not all, marine and aquatic environments and their inhabitants.

EXPOSURE TO PERSISTENT POLLUTANTS [DAMAGES] REPRODUCTION, GROWTH, AND DEVELOPMENT, AS WELL AS IMMUNE RESPONSES TO DISEASE.

PCBs, although banned in many countries, still pollute even the most remote marine polar environments. While some of the highest PCB contamination occurs in Chinese coastal areas and estuaries[84], concentrations of PCBs in fish from Antarctica are still rising[207], while in some areas of the Arctic, PCB metabolites are also increasing.[244]

The exposure to persistent pollutants adversely affects fish, aquatic invertebrates, and marine mammals, damaging their reproduction, growth and development, as well as their immune responses to disease. Pesticide exposures are known to cause death, cancers and lesions, reproductive inhibition and failure, suppression of the immune system, disruption of the endocrine system, and cellular and DNA damage.[168] Chemical exposures can also cause behavioral changes that alter an animal's survivability[152] and in turn affect population dynamics.

Widely used pyrethroid insecticides are toxic to aquatic macroinvertebrates (crayfish and aquatic snails, worms, and aquatic insects) and zooplankton at levels which are already evident in the environment.[86] The neonicotinoid insecticides, imidacloprid and clothianidin, plus the chemically similar insecticide fipronil, are extremely toxic to crustaceans including shrimp, crabs, lobster, aquatic insects, and zooplankton at very small doses. As well, they can cause sub-lethal effects, such as impaired immune function, reduced growth and reproductive success, and genotoxic impacts, damaging genetic information. These effects happen at exposure concentrations currently seen in the environment and well below those associated with mortality.[80]

**Many electronic devices contain brominated flame retardants. Levels of these toxins are increasing in marine environments.**

Some industrial flame retardant chemicals, such as PBDEs, can act in combination and cause developmental neurotoxicity, adversely affecting the developing nervous system at environmentally relevant concentrations.[45, 221] Levels of these highly persistent PBDEs are still increasing in the marine environment, as evident in rising concentrations in Antarctic krill and phytoplankton.[143]

Toxic chemicals and metals can bio-magnify as they move up the aquatic food chain, reaching very high concentrations in top-order predators such as sharks, halibut, rockfish, tuna, and swordfish.

The impact of these chemical mixtures on marine life is unpredictable. The effects may be additive or even synergistic, that is, where chemicals increase each other's toxicities.[225] A synergistic impact was seen when the aquatic larval midge *Chironomus dilutus* was exposed to a mixture of neonicotinoid pesticides, which proved to be far more toxic than predicted by the individual toxicities.[142]

Both the sequence and timing of exposures affects the toxicity of a pollutant to an aquatic organism. Freshwater crustacea experienced different toxic effects when the exposure order of two chemicals was reversed, while maintaining the same dose.[11] Exposures at critical and sensitive developmental stages can disrupt natural processes changing the structure or functions of living organisms, sometimes irreversibly. These impacts can be transgenerational with the effects of pollution being felt over generations.[31] For example, following exposure to PFOS, declines in survival rates of zebrafish (*Danio rerio*) were seen over a number of generations.[119]

Water pollution can also have indirect impacts on fish populations by adversely affecting their food sources, such as killing off sediment dwelling invertebrates. Reduced availability of forage for fish larvae will inevitably reduce fish larval survival and in turn impact fish populations.[80]

## 2.1 ENDOCRINE DISRUPTION – LONG-TERM THREAT TO FISHERIES

Endocrine disrupting chemicals (EDCs) represent a long-term threat to all aquatic life. Exposure to EDCs disrupts an organism's endocrine system by interfering with normal hormonal activity. This can cause developmental, reproductive, neurological, and cardiovascular damage, as well as immune effects resulting in increased susceptibility to disease and parasites.[220]

The impacts of EDCs were first identified in gastropods (marine snails) and then quickly became evident in fish, frogs, alligators, and ultimately in humans. In the most extreme cases, animals developed both male and female sexual characteristics making reproduction impossible. EDCs can affect the biological systems of all aquatic species.

**EDCs affect all aquatic creatures — fish, amphibians, reptiles, mammals, and seabirds as well as the vast array of insects and aquatic invertebrates on which they depend.**

*Continued on page 20*

## MERCURY AND FISH

It is predicted that mercury concentrations will double in the North Pacific Ocean by 2050.[211] Coal combustion and small-scale gold mining account for more than two-thirds of total global anthropogenic mercury emissions.[112]

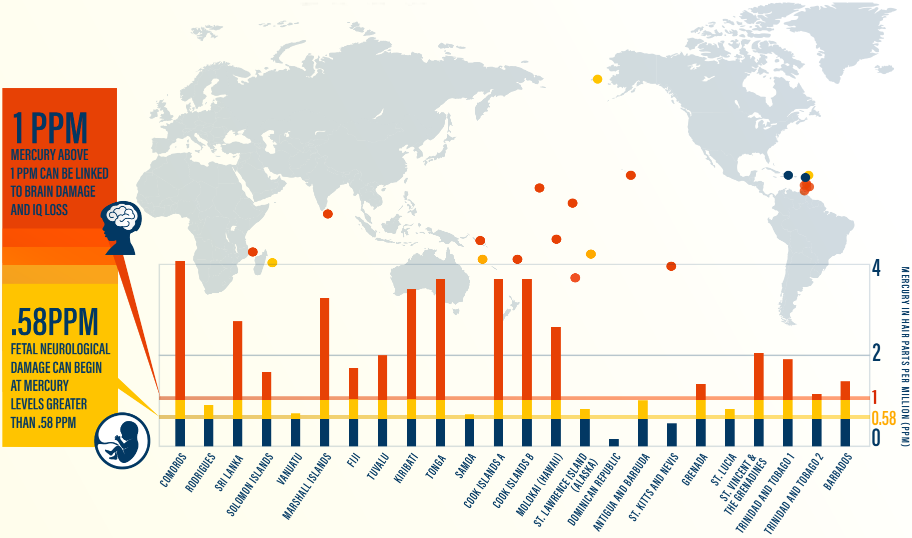
In aquatic environments, inorganic metallic mercury is converted by bacterial organisms to the highly toxic methylmercury. Similar to persistent organic pollutants (POPs) in terms of toxicity, persistence, bioaccumulation, and capacity for long-range transport, methylmercury bioaccumulates in aquatic organisms.

Mercury is a potent neurotoxin and the accumulation of mercury can cause damage to fish brains. Mercury is also linked to reproductive impairment in many fish species.[248] Exposure of fish to mercury at environmentally relevant levels resulted in significant reduction in the number of cells in the hypothalamus, optic tectum and cerebellum and was accompanied by changes to swimming behavior, related both motor function and mood (anxiety-like) status.[249]

Island communities highly dependent on seafood for their protein suffer a chronic, disproportionate, and more dangerous exposure profile to toxic mercury.

Methylmercury levels in some top-order fish species can be up to a million times higher than the levels in the surrounding water.[98] Fish high on the marine food-chain, such as swordfish from the southern Atlantic Ocean, have the highest average mercury levels, followed by Pacific bluefin tuna from the northern Pacific Ocean.[112]

Island communities highly dependent on seafood for their protein suffer a chronic, disproportionate, and more dangerous exposure profile to toxic mercury. Women from Small Island Developing States (SIDS) in the Pacific have very high levels of mercury in their bodies compared to other locations, as their diet is rich in seafood. The




large predatory fish they eat have high methylmercury concentrations in their flesh.[113]

Nearly 90% of the hair samples from the Cook Islands' residents exceeded the U.S. EPA reference dose (RfD) for mercury of 0.1 microgram per kilogram (1 ppm) of body weight per day.[112] An "acceptable dose" for methylmercury may not even be appropriate as there may not be a threshold for methylmercury's adverse neuropsychological effects.[185]

High levels of methylmercury in the bloodstream of unborn babies and young children can damage the developing nervous system and impact their development, potentially reducing IQ. Extremely high levels in the case of Japan's Minamata Bay caused a devastating neurological syndrome with a range of destructive symptoms, including ataxia, numbness in the hands and feet, general muscle weakness, narrowing of the field of vision, and damage to hearing and speech. The effects were trans-generational, being passed from mother to child.

In an effort to protect people from mercury exposures, regulators have introduced food guidelines, particularly for pregnant women. In the north Pacific and Bering Sea, there are also national warnings against consumption of large halibut and other large, high trophic level fish, including certain freshwater fish such as northern pike.[245] In 2017, U.S. regulators warned women of childbearing age not to eat certain fish including king mackerel, marlin, orange roughy, swordfish, and shark. They also warned against some recreationally caught freshwater fish like large carp, catfish, trout, and perch.[212]

*Continued from page 17*

There are many EDCs, both natural and synthetic, found in marine and aquatic environments, including industrial chemicals such as PCBs and dioxins, perfluorinated chemicals (e.g., PFAS) and brominated chemicals (e.g., PBDEs) used in many consumer goods, DDT and currently used pesticides, pharmaceuticals, detergents (e.g., alkylphenols), as well as plastics additives such as bisphenol A (BPA) and phthalates.[198, 229]

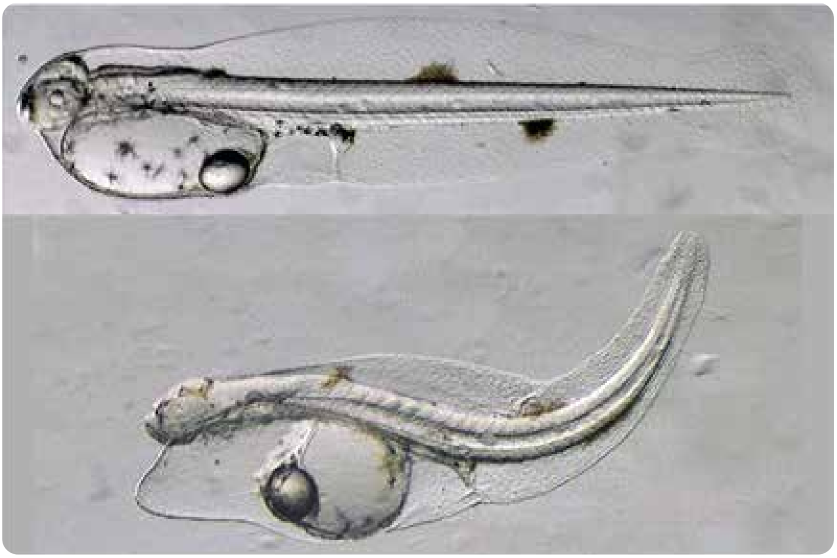
A developing organism is particularly vulnerable to EDCs, and exposure in early life stages can result in structural and physiological defects.[40] Critical "windows of susceptibility" are acknowledged in human toxicology and the effect is similar in aquatic animals such as fish, shrimp, and shellfish.

However, rather than the embryo being within the womb, as in mammalian reproduction, many aquatic animals spawn directly into the water and the embryo incubates in the "womb" of the water body. An embryo faces exposure to pollutants—those deposited in the egg and yolk sac for fish, and those myriad chemicals in the water—that can cause mortality, deformity, and lifelong changes in metabolism. For example, hydrocarbons from oil spills and drilling affected heart development in the larvae of tuna and kingfish.[157, 29]

Persistent and bioaccumulative EDCs found in the yolk of eggs result in toxic exposures in the very early larval stages, as the developing young draws upon the yolk reserves as it grows. In one U.S. East Coast estuaries study, biologically significant levels of PCBs, PBDEs, and current-use and legacy pesticides were detected in all egg samples from river-collected fish. Abnormal brain and liver development and impacts on overall growth were evident in the larvae from the river-collected fish.[169]

PBDEs are known to affect thyroid hormones[222] and cause reproductive, developmental, and neurological toxicity as well as effects on the immune system.[221, 222, 223] In fish embryos and larvae exposed to PBDEs, developmental abnormalities occurred at very low exposure concentrations. The offspring of POPs-exposed parents experienced decreased hatching rates, altered thyroid hormone levels, and inhibition of growth.[117]

Freshwater fish with lifelong exposure to mixtures of POPs (e.g., PBDE, PCB, DDT metabolites) at environmentally relevant concentrations demonstrated developmental and reproductive impacts. These included premature sexual development, changes to male/female sex ratio, differences in body weight, and changes in the regulation of genes.[141] The rate of deformity in fish increased with closer proximity to polluted estuaries[133],



**Compared to a normal yellowfin tuna larva (top), a larva exposed to Deepwater Horizon crude oil during embryonic development (bottom) shows a suite of life-threatening abnormalities to the heart, fins, and eyes.**
Photo John Incardona, NOAA

affecting both breeding success and the viability of populations as the survivability of deformed fish is diminished.

The fertility of marine fish decreased as they bioconcentrated persistent EDCs such as POPs. In the male fish of several wild species, alterations to sperm density and fertility were seen, while in female fish, negative outcomes on egg growth were evident.

Even the smallest aquatic crustaceans are affected by EDCs. Exposure to environmentally relevant concentrations of nonylphenol (NP) on the mysid *Americamysis bahia*, a small shrimp-like crustacean found in marine, fresh and brackish water, resulted in reduced body length and total number of moltings, which negatively affected their overall growth.[146] Organophosphate pesticides have been shown to interfere with thyroid hormone and slow metamorphosis in flounder resulting in a failure of eyes to form on the upper surface of the flat fish.[247]

EDCs frequently have unconventional dose-responses called non-monotonic dose-responses.[130] The effects are not linear and the impacts of low-dose exposure cannot be predicted from high-dose exposure experiments. In some cases, low doses may cause greater biological impact than high

doses for a specific response. Still, higher rates of reproductive problems are generally found in animals with higher exposures to EDCs.[220]

Some EDCs can mutate DNA or cause epigenetic changes[36]—heritable changes that affect the way cells read the genes. These modifications although capable of being passed on to subsequent generation do not change the actual DNA sequence.

EDCs are now widely dispersed in the freshwater and marine environments even in the most remote areas[207, 84, 114, 166, 216]. High concentrations of PCBs, known EDCs, were found in the bodies of shrimp-like crustaceans amphipods living almost 10 kilometers beneath the ocean's surface.[114]

However, there are higher EDC risks in coastal waters than in the open seas.[135] In Australia's Great Barrier Reef catchment, coastal fish are exposed to estrogenic compounds associated with the pesticide run-off from production of sugar cane and bananas, as well as other agricultural activities.[128]

There is now ample evidence strongly implicating the role of EDCs in reduced population numbers of amphibians, reptiles, freshwater and marine fishes, and invertebrates.[220]

### 2.1.1 INTERSEX AND IMPOSEX

Intersex or imposex is the presence of both male and female sex characteristics within the same organism. It is a clearly observable manifestation of endocrine disruption in aquatic species including fish, frogs, and other reptiles. First reported in molluscs over three decades ago[182,62], it is now observed in fish in many streams across the US.[229]

Tributyltin (TBT), used previously in antifouling paint on boats, destroyed commercial shellfish beds. At very low concentrations, TBT caused female molluscs to develop male sex characteristics, which blocked the release of eggs.[182] In 1995, a survey of marine gastropods from the South Australian coast revealed 100% demonstrated "imposex".[62] The sensitivity of marine molluscs to EDCs became an important indicator of endocrine disruption in the marine ecosystem.[106]

In freshwater systems, the herbicide atrazine, one of the most commonly detected pesticides in ground water, surface water, and precipitation, was shown to alter male fish reproductive tissues when they were exposed during development. Atrazine demasculinized and feminized male fish, amphibians, and reptiles. This was evident in reduced spermatogenesis, the appearance of ovaries in male fish, production of the protein, vitellogenin, normally synthesized by females and egg production in males.[89]

The occurrence of intersex in male, smallmouth bass in the Potomac River, and its tributaries in Virginia, U.S., was particularly high during the spawning season with higher incidence of intersex occurring in streams that drain areas with intensive agricultural production and high population, when compared to non-agricultural and undeveloped areas.[22]

**Herbcides like atrazine can alter the sex and reproductive processes in animals.**

Similarly, male fish downstream of wastewater outfalls have been feminized.[230, 125] In some cases, they produced vitellogenin and showed early-stage eggs in their testes. This was attributed to the presence of estrogenic substances, such as the synthetic estrogen birth-control pills, and estrogen mimics, such as nonylphenol found in the wastewater.[125] In Argentina, fish in a shallow lake located in an agricultural area also produced vitellogenin, and developed lesions in their gills and liver associated with high levels of the endocrine disruptor endosulfan in these organs.[16] Fish living upstream and downstream of Formerly Used Defense (FUD) sites on St. Lawrence Island in the Bering Sea were contaminated with PCBs and the vitellogenin concentrations in males indicated exposure to estrogenic contaminants. Downstream fish also demonstrated impacts on DNA.[246]

Scientists from the U.S. Geological Survey documenting the presence of endocrine disrupting contaminants in rivers and streams across the United States have warned of the "ruinous impacts on fish populations" from EDCs.[229]

### 2.1.2 IMPACTS ON THE IMMUNE SYSTEM

EDC pollution can also have immune impacts and increase the susceptibility to disease of aquatic and marine species, including fish and invertebrates.[77] Research as early as the 1970s showed that infection with *Baculovirus* in shrimp increased in intensity when the crustaceans were exposed to increasing levels of PCBs.[46]

By the mid 1990s, POPs including PCBs, had been linked to immunosuppression and disease in seals.[167] Researchers also concluded that a number of heavy metal pollutants, including cadmium, chromium, copper, lead, manganese, nickel, and zinc, were immunotoxic. These heavy metals were shown to alter immunoregulatory functions in a variety of fish species, ultimately leading to increased host susceptibility to infectious and malignant diseases.[241]

A comprehensive review[51] of POPs impacts on Arctic biota (e.g., northern fur seal, Steller sea lion, polar bears, Arctic char) reported associations between concentrations of some POPs and biomarkers relating to resistance to infection. Similarly, studies have shown that environmentally relevant concentrations of mercury, polychlorinated biphenyls (PCBs), and 4,4′-DDE (dichlorodiphenyl-dichloroethylene) can affect the immune function and health of loggerhead sea turtles, *Caretta caretta*.[231] For example, in loggerhead sea turtles from South Carolina and Florida, as mercury levels in their blood went up, their lymphocyte numbers and immune responses went down. These negative impacts on the immune function were observed at environmentally relevant concentrations.[49]

Investigations into a massive mortality event of the Pacific oyster *Crassostrea gigas*, revealed that exposure to the herbicide diuron suppressed different genes involved in immune responses.[138] Similarly, exposure of freshwater molluscs to pyrethroid insecticides, cypermethrin and

## PFAS FOREVER CHEMICALS UBIQUITOUS IMMUNO-TOXICANTS

Many POPs and other pollutants are known to affect the immune systems of living organisms. Of considerable concern are the ubiquitous marine contaminants, PFASs, including the three POPs chemicals, perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexane sulfonate (PFHxS). They are extremely persistent, bioaccumulative and damage the immune system of animals and people.[227] PFASs are ubiquitous contaminants found in even the most remote areas including in the Arctic and Antarctic marine environment and its inhabitants.

To date, regulatory focus has been on only a handful of PFAS chemicals, yet there are between 3,000 [65] and 4,730 PFAS compounds [99], many of which have not been assessed for adverse effects but are found in marine environments. One group, the perfluoroalkyl carboxylic acids, have been detected in more than 80% of 30 surface seawater samples from the north Pacific and Arctic oceans.[132]

Significantly higher concentrations of PFAS were found on the sea's surface than in the corresponding subsurface water (>30 cm depth).[239] The sea surface microlayer, the <50 μm thick layer where exchange happens between the atmosphere and the ocean, provides vital habitat for biota, including the fish eggs and larvae of many commercial fishery species and their phytoplankton food resources. Contamination of the sea surface microlayer in polluted areas has led to significantly higher rates of mortality and abnormality of fish embryos and larvae.[242]

PFAS are found in fish and other marine wildlife across the globe.[166, 216] In Australia, PFAS were found in high levels in yabbies (crayfish), and freshwater fish associated with Defence bases.[96] In China, fish from the Yangtze River and Tangxun Lake were analysed for PFAS. In addition to common PFASs (e.g., PFOS, PFOA, PFHxS, PFBS) over 330 other fluorinated chemicals were detected in fish livers.[136] In the US state of South Carolina, nine PFASs were found in the fish fillets of six species with PFOS at levels exceeding screening values and considered to represent a potential risk to wildlife predators.[67]

Frequent consumption of wild fish could pose health risks to some local populations. Cooking the majority of seafood does not reduce PFAS concentrations and in some cases can increase dietary exposure. PFOS, PFHxS and PFOA concentrations in school prawn effectively doubled after boiling while baking some fish also increased PFOS concentrations.[213]

fenvalerate, resulted in significant damage to their themocytes, the cells of molluscs that perform diverse immunological functions.[181] Studies of extensive fish kills in the Shenandoah River, U.S., reported that many of the fish were unable to manufacture normal disease-fighting white blood cells.[187]


**Glyphosate has been linked to disease in fish.**

Fish parasites represent a major part of aquatic biodiversity.[170] The balance between parasites and hosts can be affected by many factors including the presence of chemical contamination, heat, and nutritional stress, as well as infection with certain pathogens; all affect the immune response of the host to the parasite.

Glyphosate based herbicides (GBHs) have been linked to an increase in the risk of disease in fish, as parasites and GBHs can act synergistically at environmentally relevant concentrations, magnifying each other's adverse effects.[121]

Nevertheless, establishing clear causative links in wild fish populations exposed to pollutants and infectious disease remains difficult due to the multiplicity of exposures. Many fish are asymptomatic carriers of bacteria and viruses that under normal conditions would not cause disease. But when their immune systems are impaired by pollutants or temperature increases or other stresses, disease-causing agents can multiply and sicken the host. Altering long-established host-parasite or host-pathogen relationships with immune toxicants has adverse consequences.[46]

### 2.1.3 BEHAVIORAL AND INDIRECT IMPACTS

The impacts of pollutants on marine species may not always be immediately evident. Marine animals exposed to toxic substances can suffer a loss of resilience, with sub-lethal exposure to chemical pollutants making fish more susceptible to heat and other stressors, altering their behaviors.[199]

Subtle changes to behaviors, eating and "molting" habits can significantly affect the viability of the population of fish or invertebrates. For example, the neonicotinoid pesticide imidacloprid has the potential to indirectly cause lethality in aquatic invertebrate populations at low, sub-lethal concentrations by impairing movements and thus feeding.[164] With constant low dose exposures to imidacloprid, the aquatic arthropod *Gammarus pulex*[81] simply starved to death.

CASE STUDY

## NEW ZEALAND WHITEBAIT DECLINE: SYNERGISTIC EFFECTS OF GLYPHOSATE FORMULATION AND PARASITE INFECTION

Whitebait, *Galaxias anomalus*, is a mass spawning freshwater fish that travels up and down rivers to complete their spawning run and to access habitat and food for their young. A range of fish species all over the world complete similar heroic river journeys to complete their reproductive cycles.

In previous times, whitebait populations have been so abundant people could literally stand on the riverbank and scoop them up in hand nets. They turned them into whitebait fritters, which are considered a national New Zealand delicacy. It was observed that whitebait populations started to diminish in rivers where industrial-scale dairy farming had expanded into the catchments. Wetlands were drained, streams artificially channelled, and vegetation removed from riverbanks with applications of the herbicide glyphosate to provide access to water for cattle.

Scientists also started to find increasing rates of deformed fish in these catchments.[121] The cause of the deformities was determined to be a parasite that embeds itself in the spines of the fish causing them to become bent. Bent fish can't swim very fast which made them more vulnerable to predation. Further investigation revealed that the parasite causing the deformities had been in the environment for some time and was first described in 1945. Whitebait populations had coexisted and thrived in their presence, so what had changed?

Research[120] found that the riverbank spraying of vegetation with glyphosate formulations containing polyoxyethylenamines (POEAs) had changed the natural balance. Glyphosate formulations containing POEAs are more cytotoxic and demonstrate more endocrine disruption effects than the active ingredient glyphosate alone.[243] If you put fish in an environmentally relevant concentration of POEA containing glyphosate formulations, they become more susceptible to infection and the intensity of parasitism goes up.

The parasite in question has a two-host lifecycle, which also involves a river snail. The research found that exposing the snails to the glyphosate formulation resulted in them producing far more parasites. Whitebait are faced with an insidious double whammy: increased challenge from more parasites and lowered resilience and tolerance to be able to fight them off.

Exposure to the organophosphate pesticide dichlorvos during early fish development also caused behavioral impairments detectable during the post-hatching period.[204] Chlorpyrifos, a widely used organophosphate insecticide with high mobility, poses serious risks to aquatic organisms and ecosystems as it has sub-lethal effects on the behavior and olfactory perception of arthropods and fish.[145, 81]

Fish embryos and larvae exposed to a series of sub-lethal doses of a POPs mixture saw changes in behavior, such as altering the swimming speed of larvae.[123] Similarly, acute, embryonic exposure to individual PFASs resulted in significant biochemical and behavioral changes in young adult zebrafish 6 months after exposure. This included reductions in the total distance travelled as well as changes in aggressive behavior. This short-term embryonic exposure to PFAS contaminants resulted in long-term and persistent impacts well into adulthood.[115, 8]

## 2.2 MICROPLASTIC POLLUTION IMPACTS ON FISHERIES

Microplastics are a form of pollution contaminating aquatic and marine habitats, including estuaries, the breeding grounds for many fish species.[15] Over 690 marine species have been impacted by plastic debris and microplastics, which are adversely affecting increasing numbers of marine organisms from all trophic levels, including zooplankton, barnacles, bivalves, decapod crustaceans, fish, marine mammals, and seabirds.[34]

Microplastics have been found in commercial (bottom-dwelling, or "benthic", and open-water, or "pelagic") fish species from the English Channel, the North Sea, the Baltic Sea, the Indo-Pacific Ocean, the Mediterranean Sea, the Adriatic Sea, and the north-eastern Atlantic Ocean.[26] All samples of deep-sea fish from the South China Sea were contaminated by microplastics.[134] Fish from the Persian Gulf also had microplastics in their gastrointestinal tracts, skin, muscle, gills, and liver, while microplastics were found in the exoskeleton—and importantly, also in the muscle—of tiger prawns from the Persian Gulf.[192]

Microplastic fibres (e.g., from synthetic clothing and ropes) were found in the digestive tract of wild fish and in their larvae from the English Channel[140] and in 63% of shrimp samples of the commercially important crustacean *Crangon crangon* from the North Sea and the Channel area.[53] Shellfish and other aquatic animals that are consumed whole pose particular concern for human exposure.[205]

Microplastics in the water column and sediment provide a direct exposure route for aquatic and marine organisms, while nanoplastics are easily transferred through aquatic food chains.[38]

## FOOD WEB IMPACTS

Pollutants can also affect the food resources on which aquatic animals depend. For example, herbicides affect seagrass viability and with loss of seagrass, food resources and habitats shrink for young shrimp and fish. Many fish feed on insects or depend on them for rearing their offspring. When small invertebrate prey is reduced due to exposure to neonicotinoid pesticides such as imidacloprid and fipronil, there is less food for fish to eat resulting in lower growth rates.[80]

Over 40% of insect species may be threatened with extinction, with four major aquatic insect orders (*Odonata*, dragonflies and damselflies; *Plecoptera*, stoneflies; *Trichoptera*, caddisflies; and *Ephemeroptera*, mayflies) already at risk. Habitat loss due to intensive agriculture, industrial and agricultural pollutants, invasive species, and climate change are all to blame. In aquatic environments, persistent residues of fipronil in sediments inhibit the emergence of dragonflies and the development of chironomids (nonbiting midges or lake flies) and other insect larvae, with negative cascading effects on dependant fish survival. Mayflies have been eliminated in streams where acidification due to smelting and mining activities have pushed water pH below 5.5. Mayfly nymphs provide food for many types of freshwater fish.[193]

The aquatic food web was severely disrupted when the synthetic oestrogen used in the birth control pill,17α- ethinylestradiol (EE2), decimated a lake's small fish population, resulting in much less food for larger predator fish such as trout, leading to a corresponding loss of condition in these predator species.[124]

Nutrient pollution and climate warming are driving algal blooms in marine waters and toxic blue-green algae and bacterial dominance in freshwater. Dinoflagellates (single-celled algae species) are very common and widespread but under some environmental conditions (e.g., increased nutrients) can grow very rapidly.

*Continued on page 30*

*Continued from page 29*

The dinoflagellate *Karenia brevis* colors the ocean surface a deep red, hence the name "red tide."

Red tides create temporarily toxic oceans, but they can also deplete the water of dissolved oxygen, causing a phenomenon known as a "dead zone". When the algae die, they are eaten by bacteria and other microbes. Like all animals, microbes require oxygen. As they feed on the dead algae, they multiply and die, consuming much of the oxygen, leaving little available for fish and other aquatic creatures.

Toxic algae in both fresh and marine water are associated with mass fish kills which are becoming an increasingly common event. While most related fish kills are due to algae bloom decomposition resulting in less oxygen in the water, some algae such as the blue-green algae *Cyanobacteria* or the golden algae *Prymnesium parvum* produce toxins that affect aquatic life.

Golden algae found in freshwater and brackish lakes, ponds and rivers, can produce a toxin that disrupts respiration in gill-breathing organisms like fish, crayfish, and some amphibians. After exposure, gills fail to properly absorb oxygen, causing internal bleeding and eventually death from asphyxiation. Large-scale fish kills have occurred throughout southwestern United States due to the presence of these toxins.[100] Shellfish naturally accumulate these toxins as they filter algae from the water for food and consumption of tainted shellfish can lead to a serious human illness.

The increasing impacts of nutrient pollution, toxic algal blooms, and climate-induced acidification on microorganisms like diatoms and benthic foraminiferans, single-celled organisms which form the very basis of the aquatic and marine food chains, coupled with the impacts of persistent pollutants, temperature increase, and other stresses, represent serious risks to the health of marine and aquatic food webs across the globe and to the fisheries on which so many communities depend.

Many suspension feeders such as oysters and mussels, as well as bottom feeders such as sea cucumbers, crabs, and lobsters, consume microplastics as they cannot differentiate between microplastics and food.[147] Microplastics are in the same size range as plankton and grains of sand, and with biofouling playing an important role, it is easy for marine life to mistake plastic for a nutritious food source.[34]


**Microplastics in the form of microflakes from degraded plastic wastes, microfibers from synthetic clothes and industry's microbeads find their way into waterways and oceans. As the COVID 19 coronavirus (SARS-CoV-2) spreads, latex gloves, polypropylene masks and bottles of hand sanitizer are a new source of plastics in the ocean.** Source: NOAA.com

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.[139]

*Daphnia* water fleas exposed to nanosized polystyrene plastics showed reduced body size and severe alterations in reproduction.[18] In mysid shrimps exposure to high concentrations of polystyrene microplastics resulted in a 30% mortality rate.[151] There was significant retardation of developmental time and decreased survival rate in the small aquatic crustacean, a copepod species *Tigriopus japonicas*[39], while when chronically exposed over successive generations, other crustaceans experienced increased mortality rates.[139]

In molluscs, exposure to microplastics altered their immunological responses, caused neurotoxic effects and genotoxicity, and damaged genetic information. Microplastics also affected the reproduction and population growth of Pacific cupped oysters[14], while mussel survival declined with increasing abundance of PVC plastics, probably due to prolonged periods of valve closure as a reaction to the particle.[188]

Microplastics in the gills, liver and digestive tract of zebrafish resulted in inflammation, oxidative stress, and disrupted energy metabolism.[137] Exposure to nanosized polystyrene plastics affected fish activity, while nanoplastics were shown to penetrate the embryo walls and find their way into the yolk sac of hatched juveniles.[38]

### 2.2.1 MICROPLASTICS AND THEIR CONTAMINANTS

Microplastics in marine environments carry ecotoxicological contaminants[79] including chemical additives from their manufacture. Some plastic additives such as the PBDE flame-retardants are EDCs and can be present in the plastics at very high levels.[76]

Microplastics also attract contaminants such as PCBs, DDT, HCB, PAHs and other petroleum hydrocarbons from the surrounding environment (e.g., sediment, seawater) and concentrate these contaminants on their plastic surface up to six orders of magnitude greater than the ambient seawater.[34]

Marine ecosystems and their inhabitants are at risk from both microplastics and the contaminates that concentrate in them. In the South Atlantic Ocean, greater micro plastic densities are associated with significantly higher concentrations of PBDEs in Myctophid fish.[189] While mussels (*Mytilus galloprovincialis*) exposed to PAH-contaminated microplastics had plastics in their hemolymph (a fluid equivalent to blood), gills and digestive tissues, as well as a marked accumulation of the PAH pyrene, the mussels also experienced adverse alterations of immunological responses and neurotoxic effects.[14] Hexabromocyclododecane (HBCDD) used in polystyrene foam (EPS/XPS) was found in oysters from aquaculture farms where polystyrene buoys containing HBCDD were used.[76]

Toxic phthalates are widely used plasticizers found in microplastics. In one study, over half the surface plankton samples analyzed contained microplastic particles with high concentrations of phthalates. Concentrations of a mono-(2-ethylhexyl) phthalate (MEHP) were also found in the blubber of stranded fin whales, which may indicate the threat of microplastics and their contaminants to marine life.[75]

There is evidence of trophic transfer through the marine food-chain of both microplastics and associated contaminants.[34] There are growing

**Lightweight polystyrene travels easily through waterways and storm drains, eventually reaching the ocean where it breaks down into smaller, non-biodegradable pieces that are ingested by marine life.**

concerns that the impacts of ever-expanding volumes of microplastics and their entrained contaminants are adding to existing stressors and may increase mortality in natural fish populations.[165]

# 3. CLIMATE, POLLUTANTS AND FISHERIES

As a result of climate change our oceans are warmer, more acidic and less productive. Storm frequency and intensity is also increasing.[111] The ecosystems that sustain fisheries and aquaculture are undergoing significant changes as a result of climate change.

Projections indicate that these changes will only get worse in the future.[71] Many regions report declines in the abundance of fish and shellfish stocks due to direct and indirect effects of global warming and biogeochemical changes have already contributed to reduced fisheries catches.[111]

Sea level rise is often paramount in people's minds when they think of climate change, but the effects on the marine ecosystem from climate change will affect every aspect of the marine food web. Increasing temperatures melt sea ice, glaciers, and permafrost, contributing not only to rising sea levels but also to changes in ocean currents, salinity and oxygen levels, as well as water temperatures, while increased carbon dioxide ($CO_2$) deposition is making the oceans far more acidic.

De-oxygenated or "dead zones" in the ocean have increased significantly as a combined result of pollution and warming waters.[28] Decreased water oxygen levels and eutrophication, as well as a proliferation of parasites and pathogens[219] all impact on the ability of fish and other aquatic species to respond and adapt to changing conditions. More intense rainfall drives greater sediment run-off and with it come any adhered contaminants such as agricultural chemicals and hydrocarbons.

Harmful algal blooms have increased in frequency in coastal areas since the 1980s in response to both climatic (ocean warming, marine heatwaves, oxygen loss, eutrophication) and non-climatic drivers, such as pollution and increased nutrients run-off into rivers.[111]

Climate change also causes declines in nutritional status as it affects the species on which the marine food chain depends, such as the marine phytoplankton and invertebrates like krill. In the Southern Ocean, the habitat of Antarctic krill, a key prey species for penguins, seals, and whales, is projected to contract southwards. Algae that grows under sea ice is also diminishing and with it some of the nutrition at the base of the food chain.

Many marine species have already undergone changes in their range and activities in response to climate change and habitat loss. The shifts in species composition, abundance and biomass production of ecosystems have contributed to decreases in catch potential.[111]

## 3.1 INTERACTIONS OF CLIMATE CHANGE AND PERSISTENT POLLUTANTS

Climate induced changes can enhance the toxic effects of contaminants. Synergistic interactions between pesticide and temperature stress were evident in crustaceans from agricultural streams[190], while chronic exposure to some pesticides (e.g., endosulfan, phenol, and chlorpyrifos) can lower fish tolerance to increased temperature.[172]

Climate warming is also changing the distribution of contaminants. Increasing temperatures are re-mobilizing historical contaminants from their "polar sinks".[19] Pollutants generated at temperate latitudes are transported to the polar regions via atmospheric and oceanic processes

## OCEAN ACIDIFICATION

As the carbon dioxide ($CO_2$) concentration in the atmosphere rises due to the use of fossil fuels and other activities such as forest clearing, more $CO_2$ dissolves in the seawater making the oceans more acidic. Water acidity has increased by 26% since the beginning of the industrial revolution.[71]

While impacts of increased acidity vary between fish species, ocean acidification causes sensory and behavioral impairment in many fish species.[44] Acidic waters can interfere with fish neurotransmitters, affecting behavior.[56] Increasing acidification also damages fish by corroding their gills, attacking the calcium content of the skeleton[177] and affecting their ability to reproduce.[149] Hatchlings or small fry may be unable to withstand the increased acidity.

Acidification has serious impacts on other sea life, including polyps, which form the basis of many coral reefs, tiny molluscs such as the pteropods [78] and the krill [95] on which so many fish, whales, and bird species rely. Diatoms at the base of the aquatic food web build their external layer out of silicate, but increased acidity has reduced their ability to do so.[175] Large populations of benthic foraminiferans that inhabit coral reef platforms are major producers of calcium carbonate ($CaCO_3$) in the reef ecosystems but ocean warming and pollution are also resulting in significant decreases in their $CaCO_3$ production. This has serious implications for the future of coral reefs.[58, 184] Commercial oyster hatcheries are already experiencing the effects of acidification with reduced larval oyster survival.[17]

where they are deposited in snow, ice, water, soils, and sediment. Higher temperatures increase the release and emissions of these persistent toxic substances, and stronger winds, flooding, and extreme weather events increase their distribution.[219, 178]

**Fire retardants as well as the ash from forest files washes into rivers. Toxic effects and acute deoxygenation can harm aquatic life.**

Ocean warming, de-oxygenation, and ocean acidification can amplify the impacts of pollution by increasing both exposure and bioaccumulation for many contaminants in the marine food web. A warmer climate affects cold-blooded organisms such as invertebrates, fish, amphibians, and reptiles by directly enhancing the internal uptake of contaminants in their gills and intestines.[219] Changes in water acidity can enhance the bioaccumulation of toxic substances such as cadmium in marine bivalves.[233]

Climate change is also increasing the bioaccumulation in fish and other marine organisms of the neurotoxins, methyl mercury (MeHg), and PCBs.[5] These are among the most prevalent and toxic contaminants in the marine food web. Warming temperatures may also increase human exposure to MeHg, by increasing MeHg production, bioaccumulation, and trophic transfer through marine food webs.[55]

There are other indirect impacts of climate change on water quality. For example, significantly increased fire activity has meant an increased use of fire retardants such as Phos-Chek. This has resulted in hazardous chemicals applied in water catchments, as some of the substances are known to be toxic to fish at various stages in their life cycle.[54] The ash from fires also washes into rivers and can cause acute deoxygenation events further harming the aquatic life.

CASE STUDY

## CLIMATE CHANGE IMPACTS KELP FORESTS

Kelp forests are dynamic carbon sinks, drawing down more $CO_2$ from the atmosphere than land-based rainforests. They also provide habitat and are a critical part of the ocean food web.

Unfortunately, warming oceans are impacting the capacity of kelp forests to survive and absorb carbon. Kelp forests in warmer waters are under severe stress from rising ocean temperatures.[174] Ocean heat waves have already killed off over 100 kilometers (km) of kelp forests and impacted a further 500 km along the south coast of Western Australia.[235]

In 2016, a mass die-off of red abalone occurred in the Northern Californian marine ecosystem as a result of sustained extreme ocean temperatures forced by a confluence of events. A toxic algal bloom in 2011 off the Sonoma coast of California killed off many of the marine invertebrates, including abalone. Then in 2013, a wasting disease seriously impacted sea stars, which were responsible for keeping sea urchin populations under control.

The sea star die-off triggered a purple sea urchin explosion and they in turn ravaged the kelp forests, leaving remaining abalone starving. Already stressed kelp forests where then subjected to *The Blob,* a marine heatwave from 2014-2016. The warm, nutrient-poor environment caused by *The Blob* made conditions unliveable for the kelp forests and they died along with the abalone.[90]

In Asia, farmed seaweed is stressed by warmer waters and pollution, which makes it produce a substance that attracts bacteria to its surface and then hardens tissues and turns them white—a disease called *ice-ice.* Seaweed production is diminishing with the onslaught of ice-ice, but because it's not a contagious disease, moving seaweed farming to cooler, deeper waters might be one way to address the problem.[217]

# 4. POLLUTANT SOURCES AND CONTRIBUTIONS

There are many sources of pollutants to the fresh and marine ecosystems. It is estimated that 80% of marine chemical pollution originates on land.[226] Waste incineration, coal-fired power stations, and fossil fuel production release tons of hazardous emissions into the atmosphere every year.[161] Combustion of fuels in automobiles, factories, and smelters introduces hydrocarbons and metals into the environment.

Many of these pollutants eventually find their way into our oceans and lakes through atmospheric deposition. This occurs when contaminants, once airborne (either as vapor or attached to dust particles), are washed out by rain or snow, or fall back to earth in the colder climates.

Industrial facilities, such as chemical manufacturing, pulp and paper mills, as well as sewerage outfalls, stormwater drains, agriculture, and mining activities all contribute to toxic chemical runoff directly into the aquatic environment. Thousands of pharmaceuticals, personal-care products, plasticizers, and emerging industrial materials (e.g., engineered nanoparticles) regularly enter lakes, rivers, estuaries, and near-shore marine environments.

These chemical contaminants can be toxic to individual marine and aquatic organisms, with effects that also magnify to impact whole populations, species, communities, and ecosystems. Pollutants also interact with and can exacerbate other chemical and non-chemical stressors.[197]

Historically, concern and regulation of water pollutants has largely focussed on end-of-pipe discharges, or so-called *point sources*, particularly in relation to nutrient, sediment, and waste discharge licenses. Yet, toxic chemicals have other more diffuse pathways of deposition and land-based runoff. Diffuse emissions of pollutants are more pervasive and difficult to detect, monitor, or regulate. Their movement through aquatic ecosystems is complex and often challenging to reliably predict via modelling.

## 4.1 INDUSTRIAL RELEASES

Industrial facilities continue to release millions of kilograms of toxic chemicals into rivers, streams, lakes, and ocean waters each year. For example, in 2010, U.S. industrial facilities dumped 226 million pounds (approx. 102.5 million kilograms) of toxic chemicals into American waterways. According to the federal government's Toxic Release Inventory, toxic chemicals were discharged to more than 1,900 waterways in all 50 states. Approximately 1.5 million pounds were linked to cancer, while 619,000 pounds of chemicals were linked to developmental disorders, and approximately 342,000 pounds were reproductive toxins.[63] Pulp and paper, iron and steel, energy supply, non-ferrous metals, and chemicals industries have some of the highest releases direct to water.[66]

## 4.2 WASTEWATER TREATMENT PLANTS

In Europe, the release of pollutants directly to water bodies by large industries has decreased, but industrial pollutants transferred through the sewer systems to urban wastewater treatment plants (WWTPs) has increased.[66] Many contaminants cannot be captured or destroyed in WWTPs and as a result are found in the sewerage sludge and effluent. Industrial and consumer halogenated chemicals such as PBDEs[154, 85] and PFAS[92, 3], are found in effluent from WWTPs[3] and contaminate oceans, rivers, and lakes across the globe.

Pesticides are also contaminants of treated wastewater. In the U.S., the pesticides imidacloprid, acetamiprid, and clothianidin were identified as "recalcitrant sewage constituents" that persist through wastewater treatment to enter water bodies at significant loadings, potentially harmful to sensitive aquatic invertebrates. Data from 13 U.S. WWTPs suggests annual discharges of 1000-3400 kilograms per year of imidacloprid in treated effluent released to rivers and lakes.[191]

## 4.3 PHARMACEUTICAL POLLUTION

Pharmaceuticals can have harmful effects on aquatic organisms, such as metabolic and sex alterations or inducing antibiotic resistance in aquatic microorganisms. At least 10 pharmaceuticals were found to be very toxic or extremely toxic to different aquatic species (alendronate, amitriptyline, carvedilol, ethinylestradiol, fluticasone, fluoxetin, fluvoxamine, midazolam, paclitaxel, and thioridazine).[24]

## PHARMACEUTICAL DRUGS IN THE ENVIRONMENT

Wastewater treatment plants are not designed to remove pharmaceutical residues. Pharmaceuticals and personal care product chemicals (PPCPs) are found throughout marine and coastal waters, as well as rivers and streams. Data from over 71 countries identified 631 different pharmaceutical agents (including their metabolites and transformation products) in the environment, including antibiotics, nonsteroidal anti-inflammatory drugs (NSAIDs), analgesics, lipid-lowering drugs, estrogens, drugs from other therapeutic groups[13], as well genotoxic drugs used in cancer chemotherapy and as immunosuppressants.

A 2019 global survey of antibiotics tested water from 165 rivers across 72 countries.[236] At 66% of sites, at least one antibiotic was found, while many had more than one and approximately 15% contained unsafe levels of antibiotics. The most commonly found was trimethoprim, used to treat urinary-tract infections. In Bangladesh, metronidazole was detected at 300 times safe levels, and high antibiotic levels also showed up in several African rivers.

The Danube was Europe's most polluted river, containing seven antibiotics, including clarithromycin at nearly four times the level considered safe. The Thames, generally regarded as one of Europe's cleanest rivers, was contaminated in some sites well above safe levels. Eight per cent of the sites tested in Europe were above safe limits.

Fish can accumulate pharmaceuticals and personal care product chemicals (PPCPs). In the plasma of caged goldfish exposed to the tertiary treated municipal wastewater effluent, 15 PPCPs were detected. The highest concentrations were for the antidepressant fluoxetine, and anxiolytic diazepam and oxazepam.[156]

Pharmaceuticals are often designed to be active at low concentrations. Chronic exposure of fathead minnow fish in a freshwater lake to low concentrations (5–6 ng/l) of the synthetic estrogen 17α-ethinylestradiol (EE2), found in the contraceptive pill, resulted in reproductive failure and the collapse of the small fish population in the lake.[125] After cessation of the EE2 addition it took 4 years for the population to return to normal.[21]

The anti-epileptic drug carbamazepine was widespread in coastal and offshore seawaters around the Baltic Sea.[20] Exposure of fish embryos to carbamazepine and other antiepileptic drugs, at environmentally relevant concentrations, disturbs their normal growth and impairs development and behavior. Such impacts can have wide-reaching repercussions on fish populations.[179]

Some sunscreen lotions and personal care products contain ingredients toxic to marine life. Exposure of corals to the UV filter oxybenzone can promote viral infections[48], cause deformities in baby coral, and damage DNA. The endocrine disrupting effect makes baby coral encase itself in its own skeleton, leading to death.[59] Between 6,000 tons (approx. 5,400 tonnes) and 14,000 tons (approx. 12,700 tonnes) of sunscreen lotion make its way onto coral reefs every year, with approximately 10% of global reefs at high risk of exposure to sunscreen damage.[108]

## 4.4 OIL POLLUTION

Oil pollution with its toxic constituents, such as polycyclic aromatic hydrocarbons (PAHs), is one of the most conspicuous and acutely damaging forms of aquatic pollution. Entering freshwater and marine environments via storm water drains, industrial discharge, untreated waste disposal, and mining, as well as shipping mishaps and recreational boating, oil pollution causes significant harm to aquatic biota and coastal fisheries.

Exposure to crude oil can disrupt cardiac function and cause heart malformations in developing fish.[157, 29] Oil exposure and ingestion can also damage the reproductive systems of fish, change growth rates, and alter behaviors.[163] Exposure to oil spills can cause immune suppression in fish making them more vulnerable to pathogens. Immunosuppression was evident in Pacific herring exposed to crude oil.[35]

After major oil spills commercially important species such as oysters, shrimp, and tuna can suffer population decline and become too contaminated to be caught and safely eaten.

### 4.4.1 POLYCYCLIC AROMATIC HYDROCARBONS

The 2010 Deepwater Horizon oil disaster in the Gulf of Mexico spilled 5 million barrels of oil and released huge quantities of complex mixtures of polycyclic aromatic hydrocarbons (PAHs) directly into critical spawning habitats for tuna, billfishes, and other top predators.[29] Approximately 47,000 barrels of the dispersants Corexit 9500 and 9527 were used as well.[87] Based on the hydrocarbon solvent ethylene glycol monobutyl ether combined with non-ionic and anionic surfactants[153], these dispersants are toxic to the immune, neurological, cardiovascular, and respiratory systems.[41]

The massive spill resulted in the die-off of tiny foraminifera in the path of the underwater plume, but these demonstrated some recovery in the following years.[200] There was also evidence of abnormal skin lesions in fish[158] and apparent drop in population of some fish species. Seafood samples from the Mississippi Gulf Coast affected by the Deepwater Horizon oil spill were collected about a month after the first leak, and high levels of total PAHs were detected in all four types of seafood samples.[238]

PAHs are very persistent and remained in coastal sediments decades after the 1989 Exxon Valdez disaster off the Alaskan coast.[97] 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, where their embryos develop, and where many invertebrate fish food resources reside.

Some PAHs and their degradation products are highly toxic, causing cancers, mutations, and birth defects in fish and other animals.[183] Exposing fish embryos to PAH mixtures and contaminated sediment resulted in mortality, abnormalities, such as cardiac malformations and long-term locomotor and behavioral changes.[32, 157]

## 4.5 MINING WASTES - DEEP-SEA DISPOSAL OF MINE TAILINGS

The mining industry is one of the world's largest waste producers.[57] Mine waste tailings consist of silt particulates, metals (including zinc, copper, arsenic, cadmium, mercury, and lead), process chemicals (e.g., flotation agents), and high quantities of sulfides. The difficulty and costs involved in managing these mine wastes has driven interest in disposing mine tailings in the deep sea. Deep-sea tailings placement (DSTP) usually involves discharging the waste as a finely ground rock slurry via an outfall to depths below 1,000 metres. The dissolved heavy metals from the tailings are likely to have a long-lasting influence on the deep-sea environment for up to 60 to 70 years.[234]

DSTP represents significant risks to a range of ecosystems and their inhabitants[155], yet DSTP from terrestrial mines is already taking place. 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. The abundance of these sediment dwellers (e.g., clams, tubeworms, and burrowing crabs) are substantially reduced across the sampled depth range (800–2020 m).[109]

## 4.6 DREDGING AND SEDIMENT

Dredging involves the removal or relocation of sediment to create deeper channels to improve marine port or river access. Dredging is also used in the remediation of contaminated sediment and for land reclamation. Sediments are inevitably re-suspended in the water column, increasing turbidity. This sediment pollution has a smothering effect on seagrass and shellfish beds with excess sediment also filling in critical deep-water fish habitat. Fish larvae can confuse sediment particles for food, which impacts their nutrition and survival.[171]

The dredging process also mobilizes legacy contaminants such as metals, hydrocarbons, nutrients, and acid into the water body.[52] In ports and harbors adjacent to urbanized or industrialized areas, sediments can contain high levels of organic and inorganic contaminants, including POPs,

*Continued on page 53*

## CASE STUDY

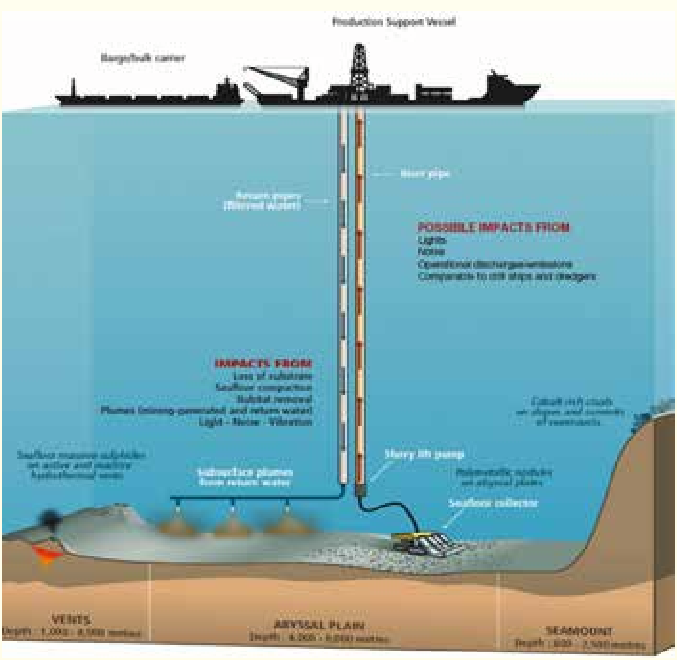
### DEEP-SEA MINING IN THE PACIFIC

> "No-one is considering the potential impacts of toxic substances and wastes produced during deep-sea mineral mining … There is so little knowledge of how ocean currents work at that depth, and it is probable that sediment containing toxins will be stirred up into a plume when the remote control vacuum device extracts the nodules, then a second plume will be created when waste-water is returned to that depth … In most countries there are regulations to ensure that the mining company reinstates the land to its former condition but how do you reinstate the seafloor 6,000 metres below the ocean surface?"
>
> *– Imogen Ingram, Environmental Researcher and traditional Cook Islands landowner, response to deep sea mining in the Cook Islands' exclusive economic zone.*

Deep-sea mining is the process of retrieving mineral deposits from the deep sea below 200 meters. There are three types of deposits: polymetallic nodules, made up of iron and manganese oxides with associated metals, e.g., Cook Island deposit; polymetallic sulfides which are concentrated deposits of sulfidic minerals resulting from hydro-thermal activity on the seabed, e.g., Papua New Guinea deposits and polymetallic crusts.[47]

Deep-sea mining inevitably affects communities of living organisms near the mining sites. Noise, light, and seabed disturbance of sediment and habitats, sediment

*Continued on page 48*



*Continued from page 47*

plumes, ore-slurry leakage, pollution, interaction with other ocean-users (e.g., fishing boats, or whales) all risk damaging unique biodiversity and ecosystems.[176] Particularly at risk are invertebrates like worms, crustaceans, sponges, mollusks, sea cucumbers, starfish, brittle stars, and sea urchins.

Seamounts known to contain high levels of valuable cobalt are also biodiversity hotspots with hundreds of associated species of fish and dominated by filter feeders such as corals and sponges fixed onto the hard substrates. These form species-rich sea gardens which in turn attract other crustaceans, mollusks, and echinoderms. Removal of either polymetallic nodules or crusts would have severe impacts on these marine ecosystems.[176]

The disturbance of seafloor sediment creates plumes of suspended particles that can affect the marine environment far beyond the mining site. Modelling studies[23] suggest the sediment discharge could be widely dispersed up to 10 kilometers from the site. This may both smother organisms and spread toxic metals and other contaminants. Plumes discharged at depth from dewatering may also carry toxic contaminants.

These impacts will not only affect benthic communities but also pelagic species, impairing feeding, growth, and reproduction. Changes in the benthic communities could persist for long periods and affect food availability and cause long-term alterations in the composition of marine communities and food webs, ultimately leading to loss of biodiversity.[43]

While deep-sea mining will have significant impacts on the deep-sea environment, the full nature and extent of these effects are not known. As such the World Bank recommends, "given the immense uncertainty," that countries exercise the highest degree of caution to avoid irreversible damage to the ecosystem.[237]

Nevertheless, there is increasing commercial interest in deep-sea mineral deposits of copper, aluminum, cobalt, and other metals, which are used to produce high-tech applications, such as smartphones and electric storage batteries. While legislation is still in its infancy, by May 2018, the International Seabed Authority (ISA) had issued 29 contracts for the exploration of deep-sea mineral deposits. While Fiji, Papua New Guinea, Solomon Islands, Tonga, and Vanuatu have granted permits for deep sea mining exploration, and the Cook Islands recently undertook a minerals exploration tender process [47], so far, only Papua New Guinea has granted a license for ocean floor mining.

**The deep-sea mining machines are gigantic robotic harvesters as large as a bus.**

CASE STUDY

## GLADSTONE HARBOUR PORT DREDGING

In 2010, Australia's largest dredging operation commenced in Gladstone Harbour within the Great Barrier Reef World Heritage area. Over a three-year period between 2010 – 2013, more than 23 million cubic meters of seabed was removed, resulting in the destruction of large areas of inner harbor seagrass, and coinciding with a multi-species marine finfish, shellfish, and crustacean disease event.[52]

The Gladstone Harbour dredging project was to enable large ship access to a new liquid natural gas (LNG) export port. The harbor has been host to a wide range of industries spanning back to the 1950s, including an alumina smelter, a coal port and a coal fired power station, a large cement factory, and a cyanide chemical factory. This resulted in contaminated sediments in the inshore areas when water velocity slows and oceanic water exchange is reduced. Heavy metals including copper, arsenic, nickel, chromium, aluminum, manganese, and zinc, as well as PAHs and TBT, have been measured in the aquatic environment and biota of the harbor.[52]

Gladstone Harbour is also home to central Queensland's largest area of inshore seagrass and is part of the Great Barrier Reef Marine Park World Heritage area, home to a wide range of fish, crustaceans, and protected marine animals. Prior to the dredging, there was a viable commercial fishery operating, including mud crabs, prawn, and scallop trawl, and a range of net fisheries for inshore fish species.

The estimated AUD$5 million environmental assessment of the dredging project identified "at risk" fauna under Australian legislation, including dugongs, turtles, and dolphins, which were all residents in the harbor. There was also a coral reef within the footprint of the project. It was anticipated that only small amounts of seagrass would be lost in an area where it was proposed the dredge spoil would be disposed of, on top of a seagrass meadow. The remainder of the predicted impacts were limited to the footprint of the dredging and channel.

What ultimately occurred was an impact that spanned more than 50 kilometers.

The dredge spoil was contaminated with heavy metals and acid-sulphate sediments, which when mobilized can activate metals into a more toxic form that have greater biological impact. Several million tons of dredge spoil were deposited at sea for ocean disposal only a kilometer from the edge of the Great Barrier Reef Marine Park boundary.

Other more toxic sediments were supposed to be contained in a constructed bund wall area, but due to economic considerations, designs were changed and the modified bund wall turned out to be porous. As a result, large quantities of dredged sediment slurry exited from the bund wall. The sediments were quite acidic and contained very high metal loads that were mobilized into the local ecology and the local food webs.

After a significant flood event as a result of a cyclone, the saltwater harbor had an influx of freshwater. While temporary turbidity elevation was expected, excessive turbidity remained for more than a year due to the dredging and dredge disposal activity. This shaded out much of the seagrass and caused significant seagrass meadow losses.

Baselines for the acceptable levels of turbidity were changed, which ensured the dredging project could continue even though the levels were excessive and associated with declines in seagrass meadows. This was set against a backdrop of the loss globally of 30% of seagrass, a loss which is accelerating at around 7% per year.[232]

The dredging coincided with a multi-species marine finfish, mollusk, and crustacean disease event. Disease and mortality were observed in the harbor's aquatic species, including bony fish, sharks and rays, crustaceans, mollusks, turtles, dolphins, and dugongs.[52]

There was a very high rate of skin disease across all species of fish in the harbor and significantly higher prevalence of parasitism in a range of species. The elevated levels of parasites suggested that the fish were immuno-compromised from the degradation of the water quality.

High levels of parasitism were found in moribund and deceased green sea turtles from the Gladstone coastline.[72] During early 2011, the mortality rate among sea turtles of the area was approximately 5 times higher compared to previous years. High levels of

**Curtis Island, Gladstone Australia, where the development of three gas compression plants required vast dredging of a world heritage area, and killed much wildlife with sediments, metal, acids, and nutrient pollutants.**

metals, including cadmium, cobalt, mercury, and arsenic, were found in their blood.[37] It is likely they ate seagrass, which had aggregated some of the mobilized metals and as it moved from their stomachs into their blood, caused them to become sick from heavy metal intoxication. Mortality rates of other wildlife species also increased as a result.

Mud crabs demonstrated a much higher prevalence of shell lesions.[52] Excessive levels of copper and aluminium and other metals are known to interfere with their moulting process and their ability to re-calcify their shells. Large numbers of crabs developed holes in their shells or rust spots, which meant they were unsaleable as commercial catch and had higher mortality rates. The area that the damage spanned was considerable and caused a collapse in the local scallop fishery, as scallops are very sensitive to sediment.

Dredging is highly disturbing to the aquatic environment. Through resuspension of the seabed, contaminants present in the sediment, such as heavy metals and POPs, are mobilized becoming more bioavailable to marine biota. In this case, disease in marine animals clearly corresponded to the distribution of resuspended sediments from dredging and disposal based on direct measurements of turbidity as well as interpretation of corresponding satellite imagery.[52]

A legal class action is now pending with commercial fishermen suing the Gladstone Ports Corporation who were the proponents of the project. They are claiming losses of many millions of dollars as a result of the dredging operation.

*Continued from page 52*

pesticides, petroleum hydrocarbons, and PAHs, as well as heavy metals, including copper, lead, chromium, cadmium, mercury, and arsenic.[64] Resuspension of these pollutants has resulted in lesions, increased parasitism, skin redness, and ulceration in fish and crabs, while turtles can become sick and die from eating seagrasses contaminated with heavy metals.[73]

## 4.7 PESTICIDES

Pesticides—which include insecticides, fungicides, herbicides, miticides—are used in agriculture and urban pest management. They enter aquatic and marine environments through wastewater treatment plants and storm water systems, rivers and streams, as direct runoff, vapor 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, and other stressors such as temperature increases, oxygen levels, pH/acidification, pathogens, and nutrient levels all influence the effects pesticide exposures can have on an aquatic environment.

The history of synthetic pesticide manufacture and use over the past eighty years reveals a treadmill of pesticide classes—organochlorines, organophosphates and carbamates, synthetic pyrethroids, and neonicoti-

noids— each one proclaimed as safer than the last, but invariably shown to cause "unintended" harm once used at commercial scale.

For instance, pyrethroid insecticides were found to be consistently more toxic to aquatic macroarthropods (crayfish and water bugs) than organophosphates.[86] The newer replacement neonicotinoids insecticides are now being shown as highly persistent and extremely toxic to off-target organisms (see section 4.7.2).

Pesticide regulations differ around the globe. While there have been improvements in toxicology, laboratory detection methods, and pesticide regulation over the decades of use, the fact remains that many pesticides known to cause harm to aquatic organisms are still in widespread use and are still being detected at unsafe levels in aquatic environments.

Most commercial formulations of pesticides are complex mixtures of active/s and other ingredients. Information regarding "other ingredients" is usually considered proprietary business information and is often not publicly available. Many ingredients in current pesticide formulations are potentially toxic to marine organisms, including the active constituents, as well as the formulating chemicals like surfactants, as well as impurities and metabolites. Surfactants such as alkylphenol ethoxylates are commonly co-applied with herbicides and other pesticides to increase their uptake by the weeds being targeted, but their presence could also increase the bioavailability of insecticides.

The impact of pesticide residues on the ecology goes largely unnoticed unless specific monitoring and research is carried out to detect it. Acute poisoning events such as mass fish kills are highly visible and generate publicity and speculation. While it can be difficult to attribute mass fish kills to pesticides, it certainly does occur. For instance, a database of fish kills kept by Australian state governments, showed that fish kills were reported more often from cotton-growing areas and during cotton-growing season, with more than half of the 98 recorded fish kills associated with pesticides.[159]

### 4.7.1 CUMULATIVE ECOLOGICAL IMPACTS OF PESTICIDES

Our knowledge of how aquatic ecosystems react to, and recover from, pesticide exposures is deficient, despite the importance of such information for realistic and effective ecological impact assessments of pesticides.

Pesticide exposures impact macroinvertebrate communities and microorganisms in aquatic environments. In 24 stream sites in southeast Austra-

**ENDOSULFAN CONTAMINATES KRILL**

Endosulfan, an organochlorine POPs insecticide, was used extensively in cotton growing around the globe. It is highly toxic to aquatic invertebrates and fish with its breakdown product, endosulfan sulfate even more persistent and toxic. Endosulfan persists in the atmosphere, and in water and sediments, and is found in 40% of samples of Antarctic krill.[224] In Greenland, endosulfan was measured in freshwater fish, seabirds, marine organisms like shrimp and crabs, and in marine mammals. Despite its safety being touted for decades, in 2011 its manufacture, use, and export were globally banned under the Stockholm Convention after it was finally accepted to be genotoxic, neurotoxic, and an endocrine disruptor.

lia, macroinvertebrate and selected microorganisms (bacteria, flagellates, ciliates, amoebas, nematodes, and gastrotrichs) were sampled along with 97 pesticides. The study clearly demonstrated that current-use insecticides and fungicides can affect macroinvertebrate communities in complex mixtures at low exposure doses.[196]

Similarly, in France, a study of pesticide impacts on ponds found that regardless of the pesticides used, or the number of treatments and application rate, there were still significant direct negative effects on various invertebrate groups, particularly *Gammarus pulex,* a species of freshwater amphipod crustacean. Amphipods have an important functional role in the breakdown of plant and other biotic material in ponds. The insecti-

## HERBICIDES AND CLIMATE CHANGE – A DEADLY COMBINATION FOR MANGROVE SURVIVAL

Mangroves and saltmarshes are ecologically important ecosystems that provide habitat for both marine and terrestrial organisms. They are vital to the biological productivity and food webs of coastal waters and provide critical nursery areas for many fish and crustaceans, including commercially and recreationally important species. They also trap, process, and store large amounts of sediment and organic matter, and filter out pollutants such as fertilizers and pesticides.[83]

In the north east of Australia, herbicides, particularly diuron, have been linked to severe dieback of mangroves.[61] First seen in the early 1990s, by 2002, more than 30 square kilometers of mangroves were affected. Over the same period both population and agriculture had expanded in the region and increased use of agricultural chemicals saw many herbicides finding their way into estuaries, and nearshore water and sediments.

A consequence of dieback is declining coastal water quality, including increased turbidity, nutrients and sediment deposition, as well as further spread of toxic pesticides. The serious deterioration of mangroves affects fish breeding and habitat. It may also have direct and indirect effects on other estuarine and marine habitats, including seagrass beds and the coral reefs of the Great Barrier Reef lagoon. Coastal stability can be lost with mangrove die-off leading to enhanced rates of coastal erosion. Herbicide runoff is also known to further stress corals.[162]

Mangroves are already at serious risks from climate change, which in combination with El Niño caused the worst mangrove die-off in recorded history, stretching along 700 km of Australia's Gulf of Carpentaria.[60] The mass die-off coincided with a catastrophic global coral bleaching event when almost a quarter of the coral on the Great Barrier Reef was killed and almost 100 km of important kelp forests off the coast of Western Australia died.

cide bifenthrin and the fungicide cyprodinil were identified as the main culprits for their demise.[12]

### 4.7.2 NEONICOTINOIDS

Neonicotinoids ("neonics") have become the fastest-growing class of insecticides globally. Developed to replace organophosphate and carbamate insecticides, they are structurally similar to nicotine. When they were first released, it was assumed that they would show high specificity towards


insects due to the specific mode of action. However, various studies have now shown that other arthropods, including crustaceans, are equally vulnerable as they share a similar nervous system.

Neonicotinoids have been found in many water bodies, e.g., widely used neonicotinoids; imidacloprid, thiamethoxam, and clothianidin, were detected in the majority of surface water sites in Ontario, Canada.[7] Neonics are increasingly found in Australian rivers, with imidacloprid detected in all but two catchments on the northeast coast of Australia. It was also measured in 12 of 13 samples collected from rivers in the Sydney region after major rainfall events.[93]

Five neonicotinoids and the insecticide fipronil were identified in 193 samples from four estuarine sites in the Seto Inland Sea of Japan. Dinotefuran was the most frequently detected (98% of samples) with the highest concentration, followed by imidacloprid and clothianidin (35% each), thiamethoxam (19%), and acetamiprid and fipronil (12% each). The imidacloprid metabolite, desnitro imidacloprid, was also detected.[88] Imidacloprid is very persistent in water samples and does not readily biodegrade in aquatic environments.[215]

A review of 150 studies revealed toxic and indirect (e.g. food chain) effects on vertebrate wildlife including, fish, amphibians, and reptiles.[80] Two neonicotinoids, imidacloprid and clothianidin, as well as fipronil, which also acts in the same systemic manner, were the focus of the review.

Imidacloprid and fipronil were found to be toxic to many birds and most fish, respectively. They exerted sub-lethal effects, ranging from genotoxic and cytotoxic effects (toxic to cells), as well as impaired immune function, reduced growth and reproductive success, often at concentrations well below those associated with mortality. The toxicity of neonicotinoids is further complicated by their mixtures, the toxicity of which cannot be predicted using the common assumption of additive toxicity.[142]

NEONICOTINOIDS ("NEONICS") HAVE BECOME THE FASTEST-GROWING CLASS OF INSECTICIDES GLOBALLY.

Imidacloprid disturbed the feeding of the freshwater amphipod crustacean *Gammarus pulex* at concentrations two orders of magnitude lower than those causing mortality and similar to levels found in the environment.[2] The growth of the marine Mysid shrimp *Americamysis bahia* was also impaired at very low levels (0.163 μg/L) of imidacloprid.[228]

The indirect effects of neonics include reductions in invertebrate prey, which can lead to impaired growth in the fish that depend on them for food. Imidacloprid has the potential to indirectly cause lethality in aquatic invertebrate populations at low, sub-lethal concentrations by impairing movements and thus feeding.[164]

### 4.7.3 NEONICOTINOIDS THREATEN SHRIMP AQUACULTURE

Commercially important shrimp and prawn species are extremely sensitive to neonicotinoid insecticides, yet most prawn farms are located adjacent to estuaries that have multiple land-uses upstream, such as sugar cane farming, banana farming, macadamia farming, beef cattle, and urbanization. The associated uses and mobility of pesticides impact river and estuary water quality.

As a result, neonics have been detected in the intake waters of commercial prawn farms in Australia. Some concentrations were likely high enough to cause negative impacts on growth and survival, based on laboratory studies on black tiger prawns (*Penaeus monodon*).[93]

Larval and post-larval shrimp are particularly susceptible to the impacts of pesticides because of their high surface area to volume ratio and rapid growth requirements. In addition, juvenile and adult shrimp burrow in the sediment, and so they may be especially susceptible to sediment-bound contaminants like fipronil. Pesticides building up in aquaculture pond sediment can pose a risk to shrimp aquaculture that is greater than would be predicted by simply measuring pesticides in the water column.[93]

Herbicides in the contaminant mixtures that farm prawns are exposed to can alter the sensitivity of crustaceans to various insecticides. For instance, grass shrimp larvae are comparatively insensitive to the herbicide, atrazine, yet simultaneous exposure—to either atrazine and the neonic imidacloprid, or to atrazine and fipronil—was more toxic than exposure to imidacloprid and fipronil alone.[93]

### 4.7.4 GLYPHOSATE-BASED HERBICIDES

Glyphosate-based herbicides (GBHs) are the most widely used herbicides throughout the world, in part due to the introduction of glyphosate-tolerant genetically modified crops, and new uses to desiccate crops prior to harvest.

GBHs act on the enzyme that blocks the production of certain amino acids causing plant death. This biochemical pathway exists only in plant organisms, however despite the targeted mode of action, GBHs have been

related to toxic effects in invertebrates, fishes, amphibians, reptiles, birds, and mammals, including humans.[82]

Glyphosate-based herbicides have demonstrated endocrine disruption[144] and can alter microbial diversity and community composition.[206] GBHs can also promote algal blooms.[180, 173]

Most GBHs are not approved for use in the aquatic environment, yet measurable quantities of the active ingredient and surfactants are detected in surface waters. GBH residues have also been found in soil, air, and groundwater[110], and in marine sediments.[10, 206] Glyphosate is moderately or highly persistent in seawater depending on light conditions.

It has been reported that surfactants and wetting agents in commercial glyphosate formulations are themselves more toxic and increase the bioavailability and toxicity of glyphosate to non-target species.[186] There are a variety of surfactants, but the most common one is polyethoxylated amine (POEA). Aminomethylphosphonic acid (AMPA) is one of the primary microbial degradation products of glyphosate, and AMPA toxicity is comparable to that of glyphosate itself.

The effect of herbicides on non-target aquatic plants is an emerging issue in the conservation of aquatic biodiversity. Glyphosate in the aquatic environment causes the death of the macrophyte community (aquatic plants

## PESTICIDES IN THE GREAT BARRIER REEF WORLD HERITAGE AREA

Agricultural runoff is an important stressor for estuaries and marine ecosystems within the Great Barrier Reef (GBR) world heritage area, including seagrass meadows and mangrove systems. Agricultural runoff into the GBR contains fertilizers, sediments, and pesticides that reach the marine environment via rivers. It is a significant stressor in the decline of coral cover across large parts of the GBR.[126] Persistent herbicides are believed to pose one of the greatest risks to ecosystems and organisms in the GBR World Heritage Area.[118] Pesticides can affect coral reproduction, growth, and other physiological processes. Herbicides, in particular, can affect the symbiotic algae damaging their partnership with coral and resulting in bleaching.

Pesticide residues detected in GBR rivers and creeks during flood events include the herbicides diuron, atrazine (and the 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.[131] Coastal fish in and near rivers discharging into the GBR lagoon are exposed to oestrogenic compounds associated with the pesticide runoff from sugar cane land use in the GBR catchment.[128]

that grow in or near water), which serves as a microhabitat for planktonic communities (bacteria, archaea, algae, protozoa and drifting or floating animals that inhabit oceans, seas, or fresh water).

These are important for both refuge and food for fish.

### 4.7.5 ORGANOPHOSPHATES AND CARBAMATE INSECTICIDES

Organophosphates and carbamates are used in urban and agricultural environments. They are acutely toxic and their mode of action is to block the enzyme acetylcholinesterase (AChE), which is essential to the functioning of neurotransmitters, the body's chemical messengers.

The impacts of organophosphate pesticides on fish ecological fitness occurred even with short exposures at very low concentrations. Sublethal exposure to the organophosphate ethoprophos caused a significant (54%) reduction of brain cholinesterase (ChE) activity in exposed fish. This modified their escape response and detection avoidance with exposed fish slower to escape and hide from a simulated attack.[194]

**CHLORPYRIFOS WAS BANNED IN THAILAND IN 2020 DUE ITS TOXIC EFFECTS TO HUMANS**

Exposure to the organophosphate sumithion significantly decreased the abundance of benthic invertebrates in the sumithion-treated ponds[218], while azinphos-methyl, malathion, fenitrothion, and dimethoate have been identified as of potential concern in the marine environment. Mixtures of carbamate and organophosphate pesticides have the same mode of action so their toxic effects can be additive or sometimes synergistic.

Chlorpyrifos is a widely used organophosphate, and, as an EDC[240], poses serious risks to aquatic organisms and ecosystems.[81] It affects the behavior of crustaceans and fish with sub-lethal effects on fish measured in changes to olfactory perception and behavior.

Chlorpyrifos bioaccumulates in aquatic organisms and its residues have been measured in fish from the Tono Reservoir, Ghana[4], in farmed fish[210], in market fish samples from different regions of Punjab, India[160], and in the blood of free-ranging sea otters in Alaska and California.[116]

CASE STUDY

## PESTICIDES AND DISEASE IN SHRIMP AQUACULTURE

Intensive prawn aquaculture began in Asia in the 1980s, and Asia is now responsible for around 85% of global aquaculture prawn and shrimp production—the top five global producers being China, India, Vietnam, Ecuador and Indonesia.[69] Shrimp and prawns are big business with global production valued at US$38 billion in 2015, with aquaculture accounting for around two thirds.[68]

Like all creatures, shrimps have their own spectrum of viruses and bacteria. Soon after the intensification of shrimp aquaculture significant viral diseases started occurring. Despite nearly forty years of research and development, these outbreaks continue to occur and cause enormous losses in the aquaculture prawn-farming sector. In Brazil, the third largest shrimp-producing country, shrimp aquaculture has been dramatically affected mainly by five viruses (infectious hypodermal and hematopoietic necrosis virus, yellow head virus, Taura syndrome virus, white spot syndrome virus, and infectious myonecrosis virus.[201]

Successful aquaculture depends on the availability of good quality water, yet pollution in the environment continues to impact the health and resilience of prawns. The problem is so pervasive it largely goes unmanaged. Instead, the focus is on the pathogen causing disease, without understanding the significant role the polluted environment the animals live in is playing in ongoing disease outbreaks.

While many factors contribute to declines in prawn production, insecticides have specifically been shown to increase the incidence of disease.[33] Research has demonstrated that mortality in white leg shrimp (*Penaeus vannamei*) was significantly higher after combined exposure to the organophosphate insecticide, methyl parathion, and to the bacterium *Vibrio parahaemolyticus*, than it was to either stressor individually.[129]

As aquaculture continues to expand on land into traditional agricultural areas there is an even greater risk of exposure to pesticides. Exposing shrimp to pesticides induces a stress response[195], reduces the energy available for survival and growth[6], and increases the possibility of disease.[80]

Aquaculture feeds, which include commercially grown ingredients such as wheat, soy, and lupins, also represent another exposure pathway for pesticides to farmed prawns and fish. In an alternative rice and shrimp farming in Vietnam, agricultural chemical use from rice can generate lingering residues in subsequent shrimp crops, while antibiotics used in shrimp aquaculture have been detected in subsequent agricultural produce—both increasing the risk of undesirable human exposures.[27]

Pesticides occur in the environment as a result of spray drift, runoff from crops and soils, leaching, and foliar deposition. In Pakistan, persistent organochlorines

were surveyed[209] in aquaculture intake waters and shrimp from an agricultural catchment. A total of 36 organochlorine pesticides or their metabolites were detected in water and shrimp samples. All water samples contained 4-DDT, dieldrin, and methoxychlor, with methoxychlor also shown to accumulate in shrimps *Penaeus merguiensis* and *P. penicillatus*.

Sampling in Australia[93] found elevated pesticide concentrations in aquaculture intake waters from seven multiple-use catchments along Australia's north east coast. A mixture of insecticides, herbicides, fungicides, and adjuvants, including neonicotinoids (imidacloprid and clothianidin), a pyrethroid (bifenthrin), an organophosphate (chlorpyrifos), a phenyl-pyrazole (fipronil) and DEET, were detected. Prawn farms in Australia are predominantly located adjacent to estuaries which are impacted by multiple agricultural land uses upstream.

Australia was previously generally free of prawn viruses due to its geographical remoteness and relatively well managed prawn farms. However, in 2016, white spot syndrome virus arrived in the Logan River, Queensland, via imported frozen uncooked peeled prawns. Recreational anglers were using the imported prawns as bait and were depositing them into the Logan River and inlet channels of the prawn farms where they liked to fish off the bank.

The virus had arrived on Australian shores because there were breaches in the biosecurity boundary. Imported prawn products were supposed to be free of virus, but they were not. Subsequently, there have been a lot of detections in imported retail prawns in Australian supermarkets.[1]

Pesticide-monitoring programs in the Logan River immediately prior to the time of the white spot virus outbreak detected residues of neonicotinoids, pyrethroids, and organophosphates in the waters of the Logan River. The mixture of sub-lethal exposures may have compromised the health of exposed prawns, as documented in better studied terrestrial invertebrates[25], thereby facilitating the expression and propagation of the disease. The interactions between pesticide mixtures and prawn immunity and resilience to disease expression require further research to more clearly elucidate the mechanisms.

# 5. A WAY FORWARD

One of the greatest challenges faced in addressing the decline of fisheries, as well as combating climate change, is the insidious impact of pollution on the marine ecosystem. It's not just the obvious fish kills with dead bodies floating on the surface, it's the unseen impacts on future generations wrought by undermining their resilience, reproductive success, food resources, and survival as a result of exposure to pollutants.

Almost two decades ago, governments from around the world agreed to minimize the harmful effects of chemicals and waste on our health and environment. They committed to "*produce and use chemicals in ways that minimize significant adverse effects on human health and the environment*" by 2020.[102]

While there have been some advances towards more sustainable use of chemicals, with a handful of the more persistent pollutants being globally banned, governments on the whole have not made significant inroads towards the goal.

There are now an estimated 100,000 to 350,000 chemical substances commercially available[250], many of them remain unassessed for their impacts and could potentially be toxic to aquatic environments. There are some 5,000 chemicals produced in volumes exceeding one million tons a year. Overall, chemical production continues to grow steadily, at around 4% per year.[107]

The pollution of waterways and oceans with industrial wastes, consumer chemicals, pesticides, and plastics continues unabated. Industrial agriculture with its heavy reliance on fertilizers and pesticides has not only depleted soils of carbon stores, releasing them into the atmosphere, but it is also responsible for delivering large volumes of pollutants, including nutrients and pesticides, into the aquatic environment via runoff. It has also introduced chemical residues into the raw materials for aquaculture diets, which are typically untested for safety of ingestion by farmed aquatic species.

Our waterways and oceans also face new threats by groups of chemicals that may never break down, as well as toxic deep-sea mining and the ongoing pressures of population growth, further urbanization, and the climate emergency.

## 5.1 REGENERATIVE FARMING

While the challenges to our waterways and oceans are many, it is reassuring to know some effective solutions are readily available. Regenerative farming has a major role to play in addressing the combined challenges of climate change and pollution loads in aquatic environments.

As the name implies, regenerative farming aims to restore healthy ecosystems by focusing on practices that sequester carbon, increase water storage in the ground, increase biodiversity, stabilize soils, and help restore soil and ocean health through improving the quality of water coming off these landscapes.

On land, regenerative farming practices utilize diverse cover crops, in-farm fertility, crop rotations, no-till methods, and no pesticides or synthetic fertilizers.

Carbon drawdown is critical in mitigating climate change impacts and regenerative farming is ranked as one of the greatest opportunities to address it. Estimates suggest regenerative farming could sequester up to 60 tons of carbon per acre, with increases in crop productivity, improved nutrient uptake, soil water retention, and better pest resistance and financial sustainability for farmers.[104] The cleaner crop products are also likely to make improved raw materials for aquaculture diets, without the presence of pesticide residues.

## 5.2 ECOSYSTEM APPROACHES TO AQUACULTURE

Regenerative farming isn't just needed on land, it is also critical to rethink the way aquaculture farming is done. In most cases aquaculture is essentially just another form of industrial agriculture using monoculture-species, unsustainable feed inputs, pharmaceuticals and pesticides, each of which creates wastes and pollutes environments.

The rapid development of aquaculture throughout the world is often geographically concentrated in already polluted waters, and this raises significant challenges for the health of fish and other farmed species.

Regenerative aquaculture strategies could help to address pollution and provide a net positive for the marine ecosystem and community. Models such as integrated multi-trophic aquaculture (IMTA) has the potential to achieve these objectives and provide healthy food, while helping clean and maintain healthy oceans.

Through IMTA, some of the uneaten feed and wastes, nutrients, and by-products are recaptured and converted into harvestable and healthy seafood of commercial value, while bio-mitigation takes place to remove nutrients and $CO_2$ while supplying oxygen.[42]

One study[74] looking at the impacts of open sea-cage salmon farming in the Atlantic concluded up to 60% of feed nitrogen and 70% of feed phosphorous is released into the ocean as metabolic waste. This is the equivalent of dumping 52,000 tons of nitrogen and 10,000 tons of phosphorous annually on the Norwegian coastline. This accumulation can lead to phytoplankton growth and eutrophication of pelagic ecosystems.

One of the possible methods to alleviate these impacts is by co-cultivating salmon with species of lower trophic levels. Around two thirds of the nitrogen waste from salmon farming is inorganic ammonia, which is

taken up by primary producers such as phytoplankton and macroalgae. Macroalgae cultivated in the vicinity of salmon farms could utilize the dissolved inorganic nutrients released from salmon farms in open water integrated multi-trophic aquaculture systems.

There is also potential for poly-culture, vertical-ocean farming systems using macroalgae and shellfish to help draw in carbon dioxide and buffer ocean acidity while producing viable harvests.[105]

Globally, around 12 million tons of seaweed are grown and harvested annually, with China producing around three-quarters of the supply. Seaweeds grow very fast, at rates more than 30 times those of land-based plants. Increasing the rates of seaweed production through ocean macroalgal afforestation (OMA)[50] over large areas has the potential to reduce atmospheric carbon dioxide concentrations, reduce ocean acidity, and improve fish populations.

Innovative land-based aquaponics systems[202] are also being used to close the nutrient loops, reduce water use requirements for crops, eliminate effluent in streams, and generate significant volumes of produce without the use of pesticides.

Aquaponics is a system for food production utilizing aquaculture and hydroponics to cultivate fish and crops without soil. It is an inexpensive symbiotic cycle between the fish and plant. Fish wastes (ammonia) are fed into the plant bed, which acts as a bio filter and takes the nitrate essential to growing vegetation. The fresh new water is then returned to the fish enclosure to restart the cycle or is transpired through plants as a clean discharge.[9]

While aquatic ecosystems in balance are astonishingly resilient and productive, pollution, human population demands, and climate change threaten that balance and are putting at risk sustainable growth in both aquaculture and wild fishery production worldwide. Many rivers and inshore environments are already in urgent need of restoration.

THE GLOBAL SEAFOOD INDUSTRY, AND THE LIVELIHOODS AND SURVIVAL OF MILLIONS OF ARTISANAL FISHERS AND COMMUNITIES WHO DEPEND ON SEAFOOD, ARE AT A CROSS-ROADS.

The global seafood industry, and the livelihoods and survival of millions of artisanal fishers and communities who depend on seafood, are at a cross-roads. The situation demands immediate global action and prioritized resources as well as an acceptance that we live in a precarious world where business as usual is no longer an option.

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Sweden Sverige

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IPEN

for a toxics-free future

www.ipen.org

ipen@ipen.org

@ToxicsFree