Jeremy B.C. Jackson

Revaluing the Oceans

The oceans throughout history provided seemingly inexhaustible fish for people brave and skillful enough to exploit them. Whenever fish catches declined, fishers would sail farther and farther from home to meet their needs.[1] Nowadays the entire global ocean is accessible. Large factory ships and the magic of refrigeration have allowed fishers to venture out for months or years, and more efficient and diverse ways of fishing have increased catches with little care or understanding about the incremental reduction of fish stocks.[2] Before the middle of the twentieth century, no one but a few scientists worried about how long the bounty could last, until suddenly, everything began to collapse. Mini wars over fishing rights between Iceland and the United Kingdom in the 1960s and 1970s, along with increasingly protective measures by other nations, led to the unilateral establishment of exclusive economic zones (EEZs) to keep foreign fishers away, the legitimacy of which were formally recognized in 1982 under the auspices of the United Nations Convention of the Law of the Sea. Yet even still, as in Newfoundland, fisheries kept collapsing, with tragic consequences for entire communities.

The great majority of fisheries data come from coastal ecosystems including estuaries, marsh and mangrove wetlands, seagrass meadows, kelp forests, and coral reefs. In spite of great differences in their inhabitants, the dominant predators in each of these environments were historically large animals, including some combination of killer whales, sharks, seals, crocodiles, predatory fishes like tunas and sharks, and seabirds.[3] Nowadays, however, most of these animals are so severely depleted as to be ecologically extinct. Humans have taken their place as the dominant predators at almost all trophic levels above the zooplankton.[4] There is even a major fishery for krill in Antarctica, which are critically important for the survival of whales, without the necessary ecological data for an adequate stock assessment to know what is sustainable.[5]

Biomass of groundfish and sharks has been diminished by an order of magnitude in the northwest Atlantic.[6] Similar depredations have affected coral reefs, kelp forests, estuaries and coastal seas, and the high seas.[7] Many fisheries biologists originally claimed that the depletions of fish stocks were overstated, but a detailed assessment by the US National Research Council strongly supported the original claims.[8] It is now generally accepted that two-thirds of global fisheries are overfished and getting worse, while many of the remaining, better-managed fisheries are not yet sufficiently recovered to be economically viable.[9]

Global fish catches are declining in spite of

Michelle-Marie Letelier, *Outline for "The Bonding" (Still #1)*, 2017-2019. 16mm film transferred to HD. Image courtesy of the artist. The film was made as an outline for a two-and-a-half-year bonding with a farmed salmon, in current collaboration with the Institute of Marine Research in Norway. Letelier researches the history and technology of salmon aquaculture. One process involved the extraction of otolith pairs – unique crystals or bio-minerals that serve as a chemical diary of the farmed salmon. "The Bonding" is part of the ongoing project *Transpose*, which explores cross-hemispherical relations, anthropocentric management and manipulation of living marine resources, and the coexistence and disappearance of ancestral knowledge."

increased capacity supported by misguided government subsidies that only accentuate the problem.[10] The greatest losses are for large-scale industrial fisheries, whereas artisanal catches appear to be more sustainable. Risks of biological extinction are also increasing for large animals.[11] Caribbean Monk seals have already been lost, and their Hawaiian and Mediterranean counterparts are gravely threatened.[12] Killer whales are rapidly diminishing globally, especially those species that depend on highly specific overfished prey like salmon.[13] Caribbean sea turtles have declined in abundance 100-fold, and Caribbean crocodiles are threatened to endangered throughout most of their range.[14] Sharks are globally threatened with losses of numerous species exceeding 90% or more.[15]

Coastal Pollution and Habitat Loss

The oceans have long been the terminal point for our garbage, excrement, and chemicals. Coastal pollution most obviously began in the stench of estuaries like New York Harbor, which by the nineteenth century had become serious hazards to human health.[16] Soon afterwards, entire semi-enclosed seas like the Baltic and Adriatic seas, Chesapeake Bay, and embayments of the Mississippi Delta were so polluted by excess nutrients and organic matter that oxygen levels declined, and fish kills were commonplace.[17] More recently, the industrial pollution of toxic chemicals and greenhouse gases from burning fossil fuels have extended to the farthest reaches of the oceans and the atmosphere, poisoning tuna and swordfish with mercury and littering the oceans with plastic.[18]

There are currently more than 500 coastal hypoxic "dead zones" worldwide that are largely due to massive increases in nutrient runoff from intensive agriculture made possible by cheap nitrogen fertilizer manufactured from petroleum.[19] Excess nitrogen runoff fuels population explosions of phytoplankton far beyond the capacity of zooplankton and other suspension feeders to consume them. As a result, the excess phytoplankton die and sink to the seafloor where they are metabolized by microbes, a process that consumes most or all of the oxygen in bottom waters. Animals including fisheries species that cannot swim away die from asphyxia, except for a very few species that can survive in extremely low oxygen conditions.

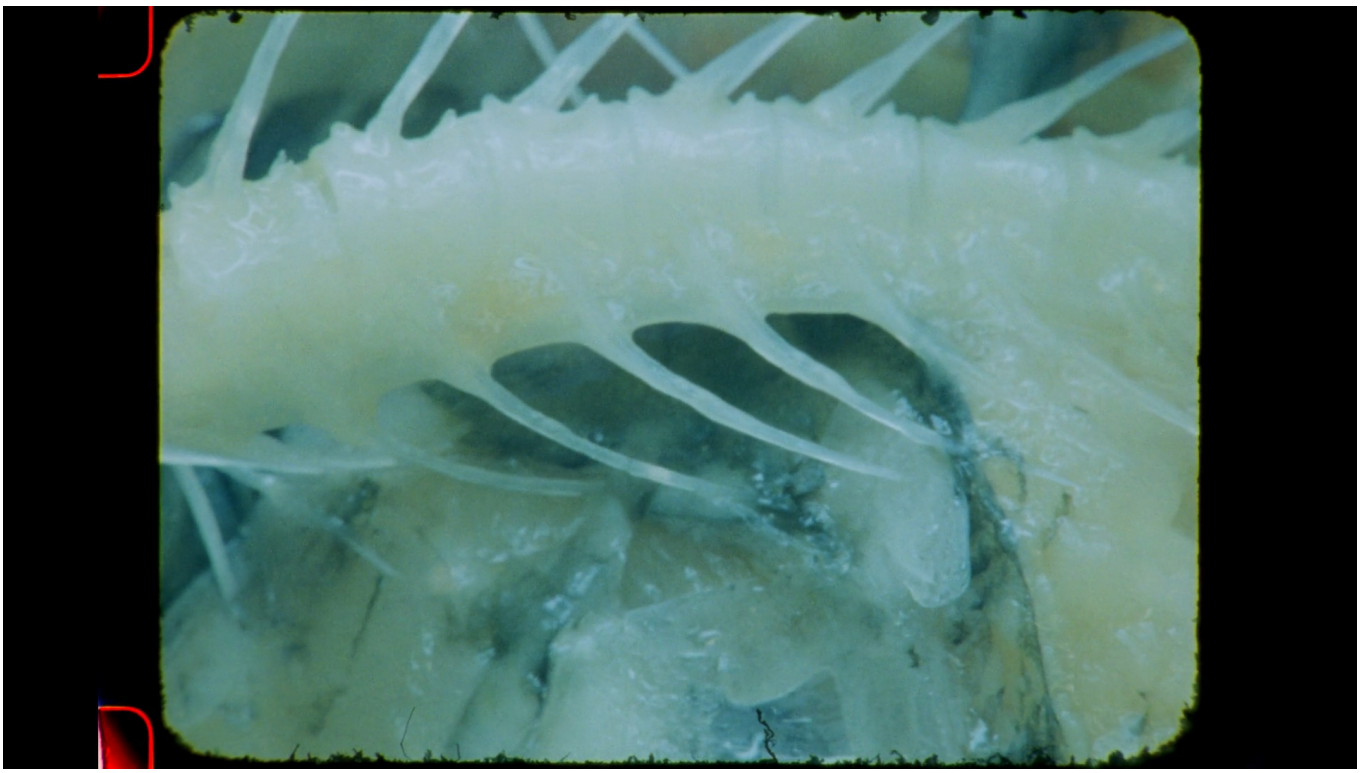
The structural integrity of coastal marine habitats, from the tropics to the temperate zone, is dependent on the abundance of a small number of structurally dominant species of mangroves, saltmarshes, seagrasses, kelps, and reef corals that stabilize sediments and provide critical shoreline protection from storms.[20] They are also important sites of carbon deposition and sequestration, and are important nursery habitats for fisheries.[21] Coastal development and climate change effectively kills the environment, reducing biological structural stability and complexity. Global losses have been alarming, reaching 50% for mangroves and 30% for seagrasses.[22] Global declines in living coral cover on reefs is also highly variable but commonly exceeds 50% throughout the Caribbean and Indo-Pacific.[23]

Other increasingly widespread forms of anthropogenic habitat change are more immediately destructive in reducing habitat complexity and biodiversity.[24] The most damaging include dynamite fishing on coral reefs to harvest the fish that float to the surface; seabed trawling for shrimp, scallops, and groundfish that transforms biodiverse underwater forests into depauperate level bottoms of mud; and deep seafloor mining that, if it is allowed to proceed, will inevitably destroy seafloor ecosystems for decades and possibly centuries.[25] Container ship traffic is also increasing almost exponentially and carries the double risk of fatal collisions with endangered whales and sound pollution that is dangerous for all cetaceans.[26] Seismic oil and gas exploration causes even more severe sound pollution that can cause mass mortalities of whales and dolphins.[27]

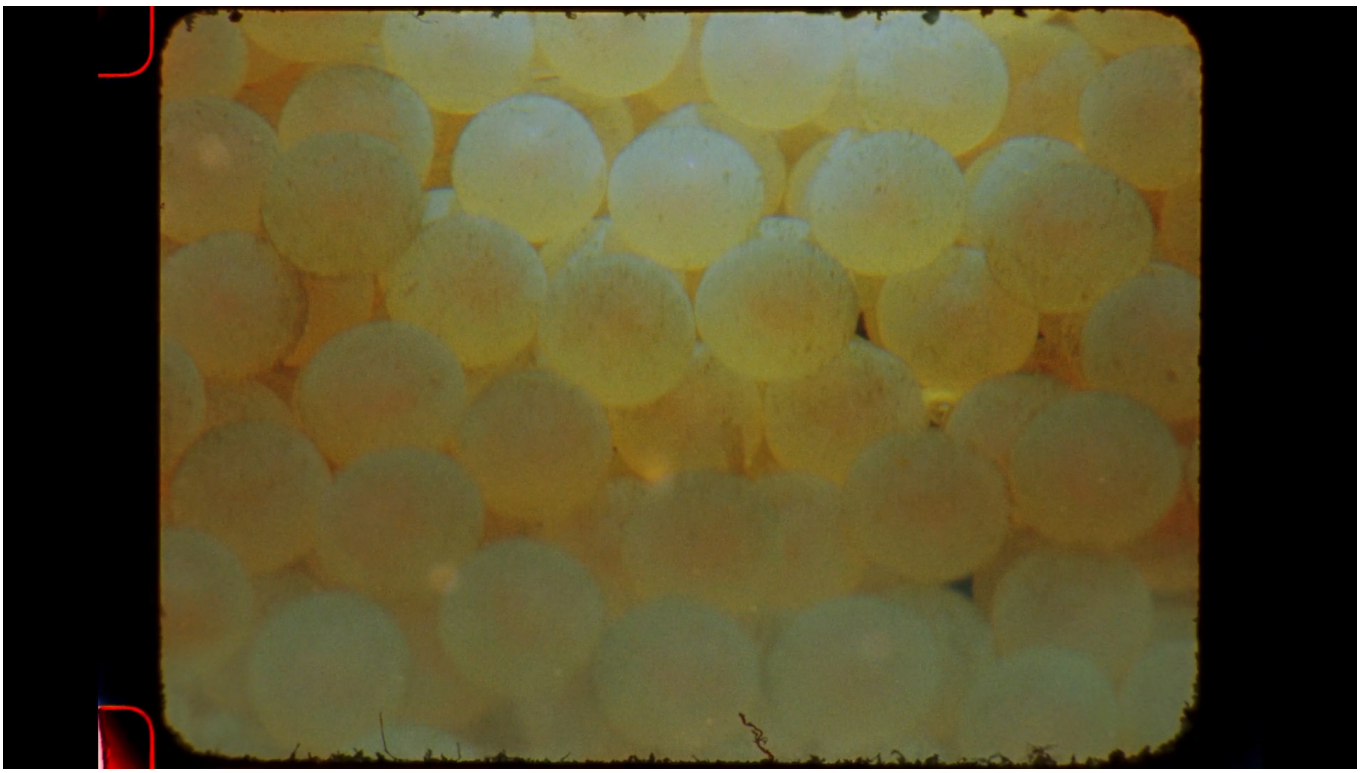
Introductions of exotic species are also increasing due to expanding ship traffic, which discharge ever-increasing volumes of ballast water that contain larval stages of invertebrates, fishes, plankton, and pathogens.[28] While the data are mostly circumstantial, the first mass mortality of the sea urchin *Diadema antillarum* occurred next to the Caribbean entrance of the Panama Canal, and the first widespread outbreaks of coral diseases in the Caribbean were recorded from nearby Colombia and adjacent Netherlands Antilles.[29] Coral diseases are exacerbated by global warming, but these first Caribbean disease outbreaks occurred two decades before the first reports of coral bleaching due to extreme warming events.[30] Introductions also occur due to deliberate or accidental release from aquaria, as with the Indo-Pacific lionfish that has devasted native fish populations of the Caribbean.[31]

Anthropogenic Climate Change

Impacts of climate change due to the burning of fossil fuels are also both direct and indirect, including rising average temperatures, extreme heating events, declining oxygen, ocean acidification, disease outbreaks, and intensification of extreme storms.[32] Sea surface temperatures are rising globally, but disproportionately, with the greatest increases in



Farmed salmon bones preserved in a laboratory in collaboration with palaeontologists at the University of Bergen, Norway. Michelle-Marie Letelier, *Outline for "The Bonding" (Still #3)*, 2017. 16mm film transferred to HD. Image courtesy of the artist.



Wild salmon eggs at Arna Sport Fishermen's Association, Norway. Michelle-Marie Letelier, *Outline for "The Bonding" (Still #5)*, 2017. 16mm film transferred to HD. Image courtesy of the artist.

polar seas and semi-enclosed basins in the temperate zones, such as the Gulf of Maine. The latitudinal limits of myriad species are rapidly increasing in response, as in the case of the Humboldt squid, whose northern limit shifted from southern California to the Gulf of Alaska in just a few decades due to a combination of climate change and overfishing that reduced the abundance of predators.[33] Most species' range shifts are more gradual but pervasive, with great implications for fisheries.[34] For example, optimal conditions for Atlantic and Barents Sea cod are moving northward out of traditional fishing grounds and into different international jurisdictions, further exacerbating the consequences of historical overfishing.[35] Tropical reef corals are also migrating towards higher latitudes, most strikingly along the southwest coast of Australia, where kelp forests are dying off and being replaced by subtropical species including reef corals.[36]

As oceans continue to warm, species characteristic of colder polar conditions have nowhere else to migrate and are at risk of extinction. Arctic species and entire ecosystems are increasingly threated by the loss of summer sea ice.[37] Populations of polar bears, which historically fed on seals captured at breathing holes, are plummeting, and starving bears are showing up around human settlements where they forage on garbage and potentially whatever else.[38] Other effects on polar food webs are still poorly understood, but the collapse of Antarctic krill, for example, would have grave impacts on the baleen whales that feed upon them.[39]

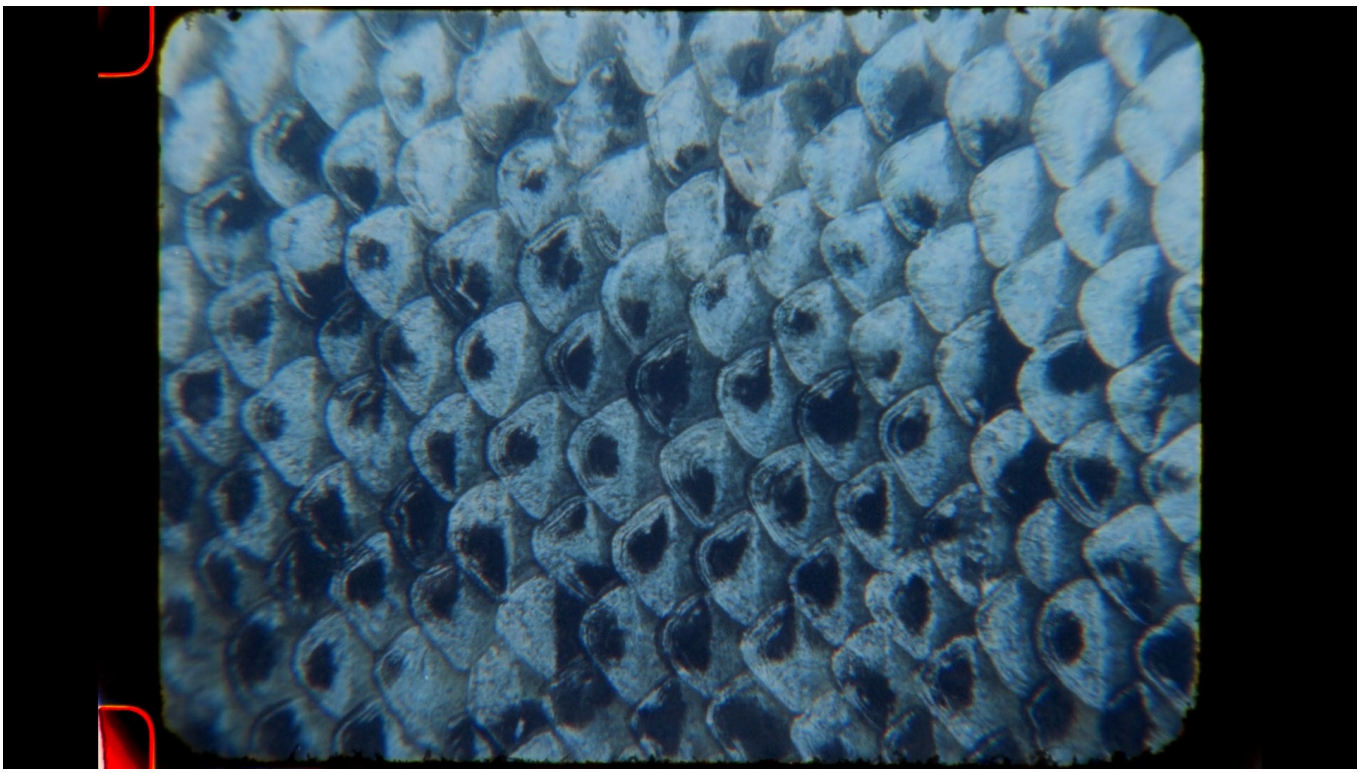
Global warming is also causing increases in the magnitude and frequency of extreme heating events wherein sea surface temperatures may rise 2 to 3°C above normal maxima in just a few months.[40] Consequences for reef corals can be catastrophic.[41] Healthy reef corals exist in symbiosis with the dinoflagellates within their tissues that are critical to coral nutrition and calcification.[42] Extreme heat breaks down this symbiosis, whereby corals evict the symbiont (which leaves them ghostly white, hence bleached). This is commonly fatal to the corals unless symbiosis is reestablished within a matter of weeks. Mass bleaching events are increasingly frequent and severe, raising questions about the very survival of coral reefs. The most recent extreme example was in 2015–2016 when most corals along the northern Great Barrier Reef bleached and died, and similar mass bleaching and mortality occurred across the Pacific.[43] Another example is the enormous blob of hot water that appeared in the northeast Pacific in 2014 that was associated with collapses in species abundance and outbreaks of diseases.[44]

Climate change also sets off a cascading series of indirect effects that magnify its impact. The impact of coral diseases has greatly increased, especially in connection with mass bleaching events.[45] Outbreaks of coral diseases are especially impactful on polluted reefs and those where overfishing has resulted in population explosions of fleshy algae, which have been shown experimentally to increase the vulnerability of corals to disease.[46] In contrast, disease outbreaks are comparatively rare on unpolluted reefs in marine protected areas with abundant grazing fishes. Lobsters along the northeast coast of North America are also more vulnerable to shell wasting disease as waters warm, effectively wiping out the fishery in Long Island Sound.[47]

Oxygen concentrations are declining in the open ocean because warming surface waters makes them lighter, which in turn slows down the vertical mixing of the oceans; a runaway process that decreases the rate of oxygen transport to the deep sea and upwelling of nutrients to the sea surface.[48] The process is especially striking in the equatorial Pacific, and in the Arctic ocean where the cover of summer sea ice is rapidly decreasing.[49] Sea ice is highly reflective, dispersing heat back into the atmosphere, whereas seawater absorbs heat and sets up a positive feedback that is effectively irreversible. Reduced nutrient upwelling and declining oxygen are strongly associated with decreases in open ocean productivity, which is the basis for high seas fisheries.[50]

The ocean is also becoming more acidic. Solution in seawater of increasing atmospheric levels of carbon dioxide has resulted in a global reduction in ocean pH of 0.1 units over the past century.[51] The biologic consequences of acidification are still poorly understood and controversial, but could affect the reproduction, physiology, growth, and development of a wide variety of plants and animals. The most obvious impacts are on organisms that form their skeletons of calcium carbonate, which is more easily dissolved under more acidic conditions. This is already affecting shellfish aquaculture industries in the state of Washington, where pH has been steadily declining.[52] Aquaculturists have been forced to raise vulnerable juvenile clams and oysters under less acidic conditions in aquaria on land before placing them in the ocean.[53] Reef corals are also vulnerable to increasing acidity. Corals grown under present-day more acidic conditions grew 15% more slowly than corals where pH was maintained at historically less acidic conditions.[54]

Reversing the Tide



Detail of farmed salmon scales, Norway. Michelle-Marie Letelier, *Outline for "The Bonding" (Still #2)*, 2017. 16mm film transferred to HD. Image courtesy of the artist.

Bird watchers were pioneers in the early rise of the conservation movement, with organizations such as the Audubon Society fighting to stop the slaughter of herons and egrets for women's hats.[55] Similarly, it's not just important for tourism that increasing numbers of people pay good money to see whales up close in the wild and increasingly to SCUBA dive with sharks.[56] Besides the thrill of witnessing their power and grace, whale and shark watchers learn about the lives and behavior of these animals and how they fit into ocean ecosystems which, in turn, leads to increased support for their protection.

Horror at the slaughter of whales was a major factor in the establishment of the International Whaling Commission in 1946 which, despite persistent opposition from a few countries, has resulted in dramatic recoveries of most whale species.[57] In addition to the ethical issues inherent in the mass slaughter of such animals, we now know that the great whales were once (and increasingly are now again) vitally important "ecosystem engineers," as predators of massive amounts of fish and invertebrates, prey for other large predators, highly mobile reservoirs of carbon and nutrients, and as carcasses, sources of energy and habitat in the deep sea.[58]

Similar public concerns about the loss of other marine mammals were a driving factor in the enactment of the United States Marine Mammal Protection Act in 1972, which prohibits the killing, harm, harassment, or collection of any marine mammal in US territorial waters or by US citizens anywhere else. It also forbids the importation of any marine mammal products or parts. Populations of most marine mammals have varyingly recovered, although their comparative success is strongly associated with their life histories, habitat requirements, and geographic range.[59] The depletion of essential forage fish due to overfishing also inhibits their recovery.[60] One obvious manifestation of success is the greatly increased abundance of seals along the east and west coasts of the US, where their activities and real or perceived impacts on fisheries are not always welcome. Their rebound has also led to increases in great white sharks near shore, restoring a degree of balance to marine food webs while generating new questions about perceived risks to humans and potential impacts on endangered species.[61]

Increased tourist revenues have also led to the banning of shark fishing on coral reefs by entire nations because the sharks are vastly more lucrative alive than dead. Economic analysis for the government of Palau demonstrated that diver tourism provides 39% of the country's total GDP, and that 21% of divers come principally to dive with sharks. The approximately 100 sharks in prime shark dive sites are each worth about US$180,000 per year in tourist revenue, or US$1.9 million during their lifetimes, versus about $110 for their fins and meat.[62] Shark diving is a burgeoning global industry that is not without its environmental concerns, although if it is done responsibly, the net conservation value appears to be generally positive.[63]

New studies of the remarkable behavior and migrations of ocean species are also increasing public support for increased protections.[64] The electronic tagging of thousands of individuals of different species of Pacific whales, seabirds, seaturtles, tunas and other large fish, and sharks has revealed striking transoceanic migrations of some species versus others that move much smaller distances.[65] Bluefin tuna, for example, move back and forth across the Atlantic and Pacific, hanging out for up to a year or more in the same general location before moving on.[66] In contrast, eastern Pacific great white sharks move back and forth between the California coast where they feed on burgeoning seal populations and an area of deep ocean halfway between Baja California and Hawaii dubbed the "White Shark Café," where they feed on vertically migrating fishes and invertebrates.[67] Over 200 of these sharks have been tagged and followed for up to twenty years.[68]

Marine Protected Areas

Marine protected areas (MPAs) are an increasingly popular and effective conservation strategy for biodiversity and habitat protection when effectively financed, administered, and enforced.[69] Unprotected "paper parks," however, can do more harm than good by lulling people into thinking everything is fine when it is not.[70] MPAs are also controversial from the perspective of fisheries management, with some arguing that MPAs are the most effective tool available versus those who believe that other management tools such as catch shares and gear restrictions are more effective in most cases than simple area closures.[71]

Cabo Pulmo in the southern Sea of Cortez is one of the most spectacular success stories of an effectively enforced MPA.[72] Although it was severely overfished at the time, Cabo Pulmo was designated as a Mexican marine national park in 1995 on the basis of its coral populations. Protections did not become effective until local villagers self-organized to enforce the entire park as a no-take area in the late 1990s. Fish biomass was less than one metric ton per hectare in 1999, comparable to other unprotected areas or paper parks throughout the Gulf of California. Subsequent to the villager's protection, biomass increased over the following

ten protected years to about 4.5 metric tons, while all other areas failed to increase. Biomass and diversity have fluctuated since 2009, in large part due to the community evolving towards a more natural composition that includes greater populations of schooling fishes as well as more abundant corals. The greatest potential threat to Cabo Pulmo is its notorious success, which attracts burgeoning numbers of tourists and development.

A network of nine well enforced no-take MPAs and two partial-take MPAs was established around four of the northern Channel Islands off the coast of California in 2003 and revisited ten years later.[73] The biomass of preferred fisheries species approximately doubled within MPAs at three of the four islands, but non-targeted species showed little response. The biomass of targeted species outside the reserves also increased by about one quarter, possibly because of a spillover effect. Similar results were obtained the Cowcod Conservation Areas established in the southern Channel Islands in 2001, where abundances of six of eight targeted species and four of seven non-targeted rockfish species increased regionally from 1998 to 2013.[74] Rising temperatures during the study are a complicating factor. Nevertheless, 75% of targeted species but none of the non-targeted species increased inside compared to outside of the MPAs while controlling for environmental factors.

The establishment of very large marine protected areas within exclusive economic zones has increased the area of ocean within MPAs to only 3.5%, about half of which are under strong protection.[75] Meanwhile, most ocean ecosystems are hemorrhaging, as major fishing fleets continue to expand their global operations.[76] This may be changing, however, as the international community finally begins to seriously consider international governance of the high seas defined as areas beyond national jurisdictions. The first major achievement in this was the agreement to establish the world's largest marine protected area by the twenty-five-national-member Commission for the Conservation of Antarctic Marine Living Resources.[77] The agreement protects all wildlife and bans fishing for overfished krill and Patagonian and Antarctic Toothfish in 600,000 square miles in the Ross Sea for thirty-five years. Much more will have to be done, however, to preserve populations around Antarctica where these species are threatened by overfishing and rapid climate change and have ripple effects on the marine mammals and penguins that depend upon them.

The scientific case for closing the high seas to fisheries is strong. Nearly 98% of global seafood production comes from the exclusive economic zones (EEZs) of individual nations and aquaculture. What does come from the high seas is mostly luxury species such as tuna and billfishes, yet their commercial value is even less.[78] Moreover, most high seas fisheries are heavily dependent on government subsidies by a small number of wealthy countries that can afford the enormous costs.[79] Closure of the high seas to fishing would therefore have great economic and social benefits in addition to environmental protections of fish stocks and the long-distance migration routes of marine megafauna.[80] Most compellingly, the overwhelming majority of high seas fishery species are also major components of fisheries within national EEZs, which means that closure of the high seas to fishing would produce a vast MPA where commercially important species could prosper, reproduce, and spill over into EEZs whose potential catches would increase.[81] Further advantages would include simplification of policing the rampant problem of pirate fishing and transfers at sea.[82]

Ecological Restoration

While commonly overshadowed by bad news, concerted actions to reduce pollution and protect keystone species have resulted in many recoveries of marine populations and ecosystems.[83] The installation of modern sewage systems and the reduction in nutrient runoff have varyingly improved water quality, reduced excess planktonic productivity and toxic algal blooms, and restored seagrass meadows, salt marshes, and fisheries in estuaries around the world.[84] These efforts demonstrate that even greater progress could be achieved in stabilizing coastal ecosystems if adequate measures are taken to eliminate or greatly reduce pollutant runoff, and most importantly agricultural nutrients.[85] Serious efforts to do so have not yet materialized, however, because farmers don't have to pay for what they pollute. There is also a problem of scale in semi-enclosed seas like the Baltic because nutrient buildups in sediments are already so great that simply reducing nutrient runoff may not suffice.

Banning the use of fish pots around Bermuda in 1990, where fish populations had collapsed due to overfishing, resulted in rapid rebounding of fish populations dominated by schools of large parrotfish.[86] Since then, abundances have remained high except for the large predatory fish that remain overfished. Coral populations also have steadily increased due to the control of algal populations by the abundant parrotfish. Caribbean coral reefs are generally extremely overfished, but the few places where both fishing and pollution are effectively

controlled uniquely support high coral abundance.

Conclusion

Despite important accomplishments, comprehensive policies are lacking to address the unsustainability of the modern economy that is driving ecosystem collapses and threatening human wellbeing.[87] Nature is a complex system, and much of that system as we knew it is irreversibly breaking down.[88] Environmental perturbations in one place almost inevitably have repercussions down the line, be it agricultural pollution in the US cornbelt causing the dead zone in the Gulf of Mexico or the effects of runoff and overfishing on outbreaks of disease affecting reef corals. Huge energy and investment in projects to restore populations of corals in Florida and on the Great Barrier Reef are making much progress in terms of the technical details of raising, breeding, and growing corals, but they are also absurdly expensive and small scale, not to mention that putting the corals back into the same nutrient polluted environments and expecting them to somehow survive is folly. More fundamentally, they are bandaids to address the symptoms of ocean decline rather than addressing the fundamental root causes of the ocean crisis: global warming, overfishing, and land-based pollution.[89]

The most encouraging development towards adapting to and managing these realities is that large scale efforts to decarbonize the global economy are beginning to gain traction despite political intransigence, not least because, in addition to its obvious advantages for human health and the environment, green energy is financially a better option than heavily subsidized fossil fuels.[90] California, the fifth largest global economy, is committed to be carbon neutral by 2045 and is well on track, and electric cars are becoming a more practical alternative to gasoline and diesel. The outstanding question is how rapidly opposition can be overcome to speed things up and take actions on the appropriate scales.

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