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# THE EMPTY OCEAN

## PLUNDERING THE WORLD'S MARINE LIFE

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# WHAT IS KILLING THE CORAL REEFS?

"Coral reefs are the most structurally complex and taxonomically diverse marine ecosystems, providing habitat for tens of thousands of associated fishes and invertebrates," wrote marine ecologist Jeremy Jackson and his colleagues in 2001. They continued: "Recently, coral reefs have experienced dramatic phase shifts in dominant species due to intensified human disturbance beginning centuries ago. The effects are most pronounced in the Caribbean, but are also apparent on the Great Barrier Reef in Australia, despite extensive protection over the past three decades.

Corals, the building blocks of reef formations, are a variety of small, sedentary marine organisms characterized by an external skeleton of a stone-like, horny, or leathery consistency. They are classified as cnidarians, along with the jellyfish, hydroids, sea fans, and sea anemones. There are true or stony corals (scleractinians, order Scleractinia), which are the most familiar forms, occurring in various shapes, as in brain coral, mushroom coral, star coral, staghorn coral, and elkhorn coral; black and thorny corals (antipatharians, order Antipatharia); horny corals, or gorgonians (order Gorgonacea); and blue corals (order Coenothecalia). The body of a coral animal consists of a polyp, a hollow, soft cylinder ending in a mouth surrounded by tentacles; at the opposite end, the polyp is attached to some surface. The tentacles are equipped with stinging cells (nematocysts) that paralyze the coral's prey. At night, the animal withdraws into its external skeleton, a cylindrical container known as a corallite or theca. Corals reproduce either sexually, by releasing eggs and sperm into the water, or asexually by budding, wherein a finger-like extension matures into a new polyp.

Coral reefs are formations composed of the skeletons of dead corals bound together by their own limestone. Over thousands of years, coral growth, death, and cementing build a structure on which the living corals continue to attach themselves, but contributors to the reefs also include

ELKHORN CORAL
*(Acropora palmata)*

plants such as coralline algae as well as protozoans, mollusks, and tube-building worms. Most reefs occur within a band thirty degrees north or south of the equator. The corals' success as reef builders depends on their association with tiny single-celled plants called zooxanthellae, which live in the polyps' tissues. Because they are plants, the zooxanthellae require sunlight for photosynthesis, the processing of the carbon dioxide produced by the polyp. If the zooxanthellae die, the coral polyps die, and the reef, once a host of living creatures, becomes nothing more than a stony, lifeless structure. There are deepwater corals, however, that lack zooxanthellae—they are known as azooxanthellate corals—and live below the level at which light penetrates the ocean, at depths as low as 5,000 feet. These animals cannot photosynthesize, and they capture their prey with tiny, sticky tentacles.

The living corals form only a thin veneer of the coral reefs, measured in millimeters, but, as Charles Birkeland of the University of Guam wrote in 1997, "this film of living tissue has shaped the face of the Earth by creating limestone structures sometimes over 1,300 m thick, from the surface down to its base on volcanic rock (Enewetak Atoll), or over 2,000 km long (Great Barrier Reef)." Bruce Hatcher (1997) continues: "Everything that is useful



about reefs (to humans and the rest of nature) is produced by this organic film, which is approximately equivalent (in terms of biomass and carbon) to a large jar of peanut butter (or Vegemite) spread out over each square meter of reef."

What is killing the world's corals? Anything and everything, but mostly us. "Coral reefs," wrote Callum Roberts and colleagues in 2002,

> fringe one-sixth of the world's coastlines and support hundreds of thousands of animal and plant species. Fifty-eight percent of the world's reefs are reported to be threatened by human activities. Terrestrial agriculture, deforestation, and development are introducing large quantities of sediment, nutrients, and other pollutants into coastal areas, causing widespread eutrophication and degradation of biologically productive habitats. Coral reefs are often fished extensively, and in regions of the Indian and Pacific Oceans, fishing with dynamite and poisons has devastated reef habitats.

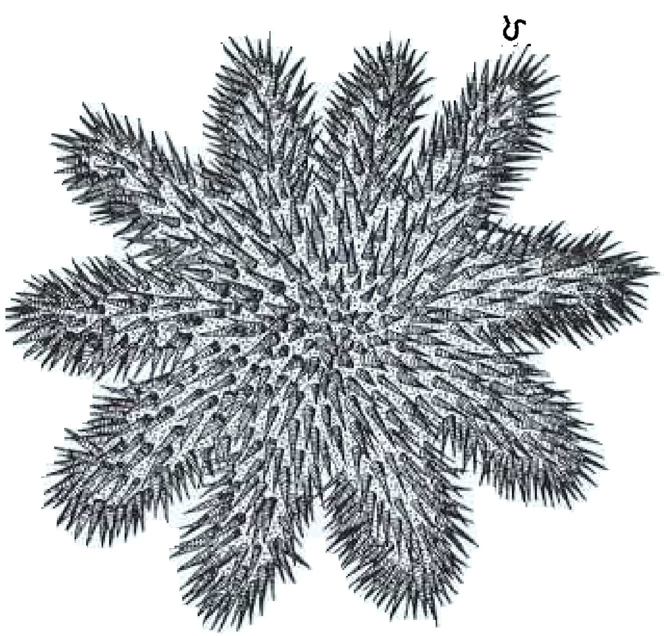
Fishing with dynamite has to be one of the most harmful techniques ever devised. Sticks of dynamite, dropped from small boats, detonate underwater in an explosion that ruptures the swim bladder of fishes, kills them, and causes them to float to the surface. They are then scooped up and hauled to shore to be cleaned and sold. If possible, the use of Alfred Nobel's invention to collect seashells is even worse.

Most people don't fully realize that the colorful and decorative shells they collect were once living animals; marine snails do not simply move into the shells, as hermit crabs do; they *manufacture* them. Moreover, most shells for sale in souvenir shops or on the Internet are collected not by beachcombers but by professional collectors. Because some of these snails (technically referred to as gastropods) live deep in rock and coral crevices, it is utterly uneconomical to dive and collect them one by one, so the collectors poison or blow up the reefs and harvest the shells of the dead snails.*

After the ubiquitous *Homo sapiens*, far and away the most dangerous and destructive creature the planet has ever known, the animal most threatening to coral is *Acanthaster planci*, the crown-of-thorns starfish. Taking its name

*I began my marine painting career by painting seashells. In 1973, I had a one-man show at a gallery on Sanibel Island, off the coast of Florida, generally considered the shell-collecting capital of the United States. But when I realized that in some small way, my glorification of shells was encouraging collecting—and therefore encouraging the dynamiters—I stopped painting shells. In 1975, *Audubon* magazine published "Why I Became an Ex-Shell Painter," in which I explained the reasons for my decision to quit.

from its long, sharp, toxic spines, the crown-of-thorns is a reddish brown, heavy-spined starfish; its seven to twenty-one arms can reach a length of eighteen inches. Females produce 12 million to 60 million eggs per spawning season. These starfish live on Pacific Ocean coral reefs from Australia to Hawaii and as far east as the Gulf of California. Their primary food item is coral polyps, but they can and will eat almost anything that crawls along the ocean bottom. Beginning about 1950, the *Acanthaster* population increased enormously on reefs off Japan, and in 1963, on Australia's Great Barrier Reef, there was a population explosion attributed to the decimation by shell collectors of the crown-of-thorns' chief predator, a large marine snail known as the Pacific triton (*Charonia tritonis*). (At a length of more than sixteen inches and with an intricate color pattern, the triton—also known as Triton's trumpet—is one of the largest and most prized of all marine snails.) Thereafter, the starfish multiplied throughout the southern Pacific, reaching Hawaii about 1970, seemingly threatening destruction of coral reefs and islands. Major outbreaks have also been recorded in Micronesia, Samoa, Fiji, the Society Islands, Malaysia, Thailand, and the Maldives (Brown 1997b). During invasions, when large numbers of this starfish appear on a coral reef,



CROWN-OF-THORNS STARFISH
*(Acanthaster planci)*



they consume most of the living polyps, leaving behind a severely altered coral community (the plants and animals that live in the reefs). During several months in 1968 and 1969, for example, along the northwestern coast of Guam, the crown-of-thorns consumed 90 percent of the living corals. Although other starfish eat corals, only the crown-of-thorns is able to reduce so dramatically the coral cover of an entire reef. Crown-of-thorns outbreaks have been increasing in recent years, throughout the starfish's range. These outbreaks occur most often near high islands and after exceptionally severe rainstorms, usually associated with tropical cyclones, have introduced large amounts of sediments into the water.

Concern among scientists and environmentalists prompted an attempt to control the crown-of-thorns' proliferation; many were killed by formaldehyde injection, and others were simply removed from the reefs and destroyed. In the late 1970s, however, new research data indicated that similar expansions, or blooms, had occurred previously, followed by periods of decline. Thus, it seemed likely that the sudden growth of the starfish population during the 1960s represented a phase in the organism's natural cycle. After crown-of-thorns outbreaks, their numbers appeared to decline, and only recently was anyone able to identify the possible cause of this decline. In 1999, Morgan Pratchett of James Cook University in Queensland examined a specimen that showed numerous dermal (skin) lesions, collapsed spines, and a completely debilitated water-vascular system. When he put pieces of the infected starfish into separate tanks with six healthy starfish, all of them died in eight to nine days. The pathogen remains unidentified.

The corals the starfish eats are often the dominant competitors for space on the reef; by removing them, the star may help to encourage and maintain coral diversity. Given that most *Acanthaster* outbreaks occur about three years after a period of abnormally high rainfall (as documented by Charles Birkeland in 1982), it can be said that coral reef diversity may be due to heavy rains—as mediated and modified by sea stars. These heavy rains cause significant runoff and nutrient enrichment in coral lagoons, and this in turn causes a plankton bloom, which feeds *Acanthaster* larvae swimming in the lagoons. It generally takes the stars about three years to grow large enough to come out and forage during the day, at which point they are noticed. "There are no early records of *Acanthaster* in undisturbed fossil deposits," wrote Jackson and colleagues (2001), "or in accounts of European explorers or fishers." This lack of evidence of *Acanthaster* outbreaks in the distant past suggests that they are a recent phenomenon, perhaps related to overfishing of prawns that feed on juvenile forms of the crown-of-thorns.

In the South Pacific Ocean and Southeast Asia, fishermen squirt cyanide into reef areas and then rip open the reefs with crowbars to get at the fishes that have taken refuge in the crevices. Because it only stuns the fish, cyanide poisoning was previously used to collect colorful tropical fishes for hobbyists, but the catch has escalated exponentially to meet the demand for live fish in restaurants in mainland China, Hong Kong, Taiwan, and other Asian countries. In researching his brilliant—and profoundly disturbing—*Song for the Blue Ocean* (1997), Carl Safina visited fisheries in Palau and the Philippines and then went to the Hong Kong fish market. He wrote:

> In Hong Kong you can see coral reef fishes—groupers, parrotfishes, surgeon-fishes and many others—in numerous locations throughout the city, looking like aquarium displays. Their proximity to restaurants hints otherwise. Looking at them, you would never guess that getting them here entails ecological disruption and human suffering on faraway reefs, nor would you likely guess the staggering sums of money involved. . . . An expanding fishery that poisons reefs with sodium cyanide is engulfing this richest one-third of the world's coral habitats, across an area spanning a quarter of Earth's circumference. Ironically, cyanide that is being used to stun fish so they can be delivered to markets alive leaves reefs dead in its wake.

Cyanide is one of the most toxic of all poisons, capable of killing coral polyps and their symbiotic algae, the zooxanthellae. In addition to being enormously destructive, cyanide fishing is enormously profitable. Charles Barber and Vaughan Pratt (1998), in an article published in the journal *Environment,* estimated that "the live reef fish trade in Southeast Asia has an estimated retail value of $1.2 billion (US dollars), $1 billion of which consists of exports of food fish (mostly to Hong Kong), and $200 million of which consists of exports of aquarium fish to Europe and North America." The fishing, a large proportion of which is done in the Philippines and Indonesia, is quite simple: Fishermen descend onto coral reefs with squirt bottles loaded with crushed cyanide pellets mixed with seawater. They squirt the solution into crevices in the reef and the fish are stunned by the mixture, at which point they are easily captured in plastic bags. Sometimes the fishermen shatter the coral heads with hammers or crowbars to make the fish easier to retrieve.

For the restaurants and the aquarium trade, the fish have to be alive, but it has been estimated that half of the poisoned fish die on the reef, and 40 percent of the survivors die in transit. The South Pacific harbors some 30 percent



of the world's coral reefs, and the cyanide kills organisms that make up the reefs. According to two regional surveys, only 4.3 percent of reefs in the Philippines are unaffected by poison, and only 6.7 percent of Indonesian reefs are unaffected. So far, there have been no studies on the cumulative effects of cyanide on those who eat the fish, but it stands to reason that regular ingestion of the cyanide-laced flesh of fishes would not be beneficial to the diner.

Although the fish in Japanese fish markets are offered dead or fresh-frozen, the tastes of Hong Kong businessmen run toward the flaky flesh of reef fishes, which they must see swimming alive in a tank before they order them for dinner. Because the fisheries are uncontrolled and unregulated, no one knows how many fish are being caught for Asian restaurants. Safina quotes one estimate of 4,600 tons and another of 15,000 tons coming into Hong Kong every year. And that says nothing of the fish caught for restaurants in Singapore, Taiwan, and mainland China—the flesh of some of which is toxic.

The dinoflagellate *Gambierdiscus toxicus* is believed to be the cause of a type of poisoning known as ciguatera, in which not the fish but the eater of the fish is stricken. The dinoflagellate attaches itself to dead or damaged coral, and its toxins are passed up the food chain from coral-grazing to carnivorous fish. When humans eat these top predators—snappers, jacks, groupers, or barracudas—they develop symptoms such as tingling in the lips, nausea, vomiting, diarrhea, weakness, and temporary blindness. The toxin is not diminished by cooking or freezing, and the affected fish, cooked or raw, is not tainted by bacteria in any way. Ciguatera poisonings, which kill some 7 percent of people affected, are connected to the destruction of coral reefs, whether natural or unnatural.

Hurricanes, cyclones, and tsunamis can, of course, inflict major physical damage on shallow-water corals, but these have been part of the natural cycle for eons, and the affected reefs have traditionally rebuilt themselves. Sewage runoff, which contains everything from human waste to phosphates and nitrates, encourages the overgrowth of microalgae, which asphyxiates coral and other marine life. Sediment washed into the sea from rivers clouds the waters and prevents sunlight, necessary for photosynthesis, from reaching the corals; pesticides such as DDT also wash into the sea from shoreside communities, poisoning the coral. Coral mining, once a big business on tropical islands, supplying coral for use in building blocks, runways, and the like, has not helped much either.

In addition to the painfully obvious degradation of shallow-water corals by fishermen who dynamite reefs or poison them with cyanide to collect fish or shellfish, corals around the world are being adversely affected by harmful bacteria and viruses. Some of these coral pathogens have been introduced by humans through sewage runoff, oil spills, and other environmental pollutants, but others appear to have arisen naturally, perhaps in response to weaknesses in the coral imposed by human activities. In an article about the worldwide degradation of coral reefs (but particularly the Great Barrier Reef), Eric Wolanski and his colleagues (2003) pointed out:

> Some human influences are acute—for example, mining reefs for limestone, dumping mine tailings on them, fishing with explosives and cyanide, and land reclamation. Pollutants, including pesticides, heavy metals and hydrocarbons, also degrade coral reefs. They can interfere with the chemically sensitive processes of reproduction and recruitment in corals and other reef organisms, such as synchronization of spawning, egg-sperm interactions, fertilization, embryological development, larval settlement, larval metamorphosis and acquisition of symbiotic zooxanthellae by young corals following recruitment.

In 1999, the Coral Reef Alliance, a California-based nonprofit organization dedicated to the preservation of coral reefs around the world, issued the following statement:

> Coral reefs are home to over 25 percent of all marine life and are among the world's most fragile and endangered ecosystems. In the last few decades, mankind has destroyed over 35 million acres of coral reefs. Reefs off of 93 countries have been damaged by human activity. If the present rate of destruction continues, 70% of the world's coral reefs will be killed within our lifetimes.

In a 2001 article discussing new methods of measuring the extent of coral damage, coastal systems analyst Peter Mumby and his colleagues wrote: "Almost three quarters of the world's coral reefs are thought to be deteriorating as a consequence of environmental stress. . . . It is predicted that coral reefs will suffer mounting stress associated with a global increase in atmospheric carbon dioxide over the coming decades, and from local disturbances such as overfishing and disease."

About 10 percent of the world's coral has already died, according to James Porter, an ocean studies specialist at the University of Georgia, and if present trends and conditions continue, another 20 to 30 percent of the world's coral will be lost by 2005. There has been a 446 percent increase in disease at 160 coral sites being monitored along the Florida coast since 1996 (Porter et al.



2001). Overall, 37 percent of all corals in Florida have died since 1996 (Porter and Porter 2002), but some species, such as the magnificently branched elkhorn coral, have suffered even higher rates of loss. On average, 85 percent of all elkhorn corals in the Florida Keys have died since 1996, and on some reefs off Key West, the mortality is more than 98 percent (Patterson et al. 2002). Elkhorn corals are the giant sequoias of the reef, and their loss would be equivalent to the loss of all the redwood forests in California. In a letter to me on January 8, 2003, Porter wrote, "These loss rates are caused by a new disease which we call white pox. The culprit is a bacterium, *Serratia marcescens*, which is commonly found in human fecal wastes. Evidence is mounting that the origin of this disease is untreated sewage. . . . It is unlikely that we are seeing a natural cycle. It seems more and more likely that we have unleashed these plagues upon the planet ourselves."

The health of the world's shallow-water corals is now in grave danger from an imposing roster of frightening diseases. So far, the coral diseases that have been identified are aspergillosis, black-band disease, dark spots disease, red-band disease, tumors and skeletal anomalies, white-band disease, white plague, white pox, yellow-blotch or yellow-band disease, rapid wasting, and bleaching. Of these, the most common are black-band disease (BBD), white-band disease (WBD), plague, and bleaching.

BBD was first reported in reefs off Belize and Bermuda in the mid-1970s, but it has since been found throughout Caribbean and Indo-Pacific waters. A sulfate-reducing cyanobacterium, *Phormidium corallyticum*, invades the coral tissue and deprives the zooxanthellae of oxygen; the bacteria then nourish themselves on the organic compounds released as the coral cells die. The result, BBD, appears as a thin black band that spreads at a rate of a few millimeters a day, killing the coral and leaving behind bare coral skeletons, which are eventually colonized by filamentous algae (Peters 1997).

In a 1997 study of the corals of St. Ann's Bay, Jamaica, Andrew Bruckner, Robin Bruckner, and Ernest Williams found that BBD had destroyed 5.2 percent of the large reef-building coral in the area and was spreading from infected to uninfected colonies in the direction of prevailing currents, an occurrence not previously documented. In a deadly circularity, as the corals died, algae moved in to colonize the skeletons, and the corals most susceptible to the disease were those overgrown by algae.

It now appears that BBD is caused not by a single organism but by several acting in concert. Examining corals in the laboratory as well as in the wild, Laurie Richardson and her colleagues (1997) concluded that the consortium of black band microbes consists of the aforementioned *P. corallyticum*, the sulfide-oxidating *Beggiatoa*, the bacterium *Desulfovibrio*, and several other microorganisms that together create a toxic, sulfide-rich environment that prevents the zooxanthellae from photosynthesizing. In his investigation of BBD in the reefs of St. Annabaai, Curaçao, Bruce Fouke of the University of Illinois at Urbana-Champaign made the surprising discovery that several of the bacteria types in the consortium were known only from human beings (Harder 2001). How people-infecting bacteria might jump to corals remains a mystery, but it has been suggested that human waste material flushed into the ocean might be the vector.

In the early 1980s, Caribbean elkhorn and staghorn corals (genus *Acropora*), which come in many colors, began to show areas of white, and by 1989, 95 percent of the elkhorn corals on St. Croix had died. These spectacular corals, the predominant corals in much of the Caribbean, are susceptible to WBD throughout their range. William Gladfelter, who described this phenomenon in 1982, wrote: "The overall decrease in live coral tissue during this time [1977–1979] was 16% while the increase in dead standing colony surface was 11%. . . . The impact of such an agent of mortality on this coral community as well as on reef growth is thus potentially catastrophic." Although Gladfelter himself could find no "consistent possible causative organism," he suggested, following Esther Peters, that bacteria could be the culprit. By 1998 the causative pathogen (or suite of pathogens) for WBD had been identified, though writing in the 1997 *Life and Death of Coral Reefs*, Peters acknowledged that "much remains to be learned about the nature of tissue sloughing in corals and how many conditions caused by different pathogens or environmental stresses may actually be represented by the same disease signs."

Another of the coral diseases is known generically as plague. In the 1980s a "white plague" epizootic hit the corals of the Florida Keys and infected seventeen of the area's forty-three scleractinian coral species (Richardson 1998). The symptoms of this disease resemble those of WBD, but it spreads much faster—as fast as three millimeters per day, in contrast with two millimeters for WBD—and can kill an entire colony in days, whereas WBD usually takes months. A fungus of the genus *Aspergillus* is probably the agent for the epizootics that have killed sea fans (gorgonians) over the past decades. As with many other coral diseases, aspergillosis opportunistically strikes animals that have been weakened by stresses imposed by pollution, other pathogens, or environmental factors such as fluctuating water temperatures, increased salinity, and the like.

In 1998, in a study of Florida corals decimated in 1995 by a new "band" disease, Laurie Richardson and eight colleagues isolated the responsible pathogen and identified it as a potential new species of *Sphingomonas*, a widespread bacterium that can survive and grow at low temperatures, under low nutrient concentrations, and even in toxic chemical environments. *Sphingomonas* species have been recovered from seawater, sea ice, river water, polluted groundwater, mineral water, and even the "sterile" water used in hospitals and as drinking water. In humans, it is associated with infectious septicemia, wound infections, and peritonitis. In the 1995 outbreak, which occurred at the Florida Reef Tract (a coral reef ecosystem extending from Key West to the Dry Tortugas), the disease infected seventeen species of scleractinian corals, in some cases killing as much as 38 percent of the colonies. Its primary victim was the elliptical star coral, *Dichocoenia stokesi*—a species previously unknown to be susceptible to any coral disease. This virulent disease, identified as "plague type II" by Richardson and three colleagues in 1998, began at the base of the coral and moved upward, an unusual pattern of tissue loss. Corals infected with plague type II exhibited a sharp line that marked the boundary between healthy and diseased tissue, and tissue was destroyed much more rapidly than in other line or band diseases. Four months after it was first spotted, the disease had killed corals to the north and south of the initial site, and by 1997 it had spread to most of the reefs in the Florida Reef Tract.

In a 2002 study, researchers identified a pathogen they suggested might be responsible for decimation of the elkhorn coral (*Acropora palmata*) in the Florida Keys. Kathryn Patterson and her colleagues identified a human fecal bacterium, *Serratia marcescens*, as a likely cause of the death of as much as 85 percent of the elkhorn corals of the Florida reefs. White pox, which specifically targets the giant elkhorn coral, is one of the fastest spreading of all coral diseases, capable of devouring ten square centimeters of living coral per day. (It differs from WBD in that it kills the whole coral rather than attacking in bands.) One of the most common bacteria known, *S. marcescens* is found in the gut of humans and other animals as well as in soil and water. It was shown to be present in corals infected with white pox but not in healthy corals, and it is believed to enter the water via sewage runoff. "This is the first time," wrote the authors, "that a bacterial species associated with the human gut has been shown to be a marine invertebrate pathogen."

When patches of dead or dying coral spread at a rate of several inches per day, the corals are said to be victims of rapid wasting disease. It was first identified on Bonaire, an island off the coast of Venezuela, in January 1997, and it has since been spotted in Mexico, Aruba, Curaçao, Trinidad, Tobago, Grenada, and the U.S. Virgin Islands, an area spanning 2,000 miles. James

Porter summed up the issue thus for the *New York Times:* "We're all stunned at the rapidity with which these new diseases are occurring. The problems are occurring at all depths, and the number of species affected is increasing as well as the number of individuals" (Yoon 1997). As with WBD, the pathogen responsible for rapid wasting disease is unknown.

Coral bleaching, another major marine threat to coral, differs from WBD in that no pathogen infects the living coral; instead, stress—induced by high ocean temperatures, low ocean temperatures, elevated ultraviolet light, sedimentation, changes in salinity, or toxic chemicals—causes the zooxanthellae to be expelled from the coral, leaving it a ghostly white as the calcium carbonate skeletons of the coral colony are exposed. Coral bleaching has been known since the mid-1980s. Describing what the reefs of the Virgin Islands were like in 1987, Barbara Brown and John Ogden, director of the Florida Institute of Oceanography, wrote in 1993: "The normally golden-brown, green, pink and gray corals, sea whips and sponges had become pure white. In some cases, entire reefs were so dazzlingly white that they could be seen from a considerable distance." Although most corals survive infrequent bleaching episodes, repeated or sustained events will eventually kill them. Warm water temperatures related to the El Niño of 1983, for example, resulted in widespread bleaching, mortality, and even extinction of corals in the eastern Pacific and bleaching at many sites in the western Atlantic and the Caribbean. The warm waters that spawned or strengthened hurricanes in the western Atlantic that year were associated with this outbreak of coral bleaching. Some reefs in Belize and many neighboring countries in the western Caribbean and the Gulf of Mexico region were mysteriously spared, however.* In 1997–1998, high ocean temperatures around the world initiated another major episode of coral bleaching, and at least in the Mediterranean Sea, researchers have tentatively identified the causative pathogen as *Vibrio shiloi.*

Corals tolerate a narrow temperature range between 25°C and 29°C (77°F to 84.2°F), depending on location. They bleach in response to prolonged temperature change but not in response to rapidly fluctuating temperatures. Laboratory experiments show that corals bleach when water reaches a constant 32°C (89.6°F), but the exact mechanism by which they bleach or the trigger that induces bleaching is unknown. Experiments have shown that the zooxanthellae are released into the gut of the polyp and then expelled through the mouth, but this has not been observed in nature. Algae may produce oxide toxicity under stress (e.g., stress caused by pathogens or temperature increases), and these toxins may induce the polyps to expel their symbiotic zooxanthellae (Brown and Ogden 1993). Another hypothesis is that stressed corals give algae fewer nutrients and thus the algae leave the polyp, which results in bleaching.

Ariel Kushmaro and colleagues (1997) conducted experiments with the coral *Oculina patagonica* by introducing the bacterium *Vibrio* AK-1 under controlled conditions to determine whether it could cause bleaching in healthy corals. When they increased the temperature to 25°C, the healthy corals exhibited observable bleaching after twenty days; at 26°C, all the corals showed bleaching after ten days, and colony death was observed shortly after fifty-two days. In 2001, William Wilson and his colleagues isolated a virus from the temperate sea anemone *Anemonia viridis;* the viral infection had been induced by elevated temperature. "We propose," they wrote, "that zooxanthellae harbor a latent viral infection that is induced by exposure to elevated temperatures. If such a mechanism also operates in the zooxanthellae harbored by reef corals, and these viruses kill the symbionts, then this could contribute to temperature-induced bleaching."

In 1997, coral reef expert John Ogden suggested that coral bleaching was afflicting nearly every reef system in the world, along the coasts of more than twenty countries, including Australia, China, Japan, Panama, Thailand, Malaysia, the Philippines, India, Indonesia, Kenya, the Red Sea states, Puerto Rico, Jamaica, and the Bahamas. Corals are inevitably among the first organisms to show the consequences of a sustained increase in sea surface temperature because of the fragile temperature dependence of the tiny zooxanthellae, which live in the coral's cells and without which the coral dies. Global warming raises sea temperatures and, as melting occurs at the poles, raises sea levels as well. "Under scenarios of global warming," James Porter wrote, "the vertical carbonate accretion rates [i.e., vertical growth] of protected coral-reef flats may be insufficient to keep up. These zones will become inundated and subjected to erosion by progressively larger waves. Seagrass and mangrove communities will be eroded and will become less effective as buffers, releasing nutrients, turbidity, and sediments, further slowing coral-reef growth rate."

*In 2001, Andrew Baker of the New York Aquarium's Osborn Laboratories of Marine Sciences published the results of a study in which he found that bleaching may be a "high-risk ecological opportunity strategy for reef corals to rid themselves rapidly of suboptimal algae and to acquire new partners." Deepwater corals transplanted to shallow sites off Panama bleached but survived by recovering new algae. "Bleaching," wrote Baker, "may ultimately help reef corals to survive the recurrent and increasingly severe warming events projected by current climate models of the next half-century. Bleaching is an ecological gamble in that it sacrifices short-term benefits for long-term advantage."

In October 2000, at a symposium in Bali, the Global Coral Reef Monitoring Network issued a report stating that two years after it announced that 11 percent of the world's coral reefs had been destroyed, a subsequent assessment had raised the estimated total to 27 percent. The network further identified another 14 percent of coral reefs as in danger of being so bleached as to be lost in the next ten years—and another 18 percent not expected to last another thirty years. In addition to the usual suspects—overfishing by explosion and poisoning and polluted runoff—we can now add the *bête noire* (or, in the case of corals, *bête blanche*) of all things environmental: global warming. Greenhouse gases have raised temperatures, particularly in the Indian Ocean, to the point that there has been a 59 percent loss of living shallow-water corals (Pockley 2000). In a discussion of the Bali symposium, Dennis Normile suggested that the corals' sensitivity to rising temperatures makes them the "silent sentinels" of global warming. At Heron Island in the Great Barrier Reef in March 2002, scientists met in an attempt to develop a research strategy to combat coral bleaching. A report in *Nature* (Dennis 2002) indicates that a major occurrence of mass coral bleaching in 1998, attributed to mild increases in ocean temperatures, destroyed one-sixth of the world's coral colonies. The 2002 rise in water temperature and resulting coral death in northeastern Australia is not related to any El Niño event, suggesting that the events are growing in frequency. "If coral adaptation cannot keep pace with increasing sea temperatures," wrote Dennis, "the survival of the world's reefs is in jeopardy."

Corals, some might say, are pretty things for snorkelers to look at when they dive at tropical reefs, and if they are threatened, well, that's too bad for the corals—and maybe even the colorful fishes that live in and around the reefs—but what does coral disease have to do with us? Everything. Whatever affects coral reefs affects the gigantic worldwide diving industry, which depends on clear waters, colorful fish species, and spectacular coral formations to attract enthusiasts. But even without this anthropocentric view, the degradation of coral reefs affects the creatures that live in them, including fishes, cephalopods, gastropods, and myriad others, because without healthy reefs, these animals cannot survive. There are increasing reports of dying coral, diseased shellfish, and waters infected with human viruses as the sea temperature rises and pollution from the land intensifies. Dying coral can even cause islands to sink. "Without coral to keep them afloat," wrote Julia Whitty in a 2001 article in *Harper's*, "atoll islands eventually disappear altogether, a fate dangerously near for the people of the Maldives—an archipelago of 1,200 atolls in the Indian Ocean so badly hit by the 1997–98 coral bleaching that virtually all coral life here has died."



As if coral diseases were not enough, a massive insult was added to the injury when the corals' housecleaners also began to die. Sometime around 1983, a still-unidentified pathogen arrived in the western North Atlantic Ocean and began killing off the superabundant sea urchin known as *Diadema antillarum*. The herbivorous, nocturnal *Diadema*, a black, long-spined urchin, kept the reefs clean of "turf algae" and permitted the corals of the Caribbean, the Gulf of Mexico, the Bahamas, and Bermuda to proliferate. In an area of more than 2 million square miles, more than 93 percent of the urchins died, an event described as "the most extensive and severe mass mortality ever reported for a marine organism" (Knowlton 2001). With the urchins gone, the algae enveloped vast tracts of the underwater landscape, smothering the corals. Parrotfish, triggerfish, and surgeonfish also graze on algae, and these ordinarily would have helped keep the algae population down, but many of them had been overfished, and without *Diadema*, they alone could not compensate for the lack of algae consumption. Bleached coral was prime real estate for the pernicious algae, and without the urchins to perform their scouring functions, more and more of the reefs were swathed in the thick blanket of greenery.

In some places—Barbados, for example—*Diadema* made a comeback (Hunte and Younglao 1988); in others, researchers tried to reintroduce the urchins, but with little success. Then, in Jamaica, Peter Edmunds and Robert Carpenter (2001) noticed that *Diadema* was experiencing a revival, unassisted by humans. At Discovery Bay, on the northern shore of the island, arguably the most extensively studied reef in the Caribbean region, microalgae had blanketed the reef, leaving less than 5 percent of the coral exposed. By the 1990s, after the disappearance of *Diadema* and two major hurricanes, the corals of Discovery Bay were believed to be hopelessly lost. In 1992, however, small colonies of *Diadema* began to appear, and by 1995–1996, the urchins had become locally abundant in shallow water. By January 2000, wrote Edmunds and Carpenter, "the expansion and coalescence of microalgae-free areas formed contiguous zones hundreds of meters in length, suggestive of a reversal in community structure."

With coral reefs in decline all over the world, even a small reversal is cause for celebration. In her 2001 article about the Edmunds and Carpenter study, coral reef specialist Nancy Knowlton wrote, "The report . . . is the best news to emerge from the Caribbean in decades, and any good news is welcome indeed." As far as we can tell, the disappearance of *Diadema* from Caribbean and western Atlantic reefs was not initiated by humans, and there was nothing anyone could do to reverse it. Because there is no evidence that the unidentified pathogen responsible for the death of millions of black urchins was introduced by people, the lesson we might learn from the recovery of *Diadema* is that nature can (sometimes) repair "natural" disasters, perhaps because they do not involve the introduction of alien or toxic organisms. Where the cause is human intrusion, however, repair or recovery is often difficult or even impossible.

As the oceans get warmer, they also get murkier, and that's bad for coral reefs. Sunlight is essential for the growth of coral: the zooxanthellae must be able to photosynthesize in order to produce the carbohydrates the corals use to build calcium carbonate. If the sunlight is blocked, the entire process is affected. Researchers led by Charles Yentsch of the Bigelow Laboratory for Ocean Sciences in Maine have found that some reefs in the Florida Keys are getting barely enough sunlight to sustain themselves, to say nothing of further growth. Diminished sunlight, however, is not the only cause of coral depletion. "Competing hypotheses for the cause of coral loss include removal of grazers, nutrient enrichment, disease, coral bleaching, increase in temperature, and excess light/ultraviolet exposure," noted Yentsch and colleagues in their 2002 study.

And now comes the news that human waste, flushed into waterways, is having a worse effect on corals than anyone imagined. In a 2002 article in *Marine Pollution Bulletin*, Erin Lipp and her colleagues at the University of South Florida found that corals off Florida's coast are being tainted with human feces containing bacteria and viruses, as well as prescription drugs, that can wreak havoc with the coral ecosystem. They wrote: "Corals and reef environments are under increased stress from anthropogenic activities, particularly those in the vicinity of heavily populated areas such as the Florida Keys. The potential adverse impacts of wastewater can affect both the environment and human health." In a *New Scientist* article, Mark Schrope (2001) pointed out, "Over 24,000 septic tanks and 10,000 illegal cesspools drain into the Florida Keys alone." The accompanying bacteria and chemicals are killing not only the corals but also the zooplankton that forms the base of the marine food chain.

In her 1997 discussion of the role of coral reefs in the earth's history—and the savage destruction of them that is occurring today—Pamela Hallock, a marine scientist at the University of South Florida, wrote:

> It can be argued that humans are simply part of nature; that exploding human populations are naturally generating another episode of mass extinction from which the Earth will recover in 20 or 30 million years. But from a human perspective there is a difference between a mass extinction event caused by meteor impact and the ongoing one caused by human activities. Human intelligence has reduced biological limitations on both the growth rate of human populations and the environmental damage that any individual human can cause. Is it too much to hope that human intelligence can be utilized to bring an end to the current human-generated mass extinction event before the most specialized communities, like reefs and rain forests, are lost to future human generations? After all, many so-called "primitive" human cultures, including Micronesian and Polynesian inhabitants of atolls and coral pinnacles, thrived in resource-limited habitats. Can "modern" humans develop a sustainable global society based on recognition of globally limited resources? Or do humans represent the latest in the series of "disaster" species that proliferate globally at mass extinction events?



When Joan Kleypas and her colleagues (1999) analyzed the effects of increased atmospheric carbon dioxide on coral reefs, they wrote that "a coral reef represents the net accumulation of calcium carbonate ($CaCO_3$) produced by coral and other calcifying organisms. If calcification declines, then reef-building also declines." Coral reefs are particularly threatened because reef-building organisms secrete substances that are unstable in the absence of certain conditions, and the effects on other calcifying marine ecosystems may be severe. In 2001, Kleypas, Robert Buddemeier, and Jean-Pierre Gattuso suggested that even if the reefs die off, the coral community could survive, perhaps enduring a sort of "life in exile" until conditions are propitious again for reef building. Corals can survive without reefs; in Hawaii and Florida, for example, corals grow on lava flows or carbonate rock rather than the skeletons of their immediate predecessors. "No matter how hard we try to care for corals, though, our children or our children's children may be the last generation to see the awesome spectacle of flourishing tropical coral reefs," Scott Norris wrote in "Thanks for All the Fish" (2001). "But if the creatures that once inhabited the reefs survive an ecological diaspora to reunite far in the future, the tragedy of the coming century may not matter much 50,000 years hence. In a strange way, that's comforting."

The news of the incipient demise of the world's coral reefs only gets worse. A report published by the National Oceanic and Atmospheric Administration titled *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States* (Turgeon et al. 2002) included a breakdown of the problems facing those regions adjacent to the United States as well as reefs surrounding former U.S. territories in Micronesia, the Marshall Islands, and Palau. The report revealed even more damage than was suspected and confirmed many of the biologists' worst fears about the effects of global warming, disease, overfishing, storms, and pollution. Of the report, John Ogden (quoted in Elizabeth Pennisi's 2002 article in *Science*) said, "It is the most sweeping statement of concern by a [U.S.] federal agency about the trajectory of coral reefs to date." In his view, the first order of business has to be preservation of the reefs, even before any more research studies are commissioned.

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# DEEPWATER CORALS

The deep oceans make up the least known—and the largest—habitat on the earth, so it should come as no great surprise that deepwater corals have been poorly studied. Living at depths of more than 1,000 feet off Alaska, the Atlantic coast of Canada, Ireland, Norway, Sweden, Australia, and New Zealand, and even in the Antarctic, these corals of darkness have no symbiotic zooxanthellae because no light is available for photosynthesis at those depths. Their carnivorous polyps take in the "rain" or "snow" of minute marine detritus that is constantly falling through the sea, capturing from it the minute zooplankton they feed on. Whereas the polyps of shallow-water corals emerge at night to feed, the deepwater corals know only darkness and feed both night and day. There are deepwater soft corals (gorgonians), but the predominant types are the hard (scleractinian) corals, with polyps that look like tiny anemones sitting in limestone cups. In the deep Atlantic Ocean, the bottom is (or was) covered in many places with thickets of yellow *Madrepora* and *Lophelia*—what Greenpeace has called the rain forests of the sea. Around the world, these various azooxanthellate corals—those without zooxanthellae—are in danger.

Deepwater corals have actually been known, at least in a fragmentary way, for centuries: in 1755, Bishop Erik Pontoppidan of Norway referred to *Lophelia* collected by fishermen and used for medicinal purposes, and Carolus Linnaeus listed the same species in the tenth edition of his *Systema Naturae* in 1758. Until very recently, deepwater corals were known only from broken bits and pieces dredged up in fishing nets and bottom trawls. Like their shallow-water counterparts, they often form "trees," but fishermen who found these fragments, unaware of what they were, usually regarded them as fossils of some sort and threw them overboard. Indeed, trawler crews regard *Lophelia* as a nuisance because it snags and damages their nets. With the introduction of research submersibles and robotic cameras, however, the world of cold-water corals has been revealed in depth, and it is not a pretty one.