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The Nemesis Effect

by Chris Bright

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Burdened by a growing number of *overlapping* stresses, the world's ecosystems may grow increasingly susceptible to rapid, unexpected decline.

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In 1972, a dam called the Iron Gates was completed on a stretch of the Danube River between Romania and what is now Serbia. It was built to generate electricity and to prevent the river from visiting some 26,000 square kilometers of its floodplain. It has done those things, but that's not all it has done.

The Danube is the greatest of the five major rivers that run into the Black Sea. For millennia, these rivers have washed tons of dead vegetation into this nearly landlocked ocean. As it sinks into the sea's stagnant depths, the debris is decomposed by bacteria that consume all the dissolved "free" oxygen (O_2), then continue their work by pulling oxygen out of the sulfate ions (SO_4) that are a normal component of seawater. That process releases hydrogen sulfide gas (H_2S), which is one of the world's most poisonous naturally occurring substances. One deep breath of it would probably kill you. The sea's depths contain the largest reservoir of hydrogen sulfide in the world, and the dissolved gas forces virtually every living thing in the water to cling to the surface or die. The Black Sea is alive only along its coasts, and in an oxygenated surface layer that is just 200 meters thick at most—less than a tenth of the sea's maximum depth.

The Danube contributes 70 percent of the Black Sea's fresh water and about 80 percent of its suspended silicate—essentially, tiny pieces of sand. The silicate is consumed by a group of single-celled algae called diatoms, which use it to encase themselves in glassy coats. The diatoms fuel the sea's food web, but any diatoms that don't get eaten eventually die and sink into the dead zone below, along with any unused silicate. Fresh contributions of silicate are therefore necessary for maintaining the diatom population. But when the Iron Gates closed, most of the Danube's silicate began to settle out in the still waters of the vast lake behind the dam. Black Sea silicate concentrations fell by 60 percent.

The drop in silicate concentrations coincided with an increase in nitrogen and phosphorus pollution from fertilizer runoff and from the sewage of the 160 million people who live in the Black Sea drainage. Nitrogen and phosphorus are plant nutrients—which is why they're in fertilizer. In water, this nutrient pollution promotes explosive algal blooms. The Black Sea diatoms began blooming, but the lack of silicate limited their numbers and prevented them from consuming all the nutrient. That check created an opportunity for other types of algae, formerly suppressed by the diatoms. Some of these were dinoflagellate "red tide" organisms, which produce powerful toxins. Soon after the Iron Gates closed, red tides began to appear along the sea's coasts.

In the early 1980s, a jellyfish native to the Atlantic coast of the Americas was accidentally released into the sea from the ballast tank of a ship. The jellyfish population exploded; it ate virtually all the zooplankton, the tiny animals that feed on the algae. Liberated from their predators, the algae grew even thicker, especially the dinoflagellates. In the late 1980s, during the height of the jellyfish infestation, the dinoflagellates seemed to be summoning the death from below. Their blooms consumed all the oxygen in the shallows and the rotten-egg stench of hydrogen sulfide haunted the streets of Odessa. Carpets of dead fish—asphyxiated or poisoned—bobbed along the shores.

The jellyfish nearly ate the zooplankton into oblivion, then its population collapsed too. But it's still in the Black Sea and there's probably no way to remove it. The red tides have increased six-fold since the early 1970s, and it doesn't look as if antipollution efforts are going to put the dinoflagellates back under the control of the diatoms. The fisheries are in a dismal state—overharvested, starved of zooplankton, periodically suffocated and poisoned. The rest of the ecosystem isn't faring much better. The mollusks, sponges, sea urchins, even the marine worms are disappearing. The shallows, where vast beds of seagrass once breathed life into the waters, are regularly fouled in a fetid algal soup laced with a microbe that thrives in such conditions: cholera.

COULD IT HAVE BEEN PREDICTED THAT THE DAM ON the Danube would end up triggering this spasm of ecological chaos? The engineers who designed the Iron Gates were obviously attempting to make nature more orderly and productive (in a very narrow sense of those terms). Could they have foreseen this form of disorder, which has no obvious relationship to the dam itself? Here is what they would have had to anticipate: that the dam would cause a downstream change in water chemistry which would combine with an increase in a certain type of pollution to produce an effect that neither change would probably have had on its own—and that effect would then be magnified by something that was going to be pumped out of a ship's ballast tank.

It seems absurd even to entertain the idea that such things could be foreseen. Yet this is precisely the kind of foresight that is now required of anyone who is concerned, professionally or otherwise, with the increasingly dysfunctional relationship between our societies and the environment. The forces of ecological corrosion—pollution, overfishing, the invasion of exotic species like that jellyfish—such forces interact in all sorts of ways. Their effects are determined, not just by the activities that initially produced them, *but by each other and by the way ecosystems respond to them.* They are, in other words, parts of an enormously complex system. And unless we can learn to see them *within the system,* we have no hope of anticipating the damage they may do.

A system is a set of interrelated elements in which some sort of change is occurring, and even very simple systems can behave in unpredictable ways. Three elements are enough to do it, as Isaac Newton demonstrated three centuries ago, when he formulated the "N body problem." Is it possible to define the gravitational interaction between three or more moving objects with complete precision? No one has been able to do it thus far. The unpredictable dynamics of system behavior have inspired an entire mathematical science, variously known as complexity or systems theory. (The most famous type of complexity is "chaos.") Systems theory is useful for exploring several other sciences, including ecology. It's also useful for exploring the ways in which we can be surprised.

Suppose, for example, that you were a marine biologist studying Black Sea plankton in the early 1970s. Had you confined your observations solely to the plankton themselves, you would have had no basis for predicting the explosion of red tides that followed the closing of the Iron Gates. Such "nonlinear" events usually come as a surprise, not because they're unusual—they're actually common—but because of a basic mismatch between our ordinary perceptions and system behavior. Most people, most of the time, just aren't looking upriver: we have a strong intuitive tendency to assume that incremental change can be used to predict further incremental change—that the gradual rise or fall of a line on a graph means more of the same. But that's not true. The future of a trend—any trend—depends on the behavior of the system as a whole.

In 1984, the sociologist Charles Perrow published a book, *Normal Accidents: Living with High-Risk Technologies*, in which he explored the highly complex industrial and social systems upon which we've become increasingly dependent. David Ehrenfeld, an ecologist at Rutgers University in New Jersey, has observed that much of what Perrow said of nuclear reactors, air traffic, and so forth could also

WOODCUTS BY ROSEMARY COVEY

apply to ecosystems—or more precisely, to the ways in which we interact with them. Here are some of the criteria that Perrow uses to define complex systems:

- many common mode connections between components . . . not in a production sequence [that is, elements may interact in ways that won't fit into a predictable sequence];
- unfamiliar or unintended feedback loops;
- many control parameters with potential interactions [that is, we have many ways to influence the system but we can't be sure what the overall result of our actions will be];
- indirect or inferential information sources [we can't always see what's happening directly];
- limited understanding of some processes.

There's something ominous in Perrow's rather bland, clinical terminology—it's like a needle pointing the wrong way on an instrument panel. "Limited understanding of some processes!" No ecologist could have put it better. Ehrenfeld wrote a paper on Perrow's relevance to ecology; he was fascinated with Perrow's treatment of nuclear accidents. What is it like to be a nuclear plant operator during a Three Mile Island event? You watch the monitors, you try to second-guess your equipment, you make inferences about the state of the core. Perrow says, "You are actually creating a world that is congruent with your interpretation, even though it may be the wrong world. It may be too late before you find that out."

Into the Theaters of Surprise

"NUCLEAR. MORE THAN YOU EVER IMAGINED." That's the slogan of the Nuclear Energy Institute, a nuclear power industry association based in Washington, D.C. To me, at least, the phrase isn't very reassuring, and I would bet that it will sound like a joke to most of the people who read this article. My guess, in other words, is that your imagination already operates well beyond the stage settings of nuclear industry PR. But how much farther are you willing to push it?

Throughout most of our species' existence, the bounds of our collective imagination have not been a survival issue in the way that they are today. Either our societies were rather loosely coupled to their environment, so there was more "give" in the system, or when we got into trouble, it was a local or regional predicament rather than a global one. But today, our rapport with the environment is growing increasingly analogous to the task of managing a nuclear power plant. We live within a set of systems that are "tightly coupled," requiring constant attention, not entirely predictable, and capable of various types of meltdown.

Consider, for example, two representative theaters of surprise. See if you find here more than you ever imagined.

1. The Forests of Eastern North America

As far as conservation is concerned, the woodlands of eastern North America might seem about as far as you can get from the highly publicized tropical scenario, with its poorly understood and rapidly disappearing forests, its desperate agrarian poverty and rapacious logging. For this scorched confusion, substitute some of the most thoroughly studied ecosystems in the world, growing over the heads of some of the world's wealthiest, best-educated, and most information-saturated people. These are highly populated woodlands too—138 million people live beneath the trees or within a few hours' drive of them.

Virtually all of the original "old growth" in the eastern United States was cut long ago, but these forests comprise one of the few large regions anywhere in the world that could be thought of as undergoing some sort of ecological renaissance. With the exception of northern New England, the loggers had done their worst to the region a century ago or more, and moved west in search of bigger timber. And over the course of the 19th century, fewer and fewer fields were being tortured by the plow, as the nation's agriculture shifted to the lavish fertility of the midwest. So the eastern second growth has quietly spread and matured, absorbing hundreds of old cutover woodlots and anonymous, abandoned farmsteads. But today these forests are in the throes of a quiet agony—a pathology that is harder to read than tropical deforestation, but which may lead to a form of degradation that is just as profound. The air they are breathing is poisoning them, the water bathes them in acid, the soil is growing toxic, they are gnawed by exotic pests, and the climate to which they are adapted is likely to shift.

A primary cause of this agony involves changes in the "nitrogen cycle." Nitrogen is an essential nutrient of plants and it's the main constituent of the atmosphere: 78 percent of the air is nitrogen gas. But plants can't metabolize this pure, elemental nitrogen directly. The nitrogen must be "fixed" into compounds with hydrogen or oxygen before it can become part of the biological cycle. In nature this process is accomplished by certain types of microbes and by lightning strikes, which fuse atmospheric oxygen and nitrogen into nitrogen oxides.

Humans have radically amplified this process. Farmers boost the nitrogen level of their land through fertilizers and the planting of nitrogen-fixing crops (actually, it's symbiotic microbes that do the fixing). The burning of forests and the draining of wetlands release additional quantities of fixed nitrogen that had been stored in vegetation and organic debris. And fossil-fuel combustion releases still more fixed nitrogen, partly from fuel contaminants, and partly through the production of nitrogen oxides in the same way that lightning works. Natural processes probably incorporate around 140 million tons of nitrogen into the terrestrial nitrogen cycle every year. (The ocean cycle is largely a mystery.) Thus far, human activity has at least doubled that amount.

As in much of the industrialized world, eastern North America is bathed in the nitrogen oxides pumped into the air from car exhaust and coal-burning power plants. In the presence of sunlight, one of these chemicals, nitric oxide (NO), produces ozone (O_3). Ozone is good in the stratosphere, where it filters out harmful ultraviolet (UV) radiation, but it's very bad in the troposphere, the thick blanket of air at the Earth's surface. Ozone is a primary component of smog. Clean air laws, understandably, aim to cut ozone levels to a point at which they are unlikely to harm people (or at least, healthy people). But the problem for the forests is that leaf tissue is far more sensitive to ozone than human lung tissue. Ozone "bleaches" leaves. According to Charles Little, a seasoned chronicler of North American forests, you might as well be spraying them with Clorox. Ozone also reduces flower, pollen, and seed production, thereby hindering reproduction.

In this region, you can just about name the tree, and ozone is probably injuring it somewhere. Ozone combines with UV radiation to burn and scar the needles of white pine, the region's tallest conifer. Ozone exposure correlates strongly with hickory and oak die-off. Ozone is hard on the tulip tree, a major canopy species especially where white oak has declined. It's injuring native magnolias as well. Nor is it just the obviously smoggy urban areas that suffer. In the Great Smoky Mountains National Park of North Carolina, researchers have found ozone damage to some 90 plant species.

In rural West Virginia, ozone is apparently working a weird, nonlinear form of forest decline: continual ozone exposure can reduce photosynthesis to the point at which the tree can't grow enough roots to support itself. Apparently minor but chronic leaf damage eventually provokes catastrophic failure of the roots, then death. This is one of several mechanisms underlying the syndrome known as the "falling forest." Reasonably healthy-looking trees just keel over and die.

Airborne nitrogen oxides also produce nitric acid, which contributes to acid rain. The other major constituent of acid rain is sulfuric acid, which derives from the sulfur dioxide released by coal-burning power plants and metal smelters. (Sulfur is a common contaminant of coal and metal ores.) Smoke stack "scrubbers" and a growing preference for low-sulfur coal and natural gas have helped reduce sulfur dioxide emissions in the United States, Canada, and Western Europe. U.S. emissions, for example, fell from nearly 30 million tons in 1970 to 16 million in 1995. (The global picture isn't so encouraging: world sulfur dioxide emissions rose from about 115 million tons a year in 1970 to around 140 million tons by 1988 and have remained relatively stable since then.)

Even in the United States, the amount of acid aloft is still substantial by ecological standards. On the fog-drenched slopes of Mount Mitchell, north on the Appalachian spine from the Smoky Mountains, the pH of the dew and ice sometimes drops as low as 2.1, which is more acid than lemon juice. The acid treatment, combined with insect attack and drought, has killed up to 80 percent of mature red spruce and Fraser fir on the most exposed slopes.

But the problem is not just the acid in the air today. Decades of acid rain have begun to leach out the soil's stock of calcium and magnesium, both essential plant nutrients. Replenishing those minerals, a process dependent on the weathering of rock, may take centuries. In the meantime, the legacy of coal is likely to be stunted forests, at least where the leaching is well advanced, as in some areas of New

England. Recent studies at the Hubbard Brook Experimental Forest in the mountains of New Hampshire, for instance, have identified minerals leaching as the main reason the vegetation there has shown no overall growth for nearly a decade.

This slowing of the trees' metabolism is not just a matter of gradual, overall decline—there are nonlinear effects here too. Acid rain is making the New England winters lethal to red spruce and balsam fir, two of the region's most important conifers. Like most conifers, these species don't lose their leaves—their "needles"—in winter, so they can't just go dormant when it gets cold. They have to maintain a metabolic rate high enough to keep the needles functioning properly. In cold weather, conifers close the stomata in their needles when light dims, in order to protect the needles from freezing. (The stomata are the microscopic pores in leaf tissue, where gas exchange occurs.) The mineral-starved trees can't readily perform this function, so sometimes the cells in the needles freeze solid. That kills needles; when enough of the needles die, the tree dies. At higher elevations in Vermont's Green Mountains, three-quarters of mature red spruce have frozen to death.

The acid rain hasn't just made the soils less nutritious—it has also made them toxic. In calcium-rich soils, the acid is generally neutralized, since calcium is alkaline. But as the calcium level drops, more and more acid accumulates and that tends to release aluminum from its mineral matrix. Aluminum is a common soil constituent; when it's bonded to other minerals it's biologically inert, but free aluminum is toxic to both plants and animals. In some Appalachian streams, you can find stones covered with a silvery-whitish tinge—that's aluminum released by acid rain. This burden of "mobilized" metal is compounded by the traces of cadmium, lead, and mercury that the air brings in along with the acid and ozone.

The metals poisoning may create a kind of synergistic overlap with ozone pollution. In some dying red spruce stands in Vermont, researchers have found elevated levels of phytochelatins, a class of chemicals that plants produce to bind to toxic metals and render them inert. But to make the phytochelatins, the spruces have to draw down their stocks of another substance, glutathione, which is used to counteract ozone. So exposure to one kind of poison leaves the spruces more vulnerable to another.

There's another big overlap here as well: the trees' ability to fight off stresses is also being weakened by nitrogen pollution. Plants don't have the same kind of immune system that animals do. Instead of killer cells and antibodies, they produce an immense arsenal of chemicals. Some of these, like phytochelatins, neutralize toxins; others kill pathogens or make leaves less palatable to pests. Excess nitrogen tends to clog the cellular machinery that produces these chemicals. Farmers don't have to worry about this problem when they apply fertilizer to crops, because crops are intensively managed for pest control and because they're generally harvested at the end of a single growing season. But trees that are exposed to high nitrogen year after year will inevitably absorb more of the material than they can possibly metabolize. So the nitrogen builds up in their tissues, where it tends to alter the recipes for all those defensive chemicals. As the chemicals lose their punch, toxins aren't effectively neutralized; soil pathogens permeate the roots, and the leaves grow more susceptible to insect attack. It has been estimated that nitrogen pollution in the eastern United States is triple the level that forests can tolerate over the long term. Nitrogen pollution can cause a kind of botanical equivalent of AIDS.

This weakening of the forests' immune system is likely to upset the balance between the trees and their pathogens. Another reason for West Virginia's "falling forests," for example, is a fungal infection called *Armillaria* root rot. *Armillaria* is a widespread type of fungus, common in forest soils all over the world. In healthy stands, it usually satisfies itself with the occasional diseased or very old tree. But in a badly stressed stand, it becomes a subterranean monster—a huge, amorphous disease organism, sprouting rootlike tentacles that probe the soil for victims. It picks away at the stand, gradually killing it, tree by tree.

But it's not just the native pests that are taking advantage of the forests' weakened state. The forests are crawling with a host of exotic insects and diseases as well. The American chestnut and the American elm succumbed to exotic pathogens earlier in the century and are now functionally extinct. (They have not disappeared completely but they are no longer functioning components of their native ecosystems.) Today many other species are in trouble. The Canadian hemlock, for example, is being attacked by an Asian insect, the hemlock wooly adelgid; in parts of New England, the adelgid is wiping out entire stands. Nitrogen pollution puts the adelgid on the insect equivalent of steroids: the excess nitrogen makes the leaves much more nutritious and can boost adelgid densities five-fold. Oaks are the principal victims of the gypsy moth, a European insect whose occasional population explosions defoliate thousands of hectares. In the nitrogen-poisoned stands, the moth droppings produce a weak solution of nitric acid on the forest floor, leaching out soil nutrients as the moth gnaws away at the canopy.

Exotic fungal pathogens are attacking the butternut, the American beech, and the eastern dogwood. The dogwood has a very broad range, which covers most of the eastern United States, and the fungus that is killing it has spread throughout that range in little more than a decade—a phenomenal rate of spread for a tree pathogen. Acid rain appears to be part of the reason for the dogwood's susceptibility, and the dogwood die-off is liable to reinforce the effects of acid rain on the soil. The dogwood is very efficient at pulling calcium out of the soil and depositing it, through its leaf litter, on the forest floor. That process reduces calcium leaching, so the disappearance of this tree could deal an additional blow to calcium-starved forests.

This is the condition of what is, by world standards, an upper middle-class forest: conifer die-offs of 70 to 80 percent in the southern Appalachians, sugar maple mortality at 35 percent in Vermont; the butternut, eastern dogwood, and red mulberry in widespread decline. The American beech and Canadian hemlock in trouble over large parts of their range. The elm and the chestnut already gone. And besides the pests and pollution, decades of fire suppression have eliminated plant communities dependent on fire for renewing themselves. Other stands are now giving way to asphalt and suburbia. Over all, according to a survey of five eastern states, tree mortality may now stand at three to five times historical levels.

Last year, climate scientists discovered that North American broadleaf forests were probably absorbing far more carbon from the atmosphere than had been previously assumed. The continent's eastern forests, it turns out, are an important part of the "missing carbon sink"—the heretofore unexplained hole in the calculations that attempt to define the global carbon budget. But if these forests continue to sicken, their appetite for carbon will eventually falter. That is likely to speed up the processes of climate change. And climatic instability will add yet another stress to a region that is already exhibiting a kind of paradoxical system effect: it is covered with new growth but many of its forests appear to be dying.

2. Coral Reefs

Coral reefs are perhaps the greatest collective enterprise in nature. Reefs are the massed calcareous skeletons of millions of coral—small, sedentary, worm-like animals that live on the reef surface, filtering the water for edible debris. Reefs form in shallow tropical and subtropical waters, and host huge numbers of plants and animals. The reef biome is small in terms of area—less than 1 percent of the earth's surface—but it's the richest type of ecosystem in the oceans and the second richest on earth, after tropical forests. One-quarter of all ocean species thus far identified are reef-dwellers, including at least 65 percent of marine fish species.

Coral is extremely vulnerable to heat stress and the unusually high sea surface temperatures (SSTs) of the past two decades may have damaged this biome just as badly as the unusual fires have damaged the tropical forests. Much of the ocean warming is related to El Niño, the weather pattern that begins with shifting currents and air pressure cells in the tropical Pacific region and ends by rearranging a good deal of the planet's weather. El Niños appear to be growing more frequent and more intense; many climate scientists suspect that this trend is connected with climate change. It's very difficult to sort out the patterns, but there is probably also a general SST warming trend in the background, behind the El Niños. That too is a likely manifestation of climate change.

When SSTs reach the 28–30° C range, the coral polyp may expel the algae that live within its tissues. This action is known as "bleaching" because it turns the coral white. Coral usually recovers from a brief bout of bleaching, but if the syndrome persists it is generally fatal because the coral depends on the algae to help feed it through photosynthesis. Published records of bleaching date back to 1870, but show nothing comparable to what began in the early 1980s, when unusually warm water caused extensive bleaching throughout the Pacific. Coral bleached over thousands of square kilometers. By the end of the decade, mass bleaching was occurring in every coral reef region in the world. The full spectrum of coral species was affected in these events—a phenomenon that had never been observed before.

In the second half of this decade, SSTs set new records over much of the coral's range and the bleaching has become even more intense. Last year saw the most extensive bleaching to date. Over a vast tract of the Indian Ocean, from the African coast to southern India, 70 percent of the coral appears to have died. Some authorities think that a shift from episodic events to chronic levels of bleaching is now underway.

The bleaching has triggered outbreaks of the crown-of-thorns starfish, a coral predator that is chewing its way through reefs in the Red Sea, off South Africa, the Maldives, Indonesia, Australia, and throughout much of the Pacific. The starfish are normally kept at bay by antler-like "branching corals," which have stinging cells and host various aggressive crustaceans. But as the branching corals bleach and die, the more palatable "massive corals" growing among them become ever more vulnerable to starfish attack. Over the course of a year, a single adult crown-of-thorns can consume 13 square meters of coral.

Overfishing is also promoting these outbreaks, by removing the fish that eat starfish. Overfishing also helps another enemy of the reefs: various types of algae that compete with coral. Floating algae can starve corals for light; macro-algae—"seaweeds"—can colonize the reefs themselves and displace the coral directly. Because reefs are shallow-water communities, they generally occur in coastal zones, where they are likely to be exposed to nitrogen-rich agricultural runoff and sewage. Nitrogen pollution is as toxic to reefs as it is to temperate-zone forests, because nitrogen fertilizes algae. Remove the algae-eating fish under these conditions, and you might as well have poisoned the coral directly. This overlap is the main reason Jamaica's reefs never recovered from Hurricane Allen in 1980; 90 percent of the reefs off the island's northwest coast are now just algae-covered humps of limestone.

In the Caribbean, over-fishing seems to have played a role in yet another complication for the reefs: the population collapse of an algae-eating sea urchin, *Diadema antillarum.* This urchin appears to have been the last line of defense against the algae after the progressive elimination of other algae-eating creatures. The first to go may have been the green sea turtle. Now endangered, the turtle once apparently roamed the Caribbean in immense herds, like bison on the Great Plains. Its Caribbean population may have surpassed 600 million. Christopher Columbus's fleet reportedly had to reef sail for a full day to let a migrating herd pass. By the end of the 18th century, the turtles had nearly all been slaughtered for their meat. In the following two centuries, essentially the same operation was repeated with the algae-eating fish.

The removal of its competitors must have given the urchin a great deal of room, and for most of this century it was one of the reefs' most common denizens. But its abundance seems to have set it up for the epidemic that struck during the El Niño of the early 1980s. In roughly a year, a mysterious pathogen virtually eliminated *D. antillarum* from the Caribbean; some 98 percent of the species disappeared over an area of more than 2.5 million square kilometers. Contemporary history offers no precedent for a die-off of that magnitude in a marine animal. The urchin is reportedly back in evidence, at least in some areas of its former range, but until its relationship with the pathogen is better understood, it won't be possible to define its longterm appetite for algae.

With the algae, the pollution, and the warming waters, the Caribbean is becoming an increasingly hostile environment for the organism that has shaped so much of its biological character. And now the coral itself is sickening; the Caribbean has become a caldron of epidemic coral diseases. The first such epidemic, called black-band disease, was detected in 1973 in Belizean waters. Black band is caused by a three-layer complex of "blue-green algae" (actually, cyanobacteria), each layer consisting of a different species. The bottom layer secretes highly toxic sulfides which kill the coral. The complex creeps very slowly over a head of coral in a narrow band, leaving behind only the bare white skeleton.

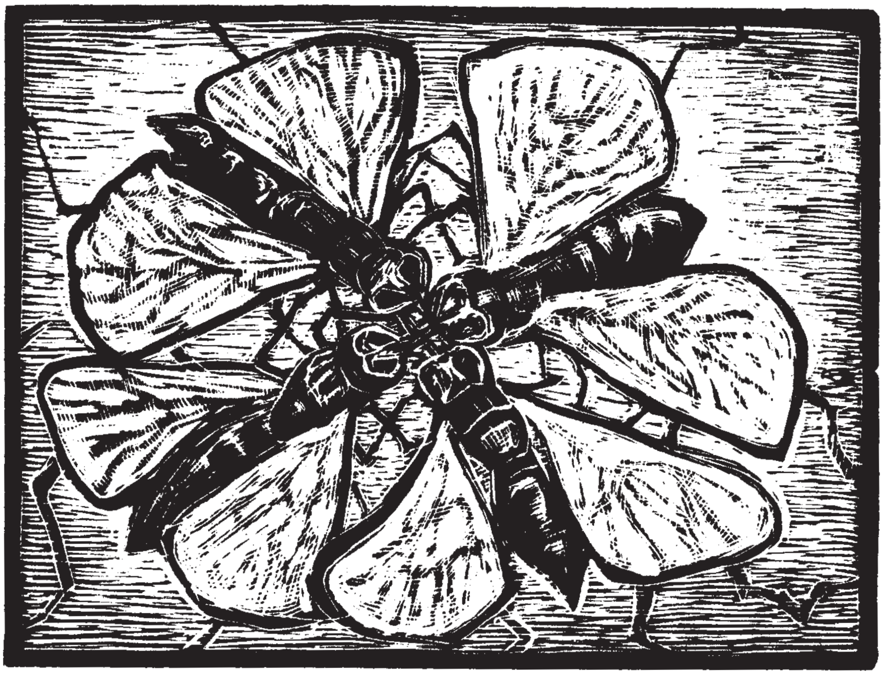
Black band has since been joined by a whole menagerie of other diseases: white-band, yellow-band, red-band, patchy necrosis, white pox, white plague type I and II, rapid-wasting syndrome, dark spot. The modes of action are as various as the names. White pox, for example, is caused by an unknown pathogen that almost dissolves the living coral tissue. Infected polyps disintegrate into mucous-like strands that trail off into the water, and bare, dead splotches appear on the reefs, giving them a kind of underwater version of the mange. Rapid wasting syndrome probably starts with aggressive biting by spotlight parrotfish; the wounds are then infected by some sort of fungus that spreads out from the wound site. On the reefs off Florida, the number of diseases has increased from five or six to 13 during the past decade. In 1996, nine of the 44 coral species occurring on these reefs were diseased; a year later the number of infected species had climbed to 28. Nor are the Caribbean reefs the only ones under attack; coral epidemics are turning up here and there throughout the Pacific and Indian Oceans, in the Persian Gulf and in the Red Sea.

For most of these diseases, a pathogen has yet to be identified; it's not even clear whether each of those names really refers to a distinct syndrome. But it's not likely that the diseases are "new" in the sense of being caused by pathogens that have recently evolved. It's much more likely that the coral's vulnerability to them is new. Take, for example, the disease that's killing sea-fan coral around the Caribbean. In this case, the pathogen is known: it's *Aspergillus sydowii*, a member of a very common genus of terrestrial fungi. The last time you threw something out of your refrigerator because it was moldy—there's a good chance you were looking at an *Aspergillus* species. In a very bizarre form of invasion, *A. sydowii* breached the land-sea barrier, and found a second home in the ocean. But it evidently took the plunge decades ago and has only been killing sea-fans for some 15 years or so. Why? Part of the answer is probably the higher SSTs: *A. sydowii* likes warmer water. Other coral diseases appear to do especially well in nutrient-laden waters.

Disease lies at one end of the spectrum of threat. Pathogens create a kind of microscopic pressure, but there are macroscopic pressures too: the ecosystems allied in one way or another with the reef biome are also deteriorating. The stretch of shallow, protected water between a reef and the coast often nurtures beds of seagrass. These beds filter out sediment and effluent that would injure the reefs, and the seagrass provides crucial cover for young fish. Seagrass is the major nursery for many fish species that spend their adult lives out on the reefs. Perhaps 70 percent of all commercially important fish spend at least part of their lives in the seagrass. But the tropical seagrass beds are silting up under tons of sediment from development, logging, mining, and the construction of shrimp farms. They are suffocating under algal blooms in nitrogen-polluted waters; they are being poisoned by herbicide runoff. According to one estimate, half of all seagrass beds within about 50 kilometers of a city have disappeared.

If you follow the seagrass-choking sediment back the way it came, you're increasingly likely to find a shoreline denuded of mangroves. In the warmer regions of the world, mangroves knit the land and sea together. These stilt-rooted trees trap sediment that would otherwise leak out to sea and they stabilize coastlines against incoming storms. Like the seagrass beds and the reefs, the mangrove ecosystem is incredibly productive—in the mangroves' case, with both terrestrial and aquatic organisms. (Mangrove roots are important fish nurseries too.)

The mangroves' importance as a sediment filter is perhaps greatest in the center of reef diversity, the Indonesian archipelago and adjoining areas. About 450 coral species are known to grow in the Australasian region; the Caribbean, by comparison, contains just 67 species. Australasia is correspondingly rich in fish too: a quarter of the world's fish species inhabit these waters. It is estimated that half of all the sediments received by oceanic waters are washed from the Indonesian archipelago alone. Nearby areas of Southeast Asia are also major contributors of sediment. But throughout the region, logging and shrimp farming are obliterating the mangroves that once filtered this tremendous burden of silt. Southeast Asia has lost half its mangrove stands over the past half century. A third of the mangrove cover is gone from Indonesian coasts, three-quarters from the Philippines.

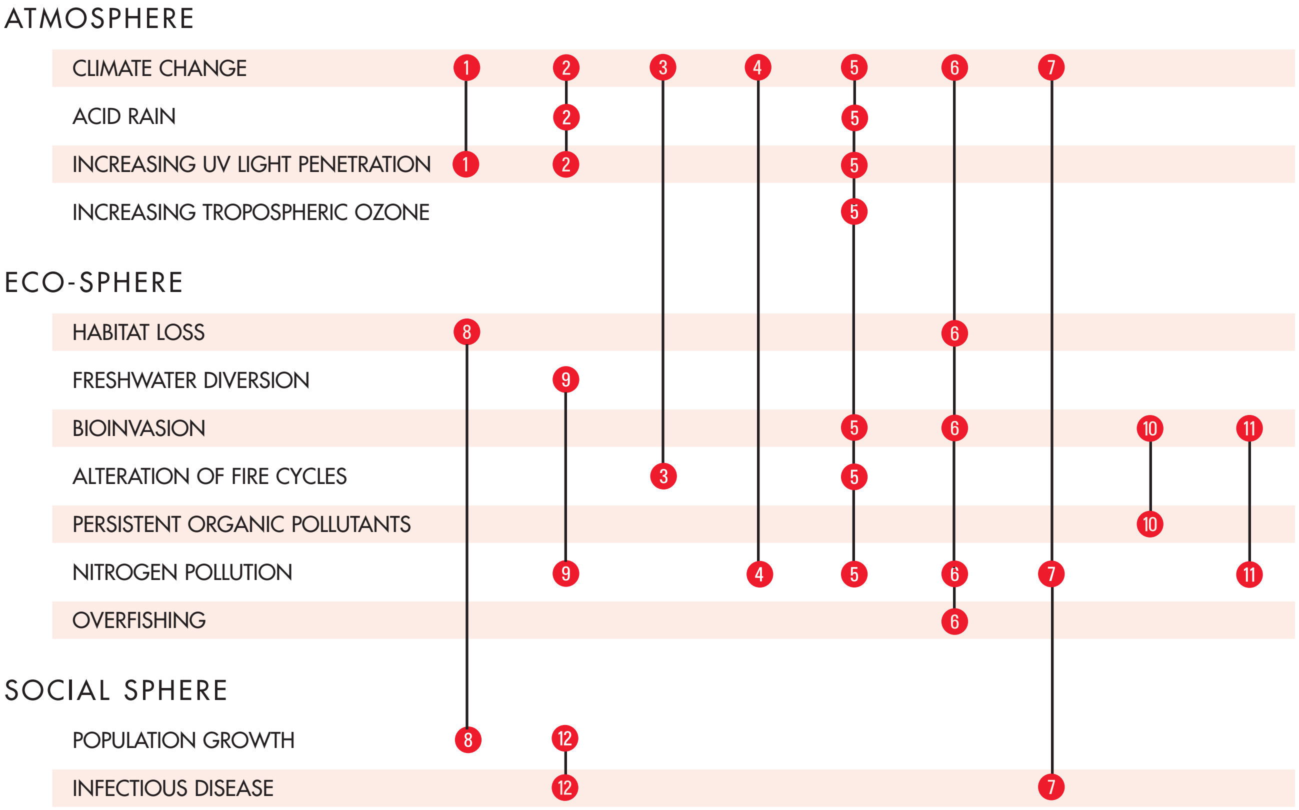


About 10 percent of the world's coral reefs may already have been degraded beyond recovery. If we can't find a way to ease the reefs' afflictions, nearly three-quarters of the ocean's richest biome may have disappeared 50 years from now. Such a prospect gives new meaning to the term "natural disaster," but it's also a social disaster in the making. Reef fish make up perhaps 10 percent of the global fish catch; one estimate puts their contribution to the catch of developing countries at 20 to 25 percent.

And there's much more at stake here than just fisheries. The death of the coral would also jeopardize the reef *structures*—leaving them unable to repair storm damage. If the reefs give way, wave erosion of the coasts behind them will increase. The coasts are already facing some unavoidable degree of damage from climate change, as sea-levels rise.

A Spreading Matrix of Trouble

Below are 13 of the worst pressures that we are inflicting on the planet and on ourselves. The lines show a few of the ways in which these corrosive forces interact. See the numbered key for each of the combinations indicated. Note that neither the list of pressures nor the set of interactions is inclusive—if your background is in environmental studies, you will almost certainly be able to extend the matrix. We welcome your thoughts (see the inside front cover for our address).



KEY TO THE MATRIX

① **Climate change + UV:** Greenhouse-forced warming of the lower atmosphere may cause a *cooling* of the stratosphere, especially over the Arctic. (Major air currents may shift, and block the warmer surface air from moving North and up.) A cooling stratosphere will exacerbate damage to the ozone layer because the colder it is, the more effective CFCs become at breaking down ozone. The ozone layer over the Arctic could grow progressively thinner as warming proceeds.

② **Climate change + acid rain + UV:** In eastern Canada, two decades of mild drought and a slight warming trend have reduced streamflow into many of the region's lakes. The lake water has grown clearer, since the weakened streams are washing in less organic debris. The clearer water allows UV radiation to penetrate more deeply—at a time when more UV light is striking the lakes in the first place, because of the deterioration of the ozone layer. (UV light can injure fish and other aquatic organisms just as it injures humans.) Acid rain, which affects northern lakes in both Canada and Eurasia, causes even more organic matter to precipitate out of the water, further opening the lakes to UV light. In some lakes, the overall effect may be to increase the depth of UV penetration from 20–30 centimeters to over 3 meters.

③ **Climate change + alteration of fire cycles:** The fire ecology of forests all over the world is in a profound state of flux; we have introduced fire into some tropical rainforests that do not naturally burn at all, while in many temperate forests, where fire is essential for maintaining the native plant community, we have suppressed it. Climate change will probably cause further instability in fire cycles, as some regions become drier and others wetter. The results cannot be predicted, but are unlikely to favor original forest composition. If the overall rate of burning increases, that could create a positive feedback loop in the climate cycle, by releasing ever greater quantities of heat-trapping carbon into the atmosphere.

(Warming water expands; that physical effect will combine with runoff from melting glaciers to push sea levels up.) Rising seas, like the crumbling reefs, will allow storm surges to reach farther inland. About one-sixth of the world's coasts are shielded by reefs, and some of these coasts, like the ones in South and Southeast Asia, support some of the densest human populations in the world. The disintegration of the reefs would leave a large portion of humanity hungrier, poorer, and far more vulnerable to the vagaries of a changing climate.

CORAL REEFS AND TEMPERATE-ZONE FORESTS—IN both of these theaters of surprise, the familiar could rapidly become something else. But you can begin to see similar system effects just about anywhere, and emerging from just about any form of environmental pressure:

- Nitrogen pollution has tripled the occurrence of low-oxygen dead zones in coastal ocean waters over the past 30 years. As in the Black Sea, excess nitrogen appears generally to be promoting the emergence of red tide organisms. (Over the past decade, the number of algae species known to be toxic has increased from around 20 to at least 85.)
- Organochlorine pollutants seem to be creating immunodeficiencies in marine mammals, triggering a growing number of viral epidemics. (Exposure to the red-tide toxins may also depress the immune systems of some marine mammals and sea turtles.)
- The hunting of birds and primates in tropical forests may become another form of deforestation, because these creatures are so important in pollinating tree flowers and dispersing seeds.
- Powerful storms, which may grow more common as the climate changes, tend to magnify invasions of exotic plants by dispersing their seeds over huge areas.
- And a whole spectrum of threats appears to underlie the global decline in amphibians: habitat loss, pollution, disease, exotic predators, and higher levels of UV exposure resulting from the disintegration of the ozone layer. (See the table opposite for some additional system effects.)

Given the pressures to which the global environment is now subject, the potential for surprise is, for all practical purposes, unlimited. We have stepped into a world in which our assumptions and prejudices are more and more likely to betray us. We are confronting a demon in a hall of mirrors. At this point, a purely reactive approach to our tormentor will lead inevitably to exhaustion and failure.

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④ **Climate change + N pollution:** As a factor in the decline of some temperate-zone forests, nitrogen pollution is probably reducing their capacity to absorb carbon from the atmosphere.

⑤ **Climate change + acid rain + UV + trospheric ozone + bioinvasion + alteration of fire cycles + N pollution:** This complex of pressures is pushing eastern North American forests into decline. (See text.)

⑥ **Climate change + habitat loss + bioinvasion + N pollution + overfishing:** This set of pressures is pushing the world's coral reefs into decline. (See text.)

⑦ **Climate change + N pollution + infectious disease:** Cool weather often limits the ranges of mosquitoes and other insects that carry human pathogens. Even relatively slight increases in minimum temperatures can admit a pest into new areas. Warm coastal ocean water, especially when it's nitrogen-polluted, creates habitat for cholera.

⑧ **Habitat loss + population growth:** Last year, the flooding of China's Yangtze River did $30 billion in damages, displaced 223 million people, and killed another 3,700. The flooding was not wholly a natural event: with 85 percent of its forest cover gone, the Yangtze basin no longer had the capacity to absorb the heavy rains. (Forests are like immense sponges—they hold huge quantities of water.) And the densely settled floodplain guaranteed that the resulting monster flood would find millions of victims. (See "Record Year for Weather-Related Disasters," 27 November 1998, at www.worldwatch.org/alerts/index.)

⑨ **Freshwater diversion + N pollution:** Extensive irrigation can turn an arid region into productive cropland, but chemical fertilization is likely to follow and make the fields a source of nitrous oxide.

⑩ **Bioinvasion + POPs:** In the Great Lakes, exotic zebra mussels are ingesting dangerous organochlorine pesticides and other persistent organic chemicals that have settled into the loose, lake-bottom muck. Once in the zebra mussels, the chemicals may move elsewhere in the food web. Over the past decade or so, poisoning with such chemicals is also thought to be a factor in the growing susceptibility of marine mammals to the various epidemics that have emerged here and there throughout the world's oceans.

⑪ **Bioinvasion + N pollution:** Nitrogen pollution of grassland tends to favor the spread of aggressive exotic weeds. Nitrogen pollution of forests tends to weaken tree defenses against pests, both exotic and native.

⑫ **Population growth + infectious disease:** Over the next half-century, the centers of population growth will be the crowded, dirty cities of the developing world. These places are already breeding grounds for most of humanity's deadliest pathogens: cholera, malaria, AIDS, and tuberculosis among them. As the cities become more crowded, rates of infection are likely to grow and "overlapping infections" are likely to increase mortality rates.

Towards a Complexity Ethic

Our predicament, essentially, is this: environmental pressures are converging in ways that are likely to create a growing number of unanticipated crises. Each of these crises will demand some sort of fix, and each fix will demand money, time, and political capital. Yet no matter how many fixes we make, we've no realistic expectation of reducing the potential for additional crises—if "fixing" is all we do. The key to controlling that demon is to do a better job of managing systems in their entirety. And whether the system in question is the global trading network, a national economy, or a single natural area, many of the same operating principles will apply. Here, in my view, are four of the most important ones.

Monoculture technologies are brittle.

Huge, uniform sectors generally exhibit an obvious kind of efficiency because they generate economies of scale. You can see this in fossil fuel-based power grids, car-dominated transit systems, even in the enormous woodpulp plantations that are an increasingly important part of the developing world's forestry sector. But this efficiency is usually superficial because it doesn't account for all sorts of "external" social and environmental costs. Thus, for instance, that apparently cheap fossil-fuel electricity is purchased with the literally incalculable risks of climatic dislocation, with acid rain and ozone pollution, with mine runoff, and in the countries that rely most heavily on coal—China, for instance, and South Africa—with a heavy burden of respiratory disease.

Yet even when the need for change is obvious and alternative technologies are available, industrial monocultures can be extremely difficult to reform. In energy markets, solar and wind power are already competitive with fossil fuel for many applications, even by a very conventional cost comparison. And when you bring in all those external costs, there's really no comparison at all. But with trillions of dollars already invested in coal and oil, the global energy market is responding to renewables in a very slow and grudging way.

More diverse technologies—in energy and in any other field—will encourage more diverse investment strategies. That will tend to make the system as a whole more adaptable because investors will not all be "betting" on exactly the same future. And a more adaptable system is likely to be more durable over the long term.

Direct opposition to a natural force usually invites failure—or a form of success that is just as bad.

In the "Iron Gates" brand of development, it is sometimes difficult to distinguish success from failure. Less obvious, perhaps, is the fact that even conservation activities can run afoul of natural forces. Take, for example, the categorical approach to forest fire suppression. A no-burn policy may increase a forest's fuel load to the point at which a lightning strike produces a huge crown fire. That's outright failure: a catastrophic "artificial" fire may consume stands that survived centuries of the natural fire cycle. On the other hand, if the moisture regime favors rapid decomposition of dead wood, the policy could eliminate fire entirely. Without burning, the fire-tolerant tree species would probably also begin to disappear, as they are replaced by species better adapted to the absence of fire. That's "success." Either way, you lose the original forest.

Sound policy often tends to be more "oblique" than direct. A vaccine, for instance, turns the power of the pathogen against itself; that's why, when there's a choice, immunization is usually a better tactic for fighting disease than quarantine. Restoration of floodplain ecosystems can be a more effective form of flood control than dams and levees, because wetlands and forests function as immense sponges. (The catastrophic flooding last year in China's Yangtze river basin was largely the result of deforestation.)

An oblique approach might also help reduce demand for especially energy- or materials-intensive goods: if large numbers of people can be convinced to "transfer" their demand from the goods themselves to the services that the goods provide, then it might be possible to encourage consumption patterns that do less environmental damage. For example, joint ownership of cars, especially in cities, could satisfy needs for occasional private transportation, with a little coordination.

Since you can never have just one effect, always plan to have several.

Thinking through the likely systemic effects of a plan will help locate the risks, as well as indirect opportunities. Every day, for example, I ride the car pool lanes into Washington D.C., and my conversations with other commuters have led me to suspect that this environmentally correct ribbon of asphalt could actually *increase* pollution and sprawl, by contributing to a positive feedback loop. Here's how I think it may work: as the car pool lanes extended outward from the city, commute times dropped; that would tend to promote the development of bedroom communities in ever more remote areas. Eventually, the new developments will cause traffic congestion to rebound, and that will create political pressure for another bout of highway widening. A more "system sensitive" policy might have permitted the highway projects only when a county had some realistic plan to limit sprawl. (According to one recent estimate, metropolitan Washington is losing open space faster than any other area in the United States outside of California's central valley.) Car pool lanes might then have become a means of conserving farmland, instead of a possible factor in its demise.

For environmental activists, "system sensitivity" could help locate huge political constituencies. Look, for instance, at the potential politics of nitrogen pollution. Since a great deal of the nitrogen that is threatening coral reefs is likely to be agricultural runoff, and since much of that runoff is likely to be the result of highly mechanized "factory farming," it follows that anyone who cares about reefs should also care about sustainable agriculture. Obviously, the reverse is true as well: if you're trying to encourage organic farming in the Mississippi basin, you're conserving Caribbean reefs. The same kind of political reciprocity could be built around renewable energy and forest conservation.

I don't know the answer and neither do you, but together we can probably find one.

A system can have qualities that exist only *on the system level*—qualities that cannot be attributed directly to any of the components within. No matter how hard you look, for example, at the individual characteristics of oxygen, nitrogen, hydrogen, carbon, and magnesium, you will never find grounds for inferring the amazing activities of chlorophyll—the molecule that powers photosynthesis. There are system properties in political life as well: institutional pluralism can create a public space that no single institution could have created alone. That's one objective of the "balance of powers" aimed at in constitutional government.

It should also be possible to build a "policy system" that is smarter and more effective than any of its component groups of policy makers. Consider, for example, the recent history of the U.S. Forest Service. For decades, environmental activists have accused the service of managing the country's forests almost exclusively for timber production, with virtually no regard for their inherent natural value. Distrust of the service has fueled a widespread, grassroots forest conservation movement, which has grown increasingly sophisticated in its political and legal activities, and now even undertakes its own scientific studies on behalf of the forests. This movement, in turn, has attracted the interest and sympathy of a growing number of officials within the service. Many environmentalists (including this author) would argue that things are nowhere near what they should be inside the service, but it's possible that what we are witnessing here is the creation of a new space for conservation—a space that even a much more ecologically enlightened Forest Service couldn't have created on its own.

It remains to be seen whether this forum will prove powerful enough to the save the forests that inspired it. But in the efforts of the people who are building it, I think I can see, however dimly, a future in which the world's dominant cultures re-experience the shock of living among forests, prairies, and oceans—instead of among "natural resources." After all, the forests and prairies are where we came from and they're where we are going. We are the children of a vast natural complexity that we will never fathom.

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A FEW KEY SOURCES

Harvard Ayers, Jenny Hager, and Charles E. Little, eds., *An Appalachian Tragedy: Air Pollution and Tree Death in the Eastern Forests of North America* (San Francisco: Sierra Club Books, 1998).

Osha Gray Davidson, *The Enchanted Braid: Coming to Terms with Nature on the Coral Reef* (New York: John Wiley, 1998).

Paul Epstein et al., *Marine Ecosystems: Emerging Diseases as Indicators of Change,* Health Ecological and Economic Dimensions (HEED) of the Global Change Program (Boston: Center for Health and Global Environment, Havard Medical School, December 1998).

Robert Jervis, *System Effects: Complexity in Political and Social Life* (Princeton, NJ: Princeton University Press, 1997).

Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (New York: Basic Books, 1984).