ECOLOGY

Global Nitrogen Overload Problem Grows Critical

Like a satiated gourmand, the biosphere is becoming glutted with nitrogen compounds. As early as the 1960s, researchers knew that some lakes and rivers were suffering because they were being overdosed with synthetic nitrogen fertilizers and nitrogen oxides discharged by cars and factories. But now, ecologists say, a surfeit of fixed nitrogen, by which they mean compounds such as ammonia and nitrogen oxides, is overwhelming entire ecosystems ranging from forests to coastal waters.

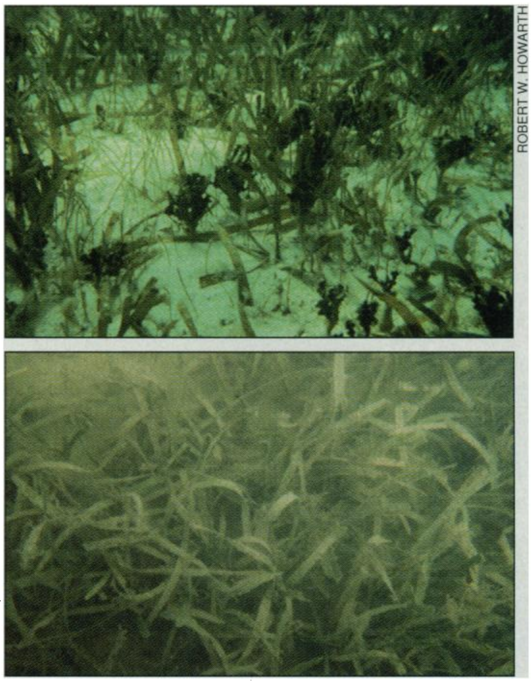
A new study shows that much land can no longer absorb or break down the increasing amounts of fixed nitrogen, so growing quantities of the compounds end up in rivers, lakes, estuaries, and oceans. The resulting nitrogen influx has touched off oxygen-consuming, coastal algal blooms, including the notorious red and brown tides, and has impaired fisheries. Other work has detailed the toll the excess nitrogen is taking on land plants. Nitrogen compounds are displacing valuable nutrients from forest soils, causing mineral deficiencies that decrease forest vitality and perhaps even harming biodiversity.

"Fixed nitrogen is essential for all life, but the added nitrogen is literally too much of a good thing," says Stanford University ecologist Peter Vitousek. Indeed, last year, both the Ecological Society of America and the international Scientific Committee on Problems of the Environment named nitrogen pollution as a "preeminent problem" that is not being given enough public recognition.*

Until the turn of the century, almost all fixed nitrogen came from Mother Nature, produced from atmospheric nitrogen (N_2) by soil microbes or lightning. It didn't accumulate, because other "denitrifying" microbes converted it back to N_2. But the widespread use of synthetic nitrogen fertilizers that began in the middle of this century, coupled with the huge increase in the burning of fossil fuels, especially by cars, shifted that balance—a shift that has accelerated in the past dozen years or so.

"The situation is changing incredibly rapidly," says Cornell University biogeochemist Robert Howarth. "In recent years, the worldwide rate of fertilizer applications has risen exponentially and, in the northeastern United States, the nitrates produced from fossil fuel emissions have increased about 20% in just the last decade." From data on current fertilizer production, fossil fuel emissions, and production of nitrogen-fixing crops like soybeans, Duke University biogeochemist William Schlesinger calculates that today, human activities produce 60% of all the fixed nitrogen deposited on land each year—far more than can be used productively in crops and other land plants or denitrified.

One sign of the nitrogen glut comes from a survey of the nitrogen input into several hundred North and South American and European rivers that Howarth and a multinational team of about 50 colleagues are now conducting. Although ecologists have known about the problems posed by nitrogen from agricultural runoff since the 1960s, even they were not prepared for what the survey is showing. By analyzing data on human sources of nitrogen in the landscape and on nitrogen fluxes in river water over parts of four continents, the researchers estimate that about 20% of the nitrogen that humans are putting into watersheds is consistently getting into the rivers.



ROBERT W. HOWARTH

Overloaded. High nitrogen *(bottom)* promotes the growth of tropical marine plants, but species are few compared to the normal situation *(above)*.

"We found a simple pattern," says Howarth. "Over a 20-fold range of nitrogen inputs, there is a linear function between the amount of nitrogen that humans put into a region and the amount that gets exported in rivers to the coast." The constancy of this nitrogen leakage was a "huge surprise," he adds, given the large differences in climate, vegetation, and human activity in the areas surveyed.

All this nitrogen runoff has caused a marked uptick in eutrophication, which occurs when excessive nitrogen concentrations lead to abundant growth of algae in the surface waters of estuaries and coastal oceans as well as lakes and rivers. Then, when these plants die, they sink to lower depths and decay, depleting the water's oxygen supply and killing deep-dwelling fish. University of Stockholm aquatic ecologist Ragnar Elmgren attributes the collapse of the Baltic Sea cod fishery in the early 1990s, for example, to nitrogen pollution. He believes that plant matter sinking from algae blooms near the surface has depleted oxygen in deep waters, interfering with cod reproduction. Elmgren attributes those blooms to nitrogen because they occur mainly in spring, when farmers apply fertilizer to their fields, and end when the nitrogen is gone. "The Baltic's nitrogen load had increased at least fourfold during this century, causing massive increases in the nitrogen-limited, spring blooms of algae," he says.

And in the Gulf of Mexico, oceanographer Nancy Rabalais of the Louisiana Universities Marine Consortium and coastal ecologist Eugene Turner of Louisiana State University in Baton Rouge have found a far-reaching "dead zone" at depths of one-half to 20 meters. "There has been a significant increase in hypoxia [oxygen depletion] in the last 20 years," says Turner. He adds that the dead zone, now the size of the state of New Jersey, is expanding westward from the coast of Louisiana into Texas waters. Rabalais and Turner have linked the dead zones to algae blooms caused by nitrogen fertilizer poured into the gulf by the Mississippi River.

In addition to polluting the world's waterways, excess nitrogen is also adversely affecting terrestrial systems. Until recently, ecologists did not know why nitrogen, which they expected to be beneficial to plants, was harmful, damaging forests in Germany and elsewhere, for example. But a 1994 study in Bavaria by Ernst-Detlef Schulze, a plant ecologist at Bayreuth University and the recently appointed director of the Max Planck Institute for Biogeochemistry in Jena, and his colleagues pointed to one possible mechanism: Surplus nitrogen oxides from burning fossil fuels, deposited as nitrates in acid rain, are impoverishing forest soils. The researchers found that the negatively charged nitrate ions leach positively charged minerals, such as magnesium, calcium, and potassium ions, out of topsoils, leading to mineral deficiencies in forest trees.

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* Also see P. Vitousek *et al.*, "Human Alterations of the Global Nitrogen Cycle: Sources and Consequences," *Ecological Applications* **7**(3), 737 (1997).

More recent studies by Schulze suggest that nitrogen oxides and ammonia released from fertilizers, animal wastes, and power stations can pass directly from the air into leaves and barks, without being carried from the soils to plant roots. The researchers came to this conclusion by measuring the nitrates and enzyme activities in samples of xylem fluid from beech trees. This fluid, which carries nutrients including nitrogen-containing amino acids up from the roots, normally contains no nitrates.

But the Schulze team found that in areas of heavy nitrogen pollution, xylem fluid carries significant nitrate concentrations, which presumably entered above ground. He estimates that, in northern Europe, such aboveground uptake now accounts for 60% of the nitrogen found in broad-leaved trees, a dramatic change from earlier years. "Plants have evolved to take in nitrogen via their roots," says Schulze. "They can't effectively regulate nitrogen from their leaves." This excess nitrogen causes rapid tree growth, he says, but because the trees are deficient in the nutrients that have been leached from the soil, they are weak and vulnerable to insects and mildews.

All these changes could impair biological diversity by fostering luxuriant growth of a few species that can thrive at high nitrogen levels at the expense of others. "We could be inadvertently reducing the number of species globally by increasing nitrogen," says Duke's Schlesinger. Indeed, he adds, this has already happened in many estuaries, where a few phytoplankton species have flourished, choking out other species. A field study by ecologists David Wedin of the University of Toronto and David Tilman of the University of Minnesota, St. Paul, also showed that grasslands receiving abundant nitrogen can lose their diversity as invasive species, which are less efficient at photosynthesis, move in (*Science*, 6 December 1996, p. 1720).

While correcting these problems will not be easy, Schlesinger says, "there are several points of optimism." One possibility is to use fertilizers more judiciously, in much the same way that pesticides are applied selectively in integrated pest management. Interplanting corn with nitrogen-fixing legumes, such as soybeans, can also reduce the need for synthetic fertilizers. Smaller cars, with reduced nitrogen oxide emissions, would help, and better protection of wetlands with their denitrifying bacteria might reduce the fixed nitrogen in the environment. But, cautions Turner, "The problem has kind of snuck up on us, and it is going to take quite a few decades to back out of it."

–Anne Simon Moffat

REEF BIOLOGY

New Threat Seen From Carbon Dioxide

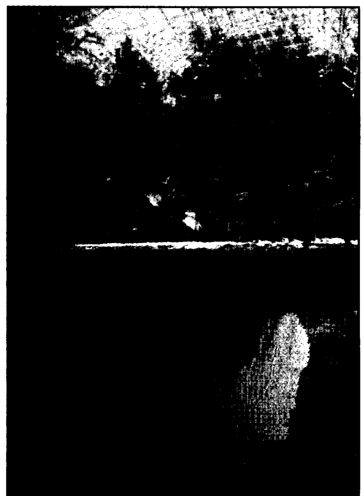
Fifteen years ago, the world's reefs began turning white, helping to galvanize concern about global climate change as reef specialists attributed this bleaching to warming seas (*Science*, 19 July 1991, p. 258). Since then, researchers have identified other problems, including disease and damage inflicted by humans, that seemed to pose a more immediate threat to reef survival. Now, new findings suggest that in decades to come, yet another threat may come to the fore: the increasing amount of carbon dioxide in the air.

The results, reported last month at a special symposium organized by the Scientific Committee on Oceanic Research and other organizations, show that the amount of carbonate dissolved in seawater has a much greater effect on coral reef growth than had been thought. When it drops, corals and other reef-building organisms have a harder time depositing their limestone skeletons. And increases in atmospheric carbon dioxide should have exactly that effect, because carbon dioxide dissolved in seawater boosts its acidity and decreases the amount of carbonate it can carry. "This [carbon dioxide-] induced weakening will make reefs more susceptible to the other pressures they face and compound their problems," says Bradley Opdyke, a marine geologist at the Australian National University in Canberra.

Several studies in the 1960s and 1970s had implied that carbonate fluctuations could affect reef growth, but because seawater is glutted—supersaturated—with carbonate, most researchers thought the fluctuations would have only minor effects. But that's not what biological oceanographer Chris Langdon of the Lamont-Doherty Earth Observatory in Palisades, New York, and his colleagues found by studying a somewhat unusual system: a coral reef established 8 years ago in the "ocean" of Biosphere II, the enclosed, self-supporting ecosystem located outside Tucson, Arizona.

In 1995, the Langdon team began examining how the growth rates of the Biosphere II reef corals varied when the researchers changed the water's carbonate concentration, either dumping in 45-kilogram bags of sodium carbonate or sodium bicarbonate to increase the concentrations, or withholding those additives for long periods of time to cause the concentrations to decline. Many reef experts expected that even if reef calcification rates dropped with the carbonate concentrations, reefs would continue to grow unless concentrations fell below saturation.

But the Langdon team found that although the Biosphere II reef grew by about 35 millimoles of calcium carbonate per square meter per day at a carbonate-ion concentration equal to 320% of the saturation level, it lost about 6 millimoles per square meter per day at 170% of saturation. For as yet unknown reasons, the organisms apparently have a harder time converting carbonate ions into limestone at these lower concentrations.



G. ARCILA / 1991 SPACE BIOSPHERES VENTURES

Stunted corals. Biosphere II corals shrank as carbonate levels dropped.

Jean-Pierre Gattuso, a biological oceanographer at the Oceanographic Observatory in Villefranche-sur-mer in France, and his colleagues saw similar trends when they studied a single coral, *Stylophora pistillata*, in the lab. They found that as the calcium carbonate concentration went from 390% of the saturation level—the current concentration in seawater—to 98%, the coral's calcification rate decreased threefold, although it did not drop as low as it did in the Biosphere II reef.

"I think we have just now hit the point where there is evidence to indicate that [carbonate concentration] is really important," says Robert Buddemeier, a hydrogeochemist at the Kansas Geological Survey in Lawrence. "This is a controlling environmental variable that has simply not been factored into reef biology at all."

It is unclear how much this variable has affected reef health to date, and as carbon dioxide rises in the future, other factors the studies don't take into account, such as warmer water, might help counter its effects. But if not, the atmospheric carbon dioxide increases expected over the next century could lead to serious problems. Langdon calculates, for example, that reef formation will decline by as much as 40% if the carbon dioxide doubles as expected in the next 70 years, halving the carbonate concentrations, and by as much as 75% if carbon dioxide doubles again. And, he adds, "it's going to be an absolutely global effect."

–Elizabeth Pennisi