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

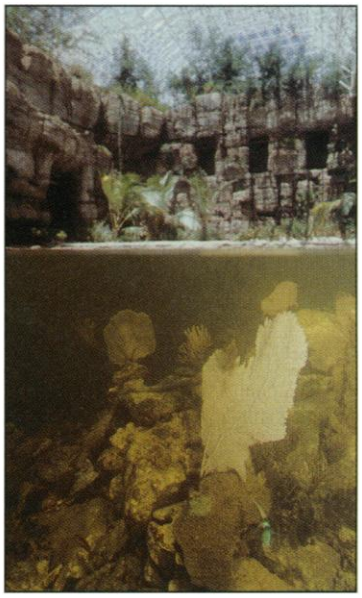
New Threat Seen From Carbon Dioxide

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.



G. ARCILA / 1991 SPACE BIOSPHERES VENTURES

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

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.

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