If approved by Congress, an ambitious plan would seek to banish a recurring nightmare from the Gulf of Mexico: a seasonal dead zone that turns the sea floor into a graveyard

Keeping the Stygian Waters at Bay

URBANA, ILLINOIS—In the summer of 1999, billions of creatures suffocated in the northern Gulf of Mexico. The killing started in the spring, when the waters were gradually depleted of life-giving oxygen. By the time the carnage ended that autumn, a swath of sea the size of New Jersey had been stripped of much of its oxygen. Fish could flee the expanding "dead zone," but bottom-dwellers such as crabs and snails couldn't crawl away and were suffocated. A similar horror has visited the gulf every summer for at least 20 years—but 1999 was the worst ever.

The gulf's woes can be attributed primarily to the 1.6 million metric tons of nitrogen, much of it from midwestern farm fields, that wash out of the Mississippi and Atchafalaya rivers each year (*Science*, 10 July 1998, p. 190). No one has offered data showing that the dead zone has harmed gulf fisheries, as trawlers and other ships have coped by moving their operations farther out to sea. And although one economically important species—brown shrimp—is declining, it's not clear whether oxygen-poor, or hypoxic, waters are to blame. Still, a bigger or longer lasting dead zone could spell disaster. The northern gulf is "a time bomb" that could explode any year, devastating the fishing industry, says marine biologist Robert Diaz of the Virginia Institute of Marine Science in Gloucester Point.

But a tonic for the gulf's ills may at last be at hand. After years of wrangling, the Clinton Administration in one of its final acts released a plan last month to shrink the dead zone by sopping up its trigger: excess nitrogen in the Mississippi Basin, which drains 41% of the continental United States. Senator John Breaux (D–LA) is planning to draft legislation to introduce key portions of the plan in Congress later this year. Although the measure would rely heavily on voluntary changes in farming practices, it could face rough sledding in a conservative Congress. And even if the plan is implemented, experts warn that the gulf's summertime blues could take more than a decade to cure. But many also feel that the measures would come in the nick of time. The northern gulf "is not too far gone," says Diaz, who thinks that the waters run the risk of reprising conditions in the Black Sea in the 1970s and 1980s: hypoxia year-round. By choking off nitrogen at its source, Diaz says, "the gulf will turn around."

Getting to the bottom of it. Sediments reveal plankton abundance in the gulf in years gone by—a proxy for measuring hypoxic conditions that can strangle bottom-dwellers, like this crab *(inset)*.

CREDITS: FRANKLIN J. VIOLA

Raising hackles

The dead zone forms each spring when nitrogen—primarily in the form of nitrates—dumped into the gulf by the Mississippi River triggers an ecological chain reaction. The nutrient spurs tiny marine plants to bloom in the surface waters. Minuscule animals called zooplankton feast on the plants, and their numbers soar. The profusion of life is more than fish and other predators can consume, so billions of dead zooplankton and their fecal pellets rain onto the sea floor. There, bacteria digest the remains, using up oxygen in the bottom waters in the process.

Surface waters, constantly replenished by the Mississippi, stay relatively oxygen-rich. But this layer floats atop the saltier and heavier ocean water, so there's little mixing with the hypoxic bottom waters. Animals that can't swim away soon die.

This seasonal phenomenon was first detected in the early 1970s by marine scientists assessing the environmental effects of pumping oil and natural gas in the gulf. It wasn't until 20 years later that a team led by marine ecologist Nancy Rabalais of the Louisiana Universities Marine Consortium in Cocodrie had mapped the hypoxic zone (see sidebar on p. 970). Every month for 5 years, the researchers measured oxygen from the surface to the sea floor at nine sites on the continental shelf. Once a year, they took similar readings at more than 60 sites scattered throughout the northern gulf. Until their findings were published in 1991, no one had realized how expansive the dead zone was or that it came back every summer. Most provocative, however, was their conclusion about the dead zone's cause: Rabalais and marine ecologist Gene Turner of Louisiana State University in Baton Rouge argued that fertilizers from farmlands in the Mississippi River Basin were poisoning the gulf.

In 1993, the Mississippi River flooded, and not coincidentally, Rabalais and Turner argued, the dead zone doubled in size from the previous year, to an area covering 17,500 square kilometers—twice as big as the Chesapeake Bay. (At its peak, the 1999 dead zone reached 20,000 square kilometers.)

Rabalais sounded the alarm, prompting environmental groups to pressure the U.S. Environmental Protection Agency (EPA) in 1995 to stop upstream states from polluting

Off Denmark, a Drawn-Out War Against Hypoxia

The first signs of a problem in the Kattegat strait between Denmark and Sweden surfaced in the late 1970s, when Danish coastal officials chronicled a series of fish kills, plankton blooms, and low oxygen readings. The hypoxic conditions suggested that fertilizer runoff from farm fields might be the culprit, but the threat didn't register with the public until a lobster die-off in 1986 in the southern Kattegat.

An intense lobbying campaign led by the Danish Society for the Conservation of Nature persuaded the government to draw up an Action Plan on the Aquatic Environment. After a series of false starts, the plan, enacted in 1987, finally appears to be paying dividends.

The plan called for halving the release of nitrogen from all major sources—agriculture, industry, and sewage treatment plants—and cutting the release of phosphorus by 80% within 6 years. The $24 million a year plan doled out money for steps such as upgrading wastewater treatment plants, paying farmers to plant winter wheat to soak up excess nitrogen from the soil during the fall and winter, and limiting the amount of manure that farmers could dump on their fields.

By 1991, it had become clear that the agricultural measures were having no effect—or were even exacerbating the problem. Planting winter wheat, for example, had led to an increase in nitrogen fertilizer use—farmers had begun applying extra fertilizer in the fall to maximize yields, according to Daniel Conley, a marine ecologist with Denmark's National Environmental Research Institute.

Danish lawmakers tightened restrictions by requiring farmers to account for all fertilizer and manure they applied to their fields (they had not been required to report this before) and extended until 2000 the deadline for achieving nutrient reductions. In 1998, when monitoring again showed scant nitrogen reductions, Action Plan II was trotted out. The government began buying land from farmers to reestablish wetlands and forests, and paying farmers to use less than optimal amounts of fertilizer.

Far greater success was achieved, meanwhile, through regulations to reduce phosphorus emissions, mainly from wastewater treatment plants and industry. Over the last 14 years, phosphorus levels have fallen 80%; today, plankton growth in some coastal areas is limited by the available phosphorus, says Peter Bondo Christensen, a biologist with the National Environmental Research Institute. Although Danish scientists have never compiled a map of the dead zone in the Kattegat strait, their measurements show that oxygen levels are on the rise in open water.

Unlike the situation in the United States, the two constituencies most threatened by Denmark's dead zone are neighbors: "We're such a small country that the farmer lives next to the fisherman," says Christensen. And that means they have to get along to solve the problem, or else be at each other's throats.

–JOHN S. MACNEIL

John S. MacNeil, a former *Science* intern, is a staff writer for GenomeWeb in New York City.

the Mississippi. In response, the EPA held a conference and in 1997 established a task force of state and federal officials to recommend a course of action.

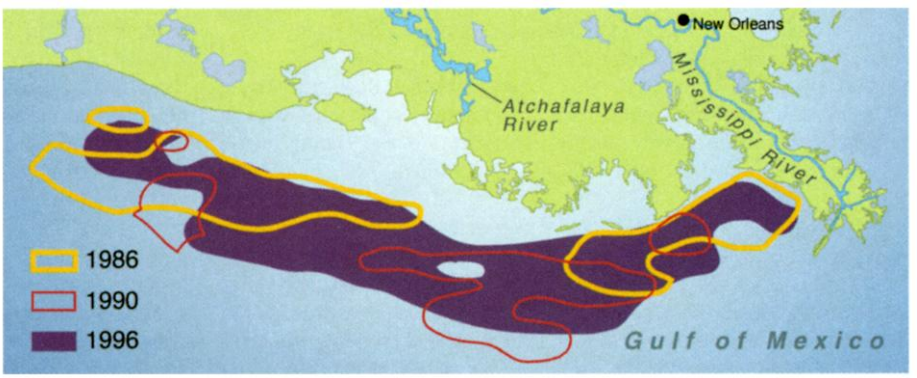
While the EPA's committee deliberated, the Clinton Administration took a baby step toward helping the gulf, proposing $117 million in new funds in 1998 to study runoff and harmful algal blooms, including those linked to the gulf's dead zone. Later that year, Clinton signed into law a measure requiring a White House advisory body, the Committee on the Environment and Natural Resources (CENR), to prepare a report on the dead zone's causes, consequences, and possible fixes. The law also called for the White House to develop an action plan to fix the dead zone by 31 March 2000—a task it entrusted to the EPA-led task force.

In May 1999, the CENR released a set of scientific reports backing the conclusion that chemical fertilizers are the main culprit. They offered several lines of evidence. In the Mississippi River, levels of nitrate—which leaches out of fertilizer-saturated soils—are three times higher now than they were in the 1950s; over the same period, chemical fertilizer use in the Midwest also tripled.

Forging a link between nitrogen levels and hypoxia are studies on sediment cores, which give clues to the gulf's past health. Rabalais and Turner measured concentrations of silicon in core samples. Silicon is a major constituent of the cell walls of diatoms, so it's a good measure of phytoplankton abundance. They found that silicon concentrations rose slowly between 1970 and 1989, tracking well with increasing nitrogen levels. Along with other groups, Rabalais and Turner have done other experiments to show that dissolved nitrates from the Mississippi supply nearly all the nutrients that fuel phytoplankton blooms in the dead zone.

Experts say they have made a compelling case tracing the bulk of the nitrates to human activity. In a study in last July's *Eos, Transactions, American Geophysical Union*, hydrologist Donald Goolsby of the U.S. Geological Survey (USGS) in Denver used water-quality monitoring data from 42 watersheds in the Mississippi Basin to model the nitrogen cycle throughout the basin. Some 7 million metric tons of nitrogen, about 30% of the total flowing into the gulf, came from fertilizer, and that total has risen sixfold over the last 50 years. An equal amount came from soil decomposition and the rest from sources such as animal manure, sewage treatment plants, airborne nitrous oxides, and industrial emissions. Goolsby also found that 56% of the nitrogen inputs into the Mississippi were from five heavily farmed midwestern states, with Iowa and Illinois the biggest sources. Other studies have come to similar conclusions.

While acknowledging that the dead zone is real, farm advocacy groups have de-

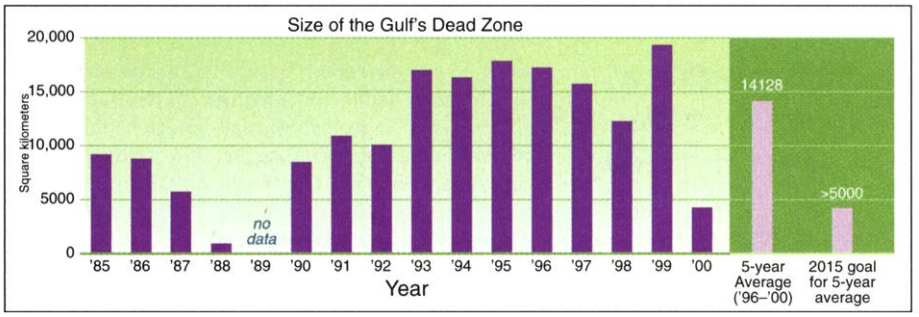


CREDIT: NANCY RABALAIS, LOUISIANA UNIVERSITIES MARINE CONSORTIUM

Hard to pin down. The dead zone encompasses different swaths of water from one summer to the next. Researchers are trying to find out which factors influence this shifting mosaic.

nounced the White House report and the supporting studies. They argue that the link between the use of nitrogen-based fertilizers and the dead zone remains unproven. "We need a cause-and-effect relationship before we can successfully pursue any remedial actions in this area, and those simply don't exist," says Terry Francl of the American Farm Bureau Federation.

As in the global warming debate, a handful of scientists disagree with prevailing scientific opinion and have provided the farm groups with ammunition. Jonathan Pennock of the University of Alabama's Dauphin Island Sea Lab and his colleagues issued a report in May 1999 that cast doubt on the role of fertilizer, instead blaming increases in river flow and organic matter swept downstream. The Fertilizer Institute, a Washington, D.C.–based industry trade group, funded the report.



A disturbing trend. The northern gulf was hammered in the 1990s, with the dead zone swelling to the size of New Jersey in 1999. The next year was dry, and the dead zone returned with a whimper.

The most visible skeptic is Derek Winstanley, chief of the Illinois State Water Survey, who argues that nitrogen levels have always been high in rivers that feed the Mississippi, and that the dead zone is a natural phenomenon that may have plagued the gulf for centuries. Winstanley has roused political opposition to any dead

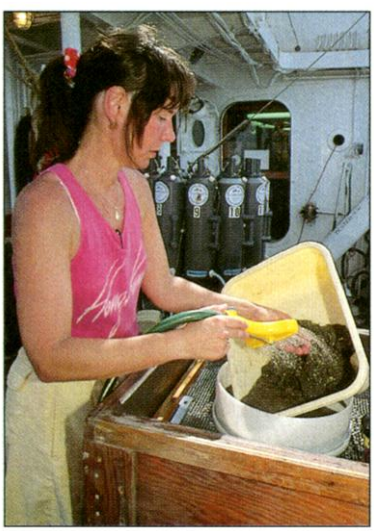
The Dead Zone's Fiercest Crusaders

Nancy Rabalais has fought to make farming states along the Mississippi River pay for the harm she says they have inflicted on the northern Gulf of Mexico; Derek Winstanley has led the counterattack in an effort to clear the Mississippi Basin's name.

Queen of the dead zone

Nancy Rabalais gets so seasick that as a graduate student in marine biology, she studied fiddler crabs just to stay ashore. But one project lured her into open water. In 1985, she and Don Boesch, then director of the Louisiana Universities Marine Consortium in Cocodrie, wanted to know how widespread was a disturbing phenomenon in the northern Gulf of Mexico: patches where the water ran low on oxygen, a potentially lethal threat to the ecosystem. Boesch asked his young research associate to take water samples up to 40 kilometers offshore.

Rabalais steeled herself and ventured out with a crew member in a 6-meter outboard. It was not the sort of boat for a landlubber, and she spent much of the day hugging offshore oil platforms in case she needed to radio for help. "The wind and seas could pick up, the engine could quit on you, you'd be too far offshore, and you could be in trouble," she says. Still, Rabalais got half her data and returned the next day for the rest. It wasn't long before she had persuaded Boesch to buy a bigger, safer research vessel. "I told Don I wasn't going to kill myself for hypoxia," she recalls.



Muck raking. Nancy Rabalais sifts gulf sediment for clues to dead zone's origin.

But Rabalais, 51, has watched herself get crucified for it. She's been demonized by farm groups for publicizing her theory that nitrogen swept down the Mississippi River is primarily responsible for the dead zone. Now, fixing the dead zone is the goal of an ambitious plan that could change farming practices throughout the Mississippi Basin (see main text). And the credit for that belongs primarily to Rabalais. "If it wasn't for her," says biological oceanographer Robert Diaz of the Virginia Institute of Marine Science in Gloucester Point, "no one in Washington would have realized there was a dead zone."

Rabalais worked her way through college at Texas A&I University (now Texas A&M University, Kingsville), grading math papers for busy middle school teachers. She fell in love with the water there (as long as it didn't involve a boat), spending every spare moment snorkeling or scuba diving. Her coming of age as an environmentalist occurred during graduate school at the University of Texas Marine Science Institute in Port Aransas, when she and others battled to stop a U.S. Army Corps of Engineers dredging project in the Corpus Christi Ship Channel that threatened a shallow sea grass bed in a local mangrove forest. Interviewed on local television, Rabalais cut a charming figure with her lilting drawl and disarming smile. Public opposition derailed the project.

The dead zone was a far greater challenge. Rabalais knew from the outset that it would take years of data to understand when, where, and how the waters become hypoxic. But reviewers kept rejecting grant proposals for long-term monitoring, arguing that the work was not innovative enough, says marine biologist Don Harper of Texas A&M University, Galveston, who joined Rabalais on many of the early cruises. "Nobody wanted to listen to this stuff," he recalls. But they cobbled together enough money to keep the project going. Rabalais felt that she had a personal stake in the gulf's health. "It's my home territory," she says.

Rabalais developed another personal connection on the gulf with Gene Turner, a marine ecologist at Louisiana State University in Baton Rouge, who in 1974 had dabbled in hypoxia by volunteering to sort fish on fisheries vessels; he drew water samples wherever the boats stopped for fish. Rabalais and Turner married in 1988, and their daughter Emily was born a year later. "Gene calls her our best reprint," Rabalais says.

By 1991, the dynamic duo had completed 5 years of monthly sampling in the gulf, which revealed the magnitude of the dead zone and the fact that it came back each summer. Since then, says Boesch, "they've put the scientific puzzle together." In 1993, when her annual summer cruise found that the dead zone had doubled, Rabalais is-

CREDITS: (TOP TO BOTTOM) SOURCE: NANCY RABALAIS, LOUISIANA UNIVERSITIES MARINE CONSORTIUM; FRANKLIN J. VIOLA

zone fix that focuses on cutting nitrogen runoff in upstream states.

CPR for the gulf

Winstanley and other skeptics have converted few experts to their cause. The data linking the dead zone to fertilizer runoff "all line up in a pretty convincing way to most folks," says biological oceanographer Donald Boesch of the University of Maryland Center for Environmental Science in Cambridge. He and others are convinced that the gulf will only be healed by cutting nitrogen runoff.

That's exactly what last month's plan intends to do. If it is approved, officials say that starting in 2002, the government would need to spend about $1 billion a year for at least 5 years on measures to wean farmers off heavy use of chemical fertilizers. It's hoped that by 2015, the measures—intended to cut nitrogen discharges to the gulf by 30%—would shrink the dead zone to an average of 5000 square kilometers, less than half its average size during the 1990s. The plan would also provide ample funding for scientific projects, mostly within the USGS and the National Oceanic and Atmospheric Administration, to monitor nitrogen levels and ecosystem health in the Mississippi Basin and in the gulf, says NOAA's Donald Scavia.

The biggest ticket item is reducing fertilizer use. Many researchers believe, for example, that midwestern farmers routinely apply about 20% more fertilizer than needed most years because fertilizer is cheap, gambling that better-than-average weather could bring higher yields, more than offsetting the fertilizer's cost. Money would go to programs that show farmers that this practice of "nitrogen insurance" doesn't pay. Other programs would aim to

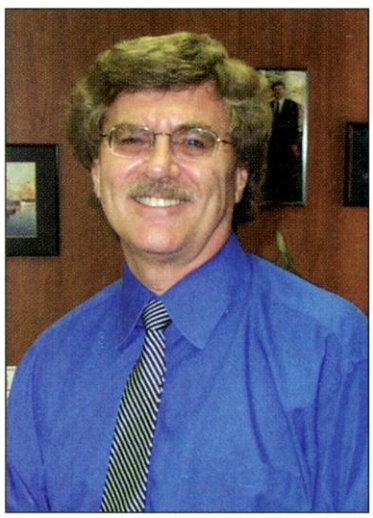
Sopping up nitrogen. This vegetation buffer slows runoff from a nearby cornfield.

sued her first press release. "The nation didn't know about it, and it was important," she says. Soon she was taking journalists and TV crews out to the dead zone and testifying before Congress. Rabalais has been heckled at public hearings by angry farmers, some of whom have accused her of raising awareness of hypoxia simply to further her career. "That one smarts—it's personal," Rabalais says. Yet she's continued to speak out. "That's taken an awful lot of courage," Boesch says. "Most scientists would say, 'Here's my paper, I don't want to get involved.' She's gone in and faced those folks directly."

Even some allies have raised questions about Rabalais's advocacy. While relaxing one evening a few years ago at a scientific meeting, Diaz told Rabalais and Turner that they should tone it down: Their rhetoric was getting ahead of the science. In 1999, however, after the government took steps to address hypoxia, Rabalais and Turner were named environmental heroes by the National Oceanic and Atmospheric Administration, and the pair received the $250,000 Blasker Award for Environmental Science and Engineering, Diaz realized they had taken the right path. "When they got that award," he says, "I took it all back."

Fighting for fertilizer

Environmental scientist Derek Winstanley heads an agency that tracks water quality in a state where farming is big business. So when a federal panel concluded in 1999 that pollution from midwestern farms is the major cause of the Gulf of Mexico's dead zone, top Illinois officials turned to Winstanley, chief of the Illinois State Water Survey (ISWS), to draft the state's response. He came through with a 27-page analysis bearing a strong message: The federal panel's conclusions were biased and unsound. Governor George Ryan signed it and sent it to Washington, D.C., in July 1999, demanding that the Clinton Administration scrap the panel's report and start over.



Farmer's friend. Derek Winstanley has written reports rebutting dead zone–fertilizer link.

Ryan's plea was ignored, but Winstanley had only begun to fight. Speaking at the annual meeting of the American Farm Bureau Federation in January 2000, Winstanley blasted the federal panel as part of a runaway regulatory effort grounded in "environmental religion" and told farmers there that federal regulations that would clamp down on fertilizer use were "a big steam train coming down the track ... right at you."

Winstanley, 55, has sought to discredit what he calls the "fertilizer hypothesis" advocated by Nancy Rabalais and others. Last June, Winstanley and ISWS colleague Edward Krug released a 172-page report arguing that Illinois rivers were loaded with nutrients before European settlers began farming the prairie in the mid-1800s, based largely on historical descriptions of these lands, and that modern agriculture had "greatly cleansed" the Illinois River in the past 50 years.

Later that month, he ripped into the federal hypoxia panel in testimony before the U.S. House Agriculture Committee, claiming it had ignored important data on natural sources of nitrogen runoff that undermine the link between fertilizer use and the dead zone. That argument netted results: Congress attached a provision to an emergency aid bill, signed into law by President Clinton last July, that blocked the Environmental Protection Agency from funding until October 2001 certain water-pollution programs meant to cut agricultural pollution.

Notwithstanding that success, a range of experts have dismissed Winstanley and Krug's conclusions. Biogeochemists Mark David and Gregory McIsaac of the University of Illinois, Urbana-Champaign, and four colleagues released a 29-page rebuttal of Winstanley's report last October. "It's politics in the guise of science," says biological oceanographer Don Boesch of the University of Maryland Center for Environmental Science in Cambridge.

Winstanley "strongly disagrees" with his critics and says he's "upset that it's got to slinging mud." He and Krug have submitted their findings to peer-reviewed journals. But if Congress approves the ambitious plan to shrink the gulf's dead zone, the results of that program would be the ultimate test of whether Winstanley's arguments hold any water.

–D.F.

CREDITS: (TOP TO BOTTOM) JASON LINDSEY; COURTESY OF DEREK WINSTANLEY

include nitrogen-fixing crops such as alfalfa in the rotation. If such were planted on just 10% of the cropland, the CENR reports stated, nitrogen discharges would decline significantly.

Some farmers say they have already cut fertilizer use and that further reductions would harm their bottom line. But analysts insist that the vast majority could alter their practices without suffering. Changes that cut nitrogen runoff by up to 25%, says agricultural economist Otto Doering of Purdue University, the lead author of the CENR report's economics section, "would not have a severe impact on farmers or on food costs."

The plan would also pay farmers to restore wetlands and plant buffer strips of trees and grasses between farm fields and streams. More vegetation would mean more denitrification, a microbial process in which nitrate is converted into nitrous oxide and nitrogen gases that escape into the atmosphere. This would right a historical wrong. Over the past 150 years, midwesterners have cleared and drained untold millions of hectares of nitrogen-absorbing bottomland forest and wetlands for agriculture, says wetland ecologist William Mitsch of Ohio State University in Columbus.

If it becomes legislation, the action plan would await an uncertain fate in Congress, where it may face opposition from conservatives and must compete for money with scores of other proposals. "I don't think it will be easy," says a Republican Senate aide familiar with the plan.

Luckily for plan backers, farm groups are sending mixed signals. Taking the toughest stand is the American Farm Bureau Federation: "There's simply no way our organization could support" the plan in its current form, says Francl, who says his organization will lobby against it. But the Fertilizer Institute sees merit in aspects of the plan that pay farmers to use fertilizer wisely and plant buffer strips. "You'll see us and many in the [agriculture] community supporting ... policies that will help reduce nutrient loss," says spokesperson Ron Phillips.

Also testifying to the plan's merits are chronicles of other dead zones around the world. Cutting fertilizer use and restoring wetlands in Sweden and Denmark have slashed nutrient inputs into the Kattegat strait, which links the North Sea and the Baltic Sea; oxygen levels are on the rise (see sidebar on p. 969). And a hypoxic zone in the Black Sea even bigger than the Gulf of Mexico's appears to be taking its last gasps. The Black Sea's problems began in the 1960s, after years of being bombarded with heavy fertilizer runoff. When the Soviet Union collapsed in 1990, so did most central support for agriculture, and chemical fertilizer use fell by more than half. By 1996, the Black Sea's dead zone had disappeared for the first time in 30 years.

Aside from those case studies, experts are putting their faith in models that predict the gulf's comeback after less nitrates are fed into it. Using reams of data on everything from oxygen levels and sunlight to temperature and phytoplankton levels, water-quality modeler Victor Bierman of Limno-Tech Inc. in Ann Arbor, Michigan, and his colleagues have predicted that a 20% to 30% reduction in nitrogen levels in the Mississippi would raise oxygen levels as much as 50%, providing enough of the molecule to prevent many hypoxia-related deaths. But it's likely to take more than a decade to see results, Bierman says.

Johnny Glover doesn't know if he can wait that long. Back in the 1970s, when he started out in the fishing business, the waters near the seaside town of Cocodrie teemed with fish. Now Glover manages 10 charter boats, and his captains must travel kilometers farther than they used to to find king mackerel, black drum, and red snapper. "We're working around [the dead zone], but it's getting harder and harder to make a living," he says. For Glover and other hard-pressed fishers, a cure for the dead zone is long overdue. **–DAN FERBER**

AVIATION

Dirigibles to Grace Skies Over Germany Once Again

Companies are betting that giant airships not seen since World War II can pay off in ferrying tourists and heavy objects—and perhaps even doing science

For people who recall images of the zeppelin *Hindenburg*'s fiery demise in 1937, the thought of the cigar-shaped ships—and flying in one—might stir an unsettling feeling. This spring, a company called Zeppelin Luftschifftechnik hopes to wipe away those disturbing thoughts with a new breed of airship to carry tourists in Germany, and eventually to other European countries.

Hot on its heels is a company designing the world's largest airship, a dirigible for transporting heavy machinery that could make its debut in about 2 years. Fueling the dirigible's renaissance is what appears to be a healthy demand from sightseers and a niche market in the cargo world. Research trips could soon follow. "This is just the starting signal for the development of new airships," says aviation engineer Ingolf Schäfer, a consultant based in Lahnau, Germany.

Dirigibles hit the comeback trail in 1988, when the company Luftschiffbau Zeppelin, which had long since gotten out of producing dirigibles and into producing radar aerials and silos, asked staff engineers Klaus G. Hagenlocher and Florian Windischbauer to study whether airships had the potential to fly again. The duo reviewed the safety and flying records of all 119 zeppelins produced before the airships were shelved in 1940. They concluded that dirigibles could offer a safe alternative to hot-air balloons and other sightseeing vessels—but that there would be too few customers to make transatlantic crossings pay.

Not just hot air. Zeppelin is back in the dirigibles business with a craft that atmospheric scientists are hoping to catch a ride in.

CREDIT: ZEPPELIN LUFTSCHIFFTECHNIK GMBH

In 1993, Zeppelin Luftschifftechnik was established to make dirigible tourism a reality. The firm was situated in a nostalgic location: Friedrichshafen, where Count Ferdinand von Zeppelin made his dirigible dream come true when he took his LZ 1 into the air on 2 July 1900. Exactly 100 years later, the count's