10

Strangled Waters

Second Wave

In August 2014, the water supply for the city of Toledo, Ohio, was poisoned. Officials issued an order to the half-million residents connected to the municipal water supply: Don't drink, cook, or brush your teeth with the water. Do not use it to bathe your children, and don't give it to your pets.[1] Stores ran out of bottled water, and residents had to wait in long lines or travel to neighboring towns to find more.

The culprit was a bright green plume of *Microcystis*, a cyanobacterium that thrives in warm water tainted with heavy loads of phosphorus and nitrogen.[2] Every spring, rains wash a pulse of nutrients off fertilized fields and send it down the Maumee and Sandusky rivers and into western Lake Erie. Every summer, as water temperatures rise, *Microcystis* forms an iridescent mat over parts of the lake's surface.[3] In early August 2014, strong winds blew a lawn of cyanobacteria over Toledo's water intake, which lies just outside the Maumee's mouth. Tests showed that the city's water contained dangerous levels of microcystin, a liver toxin produced by the bloom. The drinking water crisis was a dramatic signal of Lake Erie's descent back into eutrophication.

In the 1980s, after sewage plants in the watershed were upgraded and phosphate detergents banned, Lake Erie experienced a revival. Algal blooms faded, and populations of walleye rebounded. The lake grew a thriving tourist industry based on sport fishing. Then, in 1995, researchers recorded the lake's first widespread bloom of *Microcystis*.

Eruptions of *Microcystis* have since become a predictable event striking the western Lake Erie basin every summer. The most widespread and long-lasting blooms hit in 2011 and 2015, after intense spring rains dumped heavy loads of nutrients into the lake. Climate models forecast warmer summer temperatures and heavier spring rains for the Great Lakes region. Those conditions are a recipe for more and larger algal blooms, and are likely to favor *Microcystis* in particular.[4]

The regulatory efforts of the 1970s and 1980s made great progress in cleaning up discharges from industries and sewage treatment plants, but failed to address nonpoint source pollution flowing from farm fields and city streets. An overload of nutrients carried in storm runoff from cropland is now the major source of pollution in Lake Erie's western basin.

An emerging body of research suggests that human actions have driven the evolution of new and different kinds of harmful algal blooms (HABs)—or more specifically cyanobacterial blooms (cyanoHABs). *Microcystis* was present in the twentieth-century lake, during the days when Lake Erie was declared "dead" by the popular press, but back then it was relatively scarce. Today it dominates cyanoHABs not only in Lake Erie but in many polluted waters worldwide, including Florida's Lake Okeechobee, the Baltic Sea, Lake Taihu in China, and Lake Ohnuma in Japan. *Microcystis* blooms have been reported from 257 countries in the Americas, Europe, Asia, Australia, and Africa.[5] The organism thrives in warm waters that are rich in nutrients and low in salinity.

Delving into the ecology of *Microcystis*, scientists have begun to debunk the long-held assumption that control of phosphorus alone can rescue eutrophic lakes. Phosphorus loads do fuel cyanoHABs in Lake Erie, but excess nitrogen shifts the balance in favor of *Microcystis*, rather than diatoms, green algae, or the nitrogen-fixing cyanobacteria that dominated polluted lakes in the twentieth century. Microcystis also requires abundant nitrogen to produce toxin. "Many lakes that have *Microcystis* blooms are receiving increasing loads of nitrogen from synthetic fertilizers, urban runoff, and atmospheric pollution," says Hans Paerl, a microbial ecologist at the University of North Carolina at Chapel Hill. "Nitrogen is the new part of the story."

The principal source of both phosphorus and nitrogen flowing to Lake Erie stretches for thousands of square miles across northwestern Ohio and eastern Indiana. The rich earth and the hard work of farmers in the region produces hundreds of millions of dollars' worth of soybeans and corn, as well as wheat, vegetables, pork, and poultry. The landscape is a vast, flat expanse of tidy fields dotted with modest farmhouses and criss-crossed with county roads.

The Great Black Swamp once stood here. A missionary who passed through in 1791 described "deep and troublesome marshes, the horses at every step wading up to their knees."[6] On an 1808 map, the swamp, which covered most of northwestern Ohio, was designated as "land not worth a farthing." Settlers came anyway, felling the giant sycamores and oaks, strapping wide wooden shoes to their horses' feet to stop them from sinking into the mud. By the turn of the twentieth century, blood, sweat, and ingenuity had transformed the swamp into productive farmland.

The tough people who conquered the Great Black Swamp passed down a loathing of wetlands that remains strong to this day. "Ohio has eliminated a large percentage of our natural wetlands," says Sandusky County engineer Jim Moyer. "Well, I say *good*, because that's where I live." These attitudes are written into state law, which makes impossible any action, including wetland creation, that slows the flow of runoff through constructed drainage ditches—the conduits that, after each heavy rainfall, deliver thousands of metric tons of phosphorus and nitrogen[7] to the Maumee, and onward to Lake Erie.

In the aftermath of Toledo's drinking water crisis, wetlands expert and professor emeritus at Ohio State University William Mitsch offered up a characteristically blunt manifesto. Harmful algal blooms have become chronic in western Lake Erie, he wrote, because of the wrongheaded way people manage the watershed.[8] Mitsch proposed that a significant fraction of the region's rich cropland be taken out of production and converted to wetlands, which act as natural filters for the overload of nutrients now flowing from farm to river to lake.

Mitsch's idea strikes many locals as pure craziness, but that doesn't bother him. A bearded, bespectacled man who knows wetlands in the intimate way most of us know our hometowns, he built a wetland park at the Ohio State campus in Columbus, where he spent more than twenty years teaching and studying ecological engineering (Fig. 10.1). He coauthored a textbook that has become a bible for students of wetland ecology and management—now in its fifth edition.[9]

With an encyclopedic knowledge of close to fifty years of evolving science, Mitsch has become an eminent advocate for wetland restoration in a world where these habitats have become rare and precious. His dream for the former Great Black Swamp is based on a lifetime of studying the inner workings of wetlands.

He envisions tens of thousands of acres—or roughly 7 to 10 percent of the ground here—being restored to wetland. "You'd need 10 percent of the landscape filtering for you so you can farm the other 90 percent," Mitsch says.

That's going to be a tough sell to the region's thousands of farmers, who make their living off the soil laid down by the former Black Swamp. For them, says

Figure 10.1 Bill Mitsch at the Everglades Wetland Research Park, Naples, Florida. Photo by Sharon Levy.

Kris Swartz, a farmer and president of the Ohio Federation of Soil and Water Conservation Districts, every bit of earth is valuable. Swartz estimates that it would take a forty-acre wetland for every square mile of crops to solve the nutrient pollution problem in western Lake Erie.

"Who's going to give up the ground?" he asks.

As a graduate student in the 1970s, Mitsch ran sewage from a Florida trailer park through a native cypress swamp.[10] His experiment demonstrated that the wetland acted as an efficient natural filter, absorbing pathogenic bacteria, organic matter, nitrogen, and phosphorus. At the time, researchers in Michigan were showing that peat bogs could serve the same function. Mitsch's blue-gray eyes gleam behind his wire-rimmed glasses as he remembers that era. "We discovered this ecosystem service of wetlands cleaning polluted water," he says, "and interest in them exploded. People began to argue that wetlands should be protected because they act as nature's kidneys."

Mitsch's textbook includes a map of the original Black Swamp. He sees it as an important example of a landscape transformed, to the point where few remember it was ever a wetland. It's a pattern that has played out more than once in American history: The nation's most productive farming areas are converted wetlands. Much of the Midwestern Corn Belt was wet prairie. California's Central Valley was a vast tule marsh. The sugar fields of south Florida were a mix of cypress swamp and sawgrass wetland.

After settlers cleared the Black Swamp of its giant trees and drained it, they found themselves in possession of some of the most productive farmland on the planet. Over time, farming depleted the soil of nitrogen and phosphorus, elements key to plant growth. So farmers added manure, and later, synthetic fertilizer. Some of the nutrients were taken up by crops. Much washed down to the ditches, into the Maumee and Sandusky rivers, and on to Lake Erie.

Today, farmers in the former swamp continue to lay more lines of drain tile, spaced closer together. The clay pipes placed by their ancestors have broken; the modern version consists of plastic tubing that can be purchased by the spool.

Rainwater that percolates through the soil of farm fields and into the tile drains dissolves phosphorus. Conventional wisdom once held that phosphorus ran off agricultural land only in particulate form, attached to grains of sediment. Particulate phosphorus tends to settle out of the water column and remain, for the most part, out of reach for nutrient-hungry algae. Soluble phosphorus, known in the lingo of water pollution as dissolved reactive phosphorus (DRP), is 100 percent bioavailable.

In the mid-1990s, levels of DRP began to climb in the tributaries of the Maumee.[11] DRP fuels blooms of *Microcystis* and other kinds of cyanobacteria that have become an annual blight in Lake Erie.

The rise in DRP was triggered by a series of changes in farm management.[12] Instead of rotating their fields among a number of crops, including hay, wheat, and rye, farmers focused on highly fertilizer-dependent corn and soybeans. Subsidies for ethanol production drove yet more planting of corn. Many northwest Ohio farmers adopted no-till agriculture, in which seeds are planted through the stubble of the previous year's crop, without plowing. No-till decreases erosion and improves the health of the microbial communities that build soil. Soil in no-till fields is coarse, and tends to slow the flow of water, allowing it to seep underground and decreasing surface runoff. At the same time, it increases the amounts of dissolved nitrogen and phosphorus reaching tile drains.

In 1995, the first major bloom of *Microcystis* struck thewestern basin,[13] fueled by nutrient-rich farm runoff flowing out of the Maumee. The river that once ran clear through the northern reaches of the Great Black Swamp now carries an overdose of phosphorus and nitrogen to the lake every spring, triggering *Microcystis* blooms every summer.

"Replace a swamp with high-fertilization agriculture, and you're going to screw up something downstream," says Mitsch.

Lake Erie's most intense bloom to date occurred in the summer of 2015, after a spring of heavy rain. Climate change models predict heavier spring rains and higher summer temperatures for the region, a recipe for intensified blooms of cyanobacteria.[14] But even if reviving parts of the Great Black Swamp makes sound ecological sense, it's an unpopular idea in an area devoted to farming.

"Mitsch is right in concept," says Ken Krieger, director emeritus of the National Center for Water Quality Research at Heidelberg University in Tiffin, Ohio. "But it's very unlikely that politically and socially the climate will ever be right to take land away from farming and convert it back to wetlands."

The most impressive remnant of the Black Swamp is Goll Woods Nature Preserve. An island of forest that juts from a sea of farm fields in Fulton County, Ohio, the preserve holds some of the last old-growth trees that grew in the original swamp. Centuries-old bur oaks and sycamores stand like the abandoned pillars of a long-vanquished kingdom. Their massive trunks run straight toward the sky, supporting whorls of leafy branches that hang ninety feet up in the air. Standing in the heart of Goll Woods, immersed in the aroma of dry mud and fallen leaves, it's easy to conjure the lost wilderness. An expanse of ancient trees stretched for a million wet acres, interrupted only by stands of tall marsh grass. The residents were deer, elk, wolf, cougar, badger, beaver, bear, muskrat, and an astounding abundance of waterfowl. But in northwest Ohio, the swampy past is a very foreign country.

A federal program devoted to controlling nutrient pollution in Lake Erie's western basin supports small wetland restoration projects. The program allows the government to rent fields that are converted to marsh, and to pay landowners rates that can make at least marginal, flood-prone land more profitable than struggling to grow a crop. But relatively few farmers have signed up, and those who do hear complaints from neighbors who fear any wetland will cause water to back up and flood their crops, or who simply can't abide the untamed look of wetland plants.

"We're putting wetlands in," says Steve Davis, a watershed specialist with the federal Natural Resources Conservation Service. "Not near as many as we would want to, or as we could, or even as we have funding for." Most of the landowners who accept the idea are duck hunters, motivated to provide habitat on their property.

Brothers Christian and Peter Lenhart co-own a farm near Defiance, Ohio that's been in the family since it was first homesteaded in the 1840s. When Chris, a water resources scientist at the University of Minnesota, first brought up the idea of restoring a marsh on part of the land, local agricultural officials tried to talk him out of it.

"Ohio is much more anti-wetland than the rest of the Midwest," notes Chris, who works with Minnesota farmers to develop wetlands designed to filter agricultural runoff. "Talk to people about building a wetland in Defiance County, and they kind of think you're crazy. It goes beyond rationality. It's the communal memory of people dying of malaria in the Black Swamp."

Pete, a physician in Defiance, has grown passionate about both native plants and wetlands. To create the seasonal marsh that now thrives on the Lenhart farm's back forty, he and his daughters hand-collected seeds of rare native plants. Walking there on a sunny July afternoon, Pete runs his hand lovingly over the bright yellow blossoms of black-eyed Susan, the curling purple petals of bergamot, the bunched seedheads of Ohio spiderwort. The sedges he planted flourish on the wetland's floor, which goes dry in summer.

In spring, this ground lies beneath a sheet of water and attracts an abundance of dabbling ducks—blue-winged teal, northern shovelers, pintails. During their long migration north to breeding grounds in Canada, the birds drop down to rest on the Lenharts' wetland, a rare oasis of natural water among the drained fields. The northern harrier, a marsh-adapted hawk now endangered in Ohio, has been seen hunting here. In spring the neighbors complain of the noise from thousands of courting frogs.

The Lenhart wetland clearly works as habitat,[15] but in terms of improving the quality of water running down to the Maumee, it's not doing much. The family could not build a wetland that intercepted the flow of polluted runoff in the ditch, because the Defiance County Soil and Water Conservation District, which is responsible for enforcing state drainage laws, rejected the idea. "They're very authoritarian and incredibly powerful," says Pete, whose sardonic shorthand for drainage officials is "ditch Nazi."

The district recently came in and rehabbed the ditch that passes through the farm, over the objections of the Lenharts and other local property owners. Before the district improvements, Pete could count around fifty species of plants growing in the ditch—many of them natives. Now the area is dominated by a single species: fescue.

Jason Roehrig, administrator for the Defiance County Soil and Water Conservation District, points out that drainage ditches are manmade channels designed to keep water off the fields. By law, ditches under the district's purview must be maintained in perpetuity—not as habitat for native plants but as stable conduits that can handle intense flow in times of heavy rain. Fescue is not a native species, but Roehrig notes that it "provides a durable, dense sod that resists erosion and is relatively quick and easy to establish." By contrast, native plants are much slower to take hold.

"These fields aren't ecosystems," Pete says as he gestures at the vista of drained fields that stretches to the horizon. "They're factories." During my travels in northwest Ohio, I heard the same sentiment from several other farmers.

Ohio's ditch regulations give every landowner a right to the fastest, most efficient drainage, and make no allowance for other priorities. "The ditch commissions are in direct conflict with efforts to clean up the water flowing into Lake Erie," says Pete.

Jim Moyer, the engineer for Sandusky County, has spent much of his career designing and maintaining drainage ditches. One of the biggest challenges in his work is the flatness of the landscape. If the fields of the former Black Swamp were significantly uphill from Lake Erie, he notes, it would be easier to build wetlands into the ditch system without disrupting it. Moyer has boated through bright green algal blooms in Erie's western basin. "I don't want to swim in this lake if it's gonna be like that. I don't want to eat any fish out of it either," he says. "So I hope we come up with a solution."

He doesn't see large-scale wetland restoration as practical, however. "I try to be realistic," he says. "In our county, agriculture is important. We have corn, soybeans, and wheat, but also tomatoes, cucumbers, peppers, cabbage: those are high-dollar crops, and, boy, they cannot tolerate any excess water."

Most farmers in the region acknowledge the need to limit nutrient runoff. The federal Natural Resources Conservation Service has a three-year, $41 million program available to help farmers implement changes aimed at stopping nutrient pollution in western Lake Erie. The money can be used to fund a range of strategies, from high-tech management of fertilizer application to planting buffer strips of grass or trees at the edge of ditches. Buffer strips have been widely adopted in the former Black Swamp. They are effective in decreasing erosion, and can reduce the amount of total phosphorus running off a field by about half.[16] Tile drains running beneath the soil surface continue to carry soluble phosphorus and nitrogen off the land, however.

A recent analysis by researchers at the University of Michigan suggests that under the current levels of use, buffer strips and other best management practices (BMPs) aimed at minimizing nutrient runoff won't be enough to rescue Lake Erie.[17] The BMPs do help, but a relatively small proportion of farmers are using them.

The study found that taking 50 percent of cropland out of production and letting switchgrass grow there would bring phosphorus loads in Lake Erie down by 40 percent, the goal set in an international agreement between Canada and the US. The authors acknowledge that's never going to happen, but they included that example in their study to underscore the scale of change that will be needed to address the problem.

Mitsch agrees that BMPs alone won't solve the problem. He points to the infamous dead zone in the northern Gulf of Mexico, which is fueled by nutrients that run off farms in the Mississippi basin. In the 1990s, Mitsch was part of a committee that studied solutions to the problem, and concluded that BMPs were part of the answer, along with building wetlands back into the watershed. Twenty years later, only a few scattered wetlands have been restored. In 2017, the dead zone expanded to an unprecedented 8,776 square miles, about the size of New Jersey.[18]

Chris Lenhart has begun studying nutrient retention in the family's marsh and two other nearby wetland projects. "Our wetland is removing a fair amount of nitrogen and phosphorus," he says, "but it's not treating any additional farmland. To really treat the problem, you need wetlands that collect runoff from hundreds of thousands of acres."

There is only one place on the planet where constructed wetlands are successfully treating farm runoff on that scale: in the Everglades Agricultural Area (EAA) of south Florida. Once part of the sawgrass marsh and cypress swamp that made up the original Everglades, the EAA was drained in the early 1900s, when canals were dug to divert Lake Okeechobee's waters to Florida's coasts. As in the Black Swamp, drainage uncovered fertile wetland soils. Farm runoff degraded the surviving Everglades wetlands, which lie south of the EAA. Cattail, a wetland plant adapted to phosphorus-rich waters, displaced the native sawgrass. Herons and egrets find little prey in thick stands of cattail, and the plant's rapid expansion contributed to a 90 percent decline in the abundance of wading birds in the Everglades.[19]

By the 1980s, conservationists were demanding that Everglades National Park be protected from water pollution. In 1988, the federal government sued two Florida environmental agencies for failing to enforce the state's own water quality standards. Three years into the litigation, Governor Lawton Chiles walked into federal court in Miami and announced the state's surrender. "We want to plead that the water is dirty," he said. "We want the water to be clean, and the question is how can we get it the quickest."[20]

After more than two years of intense negotiations, the US Department of Justice and the state of Florida reached a settlement agreement. The path to clean water in the Everglades would involve converting tens of thousands of acres of farmland to constructed wetlands, designed and managed to filter out phosphorus. In addition, farmers would be required to use BMPs to limit the concentrations of phosphorus in runoff.

The first pilot treatment wetland was created on 3,815 acres of state-owned land. Scientists working on the project demonstrated that the managed marsh could remove about 80 percent of the incoming phosphorus load. Over time, cattail and other aquatic plants died and decomposed on the bottom, building a new layer of organic peat that acts as long-term phosphorus storage.[21]

The lessons of the first pilot marsh have been applied to a series of scaled-up constructed wetlands built at the southern edge of the EAA, called stormwater treatment areas (STAs) by the South Florida Water Management District. The STAs now cover more than 57,000 acres.

"The STAs do an outstanding job of filtering phosphorus," says Gary Goforth, an environmental engineer who worked on development and operation of the large-scale wetlands for two decades. When the first STAs were built in 1994, the goal was to take runoff water carrying about 200 parts per billion (ppb) phosphorus and reduce the load to 50 ppb. Nowadays, the STA effluents are well below that figure, often containing less than 20 ppb phosphorus. Walk one of the dikes that surround the wetland cells, and you'll find yourself surrounded with wood storks, roseate spoonbills, black-necked stilts and alligators.[22]

The success of the STAs has been possible in part because farmers adopted a range of BMPs, including holding water on some of their fallow fields and carefully measuring soil nutrient levels so that fertilizer is applied only where it's needed. The Everglades farming community had to be drawn into the process against its collective will. Goforth, who served as an expert witness during a long series of court cases involving Everglades restoration, recalls farmers testifying that a required 25 percent reduction in runoff phosphorus loads would put them out of business. Today, using an evolving array of BMPs, phosphorus loads in waters entering the STA system have been reduced significantly—by an average of about 50 percent in recent years.

The engineers who built the STAs and continue to monitor their function have created an extensive knowledge base on how to design and operate large treatment wetlands. Circumstances would, of course, be different in northwest Ohio, where wetlands might freeze and plant growth halts during winter. The system should be easily adapted, however.

Mitsch has been tracking two small restored wetlands he built on the Ohio State campus in 1994. They are reliably retaining phosphorus, carbon, and nitrogen. Robert Kadlec, an emeritus professor at the University of Michigan who has consulted on the design and operation of the STAs since their inception, has also demonstrated that both natural and constructed wetlands effectively absorb excess nutrients in the Midwest.[23] "What we need in the western Lake Erie watershed," says Mitsch, "is something on the scale of the STAs in Florida."

The major obstacles, whether in Ohio or Florida, are social and political. "In my experience," says Goforth, "agriculture is a very strong lobby in any state, any country. It took the federal lawsuit to bring the farmers to the table. They realized it wasn't just business as usual."

Farmers in the EAA have adapted. Keith Wedgeworth runs a farm that has been in his family since the 1920s. "We bought into the STAs, and they've done what they were supposed to," he says. Due to an array of BMPs, Wedgeworth says the runoff leaving his farm is cleaner than the water that flows in from Lake Okeechobee.

After Mitsch retired from teaching at Ohio State, he returned to south Florida. He is now director of the Everglades Wetland Research Park at Florida Gulf Coast University—living and working in America's wetland mecca. The struggle to create the STAs there was resolved when the state was able to buy land from willing sellers. Wetland peat makes rich soil, but when dried out and exposed to the air it can oxidize, vanishing in a slow, invisible burn. At the southern edge of the EAA, farmers were going out of business because the layer of soil above the limestone bedrock had worn too thin. They were willing to move on.

Still, the controversy has recently revived, because it turns out 57,000 acres of treatment wetlands may not be enough. Heavy rains struck Florida in the winter of 2015–2016, during what is usually the region's dry season. The volume of polluted water that ran into Lake Okeechobee was too much for the STAs to handle, so it was sent, untreated, down the canals that lead to the Atlantic and Gulf coasts. The stormwaters carried an intense pulse of nutrients to estuaries, triggering a guacamole-thick bloom of cyanobacteria that continued to plague the region months later.[24] Mitsch has suggested that the only solution is to buy out more than 80,000 additional acres of farmland to create more STAs.

If that is ever to happen, the question will be the same one Swartz poses in Ohio: Who will give up their ground? Wedgeworth feels that farmers in the EAA, south of Lake Okeechobee, are already doing their part. "We're part of the solution," he says. "It's in my interest to be the best steward of the land possible, so I'm able to pass it down to future generations in my family." The nutrient load tainting Lake Okeechobee flows in from the north, and Wedgeworth argues that any new water treatment projects should be built upstream.

Everglades National Park covers 1.5 million acres and is known worldwide as a wilderness gem. The Everglades is listed as a Wetland of International Importance under the Ramsar Convention, a pact aimed at protecting vital wetland habitats worldwide. The push for a global wetlands agreement began in the 1960s, fueled by concerns over vanishing habitat for migratory waterbirds, but Ramsar Convention criteria have evolved to recognize other wetland ecosystem services, including water quality protection.

Conservation groups in Ohio, meanwhile, have focused on restoring native wetland plants and providing waterfowl habitat. Altering flows to allow polluted water to slow down, spread out, and be filtered through aquatic vegetation is rarely considered, Mitsch says. The only Ramsar site in Ohio is the Olentangy River Wetland Research Park, which takes up fifty acres on the Ohio State University campus in Columbus. Mitsch drove the creation of the wetland complex beginning in 1994, when he built his two small, experimental wetlands fed with water pumped from the Olentangy.

Mitsch remains hard at work, trying to demonstrate that farming and wetlands can coexist. His latest study uses mesocosms, arrays of miniature marshes set up in tubs, which allow him to test the effects of different flow rates and plant communities on a wetland's ability to take up nutrients. One test site is near the shore of Buckeye Lake in Ohio, which has been plagued with harmful algal blooms. A second is in south Florida, and Mitsch is seeking funds for a third site on Long Island, New York.

"We're going to experiment with a clever way of trapping phosphorus in wetlands and then returning it to agriculture," says Mitsch. He won't reveal the details of the plan, which he says are proprietary—but it will be applicable to the former Black Swamp. The goal is to merge wetlands with farming, using manmade marshes to capture nutrients that can then be returned to the fields, saving farmers the cost of synthetic fertilizer.

Mitsch was encouraged when he visited Sweden and was shown a system set up to capture the nutrient pollution that has caused harmful algal blooms in the Baltic Sea. He sent me a photograph: a flat green field that might have been in northwest Ohio. What marked the place as foreign was a long strip of tall reeds, sprouting from a constructed wetland that stands between the field's edge and the drainage ditch. Swedish researchers have suggested that the government should pay farmers based on the amount of nutrients sequestered in their wetlands, a policy that would cast farmers as environmental entrepreneurs.[25]

Mitsch has been thinking big about wetlands for a lifetime. He still hopes to transform the way soggy American landscapes have been managed since settlement times, and to fit wetlands back into the picture. He insists that any real solution will have to be deployed on a grand scale, one that matches the sweeping changes made to the former Black Swamp. If we're not willing to do that, Mitsch says, we should admit we're willing to accept lakes painted bright green by blooms of cyanobacteria.

In estuaries, where rivers meet the sea, the joining of fresh and salt waters traditionally results in a profusion of life. But the same plague that has struck Lake Erie now plays out in estuaries around the globe: HABs create large areas of oxygen-depleted water in more than four hundred estuaries worldwide, where major watersheds empty their loads of human-generated nutrients into the sea.[26] In the years after World War II, the use of synthetic nitrogen fertilizers increased dramatically. The planet's coastal dead zones have expanded and intensified over the same stretch of time, fed by a human-generated glut of nitrogen.[27] (In salt water, nitrogen is most often the crucial limiting nutrient.)

A repeated pattern of destruction has been traced in eutrophic estuaries around the world. An overload of nutrients leads to blooms of phytoplankton, dominated by toxic forms that cannot be eaten by copepods and other small grazers. Meanwhile, over-harvest of larger fish, often the apex predators, means that smaller prey fish multiply, feeding on and further reducing populations of zooplankton. So phytoplankton flourish, forming larger HABs. Often an invasive marine animal tolerant of eutrophic conditions will come to dominate. When the Black Sea's ecosystem collapsed in the 1980s, native fish vanished and invasive comb jellyfish became wildly abundant.[28]

Remnants of long-dead foraminifera, tiny marine creatures that leave behind ornate shells of calcium carbonate, reveal the history of nutrient overload in great estuaries like the Chesapeake and the northern Gulf of Mexico. The diversity of foraminifera (forams for short) declined in the Gulf during the 1940s as the use of synthetic nitrogen fertilizers began in earnest. The ratio of *Ammonia parkinsoniana*, a foram tolerant of low oxygen conditions, to that of oxygen-hungry *Elphidium* spp. has proved to be a consistent sign of oxygen depletion in the Gulf, Chesapeake Bay, Long Island Sound, and other coastal areas.[29] In all these waters the ratio of *Ammonia* to *Elphidium* increased significantly after the 1950s. An oxygen-loving foram, *Quinqueloculina*, was abundant in the Gulf from 1700 to 1900, showing that hypoxia was not a problem then. Today the dominant foram is a hypoxia-tolerant creature, *Buliminella morgani*, known only from Gulf of Mexico.[30]

River flows form a lens of lower-density water as they empty into an estuary, trapping the saltier bottom waters below. As phytoplankton bloom and die, their

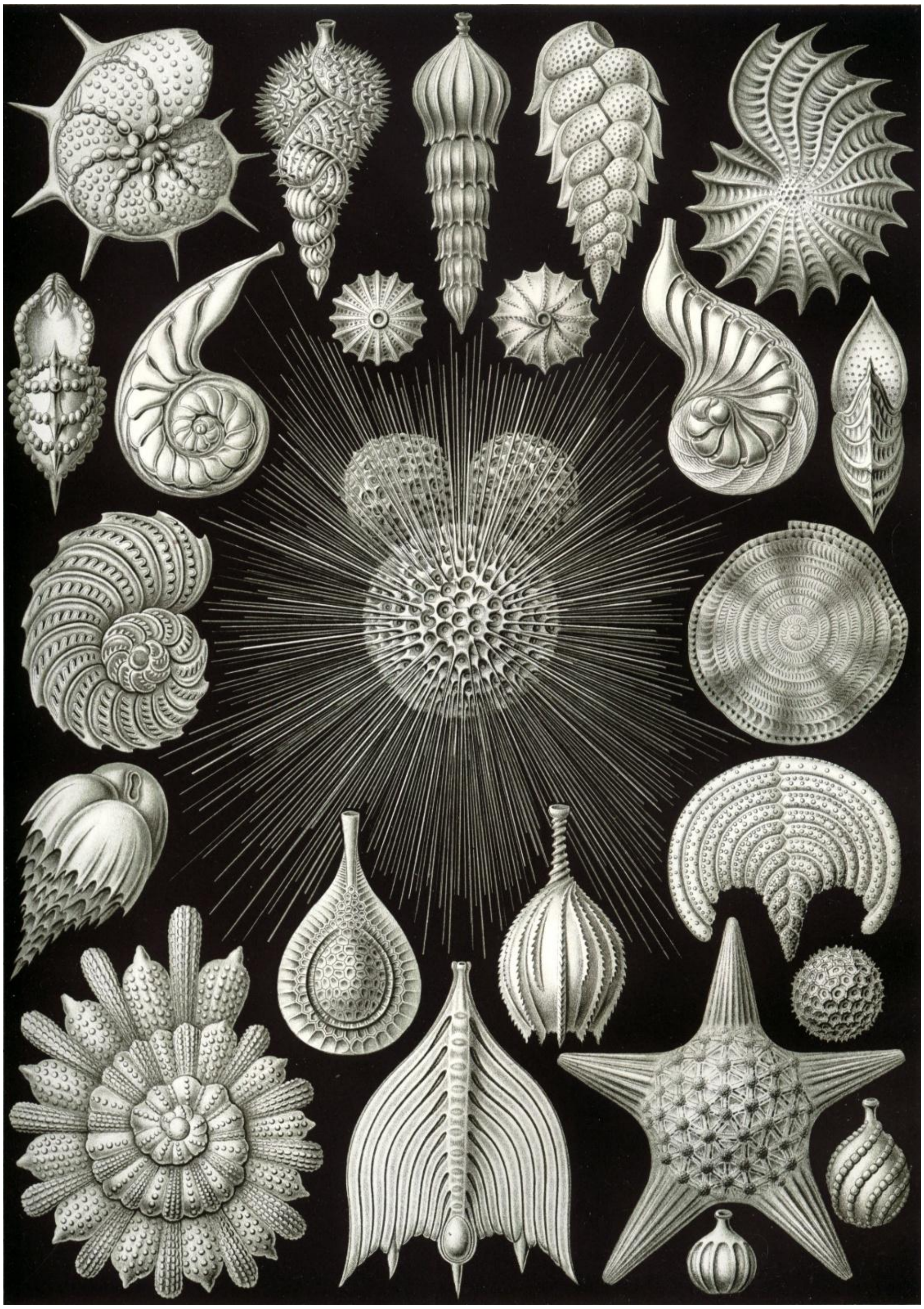

Figure 10.2 Foraminifera drawn by nineteenth-century naturalist Ernst Haeckel. Foraminifera are single-celled marine creatures that leave behind ornate shells. They can be used to track the history of nutrient pollution in estuaries. Public domain.

remains drop to the bottom, where microbes use up the available oxygen in breaking down their remains. If enough dead phytoplankton drop to the bottom layer, it will become hypoxic. When dissolved oxygen concentration drops below 2 mg per liter, every living thing that can swim away—fish, crabs, shrimp—will flee in search of oxygenated waters.

"What really gets hit," says Robert Diaz, a professor emeritus at the Virginia Institute of Marine Sciences, "are the benthic invertebrates." These creatures live burrowed into or physically attached to the bottom, and when the oxygen is gone they are doomed.

Kersey Sturdivant, a former student of Diaz who's now at Duke University, developed a camera system that showed impacts of hypoxia on Chesapeake Bay benthos in real time. As oxygen levels decreased, the chemical state of the bottom sediments changed, turning the mud from red to gray and black. Clams closed their shells, sealing themselves off from their surroundings. Worms that live burrowed into the sediment emerged and waved in the water, searching for oxygen. When oxygen plummets to zero, these creatures die. Anaerobic bacteria take over the bottom, metabolizing manganese sulfate from the sediment into poisonous hydrogen sulfide, H_2S, which tends to kill off the few benthic creatures that can survive without oxygen.

Sturdivant's studies of the benthos in Virginia's Rappahanock River, a tributary of the Chesapeake that goes hypoxic every summer, found that biological productivity drops by as much as 85 percent lower at low-oxygen sites.[31] Benthic creatures form a major part of the food chain for fish and crabs in the bay, and losing large areas of habitat and potential prey every summer likely impacts striped bass, blue crabs, and other creatures valued by Chesapeake watermen.

It can be difficult, however, to sort out the effects of hypoxia from those of over-harvest. In the 1980s, Chesapeake Bay's striped bass fishery collapsed. After a fishing moratorium was imposed, the striped bass population recovered during 1985–1995, years of intense summertime hypoxia in the mainstem bay.[32] A study of the distributions of bass and small prey fish during Chesapeake summers suggests that striped bass thrive when smaller fish are cornered in small pockets of oxygenated water, making them easy prey. But the bass population may now have reached numbers that can't be sustained by the available prey fish, which would account for a decline in striped bass numbers since 1995.

A study of long-term hypoxia in the Chesapeake found that below a threshold of 4.5 mg dissolved oxygen per liter, benthic diversity and biomass fall. Clams and oxygen-loving marine worms disappear, leaving one or two hardy kinds of polychaete worms that can survive on low oxygen. This means there is poor forage available for popular game fish like Atlantic croaker.[33] The loss of productive habitat likely depresses fish numbers, despite their ability to swim out of the dead zone.

Fish exposed to hypoxia can survive by swimming away—but they can end up impaired in serious but subtle ways. In the northern Gulf of Mexico, Atlantic croaker living in oxygen-deprived waters show impaired sexual development and produce greatly reduced numbers of sperm and eggs.[34] In nearby waters where oxygen is abundant, the sex ratio among croakers is about 50:50, but the majority of croaker in the dead zone are male. Gender is flexible among fishes, and environmental triggers can determine whether an individual becomes male or female. Hypoxia acts on genes that regulate sex determination, leading to generations of fish dominated by males. Over several generations, this pattern may threaten the survival of a population.[35]

If the pattern of nutrient overload, algal blooms, and oxygen depletion in bottom waters is the same worldwide, the life-and-death details can play out differently in each ecosystem. Which marine creatures die off has a great effect on how much a human-induced dead zone will capture human attention.

In the Kattegat, a shallow sea off the western coasts of Denmark and Sweden, a summertime dead zone built up in the 1970s. In 1975, fishers going after profitable Norway lobster had a boom year. The catch per unit effort more than doubled—but it happened because the lobsters were suffocating. Norway lobsters live in burrows in the bottom sediments. When oxygen concentrations plummet, they emerge from their burrows, making them easy targets for trawling fishermen.[36]

In 1986, more than half the lobsters caught in fisher's trawl nets were already dead or dying, victims of hypoxia. By 1988, the lobster population had collapsed. Underwater meadows of seagrass began to die off, deprived of sunlight by epiphytic algae that colonize blades of seagrass in nutrient-laden waters. Galvanized by the dramatic decline in the health of the Kattegat, the Danish Society for the Conservation of Nature lobbied the government to create policies that would curtail nutrient pollution. Upgrades in sewage treatment worked to reduce loads of nitrogen and phosphorus to some extent, but controlling nutrients in farm runoff was a tougher proposition.

The Danish government eventually put farmers on a nutrient diet, allowing them to apply only 90 percent of the fertilizer needed to produce maximum yields. Regulators tracked farmers' use of fertilizer, and penalized those who broke the rules by withholding subsidies. Denmark also initiated an ambitious plan to restore 16,000 hectares of wetlands to trap nitrogen-tainted farm runoff.[37] Less than twenty years after Denmark began to budget farm nutrients, the country reported a 50 percent drop in nitrogen and close to a 90 percent drop in phosphorus loads in its rivers and coastal seas.

Phytoplankton populations have dropped in parallel with the decline in nutrient loads. The aquatic plants of the seafloor have begun to recover, and seagrass meadows are recolonizing lost ground. But the bottom waters remain depleted of oxygen in summer, and water clarity has been slow to improve.

Scientific understanding of the damage done by eutrophication has grown tremendously in recent decades, but the process of ecosystem recovery remains little known. A eutrophic system can flip into an altered but stubbornly stable state. In the case of the Kattegat, climate change seems to have contributed.

Oxygen depletion happens in waters that are stratified. The tendency toward stratification has increased as ocean temperatures rise and winds that might mix the water column decrease. In the 1990s, the Kattegat seafloor held dense reefs of clams and mussels, filter feeders that scour phytoplankton and suspended particles out of the water. When the water column mixes freely, a healthy population of bivalves can filter the entire volume of an estuary several times a day. Once stratification sets in, filter feeders are cut off from a large chunk of the ecosystem and are also vulnerable to hypoxia.[38] Since 1990, even as Denmark worked to remedy its nutrient pollution problem, the population of filter feeders in the Kattegat declined. Their loss will slow the ecosystem's healing. The complex community may never reassemble in its original state.

The most dramatic story of eutrophication and recovery comes from the northwestern Black Sea, where the River Danube carries the drainage from watersheds spread across eleven central European nations. The loads of nitrogen and phosphorus there doubled between 1960 and the 1980s, a time when the Soviet Union subsidized synthetic fertilizer use on row crops and the creation of giant livestock farms that released heavy loads of manure.

In the 1970s and 1980s, masses of dead fish and rotting crabs, clams, and mussels began to wash up on Black Sea beaches in Romania and Ukraine.[39] At its peak in 1990, the Black Sea's dead zone covered 40,000 square kilometers. The seafloor in this vast patch, once dense with filter-feeding bivalves and benthic algae, became barren. Long-time fisheries collapsed.[40] The ecosystem's recovery began in 1989 with the demise of the former Soviet Union. Government subsidies for agriculture disappeared, and the farming economy in the region fell apart. During the 1990s, nutrient loads diminished and HABs faded. Native zooplankton and fish species returned.[41] Conservation groups in the watershed worked to limit nutrient pollution as the agricultural economy recovered.

For a short time, the Black Sea presented a hopeful example of an ecological disaster repaired. Today, however, the northwestern Black Sea once again suffers from serious pollution, and marine life is dying. War in the watershed makes conservation work difficult or impossible.[42] The fate of coastal waters is inevitably tied to human politics onshore.

Perhaps the ultimate test of humanity's ability to clean up its nutrient-polluting act lies in the Mississippi River Basin. Forty-five percent of the land in the continental US drains into the Mississippi, and much of it is intensely farmed. The earth is veined with tile drains and saturated with nitrogen from decades of growing row crops dependent on synthetic fertilizer. The nutrient overload the Mississippi delivers to the northern Gulf of Mexico has created the largest coastal dead zone in the Western Hemisphere.[43]

Worldwide, the use of synthetic nitrogen fertilizers has increased more than eight-fold since 1960.[44] Manufactured nitrogen exceeds all other sources of bioavailable nitrogen combined. One-third of humanity's protein supply now relies on synthetic fertilizers.

The Midwest has come to specialize in growing corn and soybeans, nutrient-hungry crops that leak prodigious amounts of nitrogen and phosphorus to surrounding streams. There's a direct link between the percentage of a watershed area planted in these row crops and the concentration of nitrogen flowing out of that watershed.[45]

"You can predict stream nitrate by how much row crop acreage is in a watershed," says Keith Schilling, a research scientist at the University of Iowa. "Where you have high row crop intensity, you're likely to have more livestock, greater tile drainage, greater sediment and phosphorus loss."

Federal and state subsidies encourage both the production of synthetic nitrogen fertilizers and the farming of corn. The Energy Independence and Security Act of 2007, which mandated mass production of corn ethanol to encourage energy independence in the US, led to a dramatic rise in the price of corn. The natural result was that farmers took marginal lands that had been set aside as prairie or wetland under the US Department of Agriculture (USDA)'s Conservation Reserve Program and planted them in corn, accelerating nitrogen pollution.

Eileen McLellan, a senior scientist with the Environmental Defense Fund, works to find nitrogen hotspots in the Mississippi Basin, places where a strategically placed wetland or a stretch of floodplain restored in a tributary stream can capture significant amounts of pollution.

"Any strategy to deal with eutrophication that depends upon almost universal adoption of practices is doomed to failure," explains McLellan. She cites the example of cover crops, which can be grown when a field would otherwise lie fallow and dramatically reduce the release of nitrogen. Currently, about 3 percent of Midwestern farmers use cover crops—so the practice isn't making a dent in the overall problem. Instead of hoping for widespread changes that may never come, she's working toward small projects that can have a major impact.

Using a model of nitrogen pollution in the Mississippi watershed created by the US Geological Survey, McLellan pinpoints areas that release heavy loads of nitrogen. Then she and her colleagues meet with farmers in those regions and present a number of possible options that could curb pollution. These include creation of wetlands as well as the restoration of natural floodplains. Most Midwestern streams have been channelized. Flattening out the banks of stream so that they flood during times of high flow creates habitat where nitrogen is retained and processed, much as it is in wetlands.

"We'll use planning tools to identify maybe 100 different opportunities across a small watershed, where floodplain restoration or a restored wetland could be created. We lay all that out on a map, and hope to find twenty farmers willing to do a project on their land," explains McLellan.

During a recent study funded by the USDA, McLellan spoke with farmers in three different Mississippi Valley communities. "Under the Clean Water Act, there's no legal requirement for farmers to address nonpoint pollution," she notes. "So I always imagined that the first comment we'd hear would be on the lines of 'forget it, we don't have to do anything.' But that never came up."

The farmers McLellan worked with recognize that sooner or later, they'll be held accountable for the nutrient pollution that comes with the current cropping system. "They're open to looking at all the possible tools that will help manage pollution without putting them out of business," she says. "That's even more true since Des Moines Waterworks filed its lawsuit."

The city of Des Moines, Iowa, draws its drinking water from the Raccoon and Des Moines rivers. The city's waterworks, responsible for providing drinking water to 500,000 people, lies downstream of one of the most intense nitrogen pollution hotspots in the world. The Raccoon River drains 2.3 million acres of row-cropped Iowa farmland. The watershed is also home to a number of Confined Animal

Feeding Operations (CAFOs), which raise millions of hogs. Hogs far outnumber humans in Iowa, and waste from hog CAFOs is released to the state's streams, adding to the nutrient load. Iowa occupies less than 5 percent of the Mississippi Basin but is the source of 25 percent of the nitrogen that flows downriver to the Gulf of Mexico. Most of the nitrogen flows downstream in the form of nitrate, NO_3. Nitrate can be toxic, especially to infants, so the EPA has established a limit of 10 mg nitrate per liter of drinking water. Concentrations of nitrate in Iowa streams and rivers often far exceed that limit.

In 1993, Des Moines Waterworks finished building the world's largest nitrate removal facility, a plant that pulls nitrate out of the water in an expensive, labor- and energy-intensive process. The nitrate removal plant was set up to run on an as-needed basis; it costs about $7,000 per day to run, so it was fired up only when nitrate levels in the incoming river water approached the limit of 10 mg per liter. But over time, the nitrate loads in the rivers rose and the plant had to operate more often. The summer of 2013 saw peak nitrogen loads in the Raccoon River; that year Des Moines Waterworks spent $900,000 on nitrate removal, necessitating a rate hike for its customers. When peak nitrogen loads appeared again in the summers of 2014 and 2015, managers at Des Moines Waterworks realized that the nitrate removal plant would soon need to be rebuilt and considerably enlarged, at a cost in the neighborhood of $100 million. Twenty years after it was built, the world's largest nitrate removal plant had been made obsolete by the prodigious pollution from Iowa agriculture.[46]

In 2015, Des Moines Waterworks filed a federal lawsuit against three upstream counties, demanding that they control the nutrient pollution from their drainage districts. The lawsuit, the brainchild of Waterworks CEO Bill Stowe, asks for radical changes in the way the CWA has traditionally been applied to agricultural pollution. The suit argues that the outflow from drainage districts should be regulated as point sources of pollution, just as an industrial discharge or a city sewage plant would. Focused on local problems, the suit raises serious questions of national policy.

The legal move by the Waterworks is controversial. Stowe has been criticized by both Republicans and Democrats who feel he should have allowed time for the state's voluntary plan to address agricultural pollution, the Iowa Nutrient Reduction Strategy, introduced in 2013, to work. The Iowa Partnership for Clean Water, a bipartisan group backed by the Iowa Farm Bureau, has run ads accusing Stowe of wasting hundreds of thousands of dollars on an "outrageous" lawsuit targeting farmers.[47]

Iowa's Nutrient Reduction Strategy acknowledges that currently unregulated sources create 92 percent of the state's nitrate pollution. The remedies suggested in the Strategy are all voluntary. The state offers farmers financial incentives for conservation actions that will reduce nitrate leakage, but the plan includes no timeframes or numerical criteria for pollution reduction. In Stowe's eyes, this approach is far too passive to address a widespread environmental crisis.

"The question," he says, "is how are we ever going to get industrial agriculture to rein in their practices so there is less public health risk to those of us downstream. That's what our lawsuit is about. Our state gives economic incentives to manufacturers of synthetic nitrogen fertilizer, and to animal feeding operations that produce more nitrogen pollution than all of Iowa's row crops. The agricultural model is broken."

Industrial corn and soybean farming feeds a market for low-cost food, but as it's currently practiced it precludes a real improvement in water quality. "It's your classic wicked problem," says Schilling. "The nutrient reduction strategies just work around the edges a bit. If absolutely everybody reduces their fertilizer use to the minimum, that gets you about a 10 percent reduction in nitrogen pollution." But 10 percent is not nearly enough to make Raccoon River water safe for drinking, or to begin to heal the dead zone in the Gulf.

The Midwestern focus on corn is traditional, and it's difficult to get farmers to change. Government subsidies encourage the existing system of nutrient-leaky row crops and intense hog-feeding operations. There are alternatives: Corn could be rotated with other grains, or with alfalfa. In terms of biofuel, switchgrass, a native perennial prairie grass, makes an excellent source, using a fraction of the fertilizer and requiring none of the tile drainage involved in growing corn. But a crop of switchgrass can take three years to mature, and the government isn't subsidizing the process. Most existing biofuel factories are set up to handle corn, not switchgrass. As things now stand, even the most conservation-minded farmer can't turn to switchgrass as a cash crop.

Despite its high levels of nitrate pollution, Iowa is a national leader in creating wetlands to capture nutrients in farm runoff. The state has been designing wetlands placed to capture runoff from small sub-watersheds since 2001, based on years of research by wetlands ecologist William Crumpton of Iowa State University. Shawn Richmond, now the Environmental Technology Director for the Agribusiness Association of Iowa, studied under Crumpton and has helped design and build dozens of wetlands.

"We target the heavily tile-drained parts of the state," explains Richmond. Using computerized mapping and analysis of a watershed, he searches for places in the landscape where an effective wetland can fit. An ideal location is at the base of a watershed, where natural topography creates a dip that can be transformed into a marsh by adding an earthen berm. Once researchers have found a good place for a wetland, they get on the phone to the person who owns the land. "It's cold-call conservation," says Richmond. "About one in three landowners will show interest when we call out of the blue."

The average wetland project takes up about forty acres, ten acres in wetland surrounded by thirty acres of native prairie plants. A strategically placed wetland can capture up to 70 percent of the nitrate flowing out of a sub-watershed, using only a small fraction of the total cropland. On the other hand, a farmer who gives up forty acres is making a real sacrifice.

"That's better than $250,000 worth of land taken out of production," notes Richmond. State agencies pay the cost of creating the wetland, and offer soil rental rates and a lump-sum payment to farmers who commit to keeping the wetland in perpetuity.

Iowa has about eighty of these nutrient-capture wetlands built. They're more effective than the few that have been created in Ohio, where the location of wetlands is based on the inclination of landowners, not on optimal positioning in the landscape. State biologists in Ohio often have to run the tile drains of neighboring farmers under or around a constructed wetland, minimizing its ability to capture and filter polluted runoff. While Iowa's progress on this front is impressive, there's a long way left to go.

"In Iowa, we're going to need 4,000–7,000 constructed wetlands, in addition to other conservation practices," says Richmond. Another important strategy is the construction of bioreactors, small trenches dug across the outflow of a field tile and filled with wood chips. The wood chips act as a source of carbon, essential to the process of denitrification, carried out by soil microbes. Richmond estimates the state will need about 120,000 bioreactors to bring its nitrogen pollution problem under control.

The bottleneck in Iowa's progress is funding. The state legislature appropriates about $1 million per year for wetland restoration on farmland, enough to pay for three or four projects a year.

"The science is pretty far along in terms of identifying the best locations for potential wetlands," says Schilling. "It's a question of having the money, the resources, and the will to do it."

If you do the math, and bear in mind that Iowa is in some ways more progressive than other Corn Belt states whose fields drain to the Mississippi, the future looks grim. In terms of changing the way people manage the watershed, progress will be slow, and the incentives in current federal policies are backwards.

Nancy Rabalais, a marine ecologist at the Louisiana Universities Marine Consortium, has monitored the dead zone in the Gulf of Mexico since 1985. Remains of decades-old foraminifera show that hypoxia built in the northern Gulf beginning in the 1950s, accelerated for decades, and has reached a plateau in recent years. "Healing the dead zone is going to take a societal shift in the way we farm," she says. "There are sustainable, ecologically sound ways to farm that cost less than what's done now. It's just a mindset of how agriculture is done."

The landscape itself is also likely to resist an easy shift toward lower nutrient levels. Climate models predict more frequent and intense rainstorms in the Midwest, which will trigger more nutrient-laden runoff. The vast Mississippi watershed has already built up a legacy of excess nutrients that may last for decades after ongoing pollution is controlled.

"Nitrogen fertilizer that was applied decades ago has made its way down into the groundwater," explains McLellan. "That groundwater will eventually make its way to the streams." This is why an ability to process nitrogen and pump it back into the air via denitrification must be restored to creeks and rivers, through restoration of floodplains, backwaters, and oxbows long-ago lost to our passion for levees and straight rivers.

The modern problem of nutrient pollution is the result of intense human tinkering with the flow of water and the natural cycling of nitrogen. The settle-ment of the US by a people obsessed with draining and destroying wetlands came first; the twentieth-century discovery of a way to fix nitrogen on an industrial scale sealed the fate of our coastal waters. Yet sometimes, researchers studying the deterioration of aquatic life stumble on a revival that seems to have come out of nowhere. Off the nutrient-enriched coasts of the US and Europe, the return of top predators may help rescue smothered ecosystems.

NOTES

---

[1] Fitzsimmons, E. (August 3, 2014). “Tap Water Ban for Toledo Residents.” *New York Times* (http://www.nytimes.com/2014/08/04/us/toledo-faces-second-day-of-water-ban.html?_r=0); Henry, T. (August 3, 2014). “Water crisis grips hundreds of thousands in Toledo area, state of emergency declared.” *Toledo Blade* (http://www.toledoblade.com/local/2014/08/03/Water-crisis-grips-area.html).
[2] Harke, M., Morgan Steffen, Christopher Gobler, Timothy Otten, Steven Wilhelm, Susanna Wood, Hans Paerl (2016). “A review of the global ecology, genomics and biogeography of the toxic cyanobacterium, Microcystis spp.” *Harmful Algae* **54**: 4–20.
[3] Watson, S., Carol Miller, George Arhonditsis, et al. (2016). “The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia.” *Harmful Algae* **56**: 44–66.
[4] Michalak, A., Eric Anderson, Dmitry Beletsky, et al. (2013). “Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions.” *PNAS* **110**(16): 6448–6452.
[5] Harke, M., Morgan Steffen, Christopher Gobler, Timothy Otten, Steven Wilhelm, Susanna Wood, Hans Paerl (2016). “A review of the global ecology, genomics and biogeography of the toxic cyanobacterium, Microcystis spp.” *Harmful Algae* **54**: 4–20.
[6] Kaatz, M.R. (1955). “The Black Swamp: a study in historical geography.” *Annals of the Association of American Geographers* **XLV**(1): 1–36.
[7] Scavia, D., J. david Allan, Kristin K. Arend, et al. (2014). "Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia." *Journal of Great Lakes Research* **40**: 226–246.
[8] Mitsch, W. (2015). “Restoring the Great Black Swamp to save Lake Erie.” https://www.linkedin.com/pulse/restoring-black-swamp-save-lake-erie-bill-mitsch.
[9] Mitsch, William, James Gosselink (2015). “Wetlands.” Hoboken, New Jersey: Wiley.
[10] Odum, H. T., K.C. Ewel, W.J. Mitsch, J.W. Ordway (1977). “Recycling treated sewage through cypress wetlands in Florida.” In “Wastewater renovation and reuse,” Frank M. D’Itri editor, *Marcel Dekker, Inc.*
[11] Baker, D. (2010). “Trends in bioavailable phosphorus loading to Lake Erie.” *Lake Erie Protection Fund Grant 315-07.*
[12] Ohio Environmental Protection Agency (2010). “Ohio Lake Erie Phosphorus Task Force Final Report: Executive summary.”
[13] Watson, S., Carol Miller, George Arhonditsis, et al. (2016). “The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia.” *Harmful Algae* **56**: 44–66.
[14] Michalak, A., Eric Anderson, Dmitry Beletsky, et al. (2013). “Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions.” *PNAS* **110**(16): 6448–6452.
[15] Lenhart, C., Peter Lenhart (2014). “Restoration of wetland and prairie on farmland in the former Great Black Swamp of Ohio, USA.” *Restoration Practice* **32**(4): 441–449.

[16] King, K., Mark Williams, Merrin Macrae, et al. (2015). “Phosphorus transport in agricultural subsurface drainage: a review.” *Journal of Environmental Quality* **44**: 467–485.
[17] Scavia, D., Margaret Kalcic, Rebecca Logsdon Muenich, et al. (2016). “Informing Lake Erie Agriculture Nutrient Management via Scenario Evaluation.” *University of Michigan Water Center* (http://graham.umich.edu/water).
[18] NOAA (2017). "Gulf of Mexico dead zone is the largest ever measured." http://www.noaa.gov/media-release/gulf-of-mexico-dead-zone-is-largest-ever-measured.
[19] Sklar, F., Michael Chimney, Susan Newman, et al. (2005). “The ecological-societal underpinnings of Everglades restoration.” *Frontiers in Ecology and Environment* **3**(3): 161–169.
[20] Rizzardi, K.W. (2001). “Alligators and litigators: a recent history of Everglades regulation and litigation.” *Florida Bar Journal* **75**(3): 18–27.
[21] Kadlec, R.H. (2006). “Free surface wetlands for phosphorus removal: the position of the Everglades Nutrient Removal Project.” *Ecological Engineering* **27**: 361–379.
[22] Levy, S. (August 2015). “The ecology of artificial wetlands.” *BioScience* 65(4): 346-352): 1–7.
[23] Kadlec, R.H., D.L. Hey (1994). “Constructed wetlands for river water quality improvement.” *Water Science and Technology* **29**(4): 159–168; Kadlec, R.H. (2009). “The Houghton Lake wetland treatment project.” *Ecological Engineering* **35**: 1285–1286.
[24] Henry, T. (July 24, 2016). “Lake Erie, South Florida algae crises share common toxins and causes.” *Toledo Blade*.
[25] Hansson, A., Eja Pedersen, Stefan Weisner (2012). “Landowners’ incentives for constructing wetlands in an agricultural area in south Sweden.” *Journal of Environmental Management* **113**: 271–278.
[26] Diaz, R., Rutger Rosenberg (2008). “Spreading dead zones and consequences for marine ecosystems.” *Science* **321**(5891): 926–929.
[27] Galloway, J., Alan Townsend, Jan Willem Erisman, et al. (2008) “Transformation of the Nitrogen cycle: recent trends, questions and potential solutions.” *Science* **320**: 889–892.
[28] Mee, L. (November 2006). “Reviving dead zones.” *Scientific American*, pp. 79–85.
[29] Rabalais, N., R. Eugene Turner, William J. Wiseman, Jr. (2002). “Gulf of Mexico hypoxia, a.k.a. the dead zone.” *Annual Review of Ecology and Systematics* **33**: 235–263.
[30] Rabalais, N., R. Eugene Turner, Barun K. Sen Gupta, et al. (2007). “Sediments tell the history of eutrophication and hypoxia in the northern Gulf of Mexico.” *Ecological Applications* **17**(5 Supplement): S129–S143.
[31] Sturdivant, S.K., Rochelle Seitz, Robert Diaz (2013). “Effects of seasonal hypoxia on macrobenthic production and function in the Rappahannock River, Virginia, USA.” *Marine Ecology Progress Series* **490**: 53–68.
[32] Constantini, M., Stuart Ludsin, Doran Mason, et al. (2008). “Effect of hypoxia on habitat quality of striped bass (*Morone saxatilis*) in Chesapeake Bay.” *Canadian Journal of Fisheries and Aquatic Science* **65**: 989–1002.
[33] Seitz, R., Daniel Dauer, Roberto Llanso, W. Christopher Long (2009). “Broad-scale effects of hypoxia on benthic community structure in Chesapeake Bay, USA.” *Journal of Experimental Marine Biology and Ecology* **381**: S4–S12.

[34] Thomas, P., M. Saydur Rahman (2010). "Region-wide impairment of Atlantic Croaker testicular development and sperm production in the northern Gulf of Mexico hypoxic dead zone." *Marine Environmental Research* **69**: 559–562.
[35] Cheung, C.H.Y., Jill Man Ying Chiu, Rudolf Shiu Sun Wu (2014). "Hypoxia turns genotypic female medaka fish into phenotypic males." *Ecotoxicology* **23**: 1260–1269.
[36] Baden, S., Lars-Ove Loo, Leif Pihl, Rutger Rosenberg (1990). "Effects of eutrophication on benthic communities including fish: Swedish west coast." *Ambio* **19**(3): 113–122.
[37] Kronvang, B., Hans Andersen, Christen Borgesen, et al. (2008). "Effects of policy measures implemented in Denmark on nitrogen pollution of the aquatic environment." *Environmental Science and Policy* **11**: 144–152.
[38] Riemann, B., Jacob Carstensen, Karsten Dahl, et al. (2016). "Recovery of Danish coastal ecosystems after reductions in nutrient loading: a holistic ecosystem approach." *Estuaries and Coasts* **39**: 82–97.
[39] Mee, L. (November 2006). "Reviving dead zones." *Scientific American*, pp. 79–85.
[40] Schwartzstein, P. (May 11, 2016). "The Black Sea is dying, and war might push it over the edge." *Smithsonian* (http://www.smithsonianmag.com/science-nature/black-sea-dying-and-war-might-push-it-over-edge-180959053/).
[41] Kideys, A.E. (2002). "Fall and rise of the Black Sea ecosystem." *Science* **297**(5586): 1482–1484.
[42] Schwartzstein, P. (May 11, 2016). "The Black Sea is dying, and war might push it over the edge." *Smithsonian* (http://www.smithsonianmag.com/science-nature/black-sea-dying-and-war-might-push-it-over-edge-180959053/).
[43] Rabalais, N., R. Eugene Turner, William J. Wiseman, Jr. (2002). "Gulf of Mexico hypoxia, a.k.a. the dead zone." *Annual Review of Ecology and Systematics* **33**: 235–263.
[44] Broussard, W., R. Eugene Turner (2009). "A century of land use and water quality relationships in the continental US." *Frontiers in Ecology and Environment* **7**(6): 302–307.
[45] Ibid.
[46] *Des Moines Water Works vs. Sac County, Buena Vista County, Calhoun County*." Case 5:15-cv-04020-DEO, US District Court for the Northern District of Iowa, Western Division, 2015.
[47] Masters, C. (January 21, 2016). "Iowa's nasty water war." *Politico*.