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Toxic Fertility

by Danielle Nierenberg

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Over the past half century, the amount of biologically active nitrogen circulating through the world's living things has probably doubled. In unnatural excess, an essential nutrient is becoming a kind of ecological poison.

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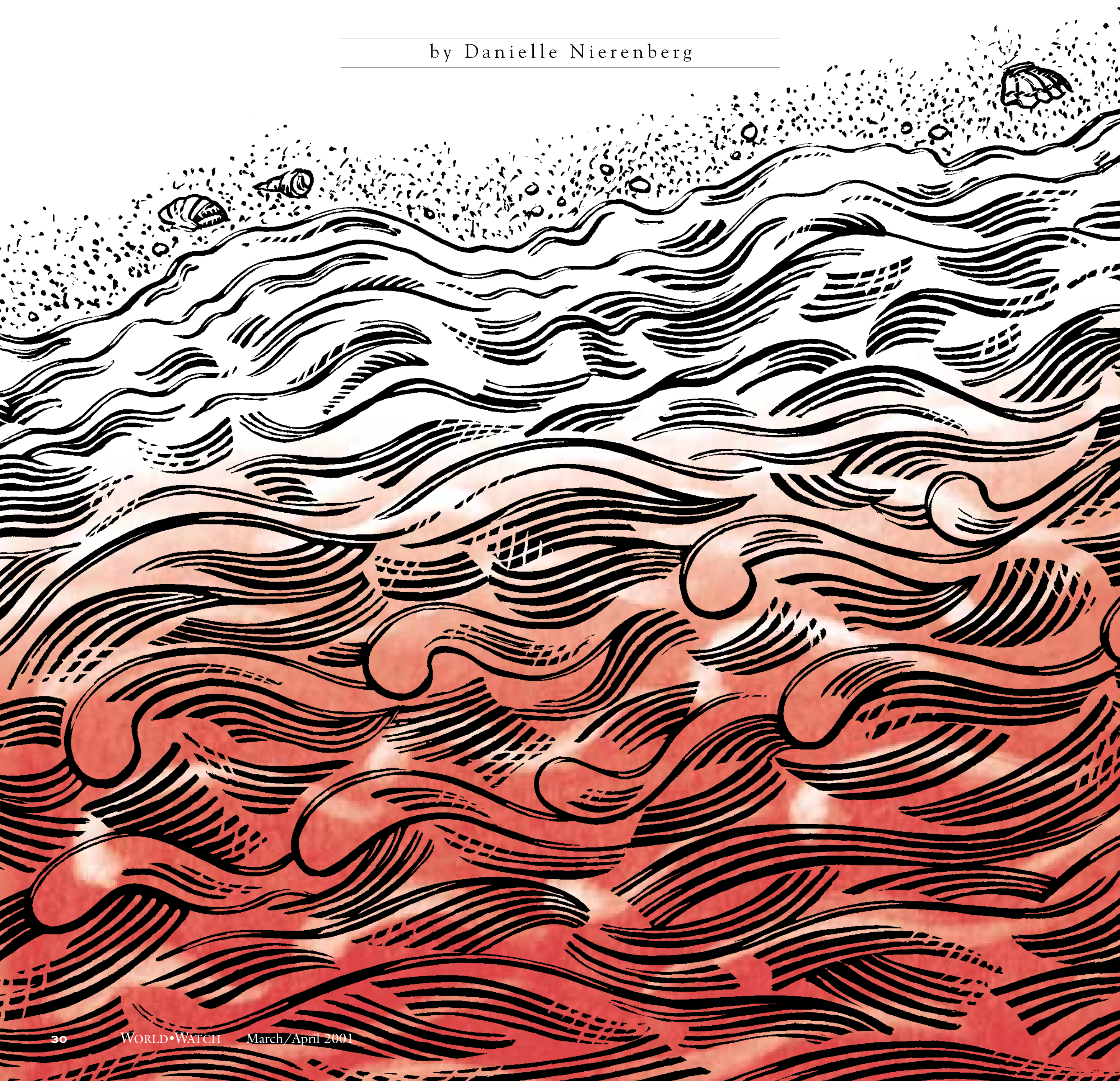
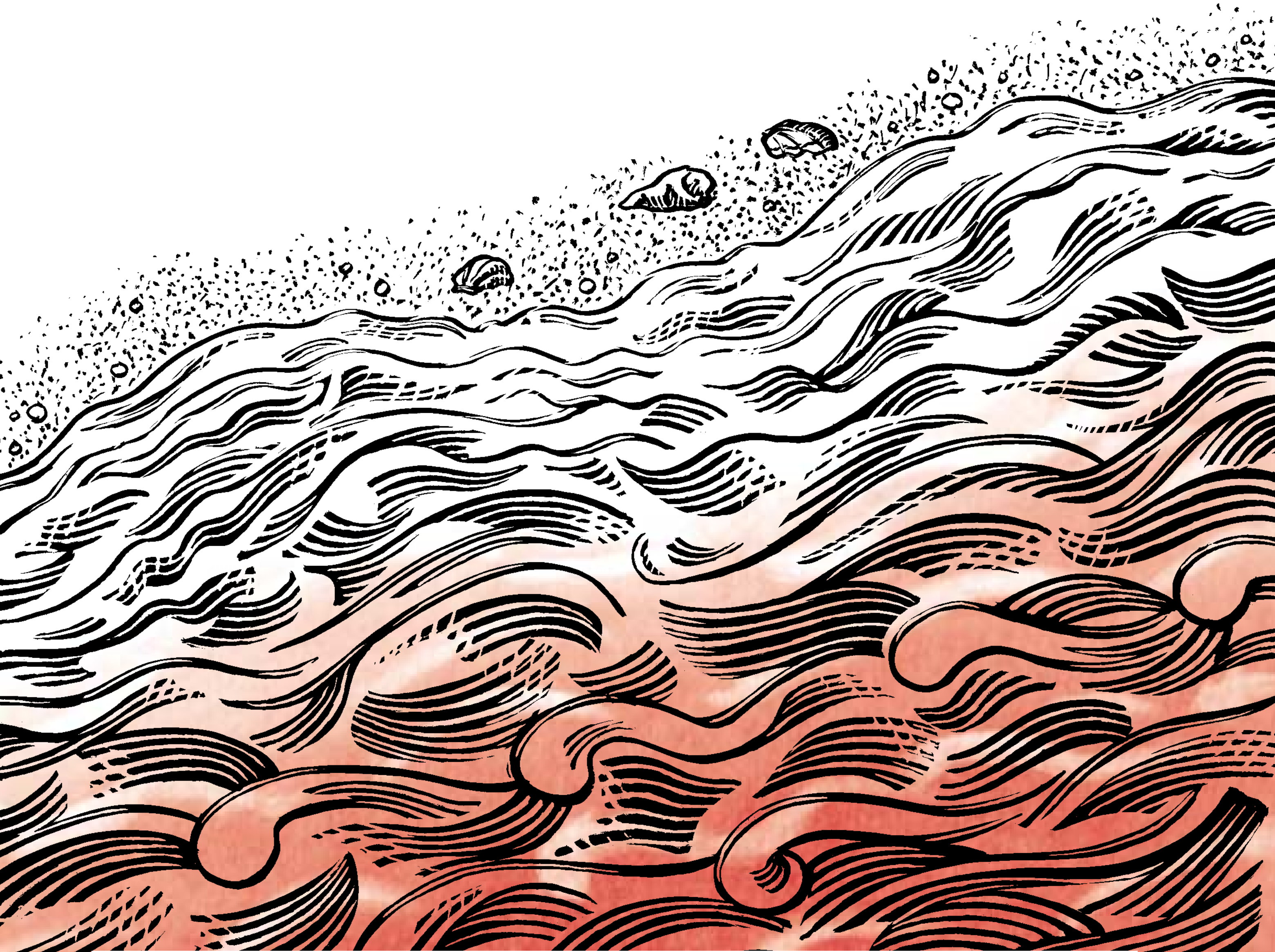




LAST DECEMBER, talks on the climate treaty reached an impasse. The treaty process is supposed to result in a blueprint for reducing carbon emissions. But when delegates met in the Hague, in the Netherlands, for their sixth official conference of the parties, the agenda focused not so much on cutting fossil fuel use as on the issue of "carbon sinks." Sinks are areas, primarily young forests, that are absorbing more carbon than they are releasing. Since they draw carbon from the atmosphere, sinks offer an attractive accounting option for the United States and some other nations that have high carbon emissions. These nations want to claim a "carbon credit" against their emissions, on the strength of their sinks. How big a credit—if any—should be allowed? In one way or another, that question underlay much of the discussion, and the delegates weren't able to agree on an answer. They failed, in other words, to agree on a way to balance the global carbon budget.

Apart from the immediate reasons for concern over this failure, there is the matter of another unbalanced natural budget. Nitrogen, like carbon, plays a key role in the vast biochemical cycles of life. And increasingly, the nitrogen cycle is being reshaped by human activity—a process that could eventually affect virtually every ecosystem on earth. Our economies are in urgent need of a "nitrogen audit."

Like carbon, nitrogen is a basic ingredient of living things. It's found, for example, in DNA, in proteins, and in chlorophyll, the pigment that drives photosynthesis. Nitrogen shares another key characteristic of carbon: it's very common. It comprises a whopping 78 percent of the atmosphere. But nearly all of this atmospheric nitrogen is elemental dinitrogen, or N_2—it exists in the form of two nitrogen

ILLUSTRATION BY MILAN KECMAN

atoms linked together. Elemental nitrogen cannot be metabolized by most living things. Nitrogen becomes biologically active only when it is "fixed"—that is, incorporated into certain other molecules, primarily ammonium (NH_4) and nitrate (NO_3). Fixed nitrogen flows throughout the food web: it is absorbed first by plants, then by plant-eating animals, then by their parasites and predators. Death at each stage of the way releases nitrogen compounds to begin the cycle anew. The fixation process is what makes the nitrogen cycle so different from the carbon cycle. Despite the abundance of elemental nitrogen, fixed nitrogen is frequently what scientists call a "limiting nutrient." Under normal natural conditions, it is often in short supply, so the level of available nitrogen is a key regulator of ecological processes.

The gate-keepers to the biological part of the nitrogen cycle are certain micro-organisms capable of fixing elemental atmospheric nitrogen. Some of these organisms live in soil, often in close association with plants that belong to the bean family. This relationship benefits both parties: the plants get the nitrogen compounds; the microbes get carbohydrates, which the plants produce through photosynthesis. (Sometimes the plants themselves are said to be nitrogen fixing, but this is a kind of terminological shorthand.) Nitrogen fixing occurs in water as well. One of the biggest mysteries of the nitrogen cycle involves marine plankton. These microscopic plants are fixing enormous quantities of nitrogen, but their role in the global cycle has yet to be clearly defined. Finally, in addition to these living portals, there is an inanimate natural process that fixes large quantities of nitrogen: lightning fuses nitrogen and oxygen to create nitrate.

Recent human activity has greatly increased the rate at which nitrogen is being fixed. Since the 1950s, the amount of nitrogen circulating through living things is thought to have doubled. And increasingly, in forests and fields, in rivers and along the coasts, scientists are blaming excess fixed nitrogen for a range of ecological problems—some of them obvious, others very subtle. Any one of these problems can usually be linked to some local or regional cause; the nitrogen balance of a river, for example, might be upset by increased sewage outflow. But when you step back and look at the cycle from a global perspective, three general activities emerge as the primary reasons for the growing fixed nitrogen glut.

First, coal and oil combustion is releasing a huge, long-buried reservoir of fixed nitrogen by burning the residues of ancient plants, in the form of coal and oil. The fossil fuel economy is disrupting not just the carbon cycle but the nitrogen cycle as well. Second, the progressive destruction of forests and wetlands is releasing the nitrogen contained in these natural areas, just as it releases the carbon. Taken together, these two activities are releasing about 90 million tons of fixed nitrogen annually; that's about 43 percent of the human addition to the nitrogen cycle. (See table below.)

The remainder of the human addition—some 120 million tons—comes from agriculture. Nitrogen-fixing crops produce about a third of that amount; the rest comes from artificial fertilizer. Fixed nitrogen is the basic component of fertilizer. Through its dependence on artificial fertilizer, modern conventional agriculture has become, in a sense, a form of industrial nitrogen management. This is a relatively recent development in agricultural history. Low-cost techniques for synthesizing ammonia emerged shortly after the Second World War. Cheap ammonia led to mass production of artificial fertilizer and heralded what the ecologist and nitrogen expert David Tilman has called "the 35 most glorious years of agricultural production."

For farmers in the industrialized countries—and increasingly, in the developing countries as well—this limiting nutrient is now available in virtually limitless quantities. As is typical of cheap commodities, a great deal of it is wasted. Fertilizer is often very inefficiently applied; much of it never reaches the crop. It leaches out of the fields and into the streams, or it's converted into a nitrogenous gas like nitrous oxide and escapes into the atmosphere.

Nearly all crops grown in the industrialized countries are now nitrogen-saturated—that is, they're being exposed to more nitrogen than they can use. But fertilizer production continues to grow, on the strength of developing world demand. At current rates of production, fertilizer is adding some 80 million tons of fixed nitrogen to the cycle; by 2020 that

Fertilizing the Nitrogen Cycle

Annual releases of fixed nitrogen caused by human activity

Source	Millions of tons
Fertilizer	80
Nitrogen-fixing crops	40
Fossil fuels	20
Biomass burning	40
Wetland drainage	10
Land clearing	20
Total human releases	210
Total natural fixed-nitrogen production*	140

*Terrestrial sources only; marine sources have not yet been reliably estimated.

Source: World Resources Institute, "Global Nitrogen Glut" table, available at www.wri.org/wri/wr-98-99/nutrient.htm.

burden is expected to reach 134 million tons—just 6 million tons shy of the total input from all natural terrestrial sources combined.

ON THE MORNING OF JUNE 22, 1995, the wall of an artificial "waste lagoon" gave way at a factory farm in North Carolina. Some 95 million liters of putrefying hog urine and feces spilled out of the lagoon, washed across several fields and a road, then poured into the New River. Millions of fish and other aquatic organisms died in what became one of the worst incidents of water pollution in the state's history. Unfortunately, it wasn't an isolated incident—or at least not for long. Very large livestock farms, known as "concentrated animal feeding operations" or CAFOs, had become a major part of the state's agricultural sector, and the CAFOs had begun to hemorrhage waste.

A couple of weeks after the New River spill, 34 million liters of poultry waste flowed down a creek and into the Northeast Cape Fear River. In August of that year, another 3.8 million liters of hog waste ended up in the Cape Fear Estuary, reports the January/February 2000 issue of *American Scientist*. But the worst was yet to come. The hurricanes of 1998 and 1999 brought a series of massive floods to North Carolina's seaboard and untold millions of liters of hog waste were washed out of various CAFO lagoons. The state's coastal ecosystems have yet to recover.

Like sewage, CAFO pollution is extremely high in nitrogen, and most of that nitrogen comes from the artificial fertilizer used to grow the animal feed. You could say that CAFOs are a consequence of chemical fertilizer, because fertilizer has allowed for the "uncoupling" of livestock and crop. When farmers get their fertilizer out of a bag, they don't need manure. And feed corn can be shipped to CAFOs just as readily as fertilizer can be shipped to corn growers. In each case, the basic input is no longer produced by the landscape in which it is used, so the local ecology no longer effectively limits the intensity of production. The environmental costs of this fractured system are likely to make it untenable over the long term. But at least for the present, fertilizer is the source of about a third of human dietary protein (from both animals and plants), according to Vaclav Smil, a professor at the University of Manitoba who has written extensively on global biochemical cycles.

The logistics of managing CAFO waste are formidable. Each of the 50,000 or so sows in one of those North Carolina facilities will produce about 20 piglets over the course of a year. A sow and its piglets will excrete some 1.9 tons of waste annually—that's enough manure to fill a pick-up truck. The waste cannot simply accumulate in lagoons, since lagoon space is obviously limited, so CAFOs require huge amounts of "spreadable acreage"—cropland on nearby farms where manure can be spread, sprayed, or injected. But crops can only use so much nitrogen. Adding too much can actually reduce yields; like people, plants can overeat, and excessive nitrogen uptake tends to interfere with a plant's ability to manufacture the various chemicals needed for its metabolism. Too much nitrogen can also throw the soil community out of balance by favoring only those organisms that thrive in high-nitrogen conditions, at the expense of many other organisms.

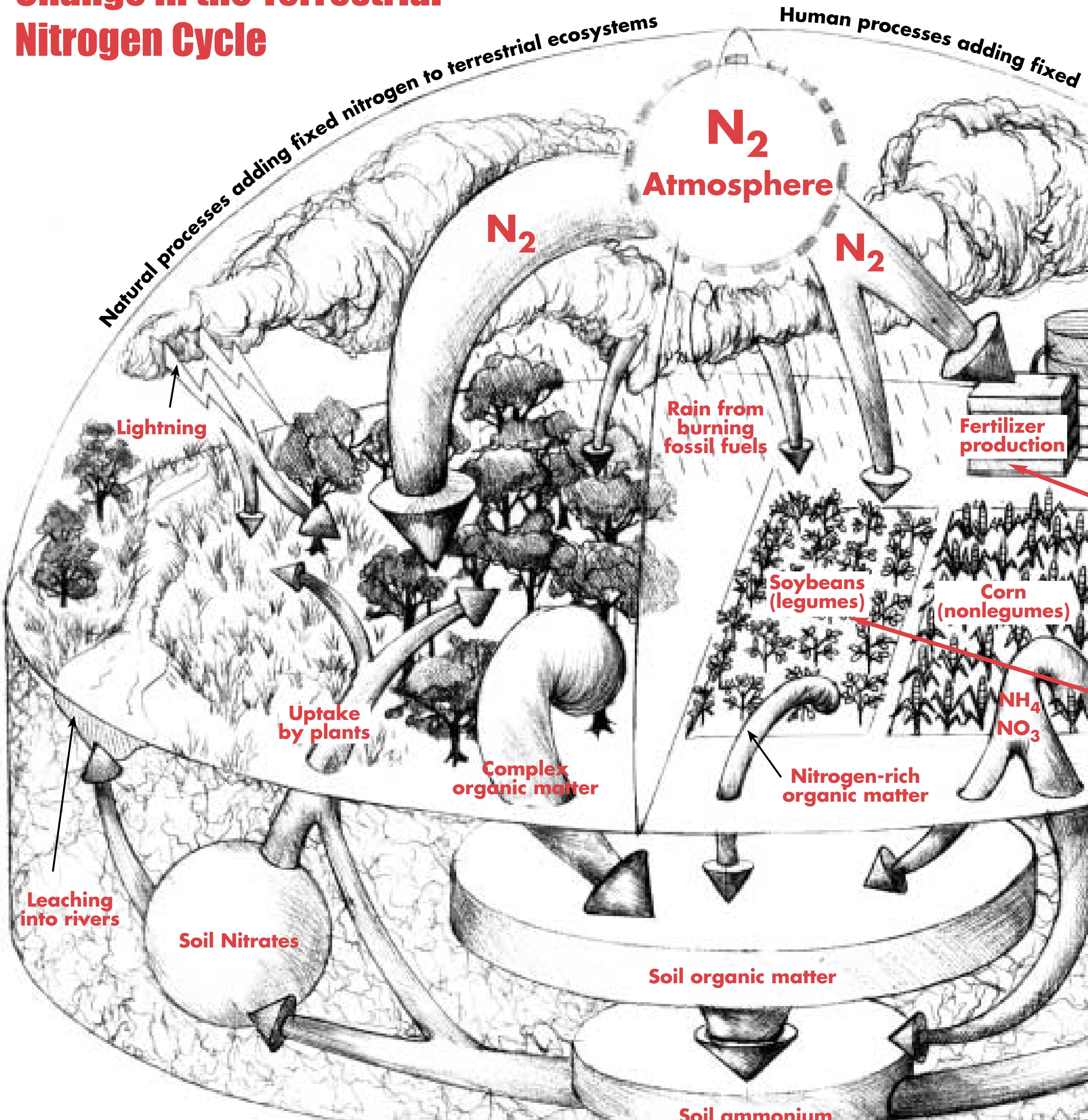
If you're trying to do a conscientious job of it, finding adequate spreadable acreage is a very difficult task indeed. For each of those sow and piglet units, a CAFO should ideally have access to 1.2 hectares (3 acres) of land. (This ratio is actually determined not by the manure's nitrogen concentration but by the concentration of phosphorus, which is also frequently a limiting nutrient and therefore capable of causing some of the same "over-fertilizing" effects that nitrogen does. Sufficient spreadable acreage for the phosphorus will—at least in the case of pig manure—accommodate the nitrogen too.) A 50,000 animal CAFO would need about 60,000 spreadable hectares. Inevitably, given the size of the CAFOs, that ideal is not attained. Frequently, far too much manure is spread on the fields. Or the manure may be spread at the wrong times in the growing season, when the crops cannot effectively take up the nutrients. Or sometimes the manure is spread on fields of nitrogen-fixing crops like soybeans and alfalfa, which require little or no additional fertilizer. In North America, it's estimated that only about half of livestock waste is now effectively fed into the crop cycle. Much of the remainder ends up as pollution—of the water, the air, and the soil itself.

Take the water pollution first. Nitrate contamination of groundwater can create serious risks for public health. (See "Groundwater Shock," January/February 2000.) For example, high nitrate levels in wells near feedlot operations have been linked to greater risk of miscarriage. In extreme cases, nitrate contamination can cause methemoglobinemia, or "blue-baby syndrome," a form of infant poisoning in which the blood's ability to transport oxygen is greatly reduced, sometimes to the point of death. Nitrate water pollution is a serious ecological concern as well, even when it doesn't involve millions of liters of hog feces. Perhaps the most obvious form of ecological disruption involves algal blooms, explosive growths of algae and cyanobacteria (so-called "blue-green algae") that can suffocate many other aquatic organisms. There are more subtle wildlife effects as well; some amphibian declines, for example, appear to be caused by chronic exposure to elevated nitrate. (See "Amphibia Fading," July/August 2000.)

But as anyone who lives near a CAFO can tell you, groundwater contamination is hardly the most noticeable environmental effect. If raw manure is exposed to air, up to 95 percent of the nitrogen in it will escape into the atmosphere as gaseous ammonia (NH_3). In the vicinity of a CAFO, the process results in an olfactory experience that is difficult to forget. But that's not all it does, since the nitrogen doesn't usually stay airborne for long—it's usually deposited within 80 to 160 kilometers of its source. In the words of Merrit Frey, who studies factory farming for the Clean Water Network, a coalition of U.S.-based nonprofits concerned about water quality, the ammonia from CAFOs is "not just a localized odor nuisance, but a regional environmental problem." Once it falls from the sky, it tends to contribute to the same problems that result from the more direct forms of soil and water pollution.

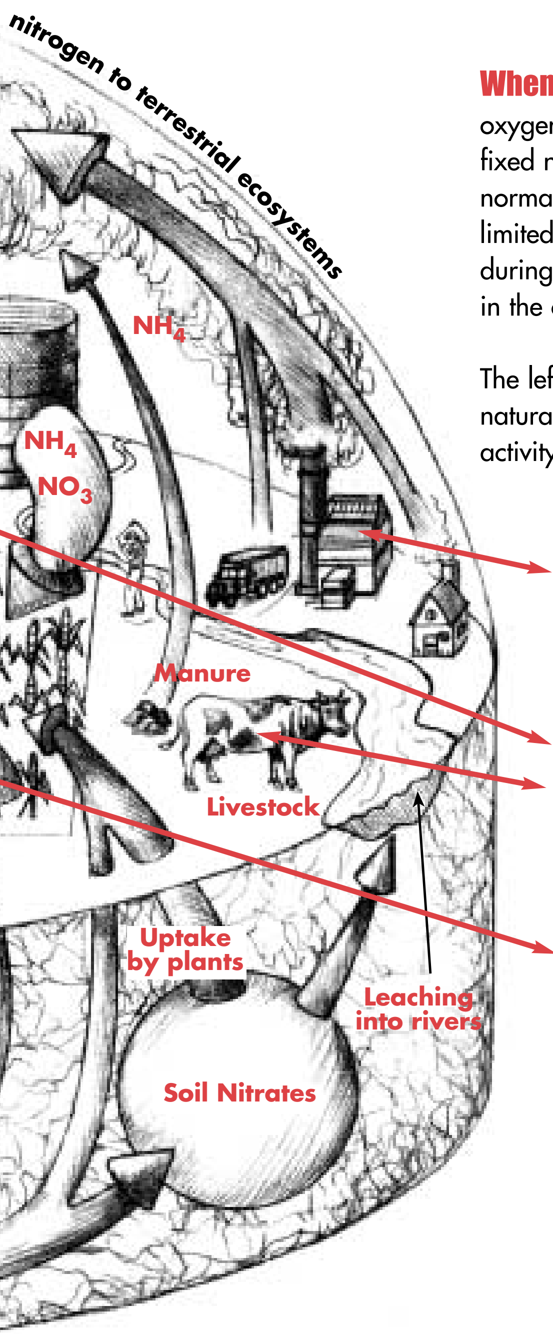
As livestock production continues to intensify,

Change in the Terrestrial Nitrogen Cycle



such problems are likely to become more common. Already, North Carolina's 7 million factory-raised hogs create more waste than do the 6.5 million human residents of the state. Intensive livestock production is the rule in the United States and western Europe, and producers are increasingly interested in setting up similar operations elsewhere. In part, such interest is the result of the growing regulatory attention that established operations are now attracting. In the United States, for example, CAFO waste is the target of new regulations recently proposed by the U.S. EPA, and of proposed amendments to the Clean Water Act. But the export of the CAFO model is also partly a variation on a standard economic theme: investment in developing markets. The demand for meat is growing in the developing world, and the costs of producing it are generally much lower there than in the United States or Europe.

China, for example, is interested in boosting domestic meat production to satisfy growing domestic demand, according to David Brubaker, an expert on factory farming at the Johns Hopkins University School of Public Health in Maryland. Brubaker says that several U.S. agribusinesses are trying to sell the Chinese on CAFO production of hogs, poultry, and cattle. In the Philippines, two such corporations, Tyson Foods and Purina Mills, opened a hog breeding facility near Manila in 1998; the facility can produce 100,000 hogs per year. Richard Levins, an agricultural economist at the University of Minnesota, says that



When inert atmospheric nitrogen (N_2) is fixed—that is, bonded to oxygen or hydrogen—it becomes an essential plant nutrient. But too much fixed nitrogen can upset basic physiological and ecological functions. Under normal natural conditions, the amount of fixed nitrogen is usually fairly limited. On land, fixation occurs naturally only in certain soil microbes and during lightning strikes, which bond nitrogen and oxygen. (Nitrogen is fixed in the oceans as well, by some types of plankton.)

The left side of this diagram shows the terrestrial nitrogen cycle as it would naturally function. The right side shows some of the ways in which human activity is increasing the amount of fixed nitrogen in the cycle:

The burning of coal and oil is releasing nitrogen that was naturally fixed—but millions of years ago when these fossil fuels were living plants. Some nitrogen is also fixed directly, as a byproduct of combustion.

Fertilizer production is artificially fixing a large amount of additional nitrogen. Much of this is released into the environment either directly, when the fertilizer is used on crops, or indirectly, in the manure of livestock fed on the fertilized grain.

The cultivation of beans and other leguminous crops, which grow in close association with nitrogen-fixing microbes, uses a natural mechanism of nitrogen fixing—but on a scale that is unnaturally large and unnaturally intense, because it involves extensive monocultures.

Finally, the destruction of forests and wetlands (not shown here), does not add fixed nitrogen to the cycle as a whole, but it releases large amounts of fixed nitrogen from long-term confinement in those ecosystems.

ILLUSTRATION BY MICHAEL ROTHMAN, COURTESY LARS HEDIN, DEPARTMENT OF ECOLOGY AND EVOLUTIONARY BIOLOGY, CORNELL UNIVERSITY.

even Canada is becoming a prime location for hog CAFO developers looking for lots of space, few people, and relatively lax environmental regulations.

Taken globally, livestock production has become a major outlet pipe for much of the nitrogen that humanity is injecting into the natural cycle. The planet's population of some 2.5 billion pigs and cattle void more than 80 million tons of waste nitrogen annually. The entire human population, in comparison, produces just over 30 million tons. Manure, once a valuable farm resource, is now being produced in such quantities that it might be better considered toxic waste.

HERE AND THERE, ALONG CHINA'S 18,000-kilometer coastline, fishers and fish farmers have long contended with an unwelcome form of marine bounty. Red tides, the toxic blooms of certain algae species, are a natural phenomenon in these waters during the spring and summer, but the frequency of the blooms is increasing. Scientists suspect that the algae are responding to two factors. Sea surface temperatures in the region are rising—a likely effect of climate change—and more and more nitrogen-rich waste is pouring into China's coastal waters. The annual load of such pollution—in the form of sewage, industrial waste, and farm runoff—now exceeds 8 billion tons.

Warmer, nutrient rich water is ideal habitat for algae, and the resulting red tides have been poisoning not just fish and shellfish, but any people unfortunate enough to consume the contaminated seafood. Nontoxic algal blooms are on the upsurge too. Even though these algae produce no poisons, they use up most of the water's available oxygen as they decompose. The resulting hypoxic "dead zones"—areas where dissolved oxygen concentrations are too low to support most forms of life—can last for months.

Algal blooms are hardly unique to China. Perhaps the most famous of these events is the recurrent bloom in the Gulf of Mexico, off the coast of Texas and Louisiana. Almost every spring, and increasingly at other seasons as well, thick clouds of algae form in these waters. The Gulf dead zone is vast—in 1999 it covered 18,000 square kilometers, about the size of the state of New Jersey—and it does millions of dollars in damage to the region's fisheries every year. Here too, nitrogen is the key factor (although increasing loads of phosphorus and silica are also apparently feeding the algae). Most of the nitrogen appears to be coming from sewage and agricultural runoff. According to a report by the White House Office of Science and Technology Policy, manure alone contributes some 15 percent of the nitrogen that makes its way into the Gulf. That's more than all nonfarm industrial nitrogen sources combined.

But farm runoff and sewage aren't the only components of the nitrogen cycle that are promoting algal blooms. In the Baltic Sea, the primary burden of excess nitrogen comes from fossil fuel emissions. A full third of the nitrogen entering the Sea—by far the largest share of the excess load—consists of nitrogen oxides produced by the combustion of coal and oil in the surrounding countries. The Baltic is a naturally low-nitrogen environment that supports a unique community of organisms adapted to those circumstances. But as the nitrogen levels have increased, cyanobacteria are responding with large, eerily beautiful blooms. The blooms are shading out the sea's "forests" of bladderwrack, a species of brown seaweed that requires clear, well lit waters. The bladderwrack is prime spawning and nursery habitat for many fish species, now threatened by the seaweed's decline. And as the blooms decompose, they steal oxygen from the water—a form of change to which the Baltic is especially sensitive, since its waters are relatively low-oxygen to begin with. The drop in oxygen is working change in the seafloor community, where bristleworms, which tolerate hypoxia, are replacing the once-dominant mussels. This change, in turn, is likely to restructure the foodweb, since mussels are an important prey item for many fish that won't eat bristleworms.

Algal blooms and dead zones are now a regular feature of coastal life in many other places around the world—off the coast of New England, for instance, off the west coast of India, and off Japan and Korea as well. Most of the world's major coastal ecosystems appear to be suffering some degree algae-induced hypoxia. And toxic blooms are an increasingly conspicuous part of this problem. According to scientists at the U.N. Food and Agriculture Organization (FAO) and the International Oceanographic Commission, the 1980s and 1990s saw a global upsurge in red tides. As these episodes have become more common, so has the number of algae species known to be involved. In the early 1990s, only about 20 species were known to produce toxic blooms; today, at least 85 have been identified.

SOME EFFECTS OF NITROGEN POLLUTION are much more subtle than algal blooms, but arguably even more dangerous. For example, the nitrogen oxides produced through fossil fuel combustion are a major component of the acid rain that is attacking soil and fresh water in many parts of the world. Waters that become increasingly acidic support fewer forms of aquatic life. In a similar fashion, the acidification of soils tends to impoverish the soil community. That's partly because the acid releases aluminum ions from the mineral matrix in which they are usually embedded. Free aluminum is toxic to plants—and to many aquatic organisms if it washes into streams. The acid also causes certain minerals to leach out of the soil. Calcium, magnesium, and potassium are essential plant nutrients and are often in relatively short supply. Where they become rare, plant growth is likely to slow, and the more mineral-hungry species may fade from the scene.

These minerals come into the soil through the weathering of rock. Since weathering is a very slow process, acidification could reduce the productivity of affected soils for centuries—or longer. The extreme case appears to involve cropland, where too much fertilizer may perform the role of acid rain. According to Phillip Barak, a professor of soil chemistry and plant nutrition at the University of Wisconsin, nitrogen-induced mineral leaching in some U.S. cropland has artificially "aged" these soils by the equivalent of 5,000 years.

Over the past couple of decades, the industrialized countries have made considerable progress in reducing emissions of one main ingredient of acid rain: the sulfur dioxide produced by the combustion of sulfur-contaminated coal. The switch to low sulfur coal and the installation of smoke stack "scrubbers" on coal-burning powerplants have greatly reduced this type of pollution. But incremental solutions aren't as useful in reducing the nitrogen compounds released by fossil fuel combustion. The fixed nitrogen in fossil fuels cannot be readily removed—and additional nitrogen is fixed as a byproduct of the combustion itself.

Excess soil nitrogen is sickening forests and fields in other ways as well. Nitrogen pollution may reduce cold hardiness in certain tree species, making them more liable to injury or death during the winter. Too much nitrogen also tends to reduce fine root density, which in turn restricts water and nutrient uptake, making plants more susceptible to drought.

On a community level, nitrogen loading is a homogenizing force, because it strongly favors fast-growing plant species that can use extra nutrient, at the expense of slower-growing species that cannot. Affected areas may show robust growth but that growth is likely to be quite uniform. Surveys in Great Britain by the Institute for Terrestrial Ecology found that near major sources of nitrogen pollution, such as large poultry farms, the ground-layer flora of nearby woodlands was dominated by dense stands of a few rank, tall grass species. The farther away from the farms the researchers went, the more varied the woodland flora became. This homogenizing tendency is also apparent in the heathlands of Northern Europe, particularly in the Netherlands, which has the greatest concentration of livestock on the planet. Formerly a diverse assemblage of shrubs and herbs, these heathlands are increasingly dominated by invasive grasses and trees. Excess nitrogen is indeed fertilizing more and more of the world's wild communities. But it is promoting the growth of a few opportunistic species, at the expense of a more diverse whole.

OVER THE PAST FEW YEARS, Indian researchers have been detecting substantial quantities of nitrous oxide rising out of the Arabian Sea, off India's west coast. The Sea's emissions are now thought to contribute up to 21 percent of total output of the gas from the world's oceans. In the upper atmosphere, nitrous oxide tends to deplete the stratospheric ozone layer, which shields the Earth against harmful ultraviolet radiation. Nitrous oxide is also a potent greenhouse gas. On a molecule-per-molecule basis, it's 200 times more effective at retaining heat than is CO_2. Luckily, it's far less common than CO_2, but it still accounts for 2 to 3 percent of overall greenhouse warming.

Why is the Arabian Sea exhaling so much of this gas? Rajiv Naqvi, a researcher at India's National Institute of Oceanography sees a link with intensifying agriculture. Over the past four decades or so, fertilizer use has grown substantially on India's western coastal plain, as it has in most of the country's croplands. (According to FAO statistics, Indian fertilizer consumption nearly doubled from 1965 to 1998, rising to over 11 million tons.) As in many of the world's coastal waters, the resulting nitrogen-laden runoff is feeding cyanobacteria and other plankton. Cyanobacteria generally produce some nitrous oxide as they grow, but their activity in these waters is affected by another powerful factor: India's June to September monsoons. Since freshwater is lighter than salt water, the hard monsoon rainfall tends to blanket the ocean surface, reducing the aeration of the saltier water beneath. That drops the oxygen level, and the lack of oxygen in turn causes the cyanobacteria to metabolize nitrogen in a way that releases larger amounts of nitrous oxide. This effect appears to have been exacerbated in recent years because of unusually heavy monsoon rains, a possible result of climate change.

Ice core data indicate that the atmospheric concentration of nitrous oxide was quite stable until about a century ago, when it began to increase. The current rate of increase is estimated at 0.2 to 0.3 percent per year. Atmospheric concentrations are now about 10 percent higher than they were at the beginning of the century.

In the abstract, this is what seems to be happening in the Arabian Sea: an increase in fixed nitrogen, possibly combined with climate change in the form of intensifying monsoons, is putting more pressure on the climate system. There is a subtle connection here between the nitrogen and carbon cycles, but this is just one of many such links. Pamela Matson, Director of Stanford University's Earth Systems Program, puts it simply: "In order to understand carbon and Earth's other cycles, we have to understand how nitrogen is changing." How will the changing nitrogen cycle affect the changing carbon cycle?

Given the climate treaty negotiations, there is a nearly irresistible political impulse to look for links that might be increasing carbon absorption from the atmosphere. Perhaps the nitrogen glut will increase the carbon sinks. At first glance, that looks like a reasonable expectation. After all, nitrogen is often a limiting nutrient; more of it should mean more plant growth, which should increase CO_2 absorption. But it doesn't seem to be that simple.

In the oceans, plankton growth out beyond the coastal waters is often limited not by nitrogen availability but by the availability of iron, another essential nutrient. So extra nitrogen doesn't automatically translate into extra CO_2 absorption. (It's true that some scientists advocate seeding the oceans with iron to increase CO_2 absorption, but given all the unforeseen problems we've already created with excess nitrogen and carbon, it would hardly be wise policy to interfere with yet another cycle.) And even in the case of the coastal algal blooms, which may increase CO_2 absorption, at least periodically, it's not clear whether that extra CO_2 will remain in the waters over the long term, or end up back in the atmosphere relatively quickly.

On land, the issue is primarily a matter of forest growth, since forests generally store more carbon than other types of terrestrial ecosystems. It's true that excess nitrogen may cause forests to grow more rapidly over the short term. But over the long term, the prospects for such forests are fairly dismal, given the acidification, aluminum poisoning, and other forms of physiological and ecological disruption that nitrogen loading tends to cause. And a declining forest is more likely to be releasing carbon than absorbing it. Despite the connections between the nitrogen cycle and the carbon cycle, there is no good reason to assume that disruption of the former will partly "cancel out" disruptions in the latter.

In terms of its technical detail, stabilizing the nitrogen cycle is likely to be just as demanding a task as is stabilizing the carbon cycle. But perhaps the most obvious aspect of this problem is its familiarity: the types of change that would make the most difference are already standard items on the environmental agenda. Three basic reforms appear to be necessary if we are to achieve major reductions of our fixed nitrogen emissions. We will need to convert the dominant mode of agricultural production from its current, "high input" paradigm to one that emphasizes organic production. (See "Where Have All the Farmers Gone?" September/October 2000.) We will need to convert our fossil fuel-based energy economy to one based on sunlight, wind, geothermal, and other forms of renewable energy. And finally, we will need to slow and eventually reverse the destruction of the planet's remaining natural areas, especially its remaining forests.

These are enormous goals, of course, but each of them shares some characteristics that can help chart the way forward. In the first place, they all aim at broad systemic reform, but they focus on the small-scale unit. Organic farming usually works best when the farms are small enough to accommodate the local landscape. Sophisticated renewable energy systems generally create networks of smaller producers rather than one or two enormous powerplants. And sustainable forest use, by definition, is carefully attuned to local ecological realities. There's a second common feature too: each of these goals emphasizes creative use of diversity. A polycultural cropping system, a range of renewable energy technologies, a combination of agroforestry, timber, and tourism—in each case, the idea is to replace a "monoculture approach" with a system that is more diverse and therefore more flexible, more likely to be sustainable over the long term. Small-scale and diverse would appear to be the way to go. You could say that the agenda points towards a high degree of local adaptation.

Humanity has reached a point at which we are dominating—not just particular ecosystems—but the cycles that regulate the basic processes on which all life depends. Our capacity to understand the effects of our interference is growing rapidly. But will we be able to use that understanding productively? Increasingly, it seems, progress on the global level will depend on our ability to reinvent our relationships to the local level—to the particular ecosystems and societies in which we actually live.

Danielle Nierenberg recently completed her M.S. in the agriculture, food, and environment program at Tufts University, in Massachusetts, and is currently working with the World Watch staff.

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