

FIXING THE GLOBAL Nitrogen Problem

Humanity depends on nitrogen to fertilize croplands, but growing global use is damaging the environment and threatening human health. How can we chart a more sustainable path? **By Alan R. Townsend and Robert W. Howarth**

KEY CONCEPTS

- Nitrogen pollution from smokestacks, tailpipes and heavily fertilized croplands creates a host of challenges for the environment and human health.
- Such ills are mounting as some countries burn more fossil fuels and pursue fertilizer-intensive endeavors, such as bio-fuels production.
- Synthetic fertilizer remains indispensable for meeting global food demands, but the world can—and should—do more with less.

—The Editors

Billions of people today owe their lives to a single discovery now a century old. In 1909 German chemist Fritz Haber of the University of Karlsruhe figured out a way to transform nitrogen gas—which is abundant in the atmosphere but nonreactive and thus unavailable to most living organisms—into ammonia, the active ingredient in synthetic fertilizer. The world's ability to grow food exploded 20 years later, when fellow German scientist Carl Bosch developed a scheme for implementing Haber's idea on an industrial scale.

Over the ensuing decades new factories transformed ton after ton of industrial ammonia into fertilizer, and today the Haber-Bosch invention commands wide respect as one of the most significant boons to public health in human history. As a pillar of the green revolution, synthetic fertilizer enabled farmers to transform infertile lands into fertile fields and to grow crop after crop in the same soil without waiting for nutrients to regenerate naturally. As a result, global population skyrocketed from 1.6 billion to six billion in the 20th century.

But this good news for humanity has come at a high price. Most of the reactive nitrogen we make—on purpose for fertilizer and, to a lesser

extent, as a by-product of the fossil-fuel combustion that powers our cars and industries—does not end up in the food we eat. Rather it migrates into the atmosphere, rivers and oceans, where it makes a Jekyll and Hyde style transformation from do-gooder to rampant polluter. Scientists have long cited reactive nitrogen for creating harmful algal blooms, coastal dead zones and ozone pollution. But recent research adds biodiversity loss and global warming to nitrogen's rap sheet, as well as indications that it may elevate the incidence of several nasty human diseases.

Today humans are generating reactive nitrogen and injecting it into the environment at an accelerating pace, in part because more nations are vigorously pursuing such fertilizer-intensive endeavors as biofuel synthesis and meat production (meat-intensive diets depend on massive growth of grain for animal feed). Heavy fertilizer use for food crops and unregulated burning of fossil fuels are also becoming more prevalent in regions such as South America and Asia. Not surprisingly, then, dead zones and other nitrogen-related problems that were once confined to North America and Europe are now popping up elsewhere.

At the same time, fertilizer is, and should be,

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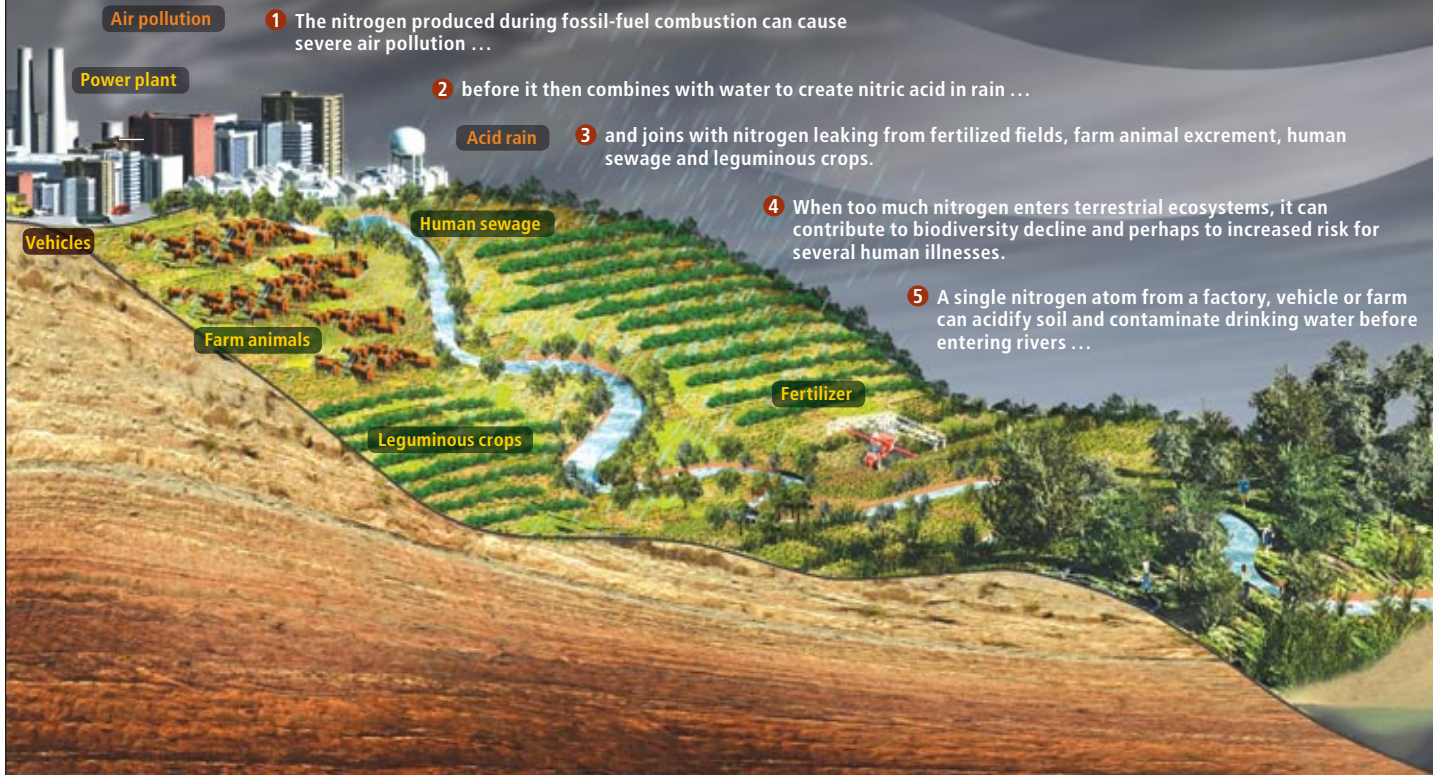
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Nitrogen's Dark Side

Doubled up as N_2 gas, the most abundant component of the earth's atmosphere, nitrogen is harmless. But in its reactive forms, which emanate from farms and fossil-fuel-burning factories and vehicles, nitrogen can have a hand in a wide range of problems for the environment and human health.



The world is capable of growing **MORE FOOD** with **LESS FERTILIZER.**

a leading tool for developing a reliable food supply in sub-Saharan Africa and other malnourished regions. But the international community must come together to find ways to better manage its use and mitigate its consequences worldwide. The solutions are not always simple, but nor are they beyond our reach.

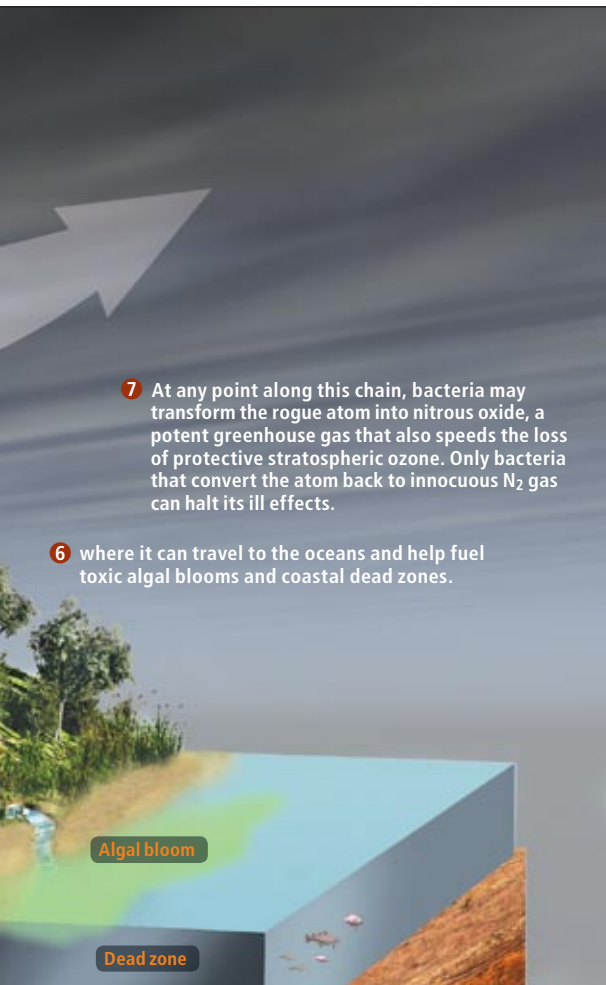
Too Much of a Good Thing

Resolving the nitrogen problem requires an understanding of the chemistry involved and a sense of exactly how nitrogen fosters environmental trouble. The element's ills—and benefits—arise when molecules of N_2 gas break apart. All life needs nitrogen, but for the vast majority of organisms, the biggest reservoir—the atmosphere—is out of reach. Although 78 percent of the atmosphere consists of N_2 , that gas is inert. Nature's way of making nitrogen available for life relies on the action of a small group of bacteria that can break the triple bond between those two nitrogen atoms, a process known as nitrogen fixation. These specialized bacteria exist in free-

living states on land and in both freshwater and saltwater and in symbiotic relationships with the roots of legumes, which constitute some of the world's most important crops. Another small amount of nitrogen gas is fixed when lightning strikes and volcanic eruptions toast it.

Before humanity began exploiting Haber-Bosch and other nitrogen-fixation techniques, the amount of reactive nitrogen produced in the world was balanced by the activity of another small bacterial group that converts reactive nitrogen back to N_2 gas in a process called denitrification. In only one human generation, though, that delicate balance has been transformed completely. By 2005 humans were creating more than 400 billion pounds of reactive nitrogen each year, an amount at least double that of all natural processes on land combined [see *top illustration on page 68*].

At times labeled nature's most promiscuous element, nitrogen that is liberated from its non-reactive state can cause an array of environmental problems because it can combine with a mul-



7 At any point along this chain, bacteria may transform the rogue atom into nitrous oxide, a potent greenhouse gas that also speeds the loss of protective stratospheric ozone. Only bacteria that convert the atom back to innocuous N₂ gas can halt its ill effects.

6 where it can travel to the oceans and help fuel toxic algal blooms and coastal dead zones.

titude of chemicals and can spread far and wide. Whether a new atom of reactive nitrogen enters the atmosphere or a river, it may be deposited tens to hundreds of miles from its source, and even some of the most remote corners of our planet now experience elevated nitrogen levels because of human activity. Perhaps most insidious of all: a single new atom of reactive nitrogen can bounce its way around these widespread environments, like a felon on a crime spree.

Reaping the Consequences

When nitrogen is added to a cornfield or to a lawn, the response is simple and predictable: plants grow more. In natural ecosystems, however, the responses are far more intricate and frequently worrisome. As fertilizer-laden river waters enter the ocean, for example, they trigger blooms of microscopic plants that consume oxygen as they decompose, leading later to so-called dead zones. Even on land, not all plants in a complex ecosystem respond equally to nitrogen subsidies, and many are not equipped for a sudden

embarrassment of riches. Thus, they lose out to new species that are more competitive in a nutrient-rich world. Often the net effect is a loss of biodiversity. For example, grasslands across much of Europe have lost a quarter or more of their plant species after decades of human-created nitrogen deposition from the atmosphere. This problem is so widespread that a recent scientific assessment ranked nitrogen pollution as one of the top three threats to biodiversity around the globe, and the United Nations Environment Program's Convention on Biological Diversity considers reductions of nitrogen deposition to be a key indicator of conservation success.

The loss of a rare plant typically excites little concern in the general public or among those who forge policy. But excess nitrogen does not just harm other species—it can threaten our own. A National Institutes of Health review suggests that elevated nitrate concentrations in drinking water—often a product of water pollution from the high nitrate levels in common fertilizers—may contribute to multiple health problems, including several cancers. Nitrogen-related air pollution, both particulates and ground-level ozone, affects hundreds of millions of people, elevating the incidence of cardiopulmonary ailments and driving up overall mortality rates.

Ecological feedbacks stemming from excess nitrogen (and another ubiquitous fertilizer chemical, phosphorus) may be poised to hit us with a slew of other health threats as well. How big or varied such responses will become remains to be seen, but scientists do know that enriching ecosystems with nitrogen changes their ecology in myriad ways. Recent evidence suggests that excess nitrogen may increase risk for Alzheimer's disease and diabetes if ingested in drinking water. It may also elevate the release of airborne allergens and promote the spread of certain infectious diseases. Fertilization of ragweed elevates pollen production from that notorious source, for instance. Malaria, cholera, schistosomiasis and West Nile virus show the potential to infect more people when nitrogen is abundant.

These and many other illnesses are controlled by the actions of other species in the environment, particularly those that carry the infective agent—for example, mosquitoes spread the malaria parasite, and snails release schistosomes into water. Snails offer an example of how nitrogen can unleash a chain reaction: more nitrogen or phosphorus run-off fuels greater plant growth in water bodies, in turn creating more food for the snails and a larger, faster-growing population

FAST FACTS

More than half the synthetic nitrogen fertilizer ever produced was applied in the past 20 years.

The production of synthetic nitrogen has skyrocketed 80 percent since 1960, dwarfing the 25 percent increase in atmospheric carbon dioxide over that same period.

If Americans were to switch to a typical Mediterranean diet, the country's fertilizer use would be cut in half.

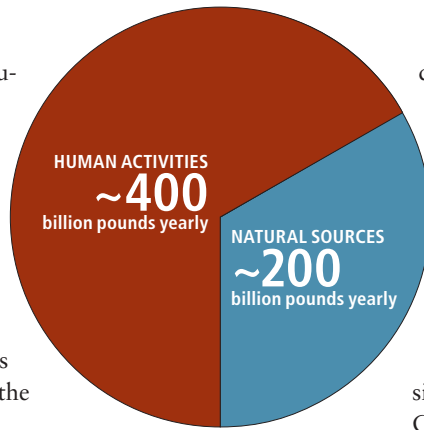
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of these disease-bearing agents. The extra nutrients also fuel an exponentially increasing effect of having each snail produce more parasites. It is too soon to tell if, in general, nutrient pollution will up the risk of disease—in some cases, the resulting ecological changes might lower our health risks. But the potential for change, and thus the need to understand how it will play out, is rising rapidly as greater use of fertilizers spreads to disease-rich tropical latitudes in the coming decades.

Mounting evidence also blames reactive nitrogen for an increasingly important role in climate change. In the atmosphere, reactive nitrogen leads to one of its major unwanted by-products—ground-level ozone—when it occurs as nitric oxide (NO) or as nitrogen dioxide (NO₂), collectively known as NO_x. Such ozone formation is troubling not only because of its threat to human health but also because at ground level, ozone is a significant greenhouse gas. Moreover, it damages plant tissues, resulting in billions of dollars in lost crop production every year. And by inhibiting growth, ozone curtails plants' ability to absorb carbon



- Synthetic fertilizer, fossil-fuel combustion, industrial uses of ammonia (plastics, explosives, etc.), cultivation of soybeans and other leguminous crops
- Nitrogen-fixing bacteria on land, lightning, volcanoes

HUMAN ACTIVITIES have tripled the amount of reactive nitrogen released into terrestrial environments and coastal oceans every year.

dioxide (CO₂) and offset global warming.

Reactive nitrogen is an especially worrisome threat to climate change when it occurs as nitrous oxide (N₂O)—among the most powerful of greenhouse gases. One molecule of N₂O has approximately 300 times the greenhouse warming potential of one molecule of CO₂. Although N₂O is far less abundant in the atmosphere than CO₂ is, its current atmospheric concentration is responsible for warming equivalent to 10 percent of CO₂'s contribution. It is worth noting that excess nitrogen can at times counteract warming—by combining with other airborne compounds to form aerosols that reflect incoming radiation, for example, and by stimulating plants in nitrogen-limited forests to grow faster and thus scrub more CO₂ out of the atmosphere. But despite uncertainties regarding the balance between nitrogen's heating and cooling effects, most signs indicate that continued human creation of excess nitrogen will speed climate warming.

What to Do

Although fertilizer production accounts for much of the nitrogen now harming the planet—

[GLOBAL PERSPECTIVES]

Shifting Hotspots

Regions of greatest nitrogen use (red) were once limited mainly to Europe and North America. But as new economies develop and agricultural trends shift, patterns in the distribution of nitrogen are changing rapidly. Recent growth rates in nitrogen use are now much higher in Asia and in Latin America, whereas other regions—including much of Africa—suffer from fertilizer shortages.



SOUTHERN BRAZIL: Rapid population growth and industrialization around Sao Paulo, poor civic sewage treatment and vibrant sugar cane production all contribute to this new South American nitrogen hotspot.

NORTH CHINA PLAIN: More vigorous application of fertilizer has produced stunning increases in maize and wheat production, but China now has the highest fertilizer inputs in the world.

roughly two thirds of that fixed by humans—abandoning it certainly is not an option. Fertilizer is too important for feeding the world. But an emphasis on efficient use has to be a part of the solution, in both the wealthy and the developing nations.

Wealthy countries have blazed a path to an agricultural system that is often exceptionally nitrogen-intensive and inefficient in the use of this key resource. Too often their use of nitrogen has resembled a spending spree with poor returns on the investment and little regard for its true costs. Elsewhere, a billion or more people stand trapped in cycles of malnutrition and poverty. Perhaps best exemplified by sub-Saharan Africa, these are regions where agricultural production often fails to meet even basic caloric needs, let alone to provide a source of income. Here an infusion of nitrogen fertilizers would clearly improve the human condition. Recent adoption of policies to supply affordable fertilizer and better seed varieties to poor farmers in Malawi, for example, led to substantial increases in yield and reductions in famine.

But this fertilizer does not need to be slathered on injudiciously. The proof is out there: studies from the corn belt of the U.S. Midwest to the wheat fields of Mexico show that overfertilization has been common practice in the breadbaskets of the world—and that less fertilizer often does not mean fewer crops. The simple fact is that as a whole, the world is capable of growing more food with less fertilizer by changing the farming practices that have become common in an era of cheap, abundant fertilizer and little regard for the long-term consequences of its use. Simply reducing total application to many crops is an excellent starting point; in many cases, fertilizer doses are well above the level needed to ensure maximum yield in most years, resulting in disproportionately large losses to the environment. In the U.S., people consume only a little more than 10 percent of what farmers apply to their fields every year. Sooner or later, the rest ends up in the environment. Estimates vary, but for many of our most



BIOFUELS FRENZY: Corn-based biofuels and their fertilizer-intensive production may contribute more to global warming than they alleviate in fossil-fuel savings.

common crops, a quarter to half immediately runs off the field with rainwater or works its way into the atmosphere.

Precision farming techniques can also help. Applying fertilizer near plant roots only at times of maximum demand is one example of methods that are already in play in some of the wealthier agricultural regions of the planet. By taking advantage of Global Positioning System technology to map their fields, coupled with remotely sensed estimates of plant nutrient levels, farmers can refine calculations of how much fertilizer a crop needs and when. But the high-tech equipment is costly, prohibitively so for many independent farmers, and so such precision farming is not a panacea.

The solutions are not all high tech. Cheaper but still effective strategies can include planting winter cover crops that retain nitrogen in a field instead of allowing a field to lie bare for months, as well as maintaining some form of plant cover in between the rows of high-value crops such as corn. Simply applying fertilizer just before spring planting, rather than in the fall, can also make a big difference.

The world can also take advantages of changes in meat production. Of the nitrogen that ends up in crop plants, most goes into the mouths of pigs, cows and chickens—and much of that is then expelled as belches, urine and feces. Although a reduction in global meat consumption would be a valuable step, meat protein will remain an important part of most human diets, so efficiencies in its production must also improve. Changing animal diets—say, feeding cows more grass and less corn—can help on a small scale, as can better treatment of animal waste, which, like sewage treatment facilities for human waste, converts more of the reactive nitrogen back into inert gas before releasing it into the environment [see “The Greenhouse Hamburger,” by Nathan Fiala; *SCIENTIFIC AMERICAN*, February 2009].

On the energy side, which represents about 20 percent of the world’s excess nitrogen, much reactive nitrogen could be removed from current fossil-fuel emissions by better deployment of

IT'S UP TO YOU

Making certain personal choices will reduce your carbon and nitrogen footprints simultaneously:

- Support wind power, hybrid cars and other policies designed to reduce fossil-fuel consumption.
- Choose grass-fed beef and eat less meat overall.
- Buy locally grown produce.

NO_x-scrubbing technologies in smokestacks and other sources of industrial pollution. Beyond that, a sustained global effort to improve energy efficiency and move toward cleaner, renewable sources will drop nitrogen emissions right alongside those for carbon. Removing the oldest and least-efficient power plants from production, increasing vehicle emission standards and, where possible, switching power generation from traditional combustion to fuel cells would all make a meaningful difference.

Of course, one source of renewable energy—biofuel made from corn—is generating a new demand for fertilizer. The incredible increase in the production of ethanol from corn in the U.S.—a nearly fourfold rise since 2000—has already had a demonstrable effect on increased nitrogen flows down the Mississippi River, which carries excess fertilizer to the Gulf of Mexico, where it fuels algal blooms and creates dead zones. According to a report last April by the Scientific Committee on Problems of the Environment (then part of the International Council for Science), a business-as-usual approach to biofuel production could exacerbate global warming, food security threats and human respiratory ailments in addition to these familiar ecological problems.

How to Get It Done

Society already has a variety of technical tools to manage nitrogen far more effectively, retaining many of its benefits while greatly reducing the risk. As for our energy challenges, a switch to more sustainable nitrogen use will not come easily, nor is there a silver bullet. Furthermore, technological know-how is not enough: without economic incentives and other policy shifts, none of these solutions will likely solve the problem.

The speed at which nitrogen pollution is rising throughout the world suggests the need for some regulatory control. Implementing or strengthening environmental standards, such as setting total maximum daily loads that can enter surface waters and determining the reactive nitrogen concentrations allowable in fossil-fuel emissions, is probably essential. In the U.S. and other nations, regulatory policies are being pursued at both national and regional scales, with some success [see “Reviving Dead Zones,” by Laurence Mee; *SCIENTIFIC AMERICAN*, November 2006]. And as much needed policy changes bring fertilizer to those parts of the world largely bypassed by the green revolution, those areas

should employ sustainable solutions from the outset—to avoid repeating mistakes made in the U.S. and elsewhere.

Promising improvements could occur even without the regulatory threat of monetary fines for exceeding emissions standards. Market-based instruments, such as tradable permits, may also be useful. This approach proved remarkably successful for factory emissions of sulfur dioxide. Adoption of similar approaches to NO_x pollution are already under way, including the U.S. Environmental Protection Agency’s NO_x Budget Trading Program, which began in 2003. Such policies could be extended to fertilizer runoff and livestock emissions as well—although the latter are more difficult to monitor than the smokestacks of a coal-burning power plant.

Other approaches to the problem are also beginning to take hold, including better use of landscape design in agricultural areas, especially ensuring that crop fields near bodies of water are fringed by intervening wetlands that can markedly reduce nitrogen inputs to surface waters and the coastal ocean. Protected riparian areas, such those promoted by the U.S. Conservation Reserve Program, can do double duty: not only will they reduce nitrogen pollution, but they also provide critical habitat for migratory birds and a host of other species.

Substantial progress may also require a rethinking of agricultural subsidies. In particular, subsidies that reward environmental stewardship can bring about rapid changes in standard practice. A recent not-for-profit experiment run by the American Farmland Trust shows promise. Farmers agreed to reduce their fertilizer use and directed a portion of their cost savings from lowered fertilizer purchases to a common fund. They then fertilized the bulk of the crop at reduced rates, while heavily fertilizing small test plots. If such plots exceeded the average yield of the entire field, the fund paid out the difference.

As one of us (Howarth) reported in a Millennium Ecosystem Assessment in 2005, such payouts would rarely be required, given the current tendency to overfertilize many crops. The average farmer in the breadbasket of the upper U.S. Midwest (the source of the great majority of nitrogen pollution fueling the Gulf of Mexico dead zones) typically uses 20 to 30 percent more nitrogen fertilizer than agricultural extension agents recommend. As predicted, farmers who participated in this and similar experiments have applied less fertilizer with virtually no de-

SOLUTIONS ARE WITHIN REACH



■ Industry can install more NO_x-scrubbing technologies in smokestacks and other sources of pollution.

■ Farmers can use less fertilizer. For many crops, applying less fertilizer would not sacrifice yield.

■ Community officials can ensure that crop fields are fringed by wetlands that can absorb nitrogen-laden runoff before it enters streams or lakes.

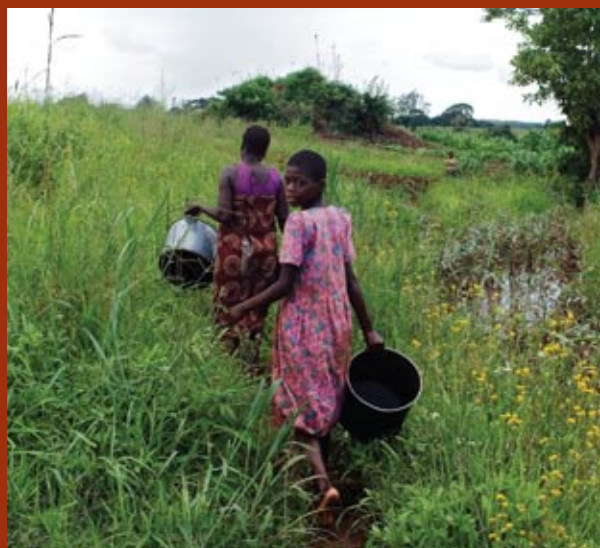
■ Nations can institute farm subsidies that reward environmental stewardship.

Where Fertilizer *Shortage* Is the Problem

Synthetic fertilizer has been, and will continue to be, critical to meeting world food demands, particularly in malnourished regions, such as sub-Saharan Africa, where increased fertilizer use is one of the leading strategies for developing a reliable food supply.

Humans already produce more than enough fertilizer to feed the world, but inequitable and inefficient distribution means that excessive use is causing problems in some places while poverty-stricken regions are mired in a cycle of malnutrition. Making synthetic fertilizer available to those who typically cannot afford it has clearly played a role in bettering food security and the human condition in parts of rural sub-Saharan Africa, where widespread malnutrition stems directly from nutrient depletion and soil erosion.

Fertilizer subsidies are one pillar of the African Millennium Villages Project, an ambitious proof-of-concept project in which coordinated efforts to improve health, education and agricultural productivity are now under way in a series of rural villages across Africa. Launched in 2004, the project was implemented on a national scale in Malawi. After a decade of repeated food shortages and famine, Malawi created subsidies that provided poor farmers with synthetic fertilizer and improved seed varieties. Although better climate conditions played a role, the approach clearly worked: Malawi went from a 43 percent food deficit in 2005 to a 53 percent surplus in 2007. —A.R.T. and R.W.H.



SYNTHETIC FERTILIZER remains critical in Mwandama, Malawi.

crease in crop yield and have saved money as a result, because what they paid into the fund is less than the amount they saved by buying less fertilizer. As a result, such funds grow with no taxpayer subsidy.

Finally, better public education and personal choice can play critical roles. In much the way that many individuals have begun reducing their own energy consumption, so, too, can people from all walks of life learn how to select a less nitrogen-intensive lifestyle.

One big improvement would be for Americans to eat less meat. If Americans were to switch to a typical Mediterranean diet, in which average meat consumption is one sixth of today's U.S. rates, not only would Americans' health improve, the country's fertilizer use would be cut in half. Such shifts in dietary and agricultural practices could simultaneously lower environmental nitrogen pollution and improve public health: nitrogen-intensive agricultural practices in wealthier nations contribute to overly protein-rich, often unbalanced diets that link to health concerns from heart disease and diabetes to childhood obesity.

Making personal choices designed to reduce an individual's carbon footprint can help—not just on the industrial side, as in supporting wind power and hybrid cars, but on the agricultural side as well. Eating less meat, eating locally

grown food and eating grass-fed rather than corn-fed beef all tackle the carbon and nitrogen problems simultaneously. Individual choices alone are unlikely to solve the problems, but history shows they can spur societies to move down new paths. The well-known trade-offs between climate and energy production that were long ignored as hypothetical now appear everywhere from presidential speeches to roadside billboards to budding regulatory schemes.

Unfortunately, the nitrogen problem is in one critical way tougher than the carbon problem. In solving the latter, it is reasonable to work toward a future of one day producing energy without CO₂-emitting fossil fuels. But it is not possible to envision a world free of the need to produce substantial amounts of reactive nitrogen. Synthetic fertilizer has been, and will continue to be, critical to meeting world food demands. Yet if we stay on a business-as-usual trajectory, with nitrogen production continuing to rise, we will face a future in which the enormous benefits of Fritz Haber's discovery become ever more shrouded by its drawbacks.

Still, as we have argued here, nitrogen cycle problems could be significantly reduced with current technology at relatively affordable costs. We can and must do better. It will take immediate and ongoing effort, but a sustainable nitrogen future is entirely achievable. ■

➔ MORE TO EXPLORE

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