

# WORLD·WATCH

WORKING FOR A SUSTAINABLE FUTURE

## **P Soup** **(the global phosphorus cycle)**

by Elena Bennett and Steve Carpenter

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# EP Soup

**It's green, but it's not good for you. That benign-looking pond scum signifies a far-reaching shift in the global phosphorus cycle.**

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by Elena Bennett  
and Steve R. Carpenter

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**T**hink of global environmental change, and you'll probably think most immediately of such sweeping atmospheric phenomena as global warming or ozone depletion. Many of the other environmental disruptions we're familiar with—toxic dumps, decimated forests, eroded fields—seem largely confined to particular localities. Yet there are some environmental changes that, while appearing to be locally confined, are in fact manifestations of worrisome global patterns. Look at the algae forming on a local farm pond, for example, and you're seeing the result of a process—the phosphorus cycle—that extends far beyond that farm.

Algae thrives (literally “blooms”) on runoff of waste fertilizer or other materials containing phosphorus. While human-caused changes in the closely related nitrogen cycle have been widely publicized (see “Toxic Fertility” in the March/April 2001 *WORLD WATCH*), impacts on the phosphorus cycle are less well known. Our research suggests, however,

that the movement of phosphorus is indeed a global phenomenon—and that that patch of algae you see in the pond at your feet may be affected by changes in the soil hundreds or thousands of miles away.

Both nitrogen and phosphorus are essential nutrients for plants and are therefore present in most fertilizers in addition to being present in agricultural and municipal waste products. As a result, the movement of large amounts of fertilizers around the planet can also mean the movement of excessive nutrients from one place to another. Typically, some of the fertilizer used on a farm does not stay there but moves downhill where it can get into a downstream aquatic ecosystem—a river, lake, or bay. Concentrations of excess nutrients in these bodies of water cause the patches of algae to expand prolifically. Such “eutrophication,” as the green blanketing of the water is called, can be a crippling process: it suffocates the life under the slime—killing fish, diminishing biodiversity, and emitting noxious odors. It



19th-century engraving of a phosphorescent sea creature.

reduces the value of the water for most human uses—whether for drinking, fishing, swimming, or even boating.

Lake Mendota, in Madison, Wisconsin is a classic example of a eutrophic lake in an urbanizing, but primarily agricultural setting. The lake has exhibited many of the symptoms associated with eutrophication since agriculture became the primary land cover in the surrounding watershed, in place of the native prairie and oak savannah. Blooms of blue-green algae

have been common here since the 1880s. Along with these blooms came dramatic changes in the food web, including loss of some native species and increased populations of non-native species such as Eurasian milfoil and carp. Eutrophication has greatly diminished the lake's recreational value.

Historically, Madison has never developed public swimming pools, because people were always able to swim in the area's plentiful lakes. Now, as eutrophication worsens, there is increasing public pressure to



develop pools because many of the lakes are no longer swimmable. For Lake Mendota alone, the cost of eutrophication has been estimated to be about \$50 million in lost recreation and property values. Even so, what happened to this lake is seen as a local story—of little interest to someone in North Carolina or South China. If the people in Madison want to deal with this problem, obviously it is their own local farms and sewer pipes they have to deal with. What's not so obvious is that what has happened here results from massive changes in the flow of phosphorus around the globe.

## Human Impact on the Global Phosphorus Cycle

Long before humans arrived on the scene, phosphorus was moving around the planet in a natural cycle that probably took millions of years to complete. A phosphorus molecule might be trapped in rock, then released by erosion to start its gravity-driven journey to the ocean. Along the way, it might be taken up by plants and then animals, then returned to the soil or water via dead vegetation or urine, to continue its slow trek downhill until it finally reached the ocean. Once in the ocean—probably after taking more detours through plants and animals along the way—it would sink into the sediment. In time, geological processes would turn this sediment to terrestrial rock—reincorporating the phosphorus molecule. The cycle would begin again.

With the advent of human agriculture and urban-

ization, the natural cycle was in some respects short-circuited. Technological advances, especially in the past 50 years, enabled us to mine phosphorus on a large scale, make fertilizer and other products from it, and transport these products around the world, dramatically accelerating the now not-so-natural phosphorus cycle. Globally, we estimate that the annual accumulation of phosphorus in the Earth's freshwater and terrestrial ecosystems has almost quadrupled, from around 3.5 terragrams per year before humans began mining and farming on a large scale, to around 13 terragrams per year now.

To understand the cycle as it was before human interventions began, it is useful to think of the cycle as a flow from the earth's crust back to earth's crust, through four main compartments (see figure, page 31). First, phosphorus-containing rock is weathered—worn by wind, rain, freezing and thawing, etc.—until it becomes soil. With the soil, it moves into lakes and rivers, which transport it to the ocean. Some of it is dissolved in water, and some adsorbed to soil particles that are carried by erosion down to the sea and, ultimately, to the ocean bottom. There it awaits the tectonic movement that will lift up the rock and make it part of the land again. The cycle is described by Aldo Leopold in his essay, "Odyssey," in *A Sand County Almanac*:

"X had marked time in the limestone ledge since the Paleozoic seas covered the land. Time, to an atom locked in a rock, does not pass. The break came when a bur-oak root nosed down a crack and began prying and sucking. In the flash of a century the rock

## A Brief History of Phosphorus

*In his book The 13th Element: The Sordid Tale of Murder, Fire, and Phosphorus, science writer John Emsley tells the story of a material that acquired a notorious reputation over three centuries—in making the nerve gas ethyl S-2 diisopropylaminoethyl methylphosphorothiolate (VX); in the organophosphate insecticides Tetraethyl diphosphate, Parathion, and Malathion; in mortar and howitzer shells; in the bombs Hitler rained on Britain; in the execution of numerous murders; and—allegedly—in the infliction of Gulf War Syndrome. But from the start,*

*as suggested by Emsley's account of its discovery, the users of phosphorus had little inkling of the damage its disruption might ultimately do:*

Uncertainty still surrounds the date on which phosphorus was first made. We can be fairly sure the place was Hamburg in Germany, and that the year was probably 1669, but the month and day are not recorded, though it must have been night time. The alchemist who made the discovery stumbled upon a material the like of which had never been

seen. Unwittingly he unleashed upon an unsuspecting world one of the most dangerous materials ever to have been made.

On that dark night our lone alchemist was having no luck with his latest experiments to find the philosopher's stone. Like many before him he had been investigating the golden stream, urine, and he was heating the residues from this which he had boiled down to a dry solid. He stoked his small furnace with more charcoal and pumped the bellows until his retort glowed red hot. Suddenly something strange began to hap-

decayed, and X was pulled out and up into the world of living things. He helped build a flower, which became an acorn, which fattened a deer, which fed an Indian, all in a single year....” The narrative continues through a journey of many adventures involving a bluestem, a plover, some phlox, a fox, a buffalo, a spiderwort, a prairie fire, another fox, another Indian, a beaver, a bayou, and a riverbank. Then, “One spring an oxbow caved the bank and after one short week of freshet X lay again in his ancient prison, the sea.”

Within each of the four compartments of this cycle—the Earth’s crust, the soil, aquatic systems and the oceans—there are more rapid cycles of phosphorus through the biosphere. In the soil phase, the phosphorus does not all just stay put in the ground. Some of it is taken up from the soil by plants, which are eaten by animals, which may in turn be eaten by other animals, before the phosphorus is eventually returned to the soil in manure or through decomposition of the animals’ bodies after they die. Of course, the phosphorus molecule can go through several more of these rapid biospheric cycles before moving to the next compartment of the global cycle. Similar biospheric cycles may then take place in the ocean.

People do several things that impact both the larger global cycle and the smaller, more rapid cycles of phosphorus through the biosphere. Most phosphorus mining takes place in only a few locations around the world—primarily in Florida, West and North Africa, and Russia. Mined phosphorus is then made into fertilizers, animal feeds, and other products and transported to agricultural areas all over the world. There

they are incorporated into the soil, either directly as fertilizers or indirectly as excess phosphorus in manure resulting from the use of high-phosphate animal feeds. Poor land-use practices further increase erosion of this phosphorus-laden soil.

Human actions thus accelerate the natural cycle at two key points: in the entry of phosphorus into the biosphere from rock, and in the movement from soil into aquatic ecosystems. Additionally, by moving phosphorus away from certain spots on the Earth’s surface (those where it is mined) and to others (primarily where it is used as fertilizer and animal feed), we radically alter the distribution of this element on the planet’s surface. The effect of shifting large quantities to places where it would not naturally be found in high concentration has become a growing concern to aquatic ecologists and others who care about maintaining supplies of clean fresh water.

Most phosphorus moves downhill attached to eroded soil particles—whether over the ground as muddy runoff or in rain-swollen streams or rivers. As people increase the amount of phosphorus in the soil through use of fertilizers, the amount of phosphorus carried downhill per kilogram of soil also increases. The higher the concentration in the soil at the outset, the more is available to release downhill. And although it is likely that less than 5 percent of the phosphorus used as fertilizer in temperate areas makes its way into aquatic ecosystems each year, that is enough to cause major changes in those environments.

Understanding what is happening in the upland soil provides a window on the future of downhill water

pen. Glowing fumes filled the vessel and from the end of the retort dripped a shining liquid that burst into flames....

That Hamburg alchemist was Hennig Brandt, a rather pompous man who insisted on being called *Herr Doktor* Brandt. His first thought was that he had at last found what he had been searching for. Surely this wondrous new material was the philosopher’s stone? If so, he had better keep the secret to himself while he made his fortune. And so for six long years he hid his discovery from the world, until his wealth

was all but spent. Magical though it was, his phosphorus stubbornly refused to bring the riches of which he dreamed. Today we know his was a vain hope, but the luminescent material he had made was to create great wealth for a few in the centuries ahead. It was to create untold misery for many more.



bodies. If we study soil uphill from lakes and rivers, we know more about the possibilities for the future of those same lakes, rivers, and the estuaries they flow into. Studying changes in the phosphorus cycle and upland soils on a global scale can help us know where to expect problems in the future and may help us reduce excess phosphorus before it is a problem.

### Messing with Eutrophication

Under natural conditions, eutrophication can be a centuries-long aging process for some lakes. When human caused (scientists call this “cultural” eutrophication), it can happen in a few years. In many cases, cultural eutrophication can be reversed by greatly reducing the amount of phosphorus entering the water.

Phosphorus is just one of many nutrients that plants need to survive and grow. However, it is particularly important to lake systems because it is the limiting nutrient. In other words, even when plants have all other nutrients in sufficient quantities, they will often lack phosphorus. When phosphorus is added to lake water, plants may suddenly grow very

rapidly because all the necessary nutrients are now present. But the excessive growth of one organism may mean the death of another. When thick blooms of algal growth block sunlight from reaching the plants below, the decay of dead algae uses up the available oxygen in the water, suffocating fish and sometimes causing whole populations of species to be lost. Eutrophication not only makes a lake look and smell putrid; it also substantially changes the way the aquatic ecosystem works. It can change the plant community, the food web, and the chemistry of a lake beyond recognition.

Although scientists have been studying eutrophication since the turn of the twentieth century, cultural eutrophication was not recognized as a widespread international problem until the 1950s and 60s, when it became a matter of growing concern in both North America’s Great Lakes region and in much of Europe. “Lakes became green and smelly, devoid of fish, unfit as sources of drinking water and unimaginable as places of recreation,” writes John Emsley in *The Thirteenth Element: A Sordid Tale of Murder, Fire, and Phosphorus*.

Scientists did not always know that phosphorus

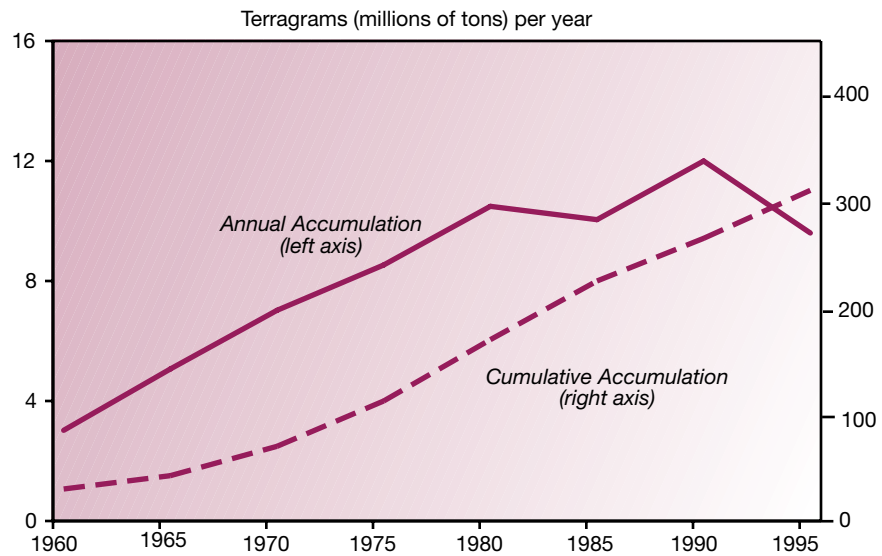




was the culprit in situations of cultural eutrophication. But in the late 1960s, a research team headed by David Schindler, a professor of Ecology at the University of Alberta in Edmonton, Canada, conducted a revealing experiment on a lake—known as “Lake 227”—in northwestern Ontario. The team divided the lake into two halves. They enriched one half with nitrogen and carbon, and the other half with phosphorus and carbon. The phosphate-enriched basin rapidly became eutrophic, while the other basin remained unchanged.

Phosphorus became widely recognized as the source of fresh water eutrophication problems, and efforts were begun to reduce phosphorus inputs to aquatic ecosystems. In most of the developed world, sewage was diverted around lakes, and most “point” sources (direct outflows of phosphorus-rich effluents from specific farms or processing plants) were cut off. By the 1990s, phosphates had been removed from most detergents, as well. Yet eutrophication persisted, in part because lakes are efficient recyclers of phosphorus. Under conditions of low oxygen at the lake bottom, phosphorus lying in the sediment reenters the water column and is once again available to be used by algae. The problem also remained because scientists had overlooked another source of phosphorus entering lakes—the non-point source runoff from surrounding lands—which proves much more difficult to control. Currently, non-point runoff from uplands is the main source of phosphorus to most aquatic systems in the developed world.

Worldwide, eutrophication in lakes, rivers, and estuaries appears to be increasing. In the Gulf of Mexico, there is now a large hypoxic zone, or “dead” zone, where the low oxygen content of the water has led to massive die-offs in ocean species. The cause has been traced to nutrient runoff from the grain-growing states of the midwestern United States, carried to the Gulf by the Mississippi River. In New Zealand, an increase in dairy farming and fertilizer use has worsened nutrient pollution in hundreds of shallow lakes and streams. By 1994, the most recent date for which we have worldwide data, significant eutrophication problems were being reported in 54 percent of all lakes and reservoirs in Southeast Asia, 53 percent of those in Europe, 48 percent in North America, 41 percent in South America, and 28 percent in Africa.



**The Rising Phosphorus Content of Terrestrial and Fresh Water Ecosystems**

The growing recognition that eutrophication is more widespread than we might have initially imagined led us to look for a larger-scale perspective on the issue and its causes. We knew that the immediate cause is human impact on phosphorus cycling: increased phosphorus in soils and increase erosion causes increased erosion to lakes. However, we wanted to understand the eutrophication problem from a global perspective because we believed that this perspective might lead to more effective long-term policies to reduce phosphorus load to aquatic ecosystems. Studying phosphorus increase in soils, as opposed to waiting until fish begin dying off in lakes, can be an effective preventive measure. So far, the systematic assessment of phosphorus in upland soils has not become a standard of the eutrophication management process.

### Management: The Global Picture

Despite widespread controlling of point source pollution, treatment of sewage, and elimination of phosphates from most soaps and detergents, eutrophication continues to worsen as a result of human activity worldwide. What to do?

The phosphorus in agricultural soils could take decades to draw down by reducing use of fertilizers. During that time, changes in farm practices, urban expansion, or climate change could accelerate erosion and—despite the lower input of phosphorus to soil—increase the rate at which phosphorus moves from the soil into aquatic ecosystems. By the time authorities see enough impairment of lakes to want to take action upstream, the fate of the lakes downstream may already have been sealed. By the same logic, however, the long time lags associated with soil phos-

## How we studied the global cycle

Although there is not much phosphorus on Earth (only about 0.1 percent of the Earth's crust is phosphorus), it is an essential nutrient for all life forms on our planet. It is found primarily in solid or liquid state and it plays a key role in DNA (the genetic material of most life) and the energy-releasing molecule ATP.

Phosphorus is mined in only a few countries, including the United States, the former Soviet Union, Morocco, and China; however, phosphorus-containing products are consumed in most countries. About 90 percent of the phosphorus mined annually is used to produce fertilizers and animal feeds. Globally, we knew that by mining phosphorus in order to put it on farms and lawns, we were likely to be creating new areas of high concentration. However, scientists knew little about where accumulation might be most severe. Answering this question would help managers prepare for future eutrophication problems.

We made a budget (analogous to a household's financial budget)

to find out how much phosphorus is accumulating in the soil compartment of the global model each year. We wanted to get a large-scale picture because we thought we might have more options for management if eutrophication was recognized as a global, rather than just local, problem.

We calculated phosphorus accumulation in soils by determining how much phosphorus enters soils each year and how much is removed. We found values for the amount of mined phosphorus that is used for animal feeds, fertilizer, and other easily biodegradable products annually, and added that to the amount of naturally weathered phosphorus. These are the inputs to Earth's soil. We also calculated how much was leaving Earth's soils each year, by estimating how much phosphorus moved into the ocean and other aquatic ecosystems. The difference between the inputs and the outputs is the amount that accumulates in soils on an annual basis, which we estimated to be between 10.5 and 15.5 million metric tons per year.

We completed a similar calculation for soil accumulation of phosphorus before widespread human impact. In the millennia before civilization began, of course, there was no mining of phosphorus—only natural weathering, which released between 1 and 6 million metric tons per year.

By making separate calculations for agricultural areas and non-agricultural, we found that although agricultural areas occupy only a small fraction of the Earth's surface (about 11 percent), most of the phosphorus accumulation occurs there. Year by year, phosphorus continues to build up in the world's farmland.

Separating calculations for poor and rich countries, we found that while poor countries once had a net loss of phosphorus, they now account for more accumulation than rich countries do. Lakes in these countries are probably becoming more susceptible to eutrophication, which is likely to worsen the quality of life of these countries in the future. ♦

phorus buildup also mean that action now can prevent expensive and persistent eutrophication problems in the future.

Efforts to control phosphorus runoff have increased dramatically in recent years. Still, most policies and regulations have approached such runoff as a problem of the particular lake, river reach, or estuary, rather than as part of a larger pattern. These efforts have generally involved reducing nearby fertilizer and manure use, limiting erosion, or removing algae from the water directly. In Lake Mendota, the city regularly runs a floating lawn mower-like machine that strips algae and other aquatic plants from the water.

To implement the long-term solution by reducing

the phosphorus stored in upland soil is more difficult. Because upland runoff originates from more dispersed sources, it is very difficult to pinpoint the landowners who are responsible. One consequence is that in the United States, programs are usually voluntary rather than mandatory. Effectiveness is limited, especially if the incentives for participation are not great enough. In some cases, local water authorities attempt to help farmers (and others) to limit phosphorus use or reduce erosion by offering cost sharing from the government. For example, if manure storage pits are needed, the government may offer to pay a share of the cost of creating a manure storage pit.

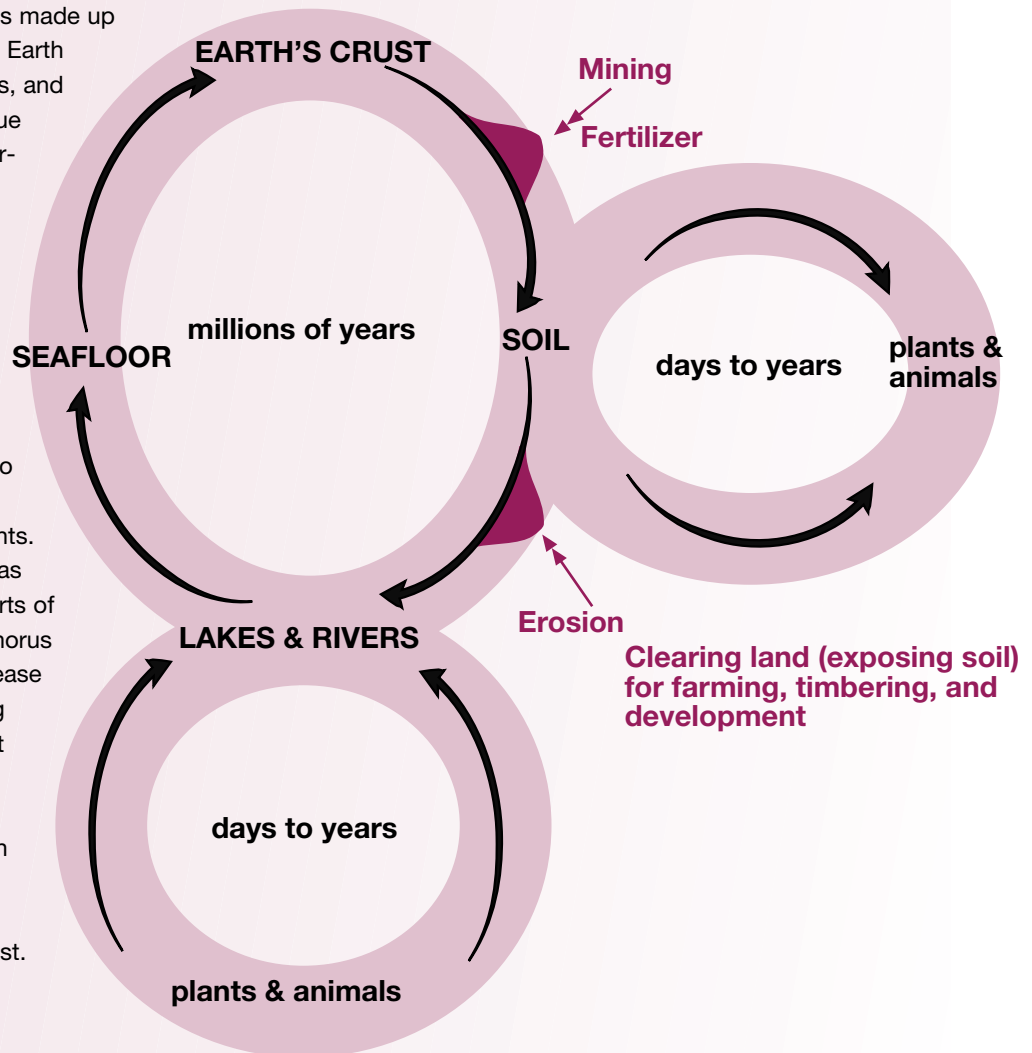
In other countries such as the Netherlands,



## The Human Impact on the Phosphorus Cycle

The global phosphorus cycle is made up of four “compartments” of the Earth (crust, soil, freshwater systems, and the ocean), through which—due to the slow process of rock formation in the ocean bottom, subsequent tectonic upheaval, and weathering of rock into soil—it takes millions of years to complete. Along the way, an atom of phosphorus may go through many more rapid, biological, cycles as it is incorporated into animals or plants in the soil, aquatic, or ocean compartments.

Human activity, however, has radically accelerated some parts of the movement. Mining phosphorus for fertilizer speeds up the release from crust to soil, and clearing land speeds up the movement from soil to aquatic systems. The result has been a more rapid buildup of phosphorus in soils, and a more widespread eutrophication of lakes and rivers, than occurred in the past.



restrictions on phosphorus use are more severe and enforced by law rather than enacted voluntarily. Eutrophication is a major concern for the Netherlands, due to the country's high population density and intensive agriculture—combined with the fact that the Rhine River water that flows into the Netherlands from other European countries is already high in phosphorus content. Therefore, Dutch farmers are subject to manure quotas: for each acre of land, they may only spread a certain amount of manure. (The amount allowed per acre often depends on the location, size, and type of farm.) For any manure used beyond that amount, the farmer must pay the costs of removal and processing.

As we begin to look at eutrophication as a global

phenomenon, we notice that around the world, water subsidizes agricultural systems. Because we do not account for the cost of water pollution when we add up the cost of agricultural production, food production seems cheaper than it actually is. In economic terms, the cost of water pollution caused by agricultural production is an externality to the agricultural production system. If this worked in the past because clean fresh water seemed infinite, it no longer makes sense to take fresh water supply for granted. Since both food and water are necessary for human survival, it might appear that we are facing a difficult choice between producing food and protecting aquatic resources. However, just as we cannot afford to ignore water pollution, we cannot afford to solve

the problem simply by reducing agricultural production. The growing human population and increasing demand for food, along with the lack of vacant arable land for use in agricultural expansion, mean that agricultural production will probably have to become more intense and efficient on land already in production.

Win-win solutions would change regulations and incentives to bring the costs and benefits of agricultural production and water quality protection into better balance. For example, governments could create markets for nitrogen and phosphorus runoff. Each farm would be allotted a certain amount of permissible pollution or runoff. If the farmer could find a way to emit less pollution, he could then sell some of his pollution rights to another farm. If set up correctly, the market would quickly adjust to the value of water—thereby internalizing the cost of water pollution. Alternatively, governments could tax fertilizer use to create an incentive for conservation, using the tax revenues to improve water quality.

Such methods can prove economically as well as environmentally beneficial. A few years ago, New York City, which gets its water supply from the Catskill mountain area, found that its water was no longer meeting EPA standards due to fertilizers and pesticides in the soil. City officials realized they would have to spend between \$6 billion and \$8 bil-

lion to build a water filtration plant to clean the water. Instead, they were able to purchase watershed land in the Catskills sufficient to naturally filter the water for only \$1.5 billion. Quality of the water supply was increased and money was saved.

Comparable solutions may be feasible at national and global scales, making it possible to conserve fertilizer, stabilize soils, and improve water quality while reducing costs. Effective policies might include the establishment of national or international phosphorus markets and better tracking of phosphorus around the world, in order to ensure that some areas are not being overwhelmed by excess nutrients. Phosphorus markets could ensure that products such as manure are moved to where they can be used.

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Steve R. Carpenter is Halverson Professor of Limnology and Professor of Zoology at the University of Wisconsin, and a past president of the Ecological Society of America. Elena Bennett is doing post-doctoral research in fresh water ecology at the University of Wisconsin. The data in this article are based on E.M. Bennett, S.R. Carpenter, and N.F. Caraco, 2001, "Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective," *BioScience* 51:227-234

