Global Population and the Nitrogen Cycle

Feeding humankind now demands so much nitrogen-based fertilizer that the distribution of nitrogen on the earth has been changed in dramatic, and sometimes dangerous, ways

by Vaclav Smil

During the 20th century, humanity has almost quadrupled its numbers. Although many factors have fostered this unprecedented expansion, its continuation during the past generation would not have been at all possible without a widespread—yet generally unappreciated—activity: the synthesis of ammonia. The ready availability of ammonia, and other nitrogen-rich fertilizers derived from it, has effectively done away with what for ages had been a fundamental restriction on food production. The world's population now has enough to eat (on the average) because of numerous advances in modern agricultural practices. But human society has one key chemical industry to thank for that abundance—the producers of nitrogen fertilizer.

Why is nitrogen so important? Compared with carbon, hydrogen and oxygen, nitrogen is only a minor constituent of living matter. But whereas the three major elements can move readily from their huge natural reservoirs through the food and water people consume to become a part of their tissues, nitrogen remains largely locked in the atmosphere. Only a puny fraction of this resource exists in a form that can be absorbed by growing plants, animals and, ultimately, human beings.

Yet nitrogen is of decisive importance. This element is needed for DNA and RNA, the molecules that store and transfer genetic information. It is also required to make proteins, those indispensable messengers, receptors, catalysts and structural components of all plant and animal cells. Humans, like other higher animals, cannot synthesize these molecules using the nitrogen found in the air and have to acquire nitrogen compounds from food. There is no substitute for this intake, because a minimum quantity (consumed as animal or plant protein) is needed for proper nutrition. Yet getting nitrogen from the atmosphere to crops is not an easy matter.

The relative scarcity of usable nitrogen can be blamed on that element's peculiar chemistry. Paired nitrogen atoms make up 78 percent of the atmosphere,

but they are too stable to transform easily into a reactive form that plants can take up. Lightning can cleave these strongly bonded molecules; however, most natural nitrogen "fixation" (the splitting of paired nitrogen molecules and subsequent incorporation of the element into the chemically reactive compound ammonia) is done by certain bacteria. The most important nitrogen-fixing bacteria are of the genus *Rhizobium,* symbionts that create nodules on the roots of leguminous plants, such as beans or acacia trees. To a lesser extent, cyanobacteria (living either freely or in association with certain plants) also fix nitrogen.

A Long-standing Problem

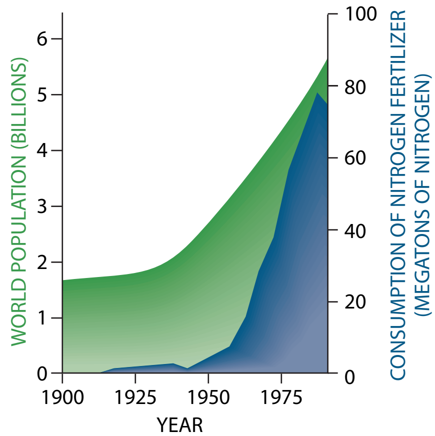
Because withdrawals caused by the growth of crops and various natural losses continually remove fixed nitrogen from the soil, that element is regularly in short supply. Traditional farmers (those in preindustrial societies) typically replaced the nitrogen lost or taken up in their harvests by enriching their fields with crop residues or with animal and human wastes. But these materials contain low concentrations of nitrogen, and so farmers had to apply massive amounts to provide a sufficient quantity.

Traditional farmers also raised peas, beans, lentils and other pulses along with cereals and some additional crops. The nitrogen-fixing bacteria living in the roots of these plants helped to enrich the fields with nitrogen. In some cases, farmers grew legumes (or, in Asia, *Azolla* ferns, which harbor nitrogen-fixing cyanobacteria) strictly for the fertilization provided. They then plowed these crops into the soil as so-called green manures without harvesting food from them at all. Organic farming of this kind during the early part of the 20th century was most intense in the lowlands of Java, across the Nile Delta, in northwestern Europe (particularly on Dutch farms) and in many regions of Japan and China.

The combination of recycling human and animal wastes along with planting green manures can, in principle, provide annually up to around 200 kilograms of nitrogen per hectare of arable land. The resulting 200 to 250 kilograms of plant protein that can be produced in this way sets the theoretical limit on population density: a hectare of farmland in places with good soil, adequate moisture and a mild climate that allows continuous cultivation throughout the year should be able to support as many as 15 people.

In practice, however, the population densities for nations dependent on organic farming were invariably much lower. China's average was between five and six people per hectare of arable area during the early part of this century. During the last decades of purely organic farming in Japan (which occurred about the same time), the population density there was slightly higher than in China, but the Japanese reliance on fish protein from the sea complicates the comparison between these two nations. A population density of about five people per hectare was also typical for fertile farming regions in northwestern Europe during the 19th century, when those farmers still relied entirely on traditional methods.

The practical limit of about five people per hectare of farmland arose for many reasons, including environmental stresses (caused above all by severe weather and pests) and the need to raise crops that were not used for food—those that provided medicines or fibers, for example. The essential difficulty came



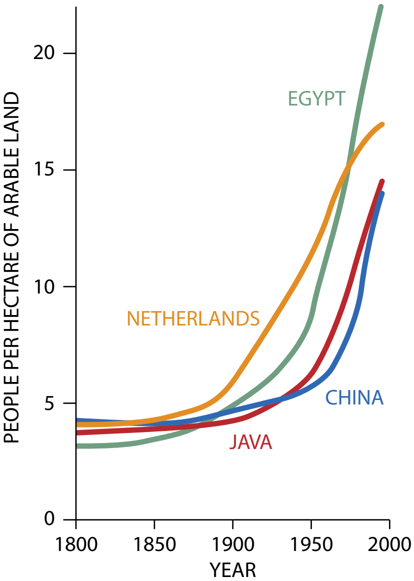
BRYAN CHRISTIE

SUDDEN GROWTH in the global consumption of nitrogen fertilizer during the 20th century has been matched by a parallel increase in world population.

JASON HAWKES *Julian Cotton Photo Library*

ERIC FREEDMAN *Bruce Coleman Inc.*

INTENSIVE AGRICULTURE, such as that practiced in these Scottish fields, relies on the industrial production of nitrogen fertilizer, using a technique that was first engineered in the second decade of this century. That same process is now implemented at scores of ammonia factories (*inset*) situated throughout the world.



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POPULATION DENSITY increased substantially in countries with intensive agriculture only after the use of nitrogen fertilizer became common.

from the closed nitrogen cycle. Traditional farming faced a fundamental problem that was especially acute in land-scarce countries with no uncultivated areas available for grazing or for the expansion of agriculture. In such places, the only way for farmers to break the constraints of the local nitrogen cycle and increase harvests was by planting more green manures. That strategy preempted the cultivation of a food crop. Rotation of staple cereals with leguminous food grains was thus a more fitting choice. Yet even this practice, so common in traditional farming, had its limits. Legumes have lower yields, they are often difficult to digest, and they cannot be made easily into bread or noodles. Consequently, few crops grown using the age-old methods ever had an adequate supply of nitrogen.

A Fertile Place for Science

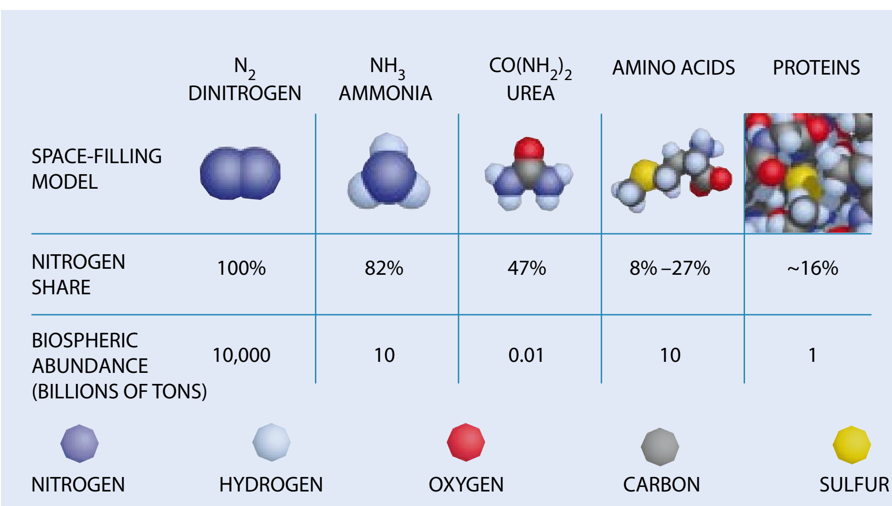
As their knowledge of chemistry expanded, 19th-century scientists began to understand the critical role of nitrogen in food production and the scarcity of its usable forms. They learned that the other two key nutrients—potassium and phosphorus—were limiting agricultural yields much less frequently and that any shortages of these two elements were also much easier to rectify. It was a straightforward matter to mine potash deposits for potassium fertilizer, and phosphorus enrichment required only that acid be added to phosphate-rich rocks to convert them into more soluble compounds that would be taken up when the roots absorbed water. No comparably simple procedures were available for nitrogen, and by the late 1890s there were feelings of urgency and unease among the agronomists and chemists who were aware that increasingly intensive farming faced a looming nitrogen crisis.

As a result, technologists of the era made several attempts to break through the nitrogen barrier. The use of soluble inorganic nitrates (from rock deposits found in Chilean deserts) and organic guano (from the excrement left by birds on Peru's rainless Chincha Islands) provided a temporary reprieve for some farmers. Recovery of ammonium sulfate from ovens used to transform coal to metallurgical coke also made a short-lived contribution to agricultural nitrogen supplies. This cyanamide process—whereby coke reacts with lime and pure nitrogen to produce a compound that contains calcium, carbon and nitrogen—was commercialized in Germany in 1898, but its energy requirements were too high to be practical. Producing nitrogen oxides by blowing the mixture of the two elements through an electric spark demanded extraordinary energy as well. Only Norway, with its cheap hydroelectricity, started making nitrogen fertilizer with this process in 1903, but total output remained small.

The real breakthrough came with the invention of ammonia synthesis. Carl Bosch began the development of this process in 1899 at BASF, Germany's leading chemical concern. But it was Fritz Haber, from the technical university in Karlsruhe, Germany, who devised a workable scheme to synthesize ammonia from nitrogen and hydrogen. He combined these gases at a pressure of 200 atmospheres and a temperature of 500 degrees Celsius in the presence of solid osmium and uranium catalysts.

Haber's approach worked well, but converting this bench reaction to an engineering reality was an immense undertaking. Bosch eventually solved the greatest design problem: the deterioration of the interior of the steel reaction chamber at high temperatures and pressures. His work led directly to the first commercial ammonia factory in Oppau, Germany, in 1913. Its design capacity was soon doubled to 60,000 tons a year—enough to make Germany self-sufficient in the nitrogen compounds it used for the production of explosives during World War I.

Commercialization of the Haber-Bosch synthesis process was slowed by the economic difficulties that prevailed



NITROGEN COMPOUNDS permeate the biosphere. The most abundant form (N_2), which makes up 78 percent of the atmosphere, is so strongly bonded that it does not engage in most chemical reactions. Plants need reactive nitrogen compounds, such as ammonia (NH_3) and urea ($CO(NH_2)_2$), which are much more scarce. (The abundance estimates shown are valid to within a factor of 10.) Plants use these substances to fashion amino acids, the building blocks of proteins, which serve myriad functions in living cells.

BIOGRAFX

a b c

DAN GURAVICH *Photo Researchers, Inc.* JEREMY BURGESS SPL/*Photo Researchers, Inc.* KENNETH W. FINK *Bruce Coleman Inc.*

NITROGEN-FIXING BACTERIA, the microbes that convert atmospheric nitrogen into reactive compounds, live in root nodules of leguminous plants, such as soybeans (*a*). They can also be found in *Azolla* ferns (*b*) and inside sugarcane plants (*c*).

between wars, and global ammonia production remained below five million tons until the late 1940s. During the 1950s, the use of nitrogen fertilizer gradually rose to 10 million tons; then technical innovations introduced during the 1960s cut the use of electricity in the synthesis by more than 90 percent and led to larger, more economical facilities for the production of ammonia. The subsequent exponential growth in demand increased global production of this compound eightfold by the late 1980s.

This surge was accompanied by a relatively rapid shift in nitrogen use between high- and low-income countries. During the early 1960s, affluent nations accounted for over 90 percent of all fertilizer consumption, but by 1980 their share was down below 70 percent. The developed and developing worlds drew level in 1988. At present, developing countries use more than 60 percent of the global output of nitrogen fertilizer.

Just how dependent has humanity become on the production of synthetic nitrogen fertilizer? The question is difficult to answer because knowledge remains imprecise about the passage of nitrogen into and out of cultivated fields around the globe. Nevertheless, careful assessment of the various inputs indicates that around 175 million tons of nitrogen flow into the world's croplands every year, and about half this total becomes incorporated into cultivated plants. Synthetic fertilizers provide about 40 percent of all the nitrogen taken up by these crops. Because they furnish—directly as plants and indirectly as animal foods—about 75 percent of all nitrogen in consumed proteins (the rest comes from fish and from meat and dairy foodstuffs produced by grazing), about one third of the protein in humanity's diet depends on synthetic nitrogen fertilizer.

This revelation is in some ways an overestimate of the importance of the Haber-Bosch process. In Europe and North America nitrogen fertilizer has not been needed to ensure survival or even adequate nutrition. The intense use of synthetic fertilizer in such well-developed regions results from the desire to grow feed for livestock to satisfy the widespread preference for high-protein animal foods. Even if the average amount of protein consumed in these places were nearly halved (for example, by persuading people to eat less meat), North Americans and Europeans would still enjoy adequate nutrition.

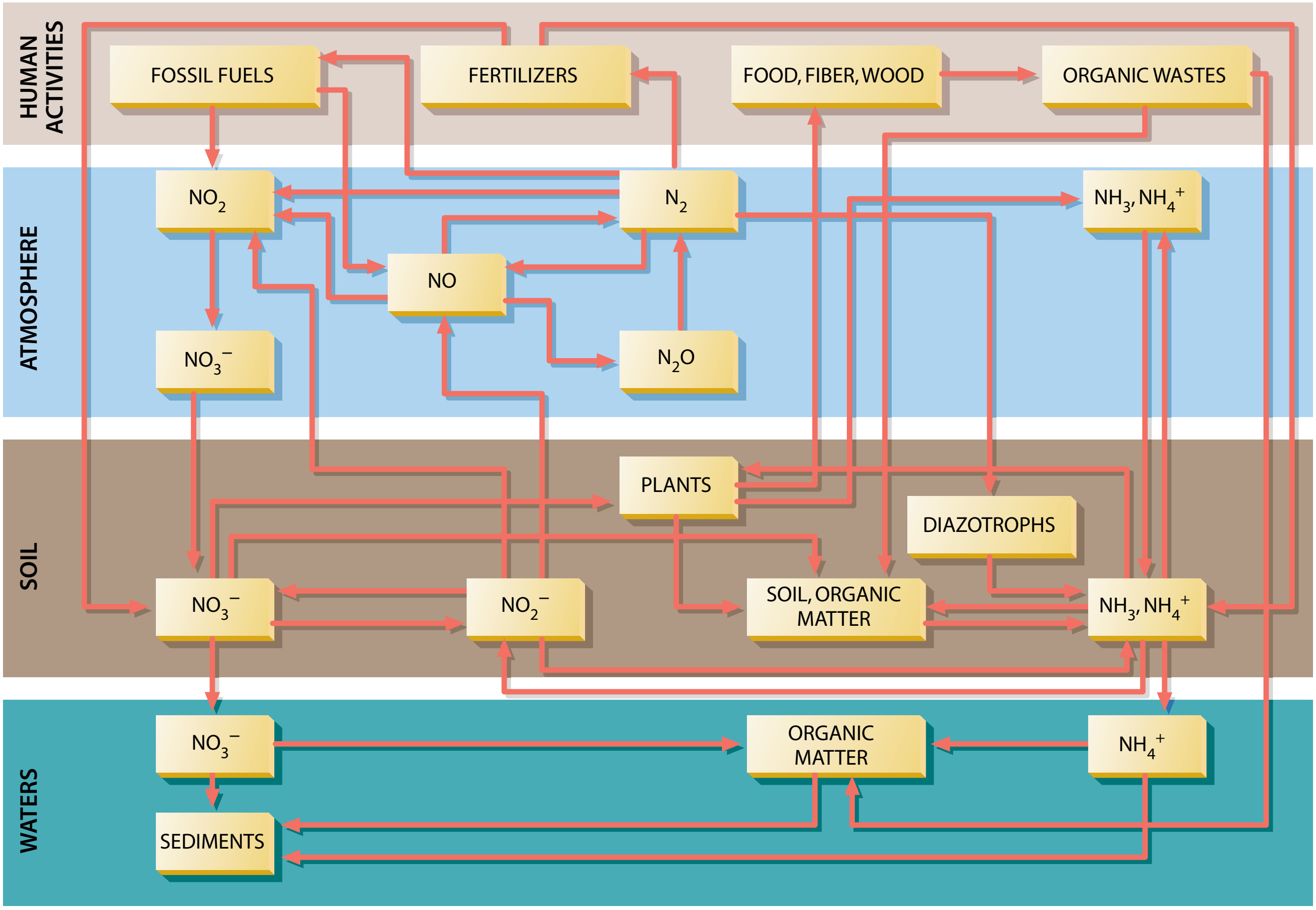
Yet the statement that one third of the protein nourishing humankind depends on synthetic fertilizer also underestimates the importance of these chemicals. A number of land-scarce countries with high population density depend on synthetic fertilizer for their very existence. As they exhaust new areas to cultivate, and as traditional agricultural practices reach their limits, people in these countries must turn to ever greater applications of nitrogen fertilizer—even if their diets contain comparatively little meat. Every nation producing annually in excess of about 100 kilograms of protein per hectare falls in this category. Examples include China, Egypt, Indonesia, Bangladesh, Pakistan and the Philippines.

Too Much of a Good Thing

Massive introduction of reactive nitrogen into soils and waters has many deleterious consequences for the environment. Problems range from local health to global changes and, quite literally, extend from deep underground to high in the stratosphere. High nitrate levels can cause life-threatening methemoglobinemia ("blue baby" disease) in infants, and they have also been linked epidemiologically to some cancers. Leaching of highly soluble nitrates, which can seriously contaminate both ground and surface waters in places undergoing heavy fertilization, has been disturbing farming regions for some 30 years. A dangerous accumulation of nitrates is commonly found in water wells in the American corn belt and in groundwater in many parts of western Europe. Concentrations of nitrates that exceed widely accepted legal limits occur not only in the many smaller streams that drain farmed areas but also in such major rivers as the Mississippi and the Rhine.

Fertilizer nitrogen that escapes to ponds, lakes or ocean bays often causes eutrophication, the enrichment of waters by a previously scarce nutrient. As a result, algae and cyanobacteria can grow with little restraint; their subsequent decomposition robs other creatures of oxygen and reduces (or eliminates) fish and crustacean species. Eutrophication plagues such nitrogen-laden bodies as New York State's Long Island Sound and California's San Francisco Bay, and it has altered large parts of the Baltic Sea. Fertilizer runoff from the fields of Queensland also threatens parts of Australia's Great Barrier Reef with algal overgrowth.

Whereas the problems of eutrophication arise because dissolved nitrates can travel great distances, the persistence of nitrogen-based compounds is also troublesome, because it contributes to the acidity of many arable soils. (Soils are



BRYAN CHRISTIE

NITROGEN RESERVOIRS of many different kinds exist within the earth's waters, soil, atmosphere and biological mantle. Nitrogen moving between these temporary resting spots takes diverse forms. The advent of large-scale fertilizer production modifies natural flows of this element enormously, unbalancing the nitrogen cycle in sometimes troubling ways.

also acidified by sulfur compounds that form during combustion and later settle out of the atmosphere.) Where people do not counteract this tendency by adding lime, excess acidification could lead to increased loss of trace nutrients and to the release of heavy metals from the ground into drinking supplies.

Excess fertilizer does not just disturb soil and water. The increasing use of nitrogen fertilizers has also sent more nitrous oxide into the atmosphere. Concentrations of this gas, generated by the action of bacteria on nitrates in the soil, are still relatively low, but the compound takes part in two worrisome processes. Reactions of nitrous oxide with excited oxygen contribute to the destruction of ozone in the stratosphere (where these molecules serve to screen out dangerous ultraviolet light); lower, in the troposphere, nitrous oxide promotes excessive greenhouse warming.

ADRIENNE T. GIBSON *Earth Scenes*

EUTROPHICATION arises in fertilizer-laden waters because excess nitrogen spurs the growth of algae.

The atmospheric lifetime of nitrous oxide is longer than a century, and every one of its molecules absorbs roughly 200 times more outgoing radiation than does a single carbon dioxide molecule.

Yet another unwelcome atmospheric change is exacerbated by the nitric oxide released from microbes that act on fertilizer nitrogen. This compound (which is produced in even greater quantities by combustion) reacts in the presence of sunlight with other pollutants to produce photochemical smog. And whereas the deposition of nitrogen compounds from the atmosphere can have beneficial fertilizing effects on some grasslands or forests, higher doses may overload sensitive ecosystems.

When people began to take advantage of synthetic nitrogen fertilizers, they could not foresee any of these insults to the environment. Even now, these disturbances receive surprisingly little attention, especially in comparison to the buildup of carbon dioxide in the atmosphere. Yet the massive introduction of reactive nitrogen, like the release of carbon dioxide from fossil fuels, also amounts to an immense—and dangerous—geochemical experiment.

From Habit to Addiction

Emissions of carbon dioxide, and the accompanying threat of global warming, can be reduced through a combination of economic and technical solutions. Indeed, a transition away from the use of fossil fuels must eventually happen, even without the motivation to avoid global climate change, because these finite resources will inevitably grow scarcer and more expensive. Still, there are no means available to grow crops—and human bodies—without nitrogen, and there are no waiting substitutes to replace the Haber-Bosch synthesis.

Genetic engineers may ultimately succeed in creating symbiotic *Rhizobium* bacteria that can supply nitrogen to cereals or in endowing these grains directly with nitrogen-fixing capability. These solutions would be ideal, but neither appears imminent. Without them, human reliance on nitrogen fertilizer must further increase in order to feed the additional billions of people yet to be born before the global population finally levels off.

An early stabilization of population and the universal adoption of largely vegetarian diets could curtail nitrogen needs. But neither development is particularly likely. The best hope for reducing the growth in nitrogen use is in finding more efficient ways to fertilize crops. Impressive results are possible when farmers monitor the amount of usable nitrogen in the soil so as to optimize the timing of applications. But several worldwide trends may negate any gains in efficiency brought about in this way. In particular, meat output has been rising rapidly in Latin America and Asia, and this growth will demand yet more nitrogen fertilizer, as it takes three to four units of feed protein to produce one unit of meat protein.

Understanding these realities allows a clearer appraisal of prospects for organic farming. Crop rotations, legume cultivation, soil conservation (which keeps more nitrogen in the soil) and the recycling of organic wastes are all desirable techniques to employ. Yet these measures will not obviate the need for more fertilizer nitrogen in land-short, populous nations. If all farmers attempted to return to purely organic farming, they would quickly find that traditional practices could not feed today's population. There is simply not enough recyclable nitrogen to produce food for six billion people.

When the Swedish Academy of Sciences awarded a Nobel Prize for Chemistry to Fritz Haber in 1919, it noted that he created "an exceedingly important means of improving the standards of agriculture and the well-being of mankind." Even such an effusive description now seems insufficient. Currently at least two billion people are alive because the proteins in their bodies are built with nitrogen that came—via plant and animal foods—from a factory using his process.

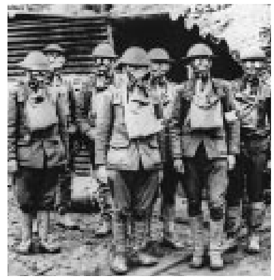
Barring some surprising advances in bioengineering, virtually all the protein needed for the growth of another two billion people to be born during the next two generations will come from the same source—the Haber-Bosch synthesis of ammonia. In just one lifetime, humanity has indeed developed a profound chemical dependence. SA

The Curious Fate of Fritz Haber

UPI/CORBIS-BETTMANN

FRITZ HABER received the Nobel Prize for Chemistry after being labeled a war criminal.

Although he was awarded the Nobel Prize in 1919 for ammonia synthesis, Fritz Haber led an essentially tragic life. As the director of the Kaiser Wilhelm Institute for Physical Chemistry during World War I, he developed the use of chlorine gas for the German general staff. Haber believed this gruesome weapon would help bring a swift victory and thus limit overall suffering. Others took a dimmer view. On the eve of the first use of the gas against Allied troops in 1915, Haber's wife committed suicide, tormented by her husband's horrific contribution to the war. And after the Armistice, the Allies considered Haber a war criminal. Haber was demoralized, but he continued to conduct research. Later, with the rise of Nazi-inspired anti-Semitism in Germany, this Jewish scientist fled and took up residence in England. Haber died in 1934 in Basel, Switzerland. —*V.S.*



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GAS ATTACKS during World War I caused enormous Allied casualties.

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Further Reading

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