Long-Range Perspectives on Inorganic Fertilizers in Global Agriculture

1999 Travis P. Hignett Lecture

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University Distinguished Professor
University of Manitoba

International Fertilizer Development Center
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Second Travis P. Hignett Memorial Lecture

The Travis P. Hignett Memorial Lecture Series was initiated during 1994 by the International Fertilizer Development Center to honor a distinguished chemist, chemical technologist and developer, author, and administrator. Mr. Hignett (1907-89) received global recognition for his many accomplishments in the fertilizer world over a period of some 50 years. After a 35-year career with the Tennessee Valley Authority, Hignett served as a special consultant at IFDC for more than a decade. Often referred to as the "Father of Fertilizer Technology," Hignett held 15 patents and was the author of approximately 150 publications. He received a number of awards, including the Francis New Memorial Medal from the Fertiliser Society of London in 1969. This lecture series is being sponsored by the Hignett Memorial Fund, which was established in 1987 to honor Mr. Hignett.

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We are at the end of the first century of increasing agricultural dependence on inorganic fertilizers, in general, and on synthetic nitrogenous compounds, in particular. Certainly the most remarkable consequence of this dependence is the fact that about 40% of today's 6 billion people are alive thanks to the Haber-Bosch synthesis of ammonia. Briefly tracing the rise of this dependence and presenting its quantitative estimates will be the focus of the first part of this lecture.

Continuing growth of the world's population and the transformation of typical diets are the two powerful factors that will result in higher demand for inorganic fertilizers. Fortunately, there are adequate resources of both minerals and energy to satisfy this demand. However, no critical assessment of long-term prospects can ignore possible consequences of intensive fertilizer applications for human health and for the quality of the environment, especially when such concerns are already limiting the use of N and P compounds in some countries. That is why the last part of the lecture will examine key environmental factors that may influence the use of inorganic fertilizers during the coming generations.

Past Achievements

The beginnings of our dependence on inorganic fertilizer can be traced back to before the middle of the 19th century, to the pioneering era in chemistry and agronomy when Justus von Liebig and Jean-Baptiste Boussingault laid down the theoretical foundations of a new science of crop production and when John Bennett Lawes began producing ordinary superphosphate.[1] At the same time, during the 1840s, shipments of Chilean nitrate began arriving in larger quantities to European and North American ports.

The beginning production of concentrated potassium fertilizers from mine spoils at Stassfurt during the 1860s, Chile's 1883 victory in the war with Bolivia and Peru, which resulted in the annexation of nitrate-rich provinces of Antofagasta and Tarapacá, and the start of Florida phosphates' extraction in the late 1880s were the most important events promoting the use of inorganic fertilizers during the second half of the 19th century. However, organic fertilizers were still dominant by the century's end.

My reconstructions of harvests and nutrient inputs show that in 1900 the global crop harvest assimilated about 11 million tonnes (Mt) N, 2 Mt P, and 9 Mt K. At the same time extraction of phosphates produced no more than 0.5 Mt P; German shipments of potassium salts delivered about 0.2 Mt K; and a combination of Chilean nitrates and recovery of ammonium sulfate from coke production supplied less than 0.4 Mt of inorganic N.[2] Typical fertilizer recovery rates at that time were well below 50%, which means that at the beginning of the 20th century inorganic compounds supplied only between 1% and 2% of the three macronutrients assimilated by harvested crops and their residues and that farming had to rely on a combination of recycled organic wastes, atmospheric deposition, weathering of rocks and the biofixation of nitrogen by leguminous crops and green manures.

The first decade of the new century brought a fundamental scientific breakthrough that was followed by a rapid commercialization of the invention. In July 1909 Fritz Haber demonstrated in his laboratory at the Technische Hochschule in Karslruhe the synthesis of ammonia from its elements. Only four years later—in September 1913—the BASF, thanks largely to innovative solutions and bold leadership provided by Carl Bosch, began operation of the world's first ammonia plant at Oppau near the company's Headquarters in Ludwigshafen.[3] One year later French geologists discovered huge deposits of sedimentary hydroxyapatite in Morocco, which remain the world's largest easily exploitable accumulation of the mineral.

World War I actually accelerated the development of ammonia synthesis because the compound became the feedstock for the German production of nitrates used for explosives. German synthesis of ammonia grew rapidly after its reversion to peaceful uses, and the early 1920s also saw the first wave of adoption of the Haber-Bosch process or its modifications by George Claude, Luigi Casale, Giacomo Fauser and Friedrich Uhde. Extraction of Moroccan phosphates also began shortly after World War I in 1921, and worldwide potassium shipments rose by 25% during the early 1920s. However, this expansion of the fertilizer industries was soon arrested by the global economic crisis and then, after a brief recovery, by World War II.

Thus, it has been only during the second half of the 20th century that the applications of nitrogen derived from synthetic ammonia, superphosphates, potash, and of a growing variety of mixed compounds have become an indispensable, and increasingly important, component of modern cropping. Two notable examples illustrate this rapid shift. In 1950 fewer than 50% of U.S. corn fields were receiving any inorganic nitrogen, but today the rate is above 99%. In 1950 China's use of inorganic nitrogen fertilizers provided less than 2% of the nutrient's total supply, but today it amounts to 75% of the total (Figure 1)!

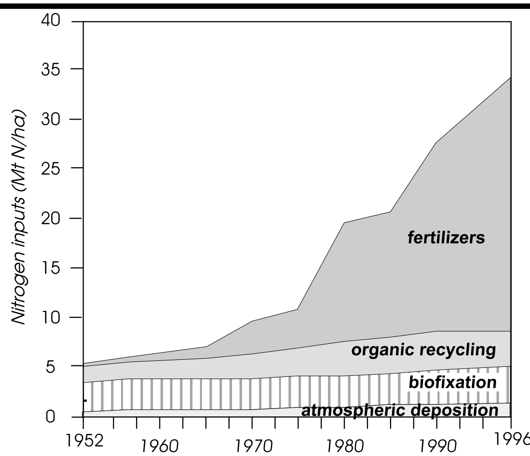

Figure 1. Nitrogen Inputs Into China's Cropping, 1952-96.

The two powerful driving forces behind this rise are obvious: growing populations and their greater affluence. The global population increased from 2.5 billion people in 1950 to slightly more than 6 billion people today. Even if the average diets remained the same, the global food output would have to become more than twice as large in just two generations—a challenge unprecedented in human history. However, the growing affluence has been accompanied by a relatively fast dietary transition marked, on one hand, by sharp declines in eating of legumes and by lower intakes of staple cereals and tubers, and on the other hand, by higher consumption of animal foods, fruits, and vegetables.[4] These trends can be seen in all high-income nations and in rapidly modernizing low- and middle-income countries. Satisfying this rising demand has required a steady intensification of cropping, a process impossible without higher nutrient supplies.

In assessing our dependence on inorganic fertilizers, I will concentrate on nitrogen and phosphorus—the two macronutrients that most commonly limit crop production. Although potassium removal by many high-yielding crops is equal to, or even larger than, their assimilation of nitrogen, the nutrient is much more readily available from the natural weathering of parental rocks. Because it is primarily incorporated in crop residues rather than in edible tissues, proper recycling of straws and stalks can return, unlike in the case of N or P, a very large share of the subsequent crop's K needs (and as I will show later, deposits of extractable K are no cause of any long-term supply concerns).[5]

The World's Dependence on Inorganic Fertilizers

The agronomic means of producing the requisite amount of food and feed are well known under a misleading term of the Green Revolution. Like so many other grand transformations in human history, this revolution has been gradual; it has progressed unevenly in different parts of the world; and it has not been without unintended, unforeseen and undesirable consequences. However, there can be no doubt about its overall positive effect (Figure 2), and the role of inorganic fertilizers in its success has been essential. I can do no better than to quote Norman Borlaug, one of the leaders in

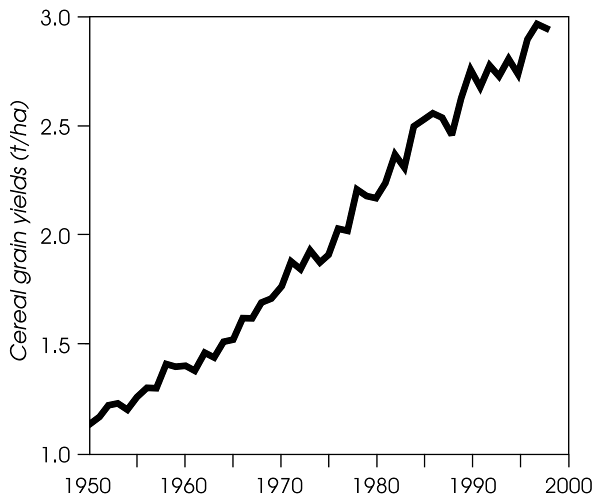

Figure 2. Average Global Yields of Cereal Grains, 1950-98; Plotted From the FAOSTAT Data (FAO, 1999).

developing and diffusing new high-yielding cultivars, who summed up the importance of fertilizer nitrogen in his speech accepting the Nobel Prize for Peace in 1970 by using a memorable kinetic analogy:[6]

> If the high-yielding dwarf wheat and rice varieties are the catalysts that have ignited The Green Revolution, then chemical fertilizer is the fuel that has powered its forward thrust...

Compared to 1950 the recent global use of fertilizers is about 23 times higher in the case of nitrogen, almost eight times higher for phosphorus, and more than four times higher for potassium (Figure 3). Of course, these global means hide enormous inter- and intranational differences, and there are also great disparities in fertilizer applications to primary crops.[7] Consequently, a more meaningful approach is to use the world's major crops or the most intensively cultivated regions for longitudinal comparisons.

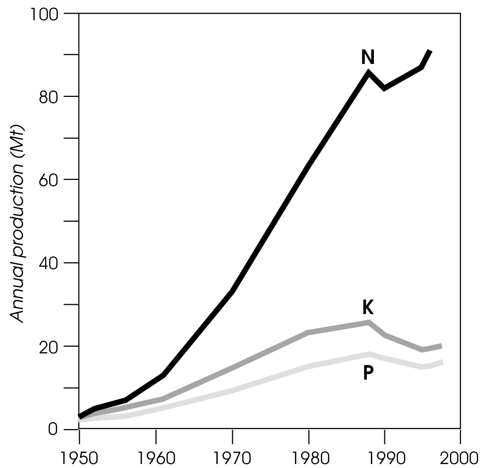

Figure 3. Global Production of Inorganic Fertilizers, 1950-2000.

Using a prime North American example, in 1950 the U.S. corn, not all of it seeded with hybrid varieties, received less than 8 kg N, 5 kg P, and about 6 kg K per planted hectare, and it yielded less than 2.5 t/ha. Today the all-hybrid and partially transgenically modified crop averages 8 t/ha, and it receives, respectively, 140, 60 and 70 kg N, P and K.[8] China's most productive double-cropped paddies in Hunan or Jiangsu, which received no inorganic fertilizer in 1950 and yielded less than 2.5 t/ha, now receive more than 400 kg N/ha, and a single crop produces over 6 t/ha.[9]

I have prepared a detailed account of nitrogen flows in global agriculture, which shows that during the mid-1990s about 85% of all nitrogen in food proteins available for human consumption (21 out of 24.5 Mt N) came directly in plant foods or indirectly via animal products from the world's cropland; the rest comes from pastures and from aquatic foods (Figure 4).[10] Because synthetic nitrogen fertilizers provided about half of the nutrient in harvested crops (the most likely range of my calculations is 44%-51%), roughly 40% (37%-43%) of the world's dietary protein supply in the mid-1990s originated in the Haber-Bosch synthesis of ammonia.

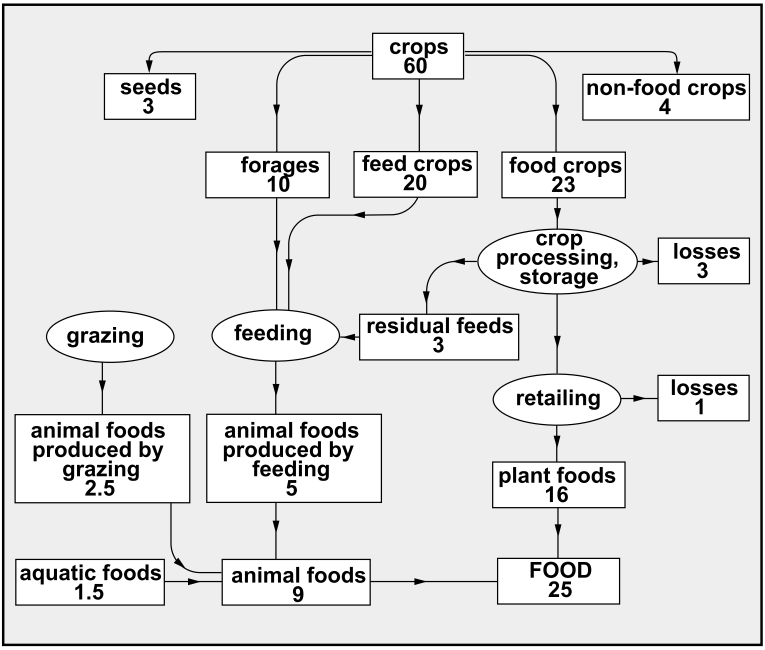

Figure 4. Nitrogen in the Global Food and Feed Harvest of the Mid-1990s (All Values Are in Mt N/Year).

This global mean both overestimates and underestimates the degree of our dependence on the Haber-Bosch process because the applications of nitrogen in affluent nations have a very different role from the nutrient's use in low-income countries.

Current global per capita mean of the dietary protein supply—about 73 g/day—is composed of two disparate parts: (1) a huge excess in the rich world (per capita mean of almost 100 g/day, including about 55 g from animal foods) and (2) a much less comfortable rate in the low-income countries of Asia, Africa and Latin America, where the 1996 per capita mean was about 66 g/day, with only about 18 g coming from animal foods.[11]

Clearly, protein supply has not been a concern in affluent nations where higher use of fertilizers during the latter half of the 20th century has merely added more meat and dairy products to diets that were already sufficient in animal protein. However, protein supply is still a challenge in most of the low-income countries

(Figure 5).[12] Estimating the share of dietary protein derived from nitrogen fertilizers that are applied in low-income countries provides a good idea of the extent of a truly existential dependence on the Haber-Bosch synthesis.

Low-income countries now consume about two-thirds of the world's nitrogen fertilizers, which provided about 55% of the total nutrient supply reaching their fields.[13] Because no less than 92% of their food proteins were derived from crops, inorganic fertilizers supplied at least half of all nitrogen in their diets. This would be an equivalent of feeding no less than 2.2 billion people or roughly 40% of the world's 1996 total population: these people now depend on the Haber-Bosch synthesis for what is, on the average, a barely sufficient supply of their basic food needs, that is, for their very survival.

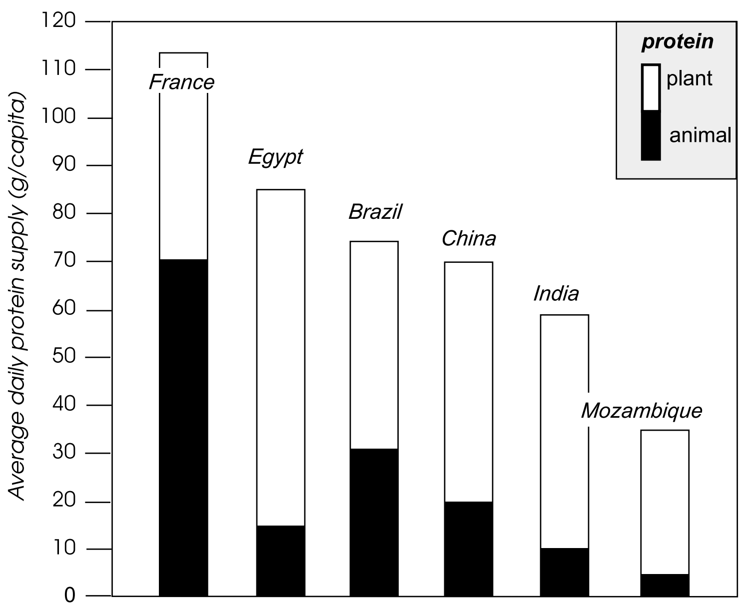

Figure 5. Average Daily Per Capita Supplies of Dietary Protein During the Mid-1990s Ranged From Surfeit in Affluent Countries to Inadequate Rates in Most of Sub-Saharan Africa.

Another estimate of our dependence on ammonia synthesis can be obtained by an entirely different approach—by calculating the population totals supportable by specified diets. In 1900 the virtually fertilizer-free agriculture was able to sustain 1.625 billion people by a combination of extensive cultivation and organic farming on the total of about 850 Mha. The same combination of agronomic practices extended to today's 1.5 billion ha of cropland would feed about 2.9 billion people or about 3.2 billion when adding the food derived from grazing and fisheries. This means that without nitrogen fertilizers no more than 53% of today's population could be fed at a generally inadequate per capita level of 1900 diets. If we were to provide today's average per capita food supply with the 1900 level of agricultural productivity, we could feed only about 2.4 billion people or just 40% of today's total.

The range of our dependence on the Haber-Bosch synthesis of ammonia is thus as follows: for about 40% of humanity it now provides the very means of survival; only half as many people as are alive today could be supplied by pre-fertilizer agriculture with very basic, overwhelmingly vegetarian, diets; and pre-fertilizer farming could provide today's average diets to only about 40% of the existing population.

The only way this global dependence on nitrogen fertilizer could be lowered would be to adopt an unprecedented degree of sharing and restraint. Because the world's mean daily protein supply of nearly 75 g/capita is well above the needed minimum, equitable distribution of available food among the planet's 6 billion people who are content to subsist on frugal, but adequate, diets would provide enough protein even if the global food harvests were to be some 10% lower than they are today.

In such a world the populations of affluent countries would have to reduce their meat consumption since hundreds of millions of people would have to revert to simpler diets containing more cereals and legumes. Realistic chances of this dietary transformation, running directly against the long-term trend of global nutritional transitions, are extremely slim, but even in such an altruistic and frugal world, ammonia synthesis would still have to supply at least one-third of all nitrogen assimilated by the global food harvest!

However, in the absence of any altruistic sharing, the only way to eliminate the existing stunting and malnutrition caused by protein shortages among hundreds of millions of disadvantaged peasants and the poorest urban dwellers in low-income countries is to intensify global food production and, hence, to increase the world's dependence on fertilizers.

Growing Dependence During the 21st Century

High absolute rates of global population growth will remain by far the most important reason for the increased used of inorganic fertilizers. There can be no doubt that the transition to low fertility—a shift completely accomplished in all affluent countries and well advanced in much of Asia and Latin America—is now under way even in sub-Saharan Africa, the largest remaining region of very high birth rates. As a result, the world's population growth has recently begun declining even in absolute terms. Depending on the more distant, and as yet uncertain, course of the fertility decline, global population may be between 7.3 and 10.7 billion people by the year 2050. The United Nations' latest medium forecast is about 8.9 billion, and this total may not increase very much afterwards (Figure 6).[14]

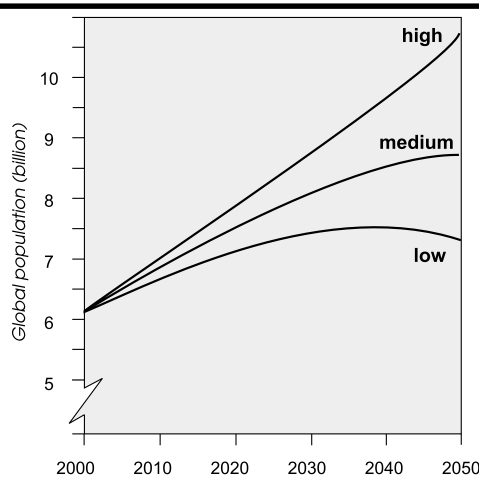

Figure 6. Possible Growth Curves of Global Population, 2000-2050.

The conclusion that yet another doubling of world population is unlikely is most welcome news, but it is still a great reason for concern regarding the future food production. The U.N.'s forecasts actually foresee that the rich world's population in 2050 will be slightly below the 2000 total, which means that virtually all net population growth between 2000 and 2050 will be in today's low-income countries. According to the U.N.'s medium forecast, this global growth would amount to about 3 billion people, surpassing the total of 2.8 billion people added throughout the poor world during the past 50 years. We may be moving toward a stabilized global population faster than anticipated, but the challenge of providing basic existential requirements for the world's poor will become greater, not smaller, in absolute terms.

About 40% of the world's population growth during the next two generations will originate in only a handful of large countries, and at least a third of the total increment will be added in Africa. Among the five countries with the largest population increases, three are in Asia—India (with almost 550 million more people), China (about 220 million), and Pakistan (almost 200 million)—and two are in Africa: Nigeria will add nearly 140 million people and Ethiopia about 110 million.

While some African and Latin American countries may be able to expand their cultivated area—albeit at the price of additional significant loss of tropical forests—worldwide opportunities for a more widespread practice of extensive farming are limited. The need for further intensification of farming will be particularly acute in Asia; with a single exception the continent contains all low-income countries that share or approach China's high dependence on nitrogen fertilizer (Figure 7). These countries have populations larger than 50 million people, and their arable land is limited to less than 0.2 ha/capita. Moreover, losses of farmland to nonagricultural uses and the declining quality of arable land will add to the naturally decreasing per capita availability of cultivable soils.

Besides China (currently with about 0.11 ha/capita), these countries include Bangladesh (0.09 ha), Indonesia (0.12), Pakistan (0.19), the Philippines (0.13), and India (0.18 ha/capita). The non-Asian exception is Egypt, which has a mere 0.05 ha/capita, and in

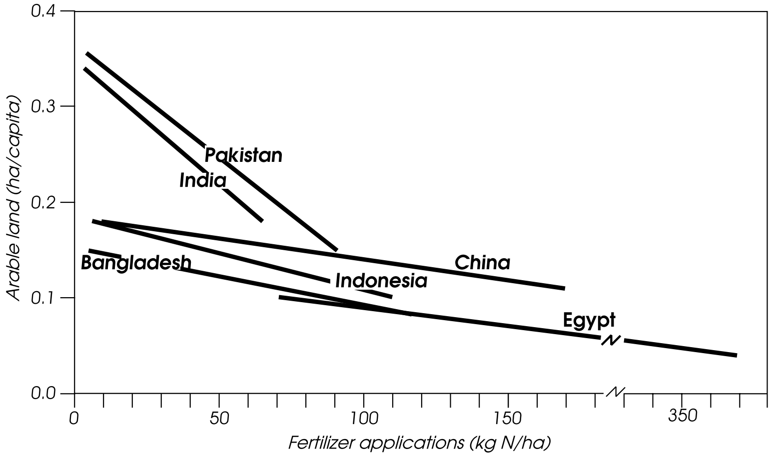

Figure 7. Increasing Dependence on Nitrogen Fertilizer in Land-Scarce Populous Nations, 1960-96.

spite of its very intensive cultivation needs high food imports.[15] Inevitably, during the coming decades the global dependence on nitrogen fertilizers would grow even if these countries merely maintained their current average per capita food supply.

That should not be enough. Nationwide means of per capita protein and food energy consumption are above the existential minimal in most low-income countries; in many of them there is hardly any safety margin; and in all of them distribution inequalities mean that protein malnutrition continues to be widespread. Moreover, the future increase of food demand throughout the modernizing world will not be limited merely to satisfying basic nutritional needs of every person.

The desire to eat more animal foods is a universal one, and many studies of long-term trends in the rich countries demonstrate an unmistakable correlation between rising incomes and dietary transitions from high levels of direct consumption of cereals, tubers, and legumes to a rising demand for meat and dairy products. Initial phases of this transition are now clearly noticeable in many relatively better-off, low-income countries. Although the poor world's daily per capita availability of animal protein remains low, it had doubled between 1970 and 1995 and has nearly tripled in China since the beginning of the country's modernization drive in the early 1980s.[16]

Another important consideration that will affect future demand for fertilizer nitrogen is the well-appreciated declining response of crop yields with increasing nutrient applications. Finally, environmental change—ranging from higher concentrations of tropospheric ozone to possibly rapid global warming and from excessive soil erosion to growing regional shortages of water—will further increase the need for intensive, high-yield cropping on the diminishing amount of prime farmland.[17] Quantifying the effects of various forms of environmental pollution and ecosystemic change is extremely uncertain; although there will be some positive effects, it is most likely that the overall impact would be somewhat negative.

A plausible conservative case of the future dependence on the Haber-Bosch synthesis is not difficult to construct. Low-income countries adding 2.9 billion people would have to use 60% more nitrogen fertilizer than they do today merely to maintain their average, and inadequate, diets. Adding 30%-40% to this minimum total to reduce the extent of malnutrition and stunting, to compensate for the declining response to higher applications, and to produce more animal foods would increase their nitrogen fertilizer consumption by as much as 85%. With unchanged food consumption in affluent countries, the world might be using about 125 Mt N in synthetic fertilizers by the year 2050; phosphorus demand rising in tandem would then be between 21 and 22 Mt P/year. A case can be made for higher consumption: Steen's most likely range for the year 2050 is 25-26 Mt P/year.[18]

Slower decline of fertilities in low-income countries, more meaty diets, and the necessity to compensate for the harvest losses due to the environmental change could further raise the dependence on inorganic compounds, but faster demographic transition, more efficient use of fertilizers, and lower food waste could reduce it appreciably. Even more unpredictable, but potentially no less important, is the impact of future transgenic crops, which might be able to use nitrogen much more efficiently.

In the presence of high concentrations of nitrogen, green alga *Chlorella sorokiniana* competes with bacteria by producing high levels of glutamate dehydrogenase (GDH); the enzyme converts ammonium directly into glutamate, which is then used in a variety of metabolic processes. Transgenic wheat-producing high levels of GDH yielded up to 29% more with the same amount of nitrogen fertilizer than did the normal crop.[19] Other transgenic crops with high GDH capacity are under development, but it is still unclear how and when Monsanto will release any commercial cultivars, and, of course, how they will be accepted and how they will perform in field conditions in the long run.

These realities and a rich testimony of notable failures of past long-range forecasts argue against offering any elaborate quantitative predictions. All that we can say with certainty is that our dependence on the Haber-Bosch synthesis of ammonia and on the extraction and treatment of phosphates will rise appreciably during the next two generations, but its actual level will be determined by a complex interplay of our rising, and all too often more wasteful, needs and of our innovative and more efficient uses.

Natural Resources for Fertilizer Production

Adequacy of requisite natural resources is the most obvious concern when facing a substantial increase in future demand. Two separate matters arise in the case of inorganic fertilizers: sufficiency of raw materials and availability of energy to convert them into final products. Once again, potassium is of the least concern among the three macronutrients. Not only is the element abundantly present in the Earth's crust, but also it can be found in conveniently concentrated deposits in both deeply buried and near-surface sediments. Even the most conservative reserve base estimates show a reserve/production (R/P) ratio on the order of 500 years at the level of the late 1990s production.[20] Mining, crushing and beneficiation of potash usually does not cost more than 10 gigajoules (GJ)/t of the nutrient, energy demand comparable to making cement, and a rate much lower than the preparation of superphosphates and synthesis of nitrogenous compounds.

Depending on the final product, energy costs of phosphatic fertilizers range from about 18 to 32 GJ/t P. Even when assuming a high average rate of about 30 GJ/t P, today's global production of phosphorus fertilizers claims about 10-11 million tonnes of oil equivalent (Mtoe), a total no higher than roughly 40% of the recent annual fuel and electricity consumption by all branches of the U.S. military (more than half of the 25 Mtoe used is jet fuel).

Phosphate deposits are not as abundant as those of potassium minerals; recently published totals range between 1.5-3.5 billion tonnes (Gt) P for reserves, 4.7-9.5 Gt P for potential reserves, and about 13 Gt P for resources.[21] At the current rate of extraction global reserves would last about 80 years, and the estimated resources could support the recent rate of application for nearly 250 years. These are R/P horizon far more distant than for most of the minerals used by modern civilizations, and they can surely be extended by tapping less accessible (but plentiful) deposits at a higher price.

Nitrogen supply for ammonia synthesis is truly inexhaustible since the atmosphere contains 3.8 quadrillion tonnes of the element. Various feedstocks can be used to obtain hydrogen, and improving efficiency of those processes has been one of the key reasons why the energy costs of ammonia synthesis have been declining for the past 85 years (Figure 8).[22] Natural gas is the preferred feedstock, and the best natural gas-based plants now use less than 27 GJ/t NH_3 (or 32-33 GJ/t N; the stoichiometric energy requirement for ammonia synthesis is

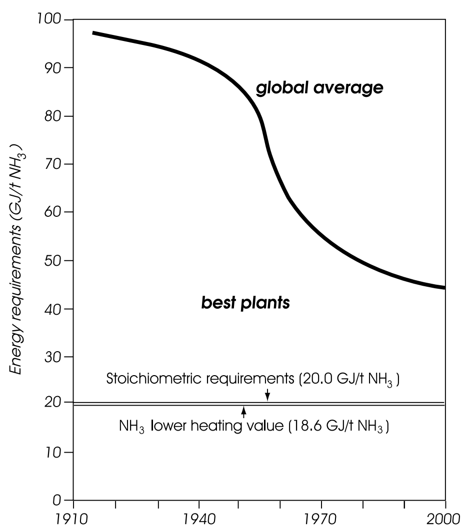

Figure 8. Energy Cost of Ammonia Synthesis, 1913-2000.

20.9 GJ/t NH_3). The global mean, which is affected by more energy-intensive reforming of heavier hydrocarbons and coal, is now between 40-45 GJ/t NH_3, roughly half of the level prevailing during the early 1950s.

Even with these huge improvements synthesis of ammonia remains a relatively energy-intensive process, at least as costly per tonne as making steel from iron ore or fine writing paper from standing timber. Annual output of fertilizer ammonia now requires an equivalent of about 100 Mtoe, but because only a small part of synthesized ammonia is used directly as a fertilizer, the additional energy cost of producing various solid and liquid compounds raises the total to about 135 Mtoe.[23] This means that the global production of nitrogenous fertilizers requires about ten times as much energy as the combined output of P and K compounds (assuming average costs of about 20 GJ/t P and 10 GJ/t K).

Even if all of the energy needed to fix the fertilizer nitrogen would come from natural gas, it would still be only less than 7% of the recent annual global consumption of the fuel and less than 2% of all energy derived from fossil fuels.[24] Clearly, there is little reason to be anxious about either the current needs or the future supplies of energy for nitrogen fixation. Moreover, there is no doubt that higher absolute energy needs caused by rising demand for nitrogen fertilizers will be partially offset by lower requirements for nitrogen fixation and by higher efficiencies of fertilizer use. Because today's low-income countries will experience much faster growth of energy needs in sectors other than the fertilizer industry, the share of global fossil fuel consumption claimed by nitrogen fixation by the middle of the 21st century may be only marginally higher than it is today.

Although the world has abundant natural gas resources, they are conservatively estimated to be between 1.1-1.7 times as large as all the natural gas that has already been extracted or found in proven reserves.[25] Nitrogen fixation could proceed easily (albeit more costly) even in the world devoid of any gas by tapping the world's enormous coal deposits or using a variety of biomass feedstocks. Moreover, if a concerted international action aimed at moderating the rate of potentially risky global warming would call for a greater energy saving, nothing would be easier than to release energy equivalent to today's demand for nitrogen fixation by improvements to many nonessential energy conversions.

Automotive transportation is the most obvious source of such efficiency gains. Replacing the current North American private car fleet (averaging about 22 mpg) by cars whose performance would equal the corporate average fuel economy of Honda Company (about 33 mpg) would save about 70 Mtoe a year—enough to produce about half of the world's nitrogen fertilizers![26] The conclusion is obvious: whatever its actual energy claim might be, future nitrogen fixation needed to produce enough food during the next two generations will not be limited by energy and feedstock supplies.

However, it would be a sign of naiveté and of intellectual irresponsibility to suggest that with no serious resource obstacles ahead of us the future of global fertilizer use will be a case of unimpeded growth. Future realities, a few of their harbingers already very much with us, will have to reckon with a much less benevolent public and regulatory acceptance of fertilizer use and with heightened concerns about the consequences that heavy applications of nitrogen and phosphorus may have for human health and for the integrity of ecosystems.

Fertilizers and Human Health

Thirty years ago health risks posed by waterborne nitrates leached from heavily fertilized fields were used by Barry Commoner to attract attention to his dire warnings about the degradation of the U.S. environment. He believed that the country's nitrogen cycle was seriously out of balance, and in his opinion the rising nitrate levels in the Corn Belt's rivers posed such health risks that limits on application rates, economically devastating for many farmers, should be adopted to avert further deterioration.[27]

Average applications in the Corn Belt and in parts of Europe and Asia have risen appreciably since the late 1960s and so have concentrations of waterborne nitrates. Average levels of nitrates in the most affected European rivers—the Thames, Rhine, Meuse, and Elbe—are now two orders of magnitude above the mean of unpolluted streams, and many European rivers had NO_3^- levels above the maximum contaminant limit of 50 mg NO_3^-/L.[28] Nitrate levels in the Mississippi River have risen nearly four-fold since 1900, and they are increasing in both of China's two largest rivers, the Huang He and Yangtze (Figure 9).[29]

Sources of this nitrogen cannot be precisely quantified, but there is no doubt that fertilizer-derived nitrates comprise a large, and

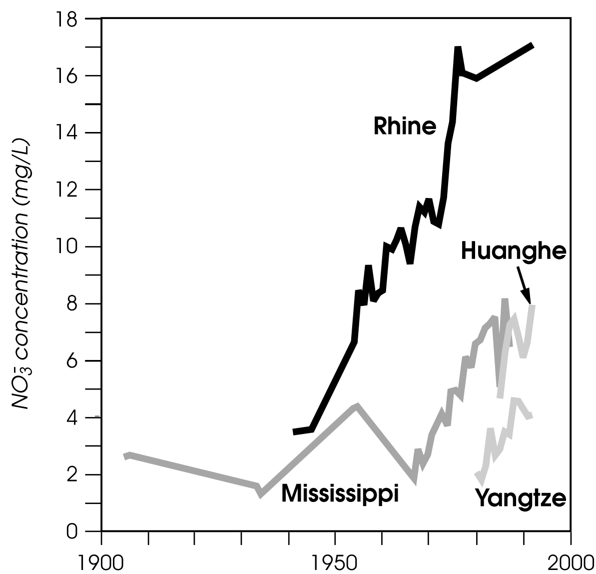

Figure 9. Nitrate Concentrations in Four Major Rivers.

often the dominant portion of the nutrient. For example, no less than 87% of nitrates accumulated in ground waters of the countries of the European Union have been leached from agricultural soils.[30] In addition, a substantial share of leaching from non-agricultural lands is also caused indirectly through the nitrification of deposited ammonia, which was volatilized from fertilized fields and from the wastes of farm animals.

And yet elevated nitrate levels have not had any serious consequences for human health. Nitrate itself is not toxic to humans in concentrations encountered even in fairly polluted waters; only after its bacterial conversion to nitrite does it pose an acute life threat to infants and a possible chronic risk to adults. However, no new cases of infant methemoglobinemia have been recently reported in any affluent country although that acute disease remains a risk in low-income countries where many wells already contain nitrate levels well above 50 mg/L.[31] Thus far, improper handling of human and animal wastes, rather than the leaching of fertilizers, has been overwhelmingly responsible for this contamination, but a rapidly growing use of nitrogen applications will obviously increase the overall risk in the future.

A suspected link between drinking nitrate-contaminated water and a higher incidence of some cancers in adults has been difficult to prove. An epidemiological association between high nitrate intake and oral, esophageal, gastric and intestinal cancers was first reported in Chile in 1970.[32] A number of studies done subsequently in Europe, North America and Asia offered some confirmation of such links and some evidence of inverse relationship between nitrate intakes and various cancers.

Even if nitrates were to be unequivocally implicated in the etiology of some cancers, their intake in drinking water is only a part of the problem. Most of the nitrate that we take in (about 4/5 of the total daily intake in the United States) does not come from water but rather from vegetables, primarily from beets, celery, lettuce, radishes and spinach, and our bodies may synthesize daily an amount that matches that total or even surpasses it.[33]

Moreover, a British study, which measured nitrate levels in saliva, found that their concentrations were significantly higher in areas where the risk of stomach cancer was low.[34] Perhaps most reassuringly, workers in fertilizer factories exposed to nitrate-containing dust do not have a higher incidence of stomach cancer, and the cancer has been declining throughout the Western world just as nitrogen applications and nitrate concentrations in drinking water have undergone unprecedented increases.[35] The most recent review of the epidemiological evidence merely extends the inconclusive judgment: although no firm links have been found between dietary intakes of nitrate and stomach, brain, esophageal and nasopharyngeal cancers, an association cannot be ruled out.[36]

Publicly much less well known but potentially fairly troublesome is the problem of heavy metals, particularly of cadmium, which is the most enriched element in phosphate rocks, occurring in concentrations almost 70 times higher than in average shale.[37] Global average of Cd levels in phosphates is about 21 mg Cd/kg of rock, but some Moroccan rocks have up to 40 mg and phosphates from Togo and Tunisia contain up to 50-55 mg Cd/kg.[38] As Florida phosphates, which have some of the lowest Cd concentrations (average just around 9 ppm Cd for Central and 6 ppm Cd for North Florida deposits), become depleted, the average content of Cd and other potentially hazardous trace elements in the global output of phosphate rock will increase. This may lead to restrictions or banning of some ores by countries trying to regulate the introduction of Cd into their environment.

The World Health Organization (WHO) suggests that the maximum daily intake should not exceed 1 µg/kg of body weight or between 50 and 70 µg/day for most adults while the recent European intakes are already as high as 40 µg Cd/day. Consequently, about a dozen countries (including Australia, Denmark, Germany, Japan and the Netherlands) have already enacted Cd limits for P fertilizers, but a universal ban on high-Cd ores would eliminate a substantial share of potential extraction from the world market. Deposits in North Carolina, Senegal, Togo, Tunisia and, above all, in Morocco would be entirely or largely affected.[39]

Removing the trace metals is possible but costly, and different processes would also increase the energy cost of P fertilizers and generate hazardous wastes. The Cd problem goes beyond inorganic fertilizers: disposal of sewage sludge can cause heavy loadings of Cd, which is very persistent in soils, and Cd in animal manures (particularly where the animals are given P supplements) can add considerably to Cd field burden. At this time it is impossible to say if the Cd problem will remain a moderately worrisome but manageable complication or if it will rise to a greater prominence in the society, which is always in search of new bad news.

Environmental Concerns

These concerns are understandable. Nutrients not assimilated by plants and not fixed for extended periods of time in soil escape into ground and surface waters. Denitrification and volatilization also put highly variable shares of fertilizer nitrogen into the atmosphere where one of those compounds contributes to global warming, and the other one adds to the nitrogen enrichment of terrestrial ecosystems.

The only truly global effect of inorganic fertilizers is due to increased generation of nitrous oxide (N_2O), an inevitable consequence of denitrification of fertilizer nitrates.[40] The process of denitrification is, of course, essential and most welcome; it is the closing arm of nitrogen's grand biospheric cycle returning fixed, reactive nitrogen in nitrates to the inert dinitrogen in the atmosphere. Because the conversions are not always completed, the bacterial denitrification generates small but far from negligible amounts of N_2O—the gas whose atmospheric concentrations have been increasing (Figure 10) and which is, mole for mole, about 200 times as effective an absorber of the outgoing long-wave radiation as is CO_2—the most abundant of anthropogenic greenhouse gases. Moreover, the gas is also involved in the depletion of stratospheric ozone.

Sources and sinks of N_2O are poorly known, but there is no doubt that fertilizer applications are the single largest man-made

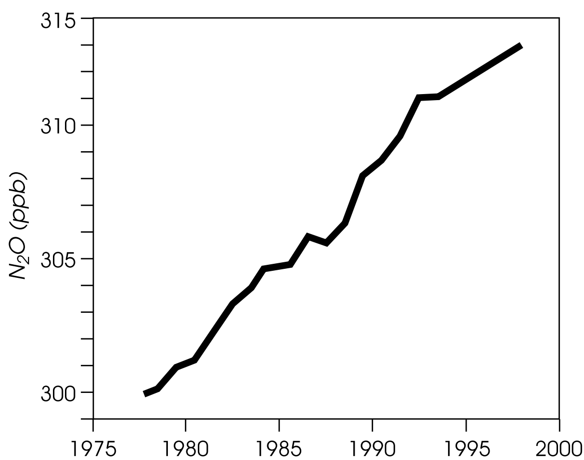

Figure 10. Increasing Concentrations of Atmospheric N_2O.

source of the gas. Emissions of N_2O can account for <0.5%-5% of the initially applied fertilizer nitrogen. Because N_2O from synthetic fertilizers accounts for less than 10% of all emissions of the gas and because N_2O is currently responsible for less than 10% of the global greenhouse effect, even the most liberal estimate must ascribe less than 1% of the global warming effect to N_2O released from denitrification of nitrogen fertilizers—hardly a major threat to the integrity of the global environment.

Eutrophication of streams, fresh water bodies, and coastal ecosystems caused by releases of nitrates and by smaller, but often even more harmful, escapes of phosphates is a more serious matter. Numerous effects of aquatic eutrophication have been studied extensively since the late 1960s.[41] Eutrophic waters have high primary productivity because large amounts of phytoplankton make them turbid and limit their transparency to less than 50 cm. Advanced eutrophication is marked by blooms of cyanobacteria and siliceous algae, as well as growths of scum-forming and potentially toxic algae.

Eventual decomposition of this phytomass creates hypoxic or anoxic conditions near the bottom or through a shallow water column. These deoxygenated waters can drive away or kill aquatic animals, particularly the bottom dwellers (shellfish, mollusca). Affected waters may also have offensive taste and odor (requiring expensive treatment before consumption), and formation of trihalomethanes during water chlorination is a serious health hazard to livestock and people, as is ingestion soluble neuro- and hepatotoxins released by decomposing algal blooms.[42] Another particularly offensive consequence of eutrophication includes the growth of thick coats of algae on any submerged substrates, including aquatic plants, stones, docks, or boats.

Eutrophication can also seriously disrupt coastal ecosystems in regions receiving high N and P inputs. Perhaps no other instance is as worrisome as the effects of nutrient discharges from Queensland's growing population and agriculture, which now release about four times as much P and ten times as much N as they did in the early 1950s.[43] Resulting eutrophication threatens parts of the Great Barrier Reef, the world's largest coral formation, by smothering it with algae and by promoting the survival and growth of the larvae of *Acanthaster planci*, the crown-of-thorns starfish, which has recently destroyed large areas of the reef.

As the Baltic unfortunately demonstrates, in the absence of vigorous water exchange with the open ocean even a whole sea can become eutrophic. In 1990 the sea received about 80,000 t P, which is eight times the rate in 1900, and the nutrient's concentrations in its water averaged about four times higher than in 1950. Nitrogen enrichment, though not as large in relative terms, was also substantial.[44] As a result, a third of the sea bottom of the Baltic proper, the southern part of the sea, is now intermittently deprived of oxygen, the condition which also results in formation of toxic H_2S by S-reducing bacteria and precludes the survival of previously very common mussels and bottom fish. On the other hand, increased phytoplanktonic production on shallow bottoms with well-oxygenated water has provided more food for herring and sprat.

The productivity of plant and algae species in most estuaries in North America—including the Long Island Sound, San Francisco Bay, and the mid-Chesapeake Bay—is limited by nitrogen, rather than by phosphorus. Hence, these water bodies are particularly susceptible to nitrate-induced eutrophication.[45] By far the worst affected offshore zone in North America is a large region of the Gulf of Mexico, where the nitrogen load brought by the Mississippi and Atchafalya Rivers has doubled since 1965 and where eutrophication creates every spring a large hypoxic zone that kills many bottom-dwelling species and drives away fish.

Terrestrial eutrophication due to the atmospheric deposition of ammonia and nitrates is yet another environmental change in which fertilizers are implicated and one that has been receiving recently a great deal of attention.[46] Introduction of relatively large external inputs of nitrogen must be expected to change the productivity of most land ecosystems, whose growth is usually N-limited, and the modes of their nitrogen storage and composition of their species. Nitrogen input to some natural ecosystems is now occurring on such unprecedented scales that it has become significant even by agricultural standards; parts of eastern North America, Northwestern Europe, and East Asia receive between 20 and 60 kg N/ha a year, and the peaks, in the Netherlands, are over 80 kg N/ha a year.[47]

Rates of about 60 kg N/ha are as high as average fertilizer applications to North American spring wheat, and they are much higher than the fertilization means in most African countries! For most forests such rates are an order of magnitude higher than the means of the preindustrial world, and they equal or surpass the quantity of the element made available through net mineralization of organic matter in the forest floor. Given the widespread nitrogen shortages in natural ecosystems, especially in temperate and boreal forests, which have developed under constant nitrogen stress, such an enrichment should initially stimulate photosynthesis and appreciably increase the carbon and nitrogen stored in plants, litter, and soil organic matter.

However, this response is self-limiting: total nutrient inputs eventually surpass the combined plant and microbial demand, and nitrogen saturation of an ecosystem leads to the element's transfer to waters and its emissions to the atmosphere. The production (and storage) phase is followed by a destabilization phase (nitrogen saturation can lead to significant changes in ecosystem composition and diversity) and then by a decline (nutrient release) phase (Figure 11).[48] In view of these complexities it is difficult to estimate what effect the nitrogen enrichment has already had and what future impact it might have on the additional storage of carbon in the terrestrial phytomass.

Naturally, nutrients responsible for aquatic eutrophication do not originate only in inorganic fertilizers: they come also from animal manures, urban wastes, industrial processes, and atmospheric deposition, but in most

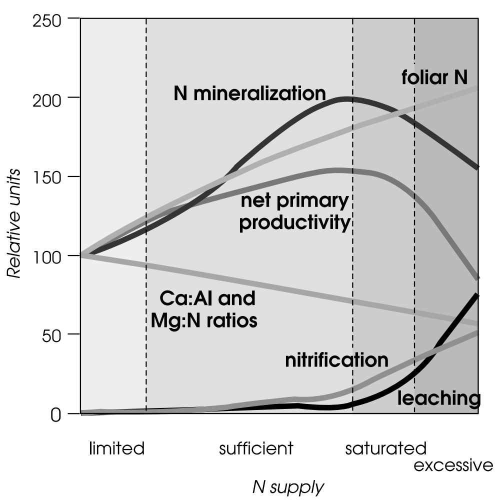

Figure 11. Stages of an Ecosystem Response to Nitrogen Inputs.

cases we do not have enough information to assign these causes with a high degree of certainty. For example, nitrogen fertilizers are estimated to account for 56% of the nutrient's presence in the Mississippi's discharge to the Gulf of Mexico, manures for 25% and municipal wastewater for only 6%, but this estimate omits entirely the considerable contribution of the atmospheric deposition.

There is a general correlation between a watershed's average rate of nitrogen fertilization and the riverine transport of the nutrient (Figure 12).[49] Because the streams or ground waters gather these inputs from large areas, nitrogen additions to coastal ecosystems may be 10 times and even more than a 100 times higher per unit of their area than they are in fairly heavily fertilized fields.[50]

Substantial local differences in the origin of water-borne nitrogen are illustrated by two recently prepared nutrient budgets for

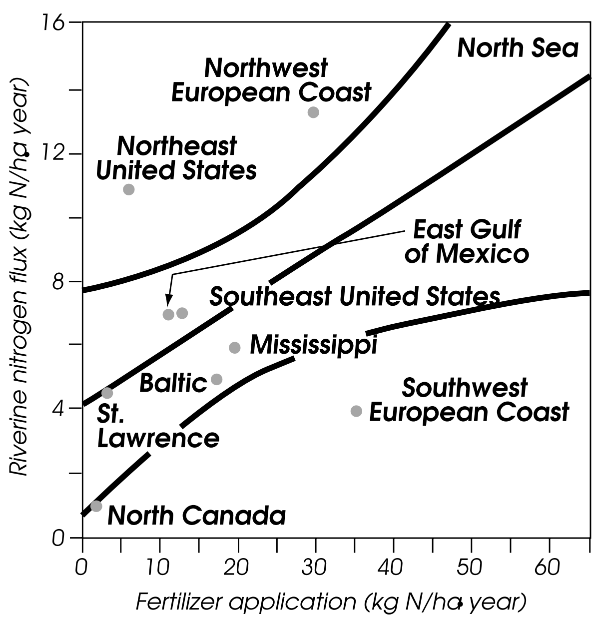

Figure 12. Correlation Between Nitrogen Fertilizer Applications and Riverine Flux of Nitrogen.

two polluted watersheds.[51] Nitrogen in the Waquoit Bay in Massachusetts comes largely from wastewater (48%) and atmospheric deposition (30%), and only 15% of it originates in fertilizers. In contrast, in a Norwegian catchment dominated by farming, atmospheric deposition accounted for only 3% of total nitrogen inputs and nitrogen fertilizers for 70 % (manures supplied the rest).

Estimating the contributions of nitrogen fertilizers to atmospheric deposition can be done only in very approximate fashion. Global total of anthropogenic gaseous emissions of reactive nitrogen compounds (NO_x and NH_x) has been recently almost 80 Mt N/year, with between 10-15 Mt N coming from inorganic fertilizers (mostly as volatilized ammonia).[52] With more than 20 Mt N/year, releases of NO_x from fossil fuel combustion remain the largest and growing source of reactive nitrogen and the one that could be readily reduced by more efficient transportation.

However, higher efficiencies of fertilizer applications are also needed to ensure that future impacts of nutrient losses from fertilizers will not be simply proportional to the rising nutritional needs of larger global populations. There are many effective ways to improve the efficiency of fertilizer applications, ranging from better agronomic practices to modified diets; their detailed discussion would make a fine topic for another Hignett lecture.

Success of some of these measures has been already well demonstrated by rising recovery rates of N and P during the past generation. Of course, the quest can be carried only so far: field cropping can never be done without some nutrient losses, and some ecosystems might be inevitably affected. For example, a corn field receiving annually 40-65 kg P/ha and losing less than 0.2 kg/ha (or no more than 0.5%) as soluble P will be releasing water with concentrations of only 0.2-0.5 mg P/L, but because of an extremely low threshold of algal response to P enrichment, particularly in shallow lakes with long hydraulic residence times, such levels are high enough to precipitate eutrophication.

This means that even the best agronomic practices may not always be able to prevent eutrophication of sensitive waters or other environmental changes. On the other hand, we can remove virtually all P from urban sewage, which is generally a much larger source of dissolved phosphorus. Similarly, we will never be able to prevent all nitrate leaching or ammonia volatilization from applied fertilizers, but we can do a much better job of reducing their releases by cities, transportation, industries and huge feedlots. Cropping should follow manufacturing by striving for precision and higher efficiency, but it can never achieve a comparable degree of control and some environmental impacts are unavoidable. The alternative—cropping without fertilizers—is fine for a few nations with plenty of farmland, but it is not an option to feed most of the world's six billion people demanding better diets.

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