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Perspective

Nitrogen fertilizer: Retrospect and prospect

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The rising fertilizer use accompanying more people eating more has been called exponential (1) and prompted fears of polluted water and consequent methemoglobinemia (2) and hypoxia (3). It also has raised alarm about greenhouse warming (4) and an altered global N cycle and thus primary production (5) and diversity (1) of vegetation. In this plethora of issues we concentrate on a few, beginning with the fundamental one of how fast N fertilizer use has risen in the world and in an industrial nation, the United States, where early, rapid adoption may foretell the course in the world. We also shall explore how much deposition of N from the atmosphere has increased. After examining the changing ratio of fertilizer N application to its intended incorporation in crop yield, we shall discuss prospects for more or less N fertilizer by 2070 when the earth's farmers may be feeding 10 billion people and sparing more or less habitat for nature.

Use

Because nitrogen (N) comprises fully 16% of protein, neither we, other animals, nor plants grow and survive unless roots extract it from the soil. Medieval wheat crops of only 1,000 kg hectare $(ha)^{-1}$ extracted 21 kg of N (6). Some N deposited by precipitation or fixed by legumes helped replenish the supply. By rotating their wheat crops onto one of the other, say, 4 ha of the farm or collecting manure from it, medieval farmers could complete the replacement of the N annually removed by 1 ha of wheat. The farm could sustain only a few people because N inevitably escapes from the cycle of deposition, fixation, crops, and animals, and each person requires at least 3 kg of N per year (7).

During the 19th century, mining Chilean nitrate and Peruvian guano somewhat relieved this seemingly iron rule that precipitation and rotation must supply the 3 kg of N for each person. In 1908 Fritz Haber combined N from the air with hydrogen from gas to synthesize ammonia (NH_4-N), and in 1914 Karl Bosch completed the first large manufacturing plant. By the middle of the century the new technology lowered the price of N fertilizer enough that farmers began applying near 100 $kg{\cdot}ha^{-1}$ and raising yields in step. Fertilizer N relieved the dependence on N from precipitation, legumes, and mines. With the technology, farmers increased the number of people 1 ha could feed, fed them more than bare necessity, and spared land from tillage. Today Americans annually eat protein containing 6 kg of N.

In 1930 world farmers applied 1.3 million metric tons (Tg) of N in fertilizers, and after World War II they still were applying only 3–4 Tg. Use then began climbing about 10% a year. In the 1960s, however, the rise moderated (Fig. 1). During the 1973 oil shock, use fell for the first time. It climbed again, only to pause in 1981 and 1985 before reaching a maximum near 80 Tg in 1988, a level one can safely call at least 100-fold more than in 1900.

But, from its 1988 maximum, use fell. Although the world use decline after 1988 was aggravated by falls in Central Europe, the former USSR, and Western Europe, it extended the slowing that Fig. 1 shows was long evident. Although world consumption began to recover in 1993, it scarcely reached its 1988 maximum by 1995. The annual rate of change slowed from faster than 10% in the 1960s until it stagnated after 1988 (Fig. 1).

Comparison of the rate of change of U.S. to world use (including U.S.) illuminates two points (Fig. 1). First, because the U.S. adopted fertilizer early and rapidly, its rate of change slowed about a decade sooner. Second, the slowing rate of change and even decline in the U.S. confirm that use can stagnate without the crises in the old Soviet Union. In the U.S., the federal program that shrank harvested cropland about one-sixth in 1983 caused a notable dip. Another feature, a peak in 1994, followed Midwestern floods. After the U.S. capacity to manufacture N fertilizers more than doubled from 1964 to 1981, plant closures and little construction lowered capacity 15% by 1995. Specific causes of specific dips and peaks can be named for both the world and U.S. The general cause of the inexorable slowing, however, is the inevitable limit of the need for more new technology.

Thus N fertilizer use appeared to rise exponentially as many new technologies do in their early ages. In retrospect, however, we see that the rise of N fertilizer has been slowing since the 1960s, first in developed nations that adopted fertilizers earlier, and later over the whole world. Instead of an exponential curve, the world rise now seems a logistic one that leveled a decade ago, to be followed perhaps by another adumbrated by the recent 1–2% annual rise in the U.S.

Is Deposition Increasing?

Humanity's increase of fixation and mobilization of N by fertilization and combustion, it is feared, is increasing emission and thus deposition of N oxides and NH_4-N. For example, Wedin and Tilman (8) wrote that atmospheric deposition rates had increased more than 10-fold over the last 40 yr to as much as 60 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$. NH_4-N can acidify soil, whereas NO_3-N can europhy waters. The increased deposition, it also is feared, would encourage plants favored by a rich N supply to displace others, thus decreasing diversity (1). The specific mechanism that would cause the emission of large amounts of fertilizer N into the air to be deposited later is not clear.

The scale of changing deposition that matters can be judged by the European "critical loads" that range from 3 to more than 20 $kg{\cdot}ha^{-1}$ according to soil and vegetation (9). The 95% safety level for eutrophication is less than 3 or more than 10 $kg{\cdot}ha^{-1}$ in some places but generally 3–10 $kg{\cdot}ha^{-1}$. Alternatively, changing deposition can be judged by incremental loads as low as 10 but sometimes not less than 54 $kg{\cdot}ha^{-1}$ that decreased species richness in N-poor soil made responsive to N by fertilization with other plant nutrients (10). How much has N deposition risen generally during this century and during recent decades compared with these critical loads?

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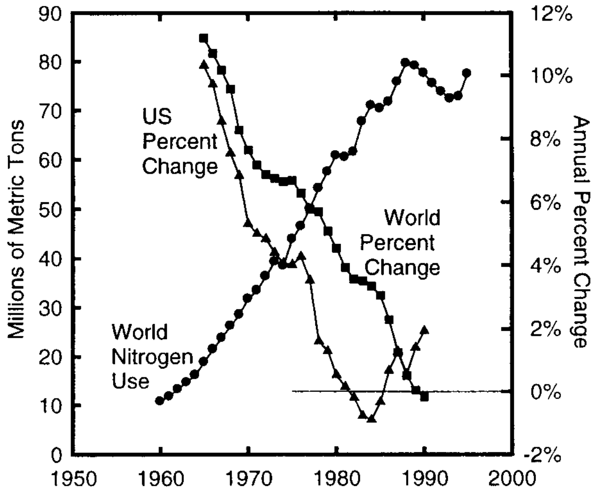

FIG. 1. The world rise in millions of metric tons (Tg) of N in fertilizer, and plotted above each year, the annual percentage change in the world and U.S. calculated from 4 yr before until 5 yr later [source: World, http://www.fertilizer.org; for U.S., Agricultural Handbook 712 (USDA, Washington, DC, 1997) and http://mann77.mannlib.cornell.edu/data-sets/inputs/86012].

In the 19th century agronomists began measuring the scant N for crops that was deposited from the atmosphere by simply collecting what fell into open funnels, which now is called bulk deposition. From 1888 to 1925 annual bulk depositions in Europe and the eastern U.S. ranged from 4 to 8 kg·ha^{-1} annually. When concern about acid rain arose, scientists began measuring what they called wet deposition, which was collected in funnels only during precipitation. The National Atmospheric Deposition Program of the U.S. exemplifies measurement of wet deposition. Concerned acid-forming material would fall between rains or snows, scientists next began calculating dry deposition from a deposition velocity (length per time) multiplied by a concentration (mass per volume). They calculated the velocity from micrometeorological observations or assumed velocities according to the roughness of vegetation. They measured the concentration from air drawn through filters or estimated it from emissions—or sometimes the number of farm animals—and atmospheric models of dispersion. In addition to these depositions, they sometimes collected fog particles on fibers. They also sometimes measured or calculated throughfall, the redistribution in a forest of wet and dry deposition tempered by leaching from foliage and uptake.

Locality as well as method affects the measurement of deposition. For example, much NH_4-N and organic N were deposited near a barnyard (11), and soil showed much more N deposited a few hundred meters from a poultry farm (12). Because dry deposition is calculated for a particular plant roughness and sometimes from nearby sources, it varies from place to place. Because foliage affects throughfall, it, too, will not indicate general deposition.

Because our question asks whether deposition generally has risen as N fertilization and combustion have multiplied, we must compare observations by the same method before and after the great increase in fertilizer and combustion. And the method must not vary from place to place as when it is affected by foliage, roughness, or strong local emissions. Because the observation of bulk deposition is simple and thus robust, is more comprehensive than wet, and has been measured throughout the century, we chose it to indicate the general deposition of N.

The first five sites in Table 1 are in the northeastern U.S. The observations at Geneva and Ithaca, NY during the first quarter of the century show bulk deposition between 4 and 8 kg·ha^{-1}·yr^{-1}. About 6 was also deposited at Mays Point and Huntington Forest, NY during 1965–1980 and also at Hubbard Brook, NH during 1972–1992. In the northeastern U.S., bulk deposition has changed little during the 20th century.

Table 1. Bulk deposition during 1888–1997

	N, kg·ha^{-1}	Years	Ref.
Geneva, NY	7.4	1922–1928	19
Ithaca, NY	4.9	1918–1925	20
Mays Point, NY	6.4	1965–1979	21
Huntington Forest, NY	6.2	1980s	22
Hubbard Brook, NH	6.5	1972–1992	*
Flahult, Sweden	5.1	1909	23
Three Swedish stations	7.1	1996–1997	†
Rothamsted, U.K.	4.5	1888–1916	24
Rothamsted, U.K.	5.3	1955–1966	15
Woburn, U.K.	8.7	1987–1996	‡
Groningen, NL	6.7	1908–1910	25
Kollumerwaard, NL	14.5	1994	26

*www.hbrook.sr.unh.edu.
†Aneboda, Norra Kvill, and Boa-Berg, Sweden at www.ivl.se/index.html.
‡Woburn field near Rothamsted, wet deposition from http://www.aeat.co.uk/netcen/airqual/index/html.

Deposition also can be analyzed over shorter periods. The U.S. Geological Survey (USGS) established the first network of eight bulk precipitation stations in New York and one in Pennsylvania in 1965. Although many have searched this longest single record of deposition for trends, the U.S. National Research Council (13) concluded that evidence of any trend from 1965 to 1980 in NO_3-N concentrations was "equivocal." NH_4-N concentrations appeared to be increasing. When we examined the observations of bulk deposition at Hubbard Brook during 1972–1992, we found no trend in NO_3-N or NH_4-N deposition. [Some of these data were obtained by scientists of the Hubbard Brook Ecosystem Study and have not been reviewed by those scientists. The Hubbard Brook Experimental Forest is operated and maintained by the Northeastern Forest Experiment Station, U.S. Department of Agriculture (USDA), Radnor, PA.]

Also, the USGS (14) examined all NADP observations in the U.S. during 1983–1994 and concluded that, although the low concentrations of both NH_4 and NO_3 increased modestly in the West, concentrations of NH_4 and NO_3 in precipitation were unchanged in the eastern U.S. During the span of these analyses, N fertilizer use in the U.S. nearly tripled from 4.2 Tg in 1965 to 11.4 in 1994.

Returning to comparison over long periods in Table 1, we find little increase between the 5.1 kg·ha^{-1}·yr^{-1} deposited at Flahult, Sweden in 1909 and 7.1 in 1996–1997 at three stations near Flahult. Brimblecombe and Pittman (15) examined the record at Rothamsted, United Kingdom and concluded annual deposition rose about 1 kg·ha^{-1} between 1888 and 1966. A bulk deposition of 8.7 estimated from wet deposition during 1987–1996 at Woburn, near Rothamsted, confirms an increase, perhaps as much as 5 kg·ha^{-1}. (Wet depositions of NH_4-N and NO_3 were adjusted to bulk by division by 0.75 and 0.85, factors calculated for the Netherlands (NL; ref. 16). In a shorter span of years (1972–1989), annual deposition in northern Finland remained level while rising in southern Finland by 1.4 kg·ha^{-1} (17).

Emitting much N, NL presents an extreme. In addition to the emissions of a dense population and industry, NL has 5% as many cattle, 22% as many pigs, and 7% as many chickens as the U.S. on only 4% of the area of the U.S. The difference between 6.7 kg·ha^{-1} bulk deposition at Groningen, NL during 1908–1910 and a bulk deposition of 14.5 at nearby Kollumerwaard during 1994 indicates an increase of about 7 (Bulk was estimated from 1994 wet by the factors used for Woburn.) Calculated depositions have ranged higher. When deposition velocities for European forests have been multiplied by measured atmospheric concentrations or simply inferred from the number of farm animals, heavy depositions have been calculated (16). Nevertheless, in Europe general deposition revealed by annual bulk deposition, even in NL, has increased less than 10 kg·ha^{-1} during the 20th century.

Overall, and even in the extreme case of NL, we find little evidence that any cause, whether the orders-of-magnitude increase since the early 20th century of fertilizer use or of high-temperature combustion, is multiplying the general bulk deposition. This finding should not surprise us because even a conversion of all 80 Tg of fertilizer N into a global emission and its dispersal without such subtractions as denitrification would deposit only an average 1.6 kg·ha^{-1} on Earth's 51 billion ha. The proportion of the 80 Tg that actually could be directly emitted from soil is, of course, far less. Even if the global fuel and transport combustion emission of about 25 Tg NOx-N was added to the 80 Tg of fertilizer that might or might not be emitted to air, the global deposition still would average only 2.1 kg·ha^{-1}.

For cropland, a change of a few kg of N ha^{-1} pales beside some 100 kg·ha^{-1} of usual fertilization. Even for natural vegetation with "critical loads" of 3–20 kg·ha^{-1} or requiring some 10 kg·ha^{-1}·yr^{-1} to lessen diversity, the change of deposition does not seem large. Reasoning that the average 1.6 kg·ha^{-1} reaches forests around the globe requires assuming worldwide dispersal of the N and neglects both its depletion by heavy deposition near sources and denitrification. To reason the N finally reaching global forests would speed growth requires assessing their response; for example, 100 kg·ha^{-1} increased growth of some, but not all, young plantations about a third (18). Practically, the equivocal evidence of changed bulk deposition since the early 20th century in the northeastern U.S. and no evidence of more than 10 kg·ha^{-1} in the extreme of NL makes a weak foundation for arguing a global increase of N has caused more primary production and less biological diversity. The leveling of the rise in N fertilizer and in N emitted from high-energy combustion (http://www.epa.gov/oar/emtrnd/index.html, National Air Pollutant Emission Trends Report, 1900–1996) imply little future general increase of deposition.

Fertilizer Compared with N in Crop

Even though near 80 world or 11 U.S. Tg of N fertilizer are not enriching precipitation with N, some NO_3-N from fertilizer leaching into water and some becoming a greenhouse gas N_2O justify conserving fertilizer.

The amount of N in the crops provides one scale for judging conservation. Some N in crops can come from organic matter in the soil or biological fixation of N by legumes. Much can come from manure or crop wastes. Although the N in crops can be more or less than the N applied in fertilizer, it nevertheless provides a scale for gauging the amount applied in fertilizer.

A tally (27) of world crops in 1990 totaled 53 Tg of N, showing 146% as much N was applied as harvested. We shall abbreviate the ratio of N in fertilizer to that in crops as the ratio. A tally (28) of U.S. crops in 1996 totals 10.2 Tg of N, making the ratio 104%. Adjustment for the 5–20% of fertilizer consumed in nonagricultural uses in the U.S., such as fertilizing lawns, would lower the ratio to 83–99% (in a personal communication on July 24, 1998 Harold Taylor of the USDA wrote that industry estimates that "5–20% of fertilizer is used in nonagricultural uses").

Because the ratios of 146% and 104% are fertilizer N divided by arable crops, the addition of other sources of N raises and of other farm products lowers the ratio. The ratio combines efficiency of crop use of N and proportion of all N furnished by synthetic N. If, for example, the fixation of 10 or 300 kg·N ha^{-1} by legumes is added to the supply of N, the ratios rise to 143–296% for the world and 104–212% for the U.S. Because the invention of different ratios can go on and on and we are concentrating on fertilizer N, we conclude that its ratio to crops is about 150%, meaning about two-thirds as much N is harvested as fertilizer N is applied.

Industrial Ecology of Fertilizer Use

Seeing the prospects to 2070 requires more than ratios in 1 yr. It requires analyzing the component forces of population, wealth, use of wealth for crop production, and fertilizer efficiency that all change the tons of fertilizer. Industrial ecologists (29) customarily analyze the course of consumption of a material such as fertilizer in terms of the dollar's gross domestic product (GDP), which encompasses the total output of goods and services produced by labor and property. The product of the three factors [population (persons), GDP per person ($/person), and material per GDP] is identical to the amount of material, but separating the three components illuminates the separate effects of population, wealth, and intensity of use of the material. The material per GDP is called the intensity of use (IOU), and a rising IOU shows a growing role for the material in the total output of goods and services.

Because either a smaller role of crop production in GDP or more efficient fertilization could lower the IOU of fertilizer, however, we must dissect the components of IOU. The IOU of fertilizer N per GDP is identical to the product of three ratios: the crop per GDP (crop/$), the composition of the crop (N crop/crop), and N fertilizer/N crop (the ratio). With the proviso that the annual changes in the components be small, the sum of their percentage changes is effectively identical to the percentage change in Tg N used in the world: percentage change of Tg N ≡ percentage changes of (persons + $/person + crop/$ + N crop/crop + ratio).

We calculated the changes of persons and $/person from standard tables and the change in crop/$ from indices of crop production that summarize the changing physical quantities of crops weighted according to their economic value (http://apps.fao.org/cgi-bin/nph-db.pl; ref. 30). We assumed that (N crop/crop) did not change. (Because the N composition of the combined production of wheat, corn, rice, and soybeans rose only 0.2% per yr from 1960 to 1996, assuming unchanging composition scarcely affects the percentage change of the ratio, which we shall see ranges from +8% to −2%.) The assumption of negligible change in crop composition allowed us to calculate the change in ratio from the change in fertilizer per crop production index.

World Components. Population growth, the first causal component of world fertilizer use, gradually slowed from 2.0% per yr during the 1960s to 1.5% during 1986–1995 (Fig. 2). During the 1960s, the 4.3% rise per yr of GDP per person plus the population increase raised world GDP faster than 6% per yr. Then the change in GDP per person slowed until about 1980, sped up in the 1980s, and then slowed again.

The intensity of crops per GDP traveled a different path. It slowed as much as 3% per yr during the first years as agriculture played a smaller role in the world. During the slower economic growth of the 1970s its change was near zero; then the decline of crops per GDP began anew in the 1980s but recently has slowed. Because consumption of crops varies less from decade to decade than GDP, in Fig. 2 the course of crop per GDP logically reflects GDP per person.

The new technology of N fertilizer followed still another path. It boomed at first, increasing the ratio of fertilizer to crop N as fast as 8% per yr in the 1960s. Then farmers decelerated the ratio until the N to grow a crop began decreasing during the 1980s and continues to decrease. The path of the ratio suggests several factors at work. At the beginning of the record in Fig. 2, farmers began to furnish N from bags of fertilizer. New varieties and practices raised yields in step with still more fertilizer. And in their exuberance, farmers sometimes fertilized too much, which the falling ratio shown in Fig. 2 shows they are now reversing. During the 10-yr period of 1986–1995, the ratio of fertilizer to crop N fell nearly 2% per yr.

Components in a Nation that Adopted Fertilizer Early. The change of the components in a nation that adopted industrial fertilizer early may foretell the course in the world. Even though

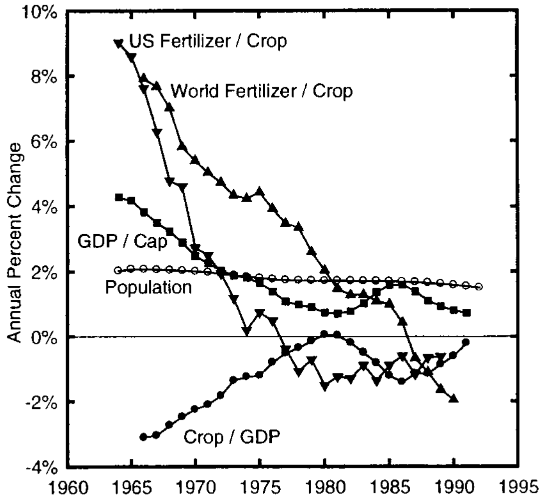

FIG. 2. The changing components that drive world use of N fertilizer plus the changing ratio of fertilizer to crop in the U.S. Change was estimated as in Fig. 1 (source: Population, www.census.gov/ipc/www/worldpop.html; GDP, sent by Endang Setyowati from World Development Indicators 1998, converted to constant dollars 1965-end by World Bank and 1960–1964 by P.E.W. by extrapolating deflator; Crops, http://apps.fao.org/cgi-bin/nph-db.pl plus various U.S. Census and agriculture sites).

U.S. population annually increased only 1.2% in the 1960s, it nevertheless slowed. The GDP per person in the U.S. changed much as that in the world. The U.S. change in crop production per GDP mirrored the world change in GDP per person, declining as rapidly as 3% per yr during the earlier record and increasing slightly during the 1970s, only to decline again during the 1980s.

For our subject, the significant difference between the U.S. and world lies in the ratio of fertilizer to crop (Fig. 2). The deceleration of the ratio in the U.S. anticipated that in the world, but instead of recently plummeting like the world ratio, the U.S. ratio has been falling steadily at about 0.8% per yr for two decades.

Periods of Changing Components in the World and U.S. The final column of Table 2 illustrates how the components in the other columns add up to drive changes in world and U.S. fertilizer use and prepares us to see prospects ahead. In all but one of the periods or rows of the table, crop production lagged behind GDP, making the change of crop/$ negative and confirming that people do not eat more in proportion to growing wealth. Most important for N fertilizer use, farmers are using less fertilizer per crop production, making the change of the ratio negative. The falling ratio in the world might be ascribed to the disintegration of the former Soviet Union or disorder in Africa, forcing the use of other sources of N. But the early and continuing decline of the ratio in the U.S. suggests that although fertilizer use may increase in countries where it plummeted or lagged, one can expect improving fertilizer efficiency to temper growth in world fertilizer use. To expect otherwise requires believing manufacturing and use of N fertilizer will increase faster than such general improvements of crop management as the application of other fertilizer elements.

Table 2. Annual percentage changes of components of N fertilizer use

	People+	$/person+	Crop/$+	Ratio	=N
World					
1970s	1.8	+1.8	−1.2	+4.2	6.6
1980s	1.7	+1.4	−0.8	+1.1	3.3
1985–1994	1.6	+0.9	−0.9	−1.6	0.0
U.S.					
1970s	1.0	+1.9	+1.0	+0.2	4.1
1980s	0.9	+2.4	−2.8	−1.4	−0.9
1985–1994	1.0	+1.2	−0.2	−0.6	1.4

The negative numbers for the 1980s and 1985–1994 hint at the future. They hint that crop production will grow more slowly than the dollars of GDP and that a falling ratio of fertilizer to crop N will temper the rise in fertilizer use that one might expect from rising population and wealth alone. Comparing fertilizer use and corn production among Midwestern states locates some sources of the falling ratio.

Falling Ratio in Four Midwestern States

By receiving about 40% of U.S. fertilizer N during the 1990s, corn showed its large role (http://mann77.mannlib.cornell.edu/data-sets/inputs/86012/to 1991; ref. 31). High yields of corn per ha require high rates of fertilizer per ha. The American average of 8,700 kg of corn ha^{-1} in 1994 contained 122 kg of N ha^{-1}. Input per ha, however, does not measure efficiency. Just as fuel per output of motion rather than fuel per area of frame measures the efficiency of an engine, N per output of yield rather than N per ha measures the efficiency of fertilizer. The winners of corn growing contests apply many kg of N ha^{-1} but show their efficiency by using slightly less N kg^{-1} of corn than other entrants (32). Or, the projected 18,000 kg·ha^{-1} of "wonder wheat" will require a rate at least the 400 kg of N ha^{-1} in the yield, but the high rate indicates input, not inefficiency (33). So, rather than measuring the effectiveness of fertilizer by a low kg·ha^{-1}, we measure effectiveness by a small ratio of fertilizer N to crop N.

Accordingly, for corn in four Midwestern states ((Illinois, Indiana, Iowa, and Nebraska) where virtually all corn is fertilized, we calculated the ratio, in this case from the N in grain rather than from a crop production index (corn yields from www.mann77.mannlib.cornell.edu/data-sets/crops/87013/1/ and N per fertilized acre from http://usda.mannlib.cornell.edu:80/usda/). In 1964 in Iowa, for example, when little fertilizer was applied and hence N in the soil was depleted to supply the grain, the ratio of fertilizer to crop N was only 74%. By the 1980s farmers in the four states applied as much as 200%, twice the N in fertilizer as harvested in corn. Since 1980, the ratio has fallen, reaching 120–160% in 1996. The falls (and SE) in percent/yr in the four states during 1980–1996 were: Illinois 1.2% (1.0), Indiana 2.2% (0.9), Iowa 1.9% (1.0), and Nebraska 1.7% (0.6). In the last three of these four Corn Belt states, significant percentages show farmers have lowered the ratio 1–3% per yr.

A comparison with world ratios sets the 1996 Midwestern ratios in perspective. With average rates of 132–66 kg of N ha^{-1}, the Midwestern states achieved ratios of 122–155%. Where 250 kg of N ha^{-1} was applied in urea and ammonia to irrigated wheat on alkaline soil in Mexico, the ratio was a high 195% (34). With rates of 155 and 185 kg of N ha^{-1}, British and French farmers achieved ratios in nonirrigated wheat of 108% and 114%, respectively. In another example, nonirrigated wheat in NL, 170 kg of N ha^{-1} achieved a ratio of only 94%, undoubtedly lowered by manure and deposition from the air. In Saudi Arabia, northern China, and Egypt, rates of 150–226 kg of N ha^{-1} produced ratios of 156–179% in irrigated wheat (estimates by knowledgeable agronomists communicated by Keith Isherwood, International Fertilizer Industry Association, May 7, 1998). The diversity of ratios shows opportunities for improvements such as achieved in three Midwestern states since 1980.

Prospects to 2070 and 10 Billion People

Does the stagnating world use of N fertilizers mean it rose logistically to a permanent ceiling or that it will rise again, albeit slowly? Forecasts have ranged from a fast 3.8% more fertilizer N per yr in developing nations (35) to a slow 0.65% for the world from 1990 to 2100 (36). We express prospects as annual percentage changes without repeating annual or per yr.

The Four Components of N Fertilizer. How does our analysis of the propelling components modify existing projections ranging from less than 1% to almost 4% more Tg N per yr? The United

Nation's medium projection of world population reaches the round number of 10 billion near 2070, an average annual increase of about 0.8% (http://www.undp.org/popin/wdtrends/execsum.htm). For GDP per person, Fig. 2 and Table 2 support an annual world increase of 1–2%; from 1960 to 1994 it rose 1.8%. Population rising 0.8% and GDP/person rising 1.8% projects world GDP rising as their sum of 2.6%. If population and wealth solely determined fertilizer use, it would multiply nearly 8-fold from 1990 to 2070.

Without either impoverishing or going hungry, however, humanity can temper the prospects for 2070 by modulating the other two components, crop/GDP and ratio of fertilizer to crop N. Although poor people eat more, especially more meat, as they grow richer, sheer capacity eventually limits what they eat. So, the proportionality between crops and GDP falls as GDP/person rises. In the world, including developing nations, it fell 1.1% from 1962 to 1996 and in the U.S. 0.6% from 1960 to 1994. Declines in other periods are shown in Table 3. Causes are exemplified by the 1967–1992 shift from beef to poultry in the U.S., heightening the effect of declining meat per GDP on feed demand (37). A long world decline of 1.0% in crops/GDP, which we project, combines with an 1.8% rise of GDP/person to lift crop per person by 0.8%. The 0.8% more per person would provide just over 10,000 calories/person by 2070, the calories for food, feed, and fiber of rich countries in the 1970s, surely an ample supply despite declining crop/GDP (38).

Farmers control the final modulating component, the ratio to produce the crop set by population, GDP/person, and crop/GDP. In Table 2, the falls of the ratio during 1985–1994 in the world and even longer, 1980–1994, in the U.S., demonstrate the ability to grow the demanded crops with less N. Choosing a conservative rate, we project the world ratio declining 0.5% per yr. The fourth component brings the change of N fertilizer to 0.8 + 1.8 − 1.0 − 0.5 = 1.1%, which would raise world N use 2.4-fold from 1990 to 2070.

The 0.5% decline would lower the ratio of fertilizer to crop N to 100% in 2070, still higher than the 94% in present wheat in NL. Opportunities for conservation include recycling the N in manure and eschewing wasteful application of NH_4 to alkaline soil and water. They include multiple applications to match fertilization to seasonal demand and slow-release formulations to decrease leaching. The program fostered by the Iowa Extension Service helps explain the lower ratio of fertilizer to crop N in Iowa than in Illinois (39). Precision or site-specific farming that tailors fertilizer application to each square meter of a field decreases waste. These conservation measures decrease the numerator of the ratio of fertilizer to crop N.

Increasing the ratio's divisor, yield, by removing other limitations also lowers the ratio. Thus, "One means of improving fertilizer use efficiency is to improve the balance between the nutrients. This has been the aim of (China) for many years, without much impact initially, but with increasing evidence of positive results. The $N{:}P_2O_5{:}K_2O$ (relationship), although still unsatisfactory, developed from 1:0.2:0.02 in 1985 to 1:0.4:0.14 in 1995"[§]. Also, high-yielding varieties, irrigation to relieve drought, pest control, and harvest and storage to protect the yield all decrease the ratio.

Adding Other Goals. A precept of industrial ecology states "Worry about the leaks from cycles rather than the quantity cycling." Although farmers converting feed into meat and milk and sewage plants disposing of the N eliminated by the people fed the meat and milk also can lessen N leaks, we concentrate on the ratio and leaks as fertilizer becomes crop yield.

While attending to sparing of N, we do not lose sight of sparing land from crops to give more habitat to nature. During the past two generations Americans halved the cropland per person while doubling their numbers and multiplying their GDP 8-fold. They also exported much food and ate better. If American farmers accommodate the next 100 million Americans by raising yields rather than expanding cropland, they can spare the land area of more than four Iowas from tillage (37). A smaller expanse of crops exposes fertilizer to less leaching.

Remembering the twin goals of sparing N and land, we summarize the prospects for 2070 in Table 3 with the Tg N fertilizer and the percent of the world taken for crops. Our reference in the first row is 1990 when farmers applied 79 Tg of N fertilizer or about 150% of the N in crops to grow the equivalent of 1,900 kg of grain containing about 38 kg of N/ha on 11% of world land.

If people raise their demand per person at 0.8% as they multiply to 10 billion in 2070, but farming stagnates at its 1990 level, farmers would apply more than three times as much N as in 1990 and would crop more than a third of the world's land (second row of Table 3).

If farmers attempted to feed the 10 billion well while relying on precipitation of 7 kg $N{\cdot}ha^{-1}$, they could coax from the land only a sustained average of 344 $kg{\cdot}ha^{-1}$, even with a ratio of 0% N in fertilizer to N in crop. Rotating onto other acreage that had collected deposition could lift yields to the 1,000 $kg{\cdot}ha^{-1}$ grain described for the medieval farm in our introduction, and legumes could augment the N, but the annual average sustained by deposition overall could be only 344 $kg{\cdot}ha^{-1}$ grain. Crops would rapidly expand onto all natural habitats on their way to the impossible 207% of world land (third row of Table 3).

More likely, farmers will use manufactured N fertilizer and with the help of research annually lower the ratio 0.5%, as we projected above. At the same time they likely will lift yields at least 0.8%, a rate about half that of recent years. They then would increase global N fertilizer 1.1% per yr and expand global cropland by three-quarters to 19% of world land (fourth row of Table 3).

Sustaining the recent rate of yield increases, although difficult, would lift yields faster. World farmers lifted world average corn, wheat, and rice yields about 2% and soybeans 1.5% from 1960 to 1996. Sustaining a 1.7% annual rise in yields would quadruple them by 2070 to 7,600 $kg{\cdot}ha^{-1}$ (near present corn yields in some

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Table 3. Compared with 1990, how four scenarios of 10 billion people fed better in 2070 affect N use, grain yields, and land taken for crops

	N Tg	Ratio, %	Yield, $kg{\cdot}ha^{-1}$	Crop N, $kg{\cdot}ha^{-1}$	Cropland, %
In 1990	79	150	1,900	38	11
Ten billion in 2070					
Farming stagnated at 1990	284	150	1,900	38	38
Relying on deposition of N	0	0	344	7	210
Slower lifting of yields but conserved N	192	100	3,800	77	19
Sustained lifting of yields and conserved N	192	100	7,600	155	10

countries) and shrink cropland for 10 billion well-fed people below today's 11% of the world's land. With the ratio lowered to 100%, N use would be 155 kg·ha^{-1}, a familiar quantity already. The shrunken expanse of cropland would expose N fertilizer to less precipitation and thus make lowering the ratio to 100% easier.

Following the precept to worry about leaks rather than quantities in a cycle, we note the ratio of 150% in 1990 implies 24 Tg leaked from fields. Reducing the ratio to 100% would diminish these leaks, and all 192 Tg fertilizer N projected for 2070 would be balanced by the N in crops. N leaks from other places in the cycle than fields, of course. It leaks from the conversion of crop to meat, milk, and eggs, leaks that are not our subject, but leaks that can be stanched by spreading manure on crops and lowering the ratio below 100%. Sewage disposal also can leak N, but means exist to stanch those leaks, too.

Although lowering the ratio to 100% and passing more of the N to animal husbandry and sewage disposal where other leaks can be closed will lessen losses, we still have projected fertilizer N annually rising 1.1% from 79 to 192 Tg by 2070. Thus between a logistic ceiling versus a further slow rise, logistic or linear, our analysis of the causal components chooses a slow rise resembling that recently evident in the U.S., perhaps to a future logistic ceiling set by future population, the limit even rich can eat, and ever smarter farming. Because fertilizer use rising 2 orders of magnitude in this century has scarcely increased deposition of N from the atmosphere, we reason that our projected future doubling of use cannot increase deposition much.

Conclusion

The growth of N fertilizer after its invention early in the century incited fears of a runaway technology causing a rain of N. Near the end of the century, however, the record shows the slowing growth typical of maturing technologies and surprisingly little change in the general deposition of N by precipitation. The rise of N in fertilizer, which has reached about 150% of the N in many crops, was propelled by the components of population growing 1–2% annually and GDP/person 1–2%. But the component of crop production/GDP annually sinking about 1% coupled with farmers lowering the ratio of fertilizer to crop about 1% tempered the rising components. If population reaches 10 billion for whom farmers provide 10,000 original calories of food, feed, and fiber, stagnation of farming at the 1990 level would triple N use and cropland. Farming that depended on N falling from the air would be impossible. Slowly evolving farming, on the other hand, would temper N use and expansion of tillage to a doubling. Better yet, energetically raising yields 2% annually while lowering the ratio of fertilizer to crop N would stanch leaks from fields while sparing a tenth of today's cropland from tillage by 2070. Nature then would be spared fully 10 times the area of an exemplar of agriculture, Iowa.

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