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Nitrogen and Food Production: Proteins for Human Diets

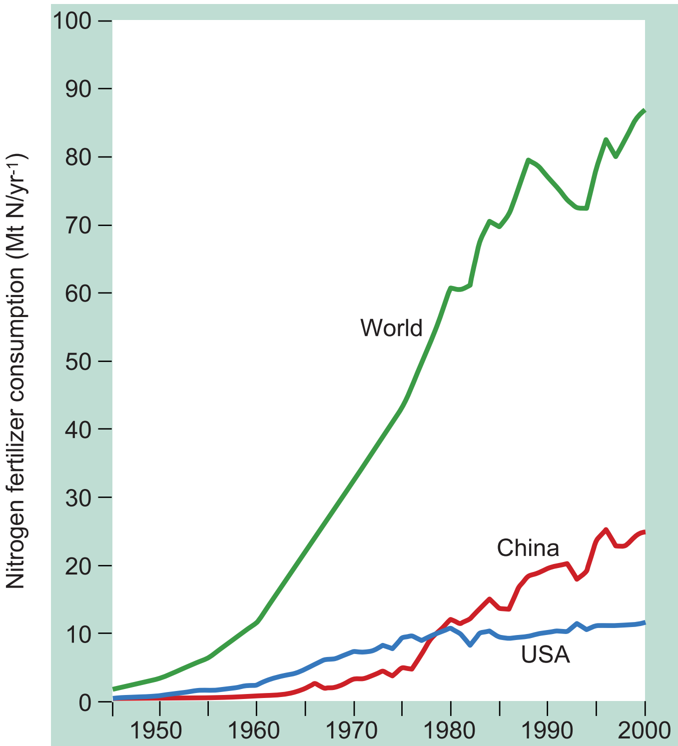
Nitrogen was the most commonly yield-limiting nutrient in all pre-industrial agricultures. Only the Haber-Bosch synthesis of ammonia broke this barrier. The rising dependence on nitrogenous fertilizers, which represents the largest human interference in the biospheric N cycle, has two different roles. In affluent nations it helps to produce excess of food in general, and of animal foods in particular, and it boosts agricultural exports. But for at least a third of humanity in the world's most populous countries the use of N fertilizers makes the difference between malnutrition and adequate diet. Our understanding of human N (protein) needs has undergone many revisions and although some uncertainties still remain it is clear that average protein intakes are excessive in rich countries and inadequate for hundreds of millions of people in Asia, Africa, and Latin America. More dietary protein will be needed to eliminate these disparities but the future global use of N fertilizers can be moderated not just by better agronomic practices but also by higher feeding efficiencies and by gradual changes of prevailing diets. As a result, it could be possible to supply adequate nutrition to the world's growing population without any massive increases of N inputs.

INTRODUCTION

Von Liebig noted in his most famous book that agriculture's principal objective is the production of digestible N (1). This task was particularly challenging in all traditional (pre-industrial) agricultures. They had 3 ways in which to provide N for crops: *i*) recycling of organic wastes (mainly crop residues and animal and human wastes); *ii*) crop rotations including N-fixing leguminous species; *ii*) and planting of leguminous cover crops (alfalfa, vetches, clovers) that were plowed under as green manures. Even the most intensive use of these practices in areas whose climate allowed year-round cropping could not supply more than 120–150 kg N ha^{-1} yr^{-1} (2).

Nationwide means were, naturally, much lower. Buck's surveys indicate that in early 20th-century China, N applications from organic recycling and leguminous crops averaged only about 50 kg N ha^{-1}, and the resulting yields could support about only 5.5 people ha^{-1} on an overwhelmingly vegetarian diet (3). In contrast, applications of inorganic N fertilizers in today's China average nearly 200 kg N ha^{-1}. In the most intensively cultivated provinces, where rice is double-cropped, they surpass 400 kg N ha^{-1}, and the country now supports more than 10 people ha^{-1} on a diet whose total food energy content is almost the same as in Japan and that contains more than twice as much animal protein than it did just 20 years ago (2, 4). Borlaug summed up the role that N fertilizer played in this grand agricultural transformation by using a memorable kinetic analogy: "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..." (5).

Figure 1. Consumption of nitrogenous fertilizers, 1950–1999. (Plotted from data in refs 2 and 6).



DEPENDENCE ON HABER-BOSCH SYNTHESIS OF AMMONIA

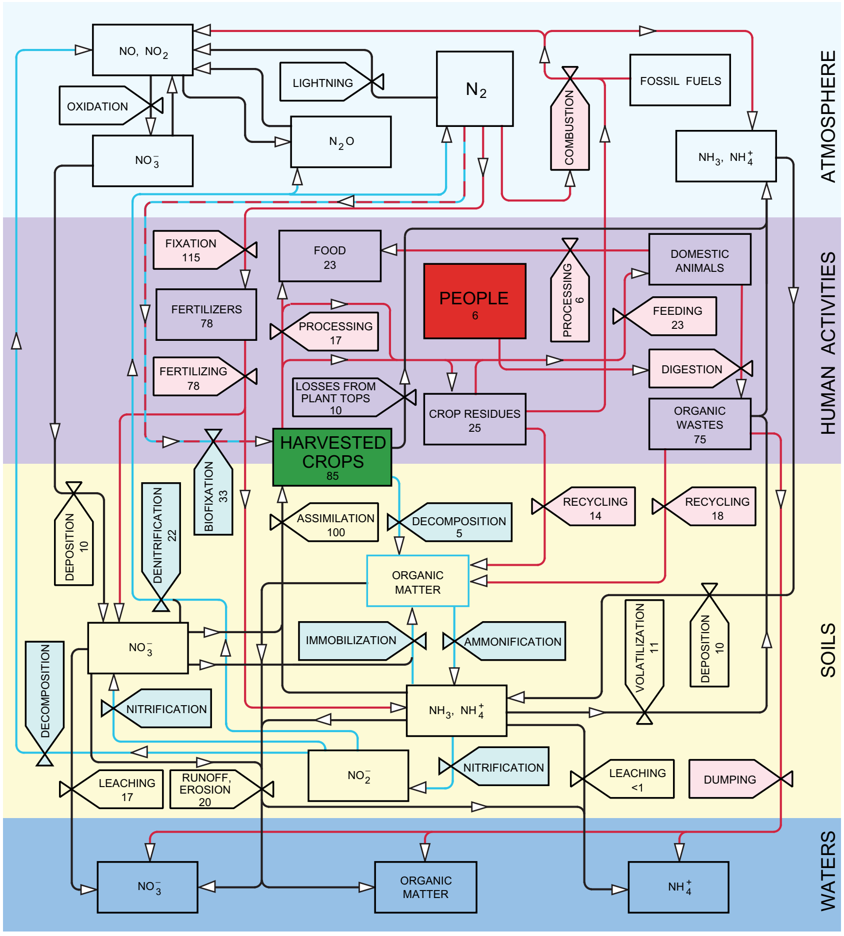
The fuel for the transformation was made available by Haber's brilliant discovery of ammonia synthesis from its elements, in 1909, and the extraordinarily rapid commercialization of this invention, led by Bosch, that made large-scale production of ammonia possible by 1913 (2). As shown in Figure 1, rapid post-1950 diffusion of N-fertilizer applications had increased their worldwide use to nearly 80 million tonnes (Mt) by the late 1980s and, after a period of stagnation, to just above 85 Mt N by the late 1990s (2, 6). Since the collapse of previously huge Soviet production the US is again the second largest user, and China is both the world's largest producer and consumer of synthetic N fertilizers and it will remain so for several decades to come. Inorganic N now supplies about 80% of the nutrient reaching the fields in China's most intensively cultivated coastal provinces, compared to about 45% in the US (2).

A detailed account of N flows in global agriculture (7) shows that synthetic fertilizers provided close to half (44–51%) of all the nutrient received by crops during the mid-1990s (Fig. 2). Contributions from symbiotic and free-living diazotrophs and the amount of N in recycled organic matter are not easy to quantify. Since about 85% of N in food proteins comes from agriculture (directly in plant foods and indirectly in animal foods produced by feeding; the rest comes from pastures and from aquatic foods) about 40% of the world's dietary protein now originates in the Haber-Bosch synthesis of ammonia. Alternative estimates of the world's dependence on ammonia synthesis could be obtained by calculating the population totals that can be supported by specified diets.

In 1900, the nearly fertilizer-free agriculture—less than 0.5 Mt N were applied to crops worldwide in Chilean nitrates and ammonium sulfate derived from coke-oven gases—supported 1625 million people by cultivating about 850 million ha (Mha). Those agronomic practices and yields extended to today's 1500 Mha could feed about 2900 million people, or about 3200 mil-

Figure 2. Nitrogen stores (rectangles, in Mt N) and flows (valves, in Mt N yr^{-1}) in the global agroecosystem. (Based on the graph in ref. 7.)

flows affected or dominated by human actions
flows mediated or dominated by bacteria
other flows



lion when adding the food derived from grazing and fisheries. And if we were to provide the recent average per capita food supply with the yields prevailing in the year 1900 we could feed only about 2400 million people, or just 40% of today's total. We can thus conclude that the Haber-Bosch synthesis now provides the very means of survival for about 40% of humanity; that only half of today's population could be supplied by pre-fertilizer farming with overwhelmingly vegetarian diets; and that traditional cropping could provide today's average diets to only about 40% of the existing population (2).

But these figures, correct as they are, both overestimate and underestimate the degree of our dependence on synthetic fertilizers. Affluent countries now consume about 35% of all N fertilizers, but they could reduce their applications by half, or even by two-thirds, and still would be able to secure adequate nutrition. Their heavy use of fertilizers does not make the difference between malnutrition and comfortable food supply: it supports unnecessarily protein-rich diets and in North America, it also helps to produce large exportable food surpluses. During the late 1990s the US agricultural exports contained about one-third of all N incorporated in the country's harvest (2). Substantially reduced fertilization in the US thus would not compromise the country's food supply but it would change its typical diet and weaken its large agricultural exports (8).

In contrast, the low-income countries now use 65% of all N fertilizers, but their supply of dietary protein remains inadequate. Successful food producers (China or Brazil) would have no protein deficiencies only if they could guarantee a perfectly egalitarian access to food, while countries with stagnating, or even falling, output (a score of them in Africa) could not do that even with the strictest food rationing. But quantifying the actual extent of the worldwide protein deficiency is not easy. We have had the basic understanding of human needs for digestible N for about a century, but we still argue about the required age-, sex-, and activity-dependent rates.

HUMAN NEEDS AND SUPPLIES OF DIGESTIBLE NITROGEN

Nitrogen is an irreplaceable constituent of amino acids that are required for the assembly of proteins, the building blocks of all metabolizing tissues and enzymes that control the chemistry of organisms. The element is also present in the nucleotides of nucleic acids (DNA and RNA) which store and process all genetic information. Adults cannot synthesize 8 amino acids that occur in proteins and hence these essential compounds must be ingested in food; children need 1 more essential amino acid. Amino acids contain between 15–18% of N, and 16% is used commonly as the average value. Additional N is also needed for the synthesis of hormones and neurotransmitters, and the body has to replace small but constant protein losses caused by breakdown and reutilization of the compounds, excretions of N, in urine, feces and sweat, shedding of skin and cutting of hair and nails (9, 10). Unavoidable N losses through excretion remain fairly constant in adulthood (41–69 mg kg^{-1}; average of 53 mg kg^{-1}) and other losses add just around 8 mg kg^{-1}.

Relative protein requirements naturally peak in infancy when both the tissue synthesis and protein breakdown rates are high. Milk intakes supporting normal infant growth can be used to set amino acid requirements. Adult protein needs have been derived mostly from the studies of N balance by feeding protein below and above predicted adequate intake and then interpolating to the zero balance level; unlike fat, protein cannot be stored and its excessive intake brings higher excretion of N-containing metabolites. The earliest recommendations of daily protein intakes differed by an order of magnitude. In 1904, Chittenden concluded that 35–50 g of protein a day were adequate for adults while Rubner argued that 165 g a day should be the norm for German soldiers (11, 12). Recommendations published during the next 50 years prorated to 3–4 g of ideal protein per kg of body weight for infants, 1.5–3 grams for teenagers and 0.3–1 g kg^{-1} for adults.

FAO's first expert committee on protein needs set the rate at 2 g kg^{-1} for infants up to six months, and at 0.35 g kg^{-1} for adults (13). Less than a decade later the second FAO assessment lowered slightly the rate for children 2–4 years old, but it raised the adult requirement by 60% (14). Based on these figures FAO and other UN agencies believed that there was a looming global protein crisis (15). This was soon shown to be an exaggerated concern. Reversing partially the previous change, the third FAO consultation on protein needs recommended a marginal lowering of adult rates while raising the requirements for children less than 12-years old (16). Finally, in 1985 FAO, jointly with the WHO and the UN University, set a standard of 0.6 g kg^{-1} of adult weight, and then raised the rate to 0.75 g kg^{-1} in order to cover demand variations within a population (9). All of these changing recommendations are charted in Figure 3. The latest FAO-led assessment of human protein needs is to be published soon.

Recommended intakes are expressed in terms of ideal protein that is intake containing adequate amounts of all essential amino acids and easily digestible. Egg and cow milk, as well as meat and fish, proteins fit this dual requirement. In contrast, plant proteins are deficient in at least one essential amino acid—cereal grains in lysine, legume grains in methionine and cysteine. Moreover, many plant proteins are also less easy to digest than milk or meat. Net protein utilization, a product of amino acid score (measure of quality) and digestibility, is well above 80% for typical US mixed diets, but it may be below 50% for largely, or purely, vegetarian Asian diets dominated by staple grains (17). Children growing up on such diets should consume daily 2.0–2.3 g kg^{-1} of dietary protein, rather than just 1.0–1.1 g kg^{-1} of milk or meat protein.

Uncertainties remain even after a century of research on dietary protein needs. Perhaps the most notable fact is that a group of the MIT researchers has concluded that the amino acid requirement values for the adults proposed by the joint FAO/WHO/UNU committee are of questionable validity as far as their use in practical human nutrition is concerned (18). They disagree with a long-held belief that adult requirements for specific amino acids are much lower than the needs of young children and that they can be met by all normal mixed diets. That is why they proposed a new set of amino acid requirements and a new amino acid requirement pattern for adults that differ markedly from those adopted by the joint FAO/WHO/UNU recommendations (19, 20). Their tentative amino acid requirement pattern for adults resembles the joint FAO/WHO recommendation (21) for pre-school (2 to 5 year old) children. And while it has been believed for most of the 20th century that protein needs are not changed by physical activity, recent evidence shows that these requirements are elevated for those who engage in regular endurance exercise (22).

If ours were a truly global and a highly egalitarian civilization none of these uncertainties would really matter, as there would be ample protein for everybody. Using the FAO's data bases (23) and standard nutritional values of foods (24) I calculated (2) that during the mid-1990s the worldwide edible harvest of crops contained about 16 Mt N. Meat and dairy products added more than 7 Mt and almost 2 Mt came from marine and freshwater catches and aquaculture (Fig. 4). The grand total of about 25 Mt N provided the per capita average of almost 75 g of protein a day (with 25 g day^{-1} coming from animal food), an adequate supply by any definition. But as so many other global rates, this total is made up of 2 very different parts.

With per capita supply averaging almost 100 g day^{-1}, including about 55 g from animal foods and showing little difference among individual countries, the affluent world has a clear surplus of dietary protein (25). In contrast, the per capita mean of less than 70 g day^{-1} that prevails in the low-income countries of Asia, Africa, and Latin America contains a much smaller share of animal proteins (only about 20 g day^{-1}) and it hides substantial inter- and intranational differences. These intakes would be adequate only with a perfectly equitable distribution. The real world, where unequal access to food generally favors better-off socioeconomic groups, males and adults, means that several hundreds of millions of people throughout the poor world, most of them children, have protein intakes below the rates compatible with healthy and vigorous life.

The latest FAO assessment of global malnutrition, for the period between 1997 and 1999, adds up to 815 million undernourished people, or about 14% of the world's population (26). Shares of undernourished people are below 3% in high-income countries. They are as high as 60%, or even 70% in some countries of sub-Saharan Africa where average diets contain often less than 50 g protein day^{-1}, with as little as 5–10 g day^{-1} coming from animal foods (25). Malnutrition rates for India and China are, respectively, about 20% and just above 10%. With just over 200 million, or roughly a quarter of the world's total, India is the country with the largest number of undernourished people, and they live in all parts of the subcontinent. China's malnourished are concentrated mostly in the arid northwestern and mountainous southwestern interior provinces, and add up to about 140 million.

All of the totals in the preceding paragraph refer to people that have been recently experiencing inadequate food energy intakes, but that condition does not always coincide with shortages in protein supply. A more accurate reflection of protein deficit is the number of children who are underweight (having low weight for age), stunted (having low height for age) and wasted (having low weight for height). FAO's latest *World Food Survey* put the numbers of these children at, respectively, about 180, 215, and nearly 50 million during the early 1990s, with the largest absolute shares in South Asia, followed by East and Southeast Asia, and sub-Saharan Africa (27). Substantial reduction of these

Figure 3. History of dietary protein recommendations issued by the FAO. (Plotted from data in refs 9, 13, 14 and 16.)

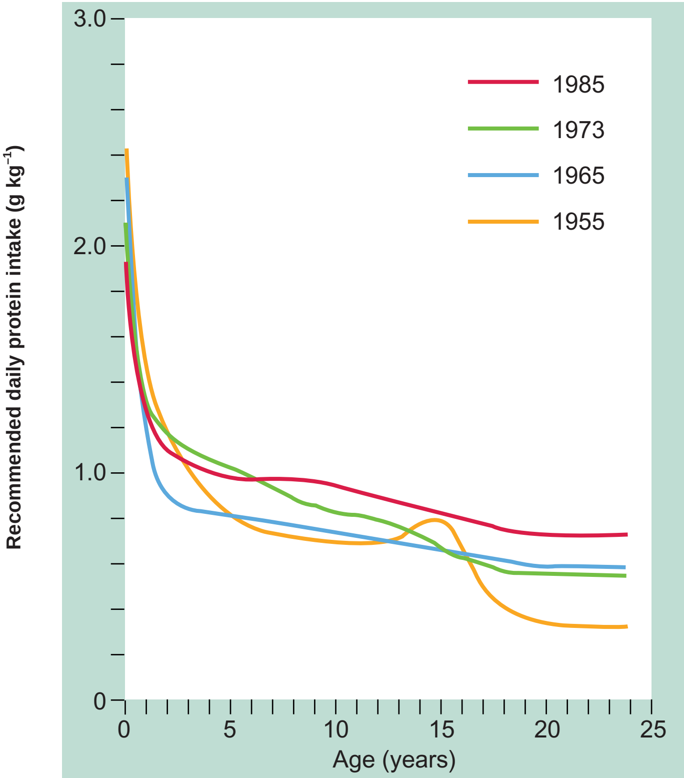
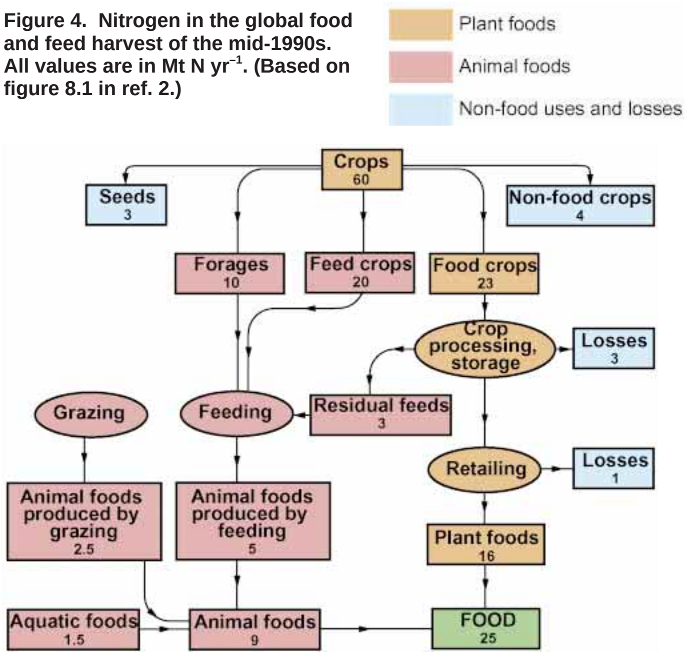


Figure 4. Nitrogen in the global food and feed harvest of the mid-1990s. All values are in Mt N yr^{-1}. (Based on figure 8.1 in ref. 2.)



large numbers will be a small part of the coming challenge of supplying enough dietary protein as even conservative forecasts see the global population growing by some 50% during the next 50 years (28).

Moreover, the task of reducing the existing protein deficit in Asia, Africa, and Latin America and securing adequate amounts of digestible N for another 3000 million people during the first half of the 21st century will be made more difficult by the need to limit the environmental impacts of nitrogenous fertilizers. Their applications have been the single largest source of human interference in the global biogeochemical cycle of the element during the last quarter of the 20th century (2, 29) and their use will inevitably increase. FAO assumes a basically stable worldwide relationship between fertilizer use and crop production until the year 2030, and forecasts N fertilizer for that year almost 40% above the 2000 level (30). Managing the environmental impact of rising N applications is difficult mainly because of the many ways the element leaks from agroecosystems.

NITROGEN LOSSES ALONG THE FOOD CHAIN

All principal flows and stores of N in the global agroecosystem are shown in Figure 2. During the mid-1990s the world's crop lands received about 170 Mt N from synthetic fertilizers, biofixation, organic recycling, irrigation water, seeds, and atmospheric deposition, while harvested crops incorporated about 60 Mt N and their residues (removed from field or directly recycled) contained another 25 Mt N (7). Consequently, crop phytomass recovered, on the average, only about 50% (45–55%) of all available N. This mean must be seen only as an approximate indicator. Actual N recovery rates vary widely not only among different crops and different agroecosystems but, influenced by weather and agronomic practices, also from year to year in the same field planted with the same cultivar.

Studies of N balances in temperate agroecosystems confirm the overall N recoveries ranging mostly between 50–60% (31) — but the rate should not be mistaken for the average N uptake from inorganic fertilizers, which is determined most reliably by using 15N-labeled compounds. Field studies of fertilizer-N uptake by rice, corn and wheat show typical N recovery rates well below 50%, with Asian rice averaging as little as 30% (32–34). These rates are appreciably lower than the uptakes measured during experiments in small plots. Overall N recovery by crops is higher than the fertilizer N uptake because the losses of the element fixed by symbiotic bacteria and bound in organic matter are lower. But even if the overall loss of applied fertilizer N were to be no more than 50% this would mean that over 40 Mt of the element would flow annually from the fields into the atmosphere and into waters—and the actual total may be easily 10–15% higher. Whatever the real flux is, it cannot be subdivided with high confidence.

Both nitrification and denitrification remove soil-N as NO and N_2O, and denitrification, the closing arm of the biospheric N cycle, restores N_2 to the atmosphere. Measured rates of NO and N_2O emissions from agricultural soils range over several orders of magnitude, ranging from mere traces to nearly 10 kg N ha^{-1} yr^{-1} and amounting mostly to between 0.5–2% of initially applied N (35, 36). Volatilization of NH_3 causes huge nutrient losses following the applications of ammoniacal fertilizers, and animal manures lose much, and often most, of their N content even before they are spread onto fields or shortly after. Volatilization losses are particularly high when urea is broadcast directly onto flooded rice fields (37). In such conditions, the overall losses may be as high as 60%, or even 70% of applied N.

Leaching of highly soluble nitrates and soil erosion, transfer often large amounts of N to ground waters, streams, lakes and coastal waters where the nutrient can cause serious eutrophication (38, 39). Highly variable leaching rates depend on levels of fertilization, compounds used (NH_3 leaches very little), soil thickness, and permeability, temperature, and precipitation. Annual leaching losses range from negligible amounts in arid and semi-arid fields to maxima over 50 kg N ha^{-1} in the most heavily fertilized crop fields of northwestern Europe and the US Midwest, and to even higher leaching losses in some irrigated crops (40, 41). Losses from tops of plants are a combination of shedding old tissues, leaching from senescing leaves, heterotrophic grazing and volatilization from leaves. They take place mostly within 2 or 3 weeks after full bloom and by the harvest time they can easily eliminate 10–30% of a plant's peak N content (42, 43). Aggregate losses from plant tops may be as large as the total for denitrification.

Widespread adoption of appropriate agronomic practices aimed at reducing field losses of applied fertilizer-N can go a long way toward moderating undesirable environmental consequences of fertilization and many of these measures are reviewed elsewhere in this issue of Ambio (30, 32, 44, 45). The success of such measures was already evident during the past 2 decades as crop yields in many countries have continued to increase while N-fertilizer applications per ha of planted area have either remained constant or even declined. US corn cropping is a particularly good example of more N-efficient practices, with average grain output rising from 42 kg of grain per kg of fertilizer-N in 1980 to 57 kg kg^{-1} N by the year 2000 (45). British winter wheat and Japanese rice are among other outstanding examples of more efficient use of N fertilizers (2).

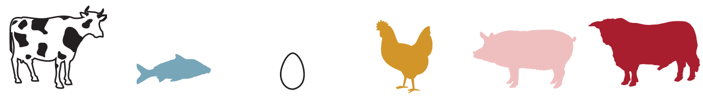
In order to follow the post-harvest fate of crop N we must first subtract the element in seeds reserved for planting and in non-food crops, and then account for inevitable metabolic losses in animal feeding, and waste and spoilage during food processing and retail (Fig. 4). This leaves us with about 16 Mt of digestible N in plant foods and 5 Mt N in animal foods produced by feeding. Crops thus supply, directly and indirectly, nearly 85% of 25 Mt of all food-N reaching the consumers. A mere 0.3% of the 23 Mt of actually digested N (at least close to 10% is household storage loss and table waste) is locked in new proteins added annually by the growing global anthropomass (46). This means that close to 23 Mt N are excreted by humans every year and as more than 50% of people on all continents, except in Africa, now live in cities, most of this waste is released directly into sewers. Unfortunately, most of the sewered waste is either released directly to streams or coastal waters, or it is treated inadequately, and the fate of this aqueous-N ranges from desirably rapid denitrification to highly undesirable nitrate contamination of aquatic ecosystems (38, 39).

After subtracting the nutrient received by fields that are used to produce industrial crops we have the following sequence for the global food production of the mid-1990s (see Figs 2 and 4). About 160 Mt N, including about 75 Mt N in synthetic fertilizers, reached the food- and feed-producing cropland. About 53 Mt N (one-third of the total initial input) were in crops destined for eventual human and animal consumption. About 21 Mt N—or about 13% of the initial input—ended up in plant and animal foods. Expressed in reverse, this means that in order to produce 1 kg of edible N in plant foods and in crop-derived animal foods it is necessary, as the global mean, to supply about 8 kg of the element to fields through Haber-Bosch fixation, biofixation, organic recycling, and atmospheric deposition (47).

Nitrogen's post-harvest fate is very different in the 2 principal food streams (Fig. 4). About 70% of N in harvested food crops become available, after processing and losses, for human consumption. In contrast, some 33 Mt N in feeds produce only about 5 Mt N in animal foods which means that, on the average, nearly 7 kg of feed N are needed to produce 1 kg of edible N in meat, eggs, and dairy products. This account makes it clear that there are enormous opportunities for reducing N leakage from the food system beyond the fields. Two related measures—more efficient production of animal foods and gradual dietary transformations—would be particularly helpful.

ANIMAL FOODS AND DIETARY TRANSITIONS

To begin with, affluent countries in Europe, North America and Oceania simply produce too much food for domestic consumption. Their average daily per capita supply of food energy is now about 3200 kcal, and in the US it surpasses 3600 kcal (25). In contrast, consumption surveys, such as the US Continuing Survey of Food Intakes by Individuals, show that actual intake, for all individuals of all ages, averages as little as 2000 kcal day^{-1} (48). Consequently, anywhere between 25–55% (average about 30%) of all available food in those countries is now wasted. The Japanese situation is somewhat better, as the average per capita supply has been steady around 2900 kcal day^{-1} for the past generation (25). Some waste at retail and household levels is inevitable, but any share in excess of 20% is indefensible, indeed immoral.



	Milk	Carp	Eggs	Chicken	Pork	Beef
Feed conversion (kg of feed/kg^{-1} of live weight)	0.7	1.5	3.8	2.3	5.9	12.7
Feed conversion (kg of feed/kg^{-1} of edible weight)	0.7	2.3	4.2	4.2	10.7	31.7
Protein content (% of edible weight)	3.5	18	13	20	14	15
Protein conversion efficiency (%)	40	30	30	25	13	5

Figure 5. Protein contents of major animal foods and feed conversion efficiencies of their production. (Based on Figure 8.4 in ref. 2.) Calculations of feed conversion efficiencies based on the latest (1999) average US feed requirements from ref. (49); they include the feeding requirements of entire breeding and meat-producing populations.

Although our species is omnivorous and vegetarianism will never be a voluntary choice of an overwhelming majority of people there are many ways to be more N-efficient consumers of animal foods. Detailed comparisons of protein costs of animal foods (4, 49) show that dairy foods can be produced most efficiently in terms of feed protein to food-protein conversion efficiency (Fig. 5). Aquacultured herbivorous fish, eggs, and chicken come close, while pork production converts feed protein to lean meat only about half as efficiently as broilers do.

Beef production is inherently the least efficient way of supplying dietary protein through animal feeding. This is because the animals are large, have long gestation and lactation periods, requiring large amount of feed for breeding females, and their basal metabolic rate is higher than for pigs (4). This inefficiency is irrelevant in broader N terms as long as the animals are totally grass-fed, or raised primarily on crop and food processing residues (ranging from straw to bran, and from oilseed cakes to grapefruit rinds) that are indigestible or unpalatable by nonruminant species. Such cattle feeding calls for no, or minimal—because some pastures are fertilized—additional inputs of fertilizer-N. Any society that would put a premium on reducing N losses in agroecosystems would thus produce only those 2 kinds of beef. In contrast, beef production has the greatest impact on overall N use when the animals are fed only concentrates, now typically mixtures of cereal grains (mostly corn) and soybeans.

Most of the US beef is actually produced by a combination of grass- and grain-feeding. During the late 1990s, the average amount of concentrate feed to produce one kg of live-weight for all beef cattle was 5.5 times higher than for broilers (49). Since a larger share of a broiler's weight is edible the multiple rises to about 7.5 times in terms of lean meat (Fig. 5). If cattle were fed mostly soybeans (without any N fertilizer) and broilers were raised only on corn (heavily fertilized) then beef's metabolic disadvantage would shrink significantly. In reality, very similar mixtures of concentrates are used in animal feeding, corn for energy needs and soybean meal for protein needs, and so the disadvantage remains. Contrary to a common belief, high-yielding US soybeans may be actually substantial net users of N: rather than satisfying their own N needs and leaving behind some residual nutrient for the subsequent non-eguminous crop they can remove up to 80 kg N ha^{-1} (50). That is why about 20% of all US area planted to soybeans now receives N fertilizer, with applications averaging about 25 kg N ha^{-1} nationwide and almost 55 kg N ha^{-1} in Iowa (51).

American beef cattle herds thus require at least five to six times the feed energy per unit of lean meat compared to the country's broiler population, and hence its production also entails losing 5 to 6 times as much fertilizer-N in producing the requisite feed. The two less N-efficient meats, beef and pork, now make up about 2/3 of the average supply of the US animal protein. Consequently, the country would have to use less than half of its concentrate feed, and hence less than half of the N fertilizer used to grow it, if its protein-rich diet were composed of equal shares of dairy products, eggs, chicken, pork and aquacultured fish. And there is also no need to eat more than 100 kg of meat a year per capita in order to enjoy healthy and active lives and to achieve high average longevity.

If the North American food consumption pattern were to be replaced by a version of the Mediterranean diet—the Greek average would be perhaps the best choice (52)—then the feed needed to produce meat protein could be cut by a further 40%. So far, the US per capita meat consumption has shown no signs of decline, but several European countries have become less carnivorous during the past generation, including a 15% drop in meat-eating in Germany and a 10% decline in France (25). Such gradual dietary changes would be also of immense importance for guiding the future consumption trends of populations with rising per capita incomes.

The desire to consume more animal foods is virtually universal but, powerful as it may be, the North American dietary pattern is not only an inappropriate attractor, it is also utterly unrealistic. Its universal adoption by some 9000 million people who will inhabit this planet 50 years from now would require them to share it with more than 3000 million heads of cattle (today's count is about 1300 million)—and with their waste. In fact, food balance sheets of the second half of the 20th century show that intakes of animal food in modernizing countries of Asia have not been moving rapidly toward the high-meat pattern (25). Consequently, I agree with Seckler and Rock (53) that what they label the Asian-Mediterranean pattern—with overall food energy availability well below 3200 kcal capita^{-1} and with animal products supplying less than 25% of food energy—should be seen as the only realistic attractor for modernizing populations.

China's recent rapid dietary transition confirms this argument. In order to see this one must go beyond misleading and exaggerated official output statistics that have the country's total meat production more than doubling during the 1990s to almost 60 Mt and that imply average per capita meat consumption of about

47 kg in 1999 (54). Annual household consumption surveys are a much more accurate indicator of actual changes. They show that in 1999 per capita purchases of meat were 25 kg in urban households, unchanged since 1990, and that rural families consumed, on the average, about 17 kg of meat per capita compared to about 13 kg a decade ago (54).

Even if these rates would increase gradually by 50% during the next generation, improved feeding efficiencies and a right mixture of animal products would make it possible for China to produce this animal protein without resorting to any massive imports of feed grain (55). As in other low-income countries, China's typical feeding efficiencies are much lower, commonly 25–50%, than is the norm in North America and Europe. And the country can enhance its supply of high-quality protein by following the example of Japan, another traditionally non-milking nation, by using more of its feed most efficiently to produce milk (56).

I will not offer any specific quantitative forecasts, as they tend to become irrelevant soon after their publication. Instead, I feel confident that the combination of reduced N losses and modified diets *could* save enough N to offset *most* of the new demand for the nutrient's applications resulting from population growth and from the desire of people in low-income countries to eat more animal foods. This would require efficiency gains along the entire food chain, beginning with more efficient use of the nutrient in cropping, continuing with reduced post-harvest losses in storage and ending with much less wasteful animal feeding and food consumption. There are no insurmountable natural, technical or managerial obstacles to do this, and it *should* be one of our major goals during the next two generations. Its achievement would go well beyond moderating the worrisome human interference in nitrogen's biospheric cycle as it would have many other economic, environmental and health benefits.

References and Notes

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