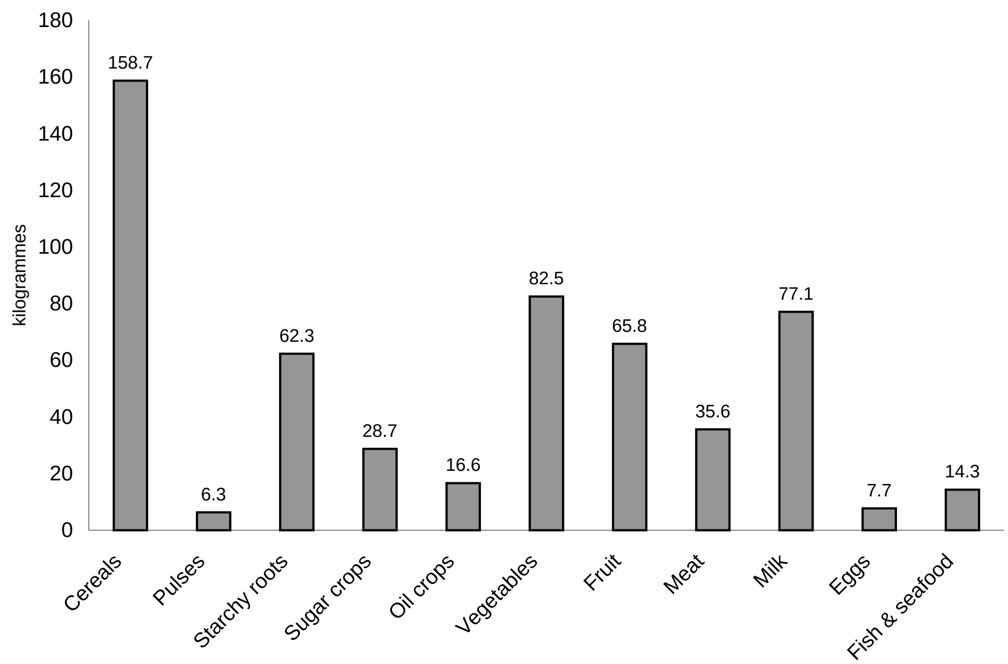
I. Food Consumption and Disruption of the Nitrogen Cycle

1. Patterns of World Food Consumption and Production

After water, food is our most vital item of consumption. About three-quarters of the human food supply comes from agriculture (the balance being supplied by fishing, hunting and gathering). Cropland and permanent pasture cover some 37 percent of the world's land area and a much higher proportion of the habitable land area.[1] Food production is by far the dominant form of land use. The human diet varies widely in different parts of the world, but Figure 1 illustrates the composition of the average food intake in 1996. Some items, such as alcoholic beverages derived from cereals and fruits, are excluded.

Cereals remain the mainstay of the human food supply, but significant changes have taken place over the past four decades. Per capita consumption of cereals and meat rose 17 percent and 36 percent respectively, while per capita consumption of fish and seafood rose 57 percent. Consumption of leguminous plants such as rice and soybeans, valued for their high protein content, rose in absolute and per capita terms. Vegetables, starchy roots (such as potatoes) and pulses all declined in

Figure 1. World Food Consumption, 1996 (kg/capita/year)



Source: FAOSTAT
Notes: Sugar crops include sweeteners; oil crops include vegetable oils

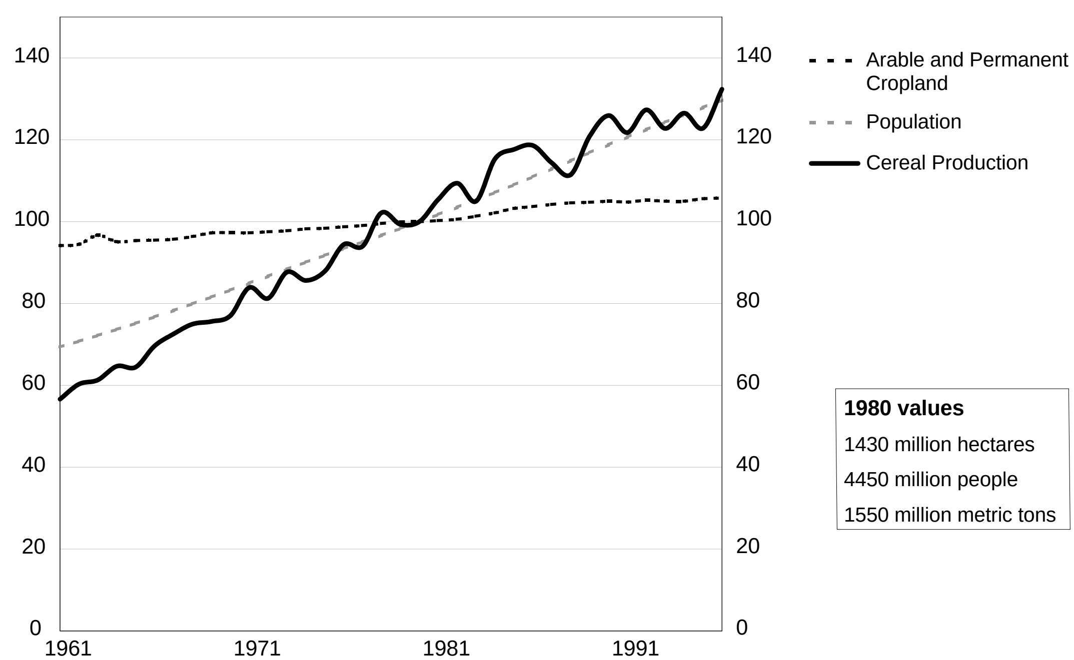
importance on a per capita basis, though total consumption increased. Also significant has been the increase in consumption of what might be termed "lifestyle" products such as coffee, tea and alcoholic beverages. Coffee production, for example, has risen by 37 percent since 1961 and the harvested area now accounts for about one percent of total arable land.[2] Rising incomes, together with the development of sophisticated food processing and distribution systems and a liberalized world trade regime, have enabled consumers in the industrialized countries, and many affluent centers in the developing world, to enjoy unprecedented choice in the foods they eat. As a result, many countries have re-oriented part of their agriculture sector towards export products including "exotic" food items, and feedstuffs for livestock.

Population Growth and Food Production

Between 1960 and 1996, the world's population rose from 3 billion to 5.8 billion, an unprecedented rate of increase which posed a major challenge to food producers. Historically, as the human population has grown, the area of land used to produce food has simply been expanded. By 1960, however, most of the world's best soils were already in use and new land could be brought into cultivation only at a relatively slow rate. The area of cropland available to feed each person therefore fell dramatically, from about 0.43 hectares per capita in 1961 to about 0.26 hectares per capita in 1996. Despite this handicap, food production kept pace with population growth, more than doubling between 1961 and 1996.[3] The relative increases in world population, cultivated land area, and cereal production are shown in Figure 2. Humans eat many things other than cereal, but cereals account for about half of our total calorie intake, and are usually accepted as a good proxy for food production.[4]

Both developed and developing countries raised their cereal production after 1961, but growth rates were highest in the developing countries, where cereal production rose at an annual compound rate of 3.3 percent. This contributed greatly to improved nutrition; the average calorie supply to people in less developed regions rose by over 30 percent and the proportion of hungry or under-

Figure 2. Population, Cultivated Land, and Cereal Production, 1961-1996, Indexed to 1980



Source: UN Population Division and FAO nourished people in the world fell from 35 to 21 percent. Nevertheless, because of population increase, the absolute number of undernourished people fell only slightly, and now stands at about 840 million people.[5]

The world's revolution in agricultural production was made possible in large part by irrigation and the increased use of inorganic nitrogen fertilizers.[6] (The precise contribution of fertilizers to raising yields is still unclear, but is estimated at between 35 and 50 per cent.[7]) Fertilizers contribute to increased crop production in several ways: by replenishing nutrients used by growing plants, by increasing the amount of biomass in the soil, which improves moisture retention and nutrient use efficiency, and by enabling the adoption of more productive varieties of cereal. New, high-yielding varieties of wheat and rice have been bred specially to utilize more nitrogen and convert it into more grain. Increased yields have accounted for more than 80 percent of the growth in cereal production in the developing countries, while expansion of cultivated land has accounted for just 20 per cent.[8]

2. Agriculture, Environmental Impacts, and the Global Nitrogen Cycle

The intensification of agriculture has reduced the need to expand cultivation into marginal and ecologically fragile areas but there have been other, considerable, environmental costs. Poor soil management, over-grazing, and inappropriate use of pesticides and herbicides are associated in many parts of the world with soil erosion, desertification, fertility declines, and contamination of soils and water supplies. This paper, however, focuses on the environmental impacts of increased nitrogen levels in soils, water, and the atmosphere, for two key reasons.

Firstly, modern agriculture is the leading source of anthropogenic (human origin) nitrogen entering the environment. Inorganic nitrogen fertilizers are an essential input to maintaining high crop yields. They cannot readily be substituted and fertilization must probably *increase* in the future if we are to feed a still-growing world population. In addition, meat consumption is rising world-wide and the numbers of livestock, and associated volumes of nitrogen-rich manure, will rise too.

Secondly, in the past decade, we have greatly advanced our understanding of the global nitrogen cycle, and it has become clear that human addition of nitrogen to the environment is disrupting entire ecosystems across a wide geographical range. What have usually been considered as distinct problems – for example, eutrophication of surface waters, or acidification of lakes and forest soils – should be seen as symptoms of a more universal assault on the global environment.

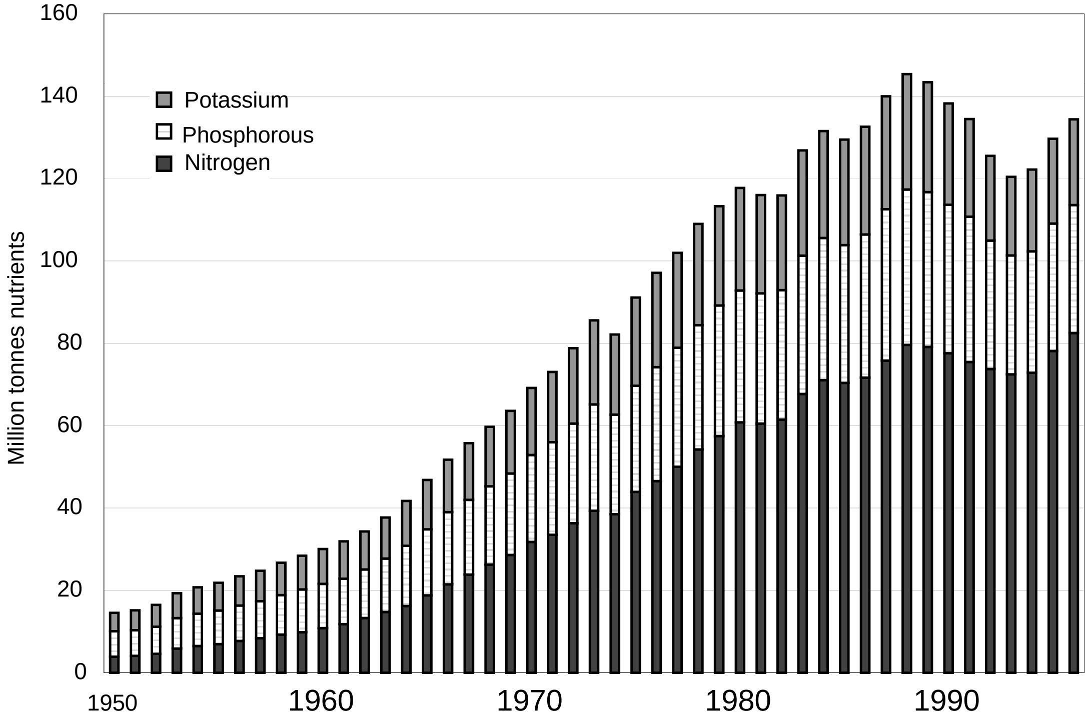
The global scale of nitrogen pollution is, at present, under-appreciated. Policy responses to the challenge of meeting future food needs without further unbalancing biological systems remain under-developed. There is a need for more long-term and coordinated thinking, and the closest analogy lies with the emergence of international efforts to manage the world's energy system and excessive emissions of carbon. Disruption of the global nitrogen cycle now appears to warrant the same degree of attention.

Trends in Nitrogen Fertilizer Use

Global consumption of fertilizer has risen spectacularly, increasing tenfold between 1950 and 1989 *(Figure 3).* The steep drop in consumption after that date was due principally to collapsing demand in the former Soviet Union, and Central and Eastern Europe, but there was also a substantial fall in Western Europe, caused by grain surpluses, low crop prices, and saturated markets. The increasing share of nitrogen in the global fertilizer mix becomes clear after about 1960, and the bias is most strongly pronounced in the developing countries, where nitrogen now accounts for 66 percent of fertilizers consumed, compared with 55 percent in the developed countries.[9]

The bias towards nitrogen fertilizers has been encouraged in part by increased production in areas where cheap natural gas is available (including major consuming regions such as South Asia and

Figure 3. Global Fertilizer Consumption, 1950/51-1996/97



Source: International Fertilizer Industry Association

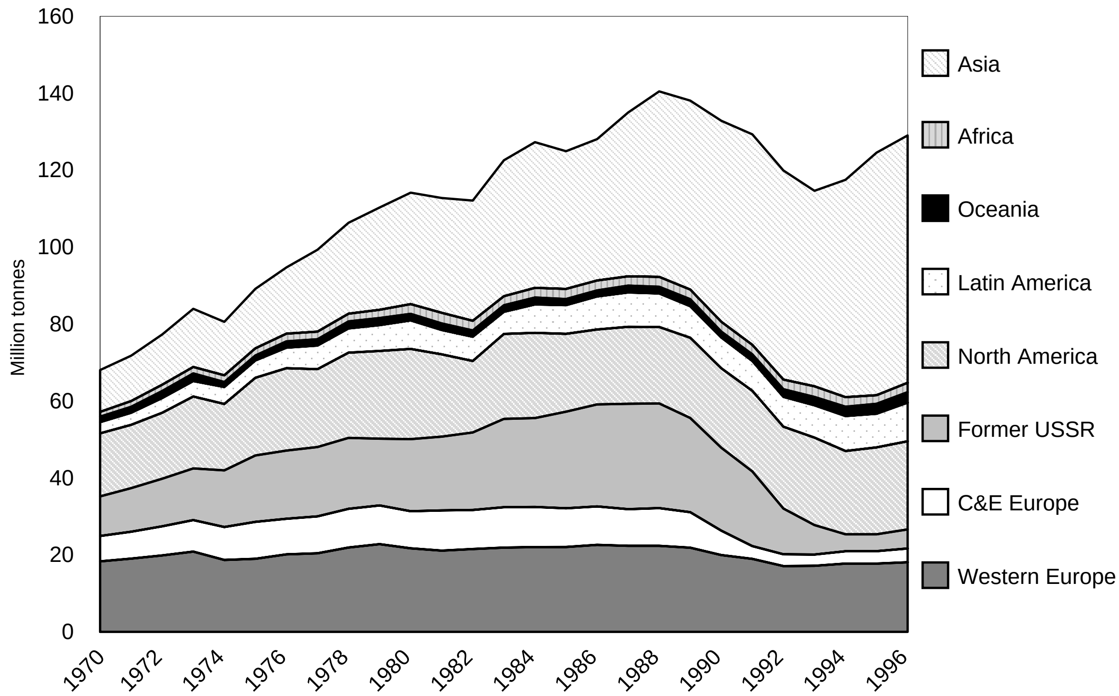
China) and in part by the perception that nitrogen delivers the most spectacular yield gains, at least initially.

The pattern of global fertilizer consumption has changed markedly over the past 30 to 40 years *(Figure 4)*. In 1960, the developing countries accounted for just 12 percent of all consumption; today the figure is nearly 60 percent. Fertilizer use in the developing world has been fuelled by rapid population growth and growing demand for food grains. This is especially true of Asia, where the scope for land expansion is limited. By contrast, the industrialized countries (with the exception of the former Soviet Union) increased their fertilizer consumption only marginally after 1980; population growth was low, most people were adequately fed, and world agricultural exports had stagnated due to economic problems in many importing countries. Asia is now the dominant player, accounting for 50 percent of world fertilizer consumption, and 86 percent of developing country consumption.

Fertilizer application rates vary widely among the major world regions and, perhaps surprisingly, are not strongly correlated either with national income or with need (as indicated by low soil fertility or food insecurity). Fertilizer use varies from a low of 10 kg/hectare in sub-Saharan Africa to a high of about 216 kg/hectare in East Asia (by nutrient weight). The world average application rate is about 83 kg/hectare; the developing countries as a whole just exceed this figure, and the developed countries as a whole fall just short of it.[10]

Fertilizer consumption has been strongly promoted in the industrialized countries and in Asia by investment in production capacity and a policy and fiscal framework encouraging liberal fertilizer use. Latin America has experienced wide fluctuations and modest overall growth, due to an unstable policy environment and economic crises throughout the 1980s. Production and consumption in sub-Saharan Africa remain very low, despite the urgent need to raise yields. Growth has been hindered by

Figure 4. Fertilizer Nutrient Consumption (NPK), 1970-1996



Source: International Fertilizer Industry Association

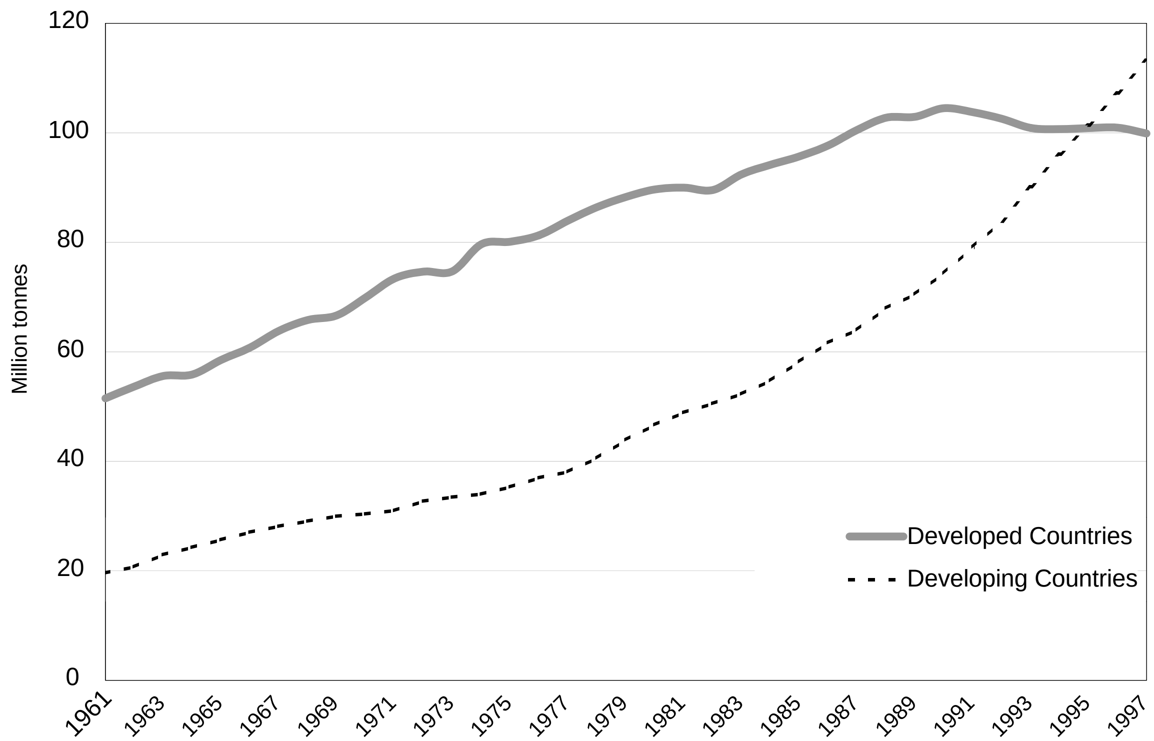
foreign exchange shortages, low crop prices, policy instability, and inadequate physical and institutional infrastructure. More than half the countries in the region are wholly dependent on fertilizer aid to meet their requirements.[11]

Livestock Farming

A second trend of key importance in the story of food consumption and the nitrogen cycle is the growing popularity of meat and dairy products in the human diet. With rising income, consumers choose to eat more meat; still greater affluence and concerns for a healthy lifestyle seem to encourage a shift from red meat to poultry. Meat production world-wide has tripled since 1961, reaching 213 million tonnes in 1997 *(Figure 5)*, with output gains concentrated in the United States, the European Union, and China. Individual consumption remains highest in the industrialized world. Average per capita meat consumption in the United States was 118 kg/year in 1996, while the average for the developed world as a whole was 76 kg/person/year. Average per capita consumption in the developing countries was 24 kg/year but the picture is rapidly changing in many parts of South America and Asia. For example, the Chinese each consumed 41 kg of meat in 1996, up from 20 kg/year just a decade earlier. Total meat consumption in the developing countries just exceeds that in the developed world and, in internationally traded meat and meat products, there is a small net inflow to the developing countries.[12]

To meet growing demand, the world's livestock population has boomed. Cattle numbers rose by 40 percent between 1961 and 1997, pigs by 130 percent and chickens by 246 percent. The world today is home to 13.5 billion chickens.[13] In industrialized countries, animals traditionally reared on rangelands or in farmyards are now increasingly concentrated in intensive feedlots, where they are fed on cereals and commercial preparations of grain, animal protein, and fish meal. This trend, in turn, is leading to the concentration of huge

Figure 5. World Meat Production, 1961-97



Source: FAOSTAT

volumes of manure, which cannot economically be redistributed back to areas where the cereals were originally grown. The nitrogen component of manure varies according to the animal and its diet but a crude global estimate is that approximately 32 million tonnes of nitrogen (derived from fodder crops and forage) are deposited into the environment via manure each year.[14]

Where animals are still free-ranging, manure may act as a fertilizer. Where animals are concentrated in feedlots, manure is increasingly viewed as a waste disposal problem. Data for the United States indicate that, of nearly 160 million tonnes of manure produced annually, some 60 percent is excreted directly onto pasture and cropland, while 40 percent is collected from animals in confinement and must somehow be disposed of.[15] Manure volumes have reached a critical point in parts of Northwestern Europe, where nitrogen deposition far exceeds the absorptive capacity of crops *(Table 1)*. Concentration of livestock in feedlots is not yet the norm in developing countries, though industrial-scale chicken farms are becoming more common, for example, in some South American countries.

3. "Fertilizing the Earth"

Great uncertainties are involved in measuring the global distribution and transport of nitrogen, how much is being stored, and where, because reactive nitrogen in its many forms is highly mobile, moving easily between terrestrial, freshwater and marine ecosystems, and the atmosphere *(Figure 6)*. But enough is known to be certain that human domination of the nitrogen cycle is responsible for serious pollution and disruption of biological processes which underpin – among other important functions – food production. Human activity is now fixing nitrogen (creating reactive nitrogen from non-reactive N_2 in the atmosphere) at least as fast as natural terrestrial processes *(Box 1)*. To some extent (which varies according to ecosystem characteristics) additional nitrogen can be utilized by plants and their productivity will be enhanced.

Table 1. Nitrogen (N) input from animal manure and fertilizer in selected countries

Country	Manure	N Supply Fertilizer	Total	N Uptake by crops	Residual N[2a]	Per hectare
		(1000 tonnes)				(kilogrammes)
Belgium[b]	380	199	580	211	369	240
Denmark	434	381	816	287	529	187
Netherlands	752	504	1,255	285	970	480

Source: Bumb and Baanante, see note 8
Notes: Totals may not add due to rounding.
[a]Because N is lost to the atmosphere, only a part of the residual N stays in the soil for possible nitrate leaching
[b]Includes Luxembourg

Beyond that point, excess nitrogen will accumulate in the environment, changing the chemistry of soils and often reducing their fertility, displacing grassland species, suffocating aquatic plants and fish, and touching off toxic algal blooms.

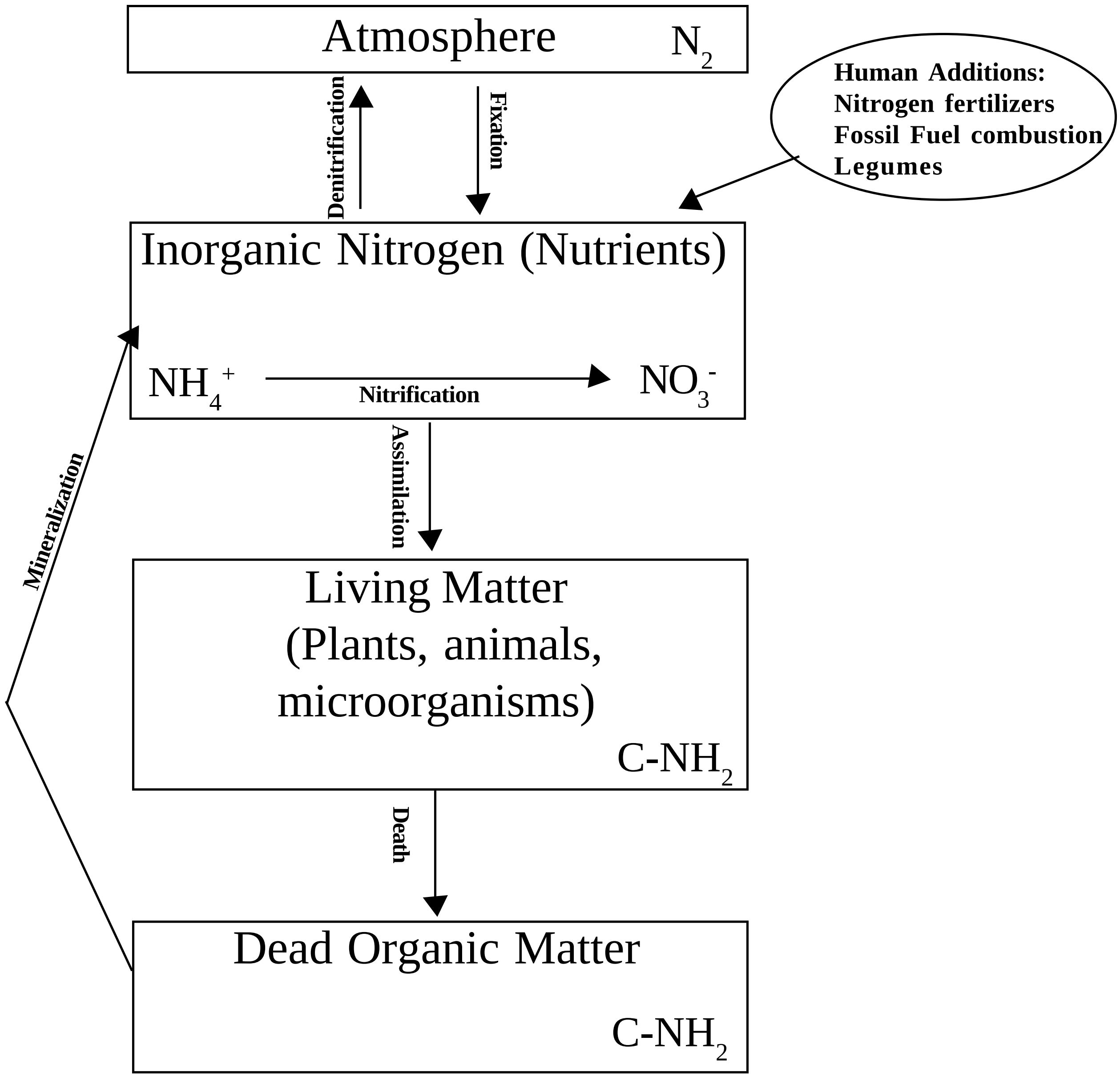
Forests, Soils and Grasslands

Increased deposition of nitrogen into the environment has two principal effects. Oxidized forms of nitrogen (NO_x and nitrates) acidify natural ecosystems and generally degrade them. For example, scientists now report that acid rain leaches forest soils of up to 50 percent of their calcium, potassium, and magnesium – crucial minerals which buffer or neutralize acids and are essential for plant growth. When soil chemistry is changed dramatically in this way, it is likely to take many decades for all the linked ecosystems to recover.[16] A related potential impact is toxification. Leached soils acidify and lose their ability to bind and sequester heavy metals, these metals are thus released for uptake by plants. Much of the “forest death” which struck Germany and other Central European countries in the 1970s may have been caused by aluminum poisoning. Toxics accumulated over decades may continue to be mobilized and leached into ground and surface waters, or taken up by plants and into the food chain.[17] The same applies in acidified lakes, where aluminum and other metallic ions which were formerly bound to soil particles can be mobilized.

In contrast, reduced forms of nitrogen (ammonium ions) fertilize whole ecosystems, increasing their net primary productivity but also disrupting them. Some forests in Europe are reported to be growing much faster in the second part of this century than they did in the first half.[18] The disturbing explanation appears to be that trees are absorbing nitrogen directly from the air into their leaves and bark. It is estimated that, in northern Europe, such above-ground uptake now accounts for 60 percent of the nitrogen found in broad-leaved trees. While the extra nitrogen increases growth, trees cannot regulate their intake as they can with nitrogen taken up via their roots; acidification of the soil also tends to leave them weak and vulnerable to insects and mildew.[19] Another consequence of over-fertilization is loss of species diversity, as nitrogen-responsive plants crowd out others with lower tolerance. In the Netherlands, intensive livestock production and high human population density have generated the highest nitrogen deposition rates in the world; the conversion of species-rich heathlands and pastures to species-poor grasslands and forests is well documented.[20] Similar trends have been reproduced on experimental grasslands in both the United Kingdom and the United States.

However, there is a limit to the amount of nitrogen which plants can absorb. At some point, other nutrients become the limiting factor, no more nitrogen can be taken up, and additional deposits are simply dispersed into surface or ground water and the atmosphere. This state is known as nitrogen saturation; it has already been reached across large areas of northern Europe, and to a lesser extent in

Figure 6. Simplified Version of the Terrestrial Nitrogen Cycle



Source: Adapted from Ann P. Kinzig and Robert H. Socolow, “Human Impacts on the Nitrogen Cycle,” *Physics Today*, November 1994, figure 4, pp. 24-31. Note based on Socolow, Robert, H., “Nitrogen Management and the Future of Food: Lessons from the Management of Energy and Carbon,” *Proceedings of the National Academy of Sciences*, forthcoming, 1999.

Note: Nitrogen is found in four forms. It is bound to itself in a two-atom molecule, *dinitrogen*, or N_2, which is abundant in the atmosphere but almost unavailable to life until broken down by specialized bacteria. Nitrogen is bound to carbon, as *organic nitrogen*, in a wide variety of organic molecules, critical to life and present long after death, including proteins and their component amino acids. And it is bound neither to itself nor to carbon, in *nitrogen nutrients* and *nitrogen gases*. The two principal nitrogen nutrients are ammonium (NH_4^+)and nitrate (NO_3^-) ions in water. The nitrogen gases include ammonia (NH_3) and various oxides of nitrogen, including nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O). A specialized vocabulary describes the transformations from one form to another. *Fixation* is the process of making atmospheric N into nitrogen nutrients, and *denitrification* is the process of rebuilding N from nitrogen nutrients. *Assimilation* is the process by which nutrients become organic nitrogen in living matter, and *mineralization* is the process by which organic nitrogen is decomposed, after death, back into nitrogen nutrients. Most of these processes occur in the soil but both air routes and water routes connect nutrient systems across large distances.

Box 1: How Humans Have Doubled the Rate of Nitrogen Fixation

Although nitrogen is the most abundant element in the atmosphere, it cannot be used by plants – and the animals that depend on them – until it is chemically transformed, or fixed, into ammonium or nitrate compounds that plants can metabolize. In natural systems, this function is performed by nitrogen-fixing bacteria in the soil and, to a much lesser extent, by lightning. Such biological nitrogen fixation is believed to provide somewhere between 90 and 140 million tonnes of nitrogen to terrestrial systems each year. Humans have wrought major changes over the last 50 years. The advent of intensive agriculture, increasing fossil fuel combustion, and the cultivation of leguminous crops and other nitrogen-fixing plants have led to huge additional quantities of nitrogen deposited into terrestrial and aquatic ecosystems and the atmosphere. It is estimated that human activities have more than doubled the amount of nitrogen available for uptake by plants. Land clearance, wetland drainage and burning of biomass also liberate nitrogen from long-term biological storage pools such as soil organic matter and tree trunks; these activities could emit up to another 70 million tonnes of nitrogen each year.

Anthropogenic Sources of Nitrogen	Annual Release of Fixed Nitrogen (million tonnes)
Fertilizer	80
Cultivation of legumes, rice etc.	40
Fossil fuel combustion	20
Total from human sources	**140**
Natural Sources of Nitrogen	
Soil bacteria, blue-green algae, lightning etc.	90-140

Source: Based on Peter M. Vitousek *et al.* "Human Alteration of the Global Nitrogen Cycle: Causes and Consequences," *Issues in Ecology,* No. 1 (1997), pp. 4-6.

northeastern USA. It is now known that a substantial portion of atmospheric nitrogen deposited in the former region moves directly from air, to land, to water, without ever being taken up by any living organisms or playing any role in biological systems.[21]

Freshwater Ecosystems

Fertilizer is the dominant source of nitrogen washed into the world's water courses, though domestic sewage is another important source (the human diet is rich in protein). Deposition from the atmosphere is another major source in some parts of the world *(Box 2).* An ironic aspect of intensive fertilization is that, on average, only half the additional nitrogen is taken up by plants, due to saturation, or local weather conditions, or because nitrogen is applied at an inappropriate point in the plants' growing cycle. As a result, nitrogen runs off the soil. It is either carried out in eroded soil, or leached out in the form of dissolved nitrate, carrying with it positively-charged minerals such as potassium and calcium. Much of the nitrogen is later denitrified by bacteria, that is, "unfixed" back into the atmosphere, while other nutrients are washed away. The net result is that nutrients can be "mined" from the soil, leaving it more impoverished than before.[22] Nitrogen run-off has doubled since pre-industrial times, which represents both a loss of nutrients and an economic loss to farmers.

Nitrogen concentrations in freshwater, so far, have been studied most intensively in industrialized countries. For example, a 1994 national survey in the United States revealed that nearly 40 percent of the country's lakes and rivers were too polluted for basic uses such as fishing or swimming; the leading source of pollution in both categories was agricultural run-off.[23] However, nitrogen is fast accumulating in developing countries too. In China, nitrate concentrations in the Yangtze River (Chiang Jiang) increased fourfold between 1963 and 1980, while concentrations of ammonium approximately doubled.[24] Much of this increase is attributable to the use of inorganic nitrogen fertilizers, which rose by a factor of about 12 over the period.[25]

Nitrogen run-off contributes to the phenomenon of eutrophication of freshwater lakes and rivers – essentially fertilization in the wrong place. Elevated loads of nutrients, chiefly nitrogen and phosphorous, stimulate abundant growth of algae and other aquatic plants. When the extra plant matter dies, it sinks to lower depths and decays, depleting the water's supply of dissolved oxygen, and killing other aquatic organisms such as deep-dwelling fish. The result is scum-covered, malodorous water, unfit for drinking or recreational activities. In many freshwater systems, phosphorous, not nitrogen, is the limiting growth factor. However, phosphorous is also supplied by agricultural fertilizers, as well as by industrial and household effluents. Eutrophication is increasingly well-documented world-wide, and is of particular concern where freshwater fish are an important source of local food. According to the FAO, some 18 percent of the global annual fish catch comes from freshwater sources (*see Chapter 3: Fish Consumption and Aquatic Ecosystems*).

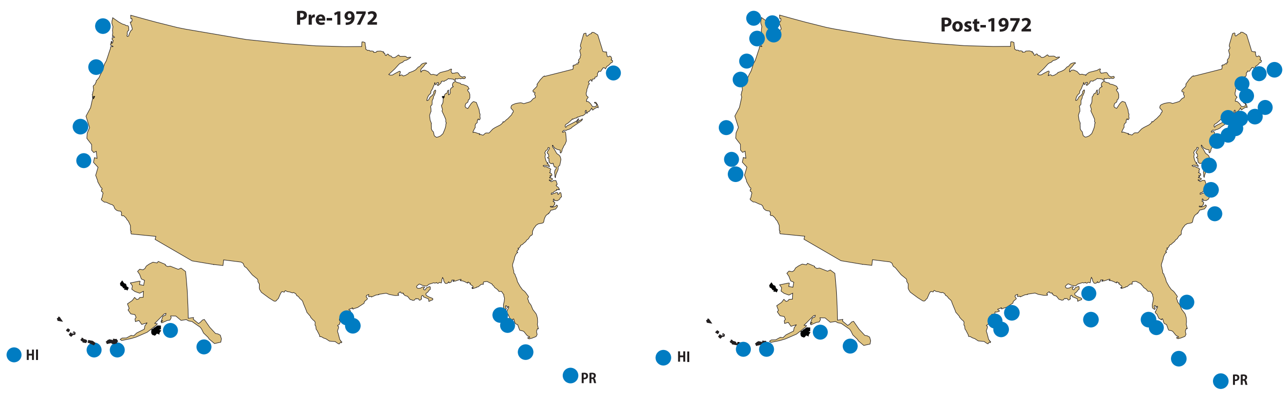
Nitrate contamination of drinking water supplies is widely recognized as a serious health threat. If exposed to high nitrate levels, young infants may develop the potentially fatal "blue-baby" syndrome, where their red blood cells cannot function properly, and fail to deliver sufficient oxygen. Adults risk contracting a variety of cancers, although the risks remain unclear. Levels of nitrates in drinking water have been closely monitored for many years in the industrialized countries, and the data confirm a historic rise in nitrogen levels in surface waters. In major rivers of the northeastern United States, nitrate concentrations have risen three- to tenfold since the beginning of the century. Nitrate contamination is also the USA's most widespread groundwater pollution problem; in a national survey, 22 percent of wells in US agricultural areas contained nitrate levels in excess of the federal limit.[26] Some communities in the worst affected States now provide free bottled drinking water to at-risk households (those with infants under six months and pregnant women) when local nitrate levels rise too high, and many are beginning to install costly purification systems.[27] Nitrates are a prime contaminant in Europe, where the European Commission has enacted a Directive establishing maximum permitted levels in drinking water and requiring costly purification or mitigation measures. In 1,000 lakes in Norway, nitrate levels doubled in less than a decade. Nitrate pollution is also widespread in Australia, and in parts of Africa, Asia, and the Middle East. No global assessment has been undertaken of nitrate pollution, but individual

Box 2: Nitrogen Deposition From the Atmosphere

World-wide, fossil fuel combustion emits more than 20 million tonnes of nitrogen (as NO_x) to the atmosphere every year. Less well known is the fact that agriculture contributes more than double this amount – some 47 million tonnes – to atmospheric emissions of nitrogen, through direct volatilization of ammonia from fertilized fields, biomass burning and animal wastes.[1] Nitrogen in various chemical states contributes to a number of environmental impacts in the atmosphere, including global warming, destruction of the stratospheric ozone layer and formation of ground level ozone (smog). Most reactive nitrogen in the atmosphere is short-lived, and is soon deposited back onto the oceans or, more seriously, into aquatic and terrestrial ecosystems. Increased nitrogen levels can both eutrophy *(see text)* and acidify. Acidification is a well documented phenomenon in Scandinavia, in Western Europe – where high fossil fuel combustion levels combine with intensive agriculture – and eastern North America. Acidification of soils, lakes and streams has caused extensive defoliation and dieback among trees, and is responsible for major fish kills. For example, studies in Norway reveal that areas with damage to fish stocks grew fivefold between 1960 and 1990; of 13,000 investigated fish stocks, 19 percent were completely lost.[2] While acid sulphur emissions in industrialized countries have been dramatically reduced over the past 30 years, fossil-fuel related NO_x emissions have remained relatively constant and agriculture-related emissions have risen. Ecosystems are not recovering as quickly as had been expected.[3] Acidification is now emerging as a major problem in the developing world, especially in parts of Asia and the Pacific region, where fossil fuel combustion and fertilizer applications are rising faster than anywhere in the world. Deposition is also increasing over Africa and South America, due to biomass burning.[4] The effects of rising nitrogen deposition are already being felt in the agriculture sector. For example, researchers in Pakistan found that crops growing in sites exposed to high ozone levels yielded between 32 and 62 percent less seed than control crops treated with a protective chemical.[5]

[1] Galloway, J.N. *et al.*, "Nitrogen Fixation: Anthropogenic Enhancement-Environmental Response," *Global Biogeochemical Cycles*, Vol. 9, No. 2.
[2] Norwegian Ministry of Environment, *State of the Environment Report 1995*. (MoE, Oslo, 1995).
[3] Likens, G.E., C.T. Driscoll and D.C. Buso, "Long-Term Effects of Acid Rain: Response and Recovery of a Forest Ecosystem," *Science*, Vol. 272, 12 April 1996, pp. 244-245.
[4] Galloway, James N., "Anthropogenic Mobilization of Sulphur and Nitrogen: Immediate and Delayed Consequences," *Annual Review of Energy and the Environment*, 1996. 21: pp. 273-274.
[5] "Rampant Urban Pollution Blights Asia's Crops," *New Scientist*, 14 June, 1997.

Figure 7. Major or Recurring Harmful Algal Blooms, Before and After 1972



Source: Donald Anderson, "Expansion of HAB Problems in the U.S.," National Office for Marine Biotoxins and Harmful Algal Blooms, Woods Hole Oceanographic Institution.

country reports indicate that nitrates are now one of the most common chemical contaminants found in drinking water.

Marine Ecosystems

Eutrophication of estuarine and coastal zones has emerged as an immense and growing problem in recent years. Over 40 million tonnes of nitrogen, in dissolved and particulate form, are transported by the world's rivers into estuaries and coastal waters each year – double the pre-industrial rate.[28] Unlike freshwater systems, where phosphorous is usually the limiting growth factor, nitrogen is usually the limiting growth factor in saline waters. Additional nitrogen can therefore promote huge algal blooms and significant oxygen depletion (hypoxia) in lower-depth waters. Some of the best-documented examples of coastal eutrophication come from the United States. According to a recent survey, 52 percent of the nation's estuaries suffer from some degree of oxygen depletion.[29] The worst affected area is the Gulf of Mexico, where 85 percent of estuaries are affected. In the most dramatic example, a so-called "dead zone" of 16,000-18,000 km^2 has developed where the Mississippi River discharges into the Gulf. Fish and shrimp have disappeared from the area, threatening the local fishing industry, while less mobile life-forms, such as starfish and clams, have died. Scientists have linked the growth of the dead zone to nitrogen fertilizers and livestock manure from farms hundreds of miles upstream. More than half the 11 million tonnes of nitrogen added to the Mississippi Basin annually comes from fertilizer, and only about 50 percent is taken up by plants. Nearly 2 million tonnes of nitrogen flow down the Mississippi each year, more than triple the amount 40 years ago[30] and the dead zone has ebbed and flowed consistently with peak river discharges and the associated nutrient flux.

The Mississippi dead zone is one of more than 50 similar oxygen-starved coastal regions which now exist world-wide, a threefold increase over the past 30 years.[31] Figure 7 illustrates the increase for the United States. Since coastal zones are among the world's richest fishing grounds, unchecked agricultural run-off poses a serious threat to commercially important fish stocks. Nitrogen pollution is blamed in part for the collapse of the Baltic Sea cod fisheries in the early 1990s,[32] as well as major fish kills (and associated human illness) following outbreaks of *Pfiesteria*, such as that affecting the Chesapeake Bay, in the United States, in the summer of 1997. Toxic algal blooms, known as "red tides" or "brown tides" are growing world-wide in frequency and severity, damaging offshore fisheries and causing losses to aquaculture enterprises.[33]

Conclusions

It is fair to say that, for the past 30-40 years, humans have been "fertilizing the earth" in a global-scale and largely uncontrolled experiment. Agriculture, through the use of nitrogen fertilizers, cultivation of leguminous crops, and deposition of animal wastes, is the leading contributor to a doubling of natural nitrogen levels in the environment. Local and regional impacts, particularly acidification and eutrophication, have been intensively studied. However, the truly global consequences of the environmental imbalances that are being set in motion currently receive scant attention; far less than the risks attending climate change, for example. Yet, if current trends continue, all these nitrogen-related problems are likely to worsen, with consequences as severe and potentially more immediate than those associated with global warming.

4. Looking Ahead: Growing the Food We Need

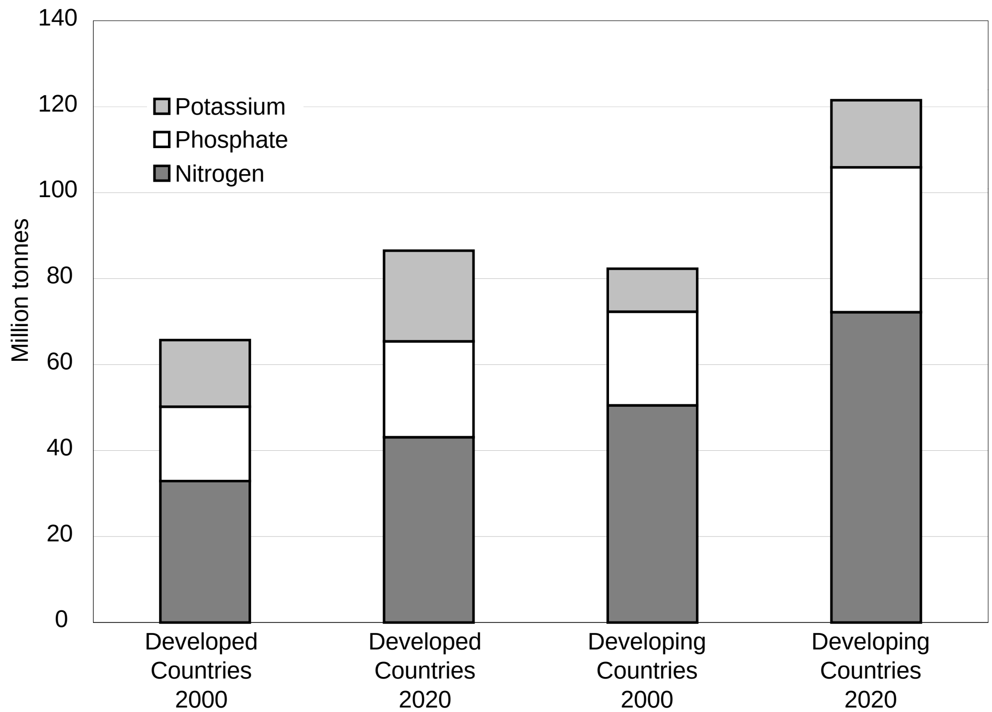
The world's population is projected to grow to about 7.3 billion by 2020, with over 90 percent of the increase occurring in developing countries.[34] More people will eat more food, and more protein since, as already described, people almost invariably choose diets which are richer in meat and dairy products as their incomes rise. This will require more cereal to be grown per capita: nearly 40 percent of total grain production is already fed to livestock[35] and the grain-to-protein conversion efficiency is low, lying between 2:1 (chickens) and 7:1 (feedlot cattle).[36] The International Food Policy Research Institute has recently projected that global demand for cereals will increase by 41 percent between 1993 and 2020, and that meat demand will rise 63 percent to 306 million tonnes.[37]

Most projections of agricultural output assume that demand for food will be met, at least at the global level, though regional and local shortages are likely to persist. A scenario developed by the Stockholm Environment Institute forecasts cereal production of just over 3 billion tonnes in 2025,[38] while the FAO has produced a shorter-term production forecast of 2.3 billion tonnes in 2010.[39] Given current production of just under 2 billion tonnes, these and other estimates indicate that production increases of up to 50 percent will be required over the next 25-30 years. How will this be achieved?

The scope for expansion of the agricultural land base is limited. Potentially fertile land still exists to be opened up for cultivation, but gains will be partially offset by the loss of productive land to soil erosion, degradation, and urban development. The FAO suggests that an additional 90 million hectares of land might be brought into production by 2010, mostly in South America and Africa, which amounts to a modest increase of barely 6 percent on today's cropland area. This alone will not be enough to offset the present trends under which both available cultivated land area and grain harvest on a per capita basis are declining sharply. In 1984, the grain harvest per person peaked at 346 kg; by 1995 it had fallen to 295 kg, the lowest level since 1967.[40] Given circumstances of a rising population, a growing appetite for meat and dairy foods, a static or declining cropland base and declining per capita cereal production, the imperative of increasing yields becomes clear.

Agricultural science has, to date, relied on three means of achieving higher yields: genetic improvements of crops, advances in agronomic practices, and synergies between the two. As an example of genetic improvement, plants have been bred to raise the share of photosynthetic product going to the seed, rather than to leaves, stems or roots. Today's wheat, rice, and corn have a "harvest index" of about 50 per cent, compared with 20 percent before improvement. Further gains appear limited, since scientists believe the theoretical maximum for photosynthetic redistribution to the seed is about 60 per cent.[41] Agronomic practices have focused on increased levels of external inputs, chiefly fertilizers, but also pest and weed control agents, and water, delivered by irrigation. Synergies have occurred, for example, new dwarf varieties of cereal, with short stalks, are able to utilize two or three times the "normal" amount of nitrogen and develop rich, heavy heads of grain without collapsing. This synergy explains the doubling and tripling of yields achieved during the first phases of the Green Revolution.

Figure 8. Fertilizer Demand Projections (NPK), 2000 and 2020



Source: Bumb and Baanante, see note 8

However, scientists have not found it possible to maintain this momentum, and the rate of yield growth in all major cereals has either plateaued or declined over the past decade. It is often argued that increased fertilizer application in the developing world will overcome yield stagnation and raise harvests closer to the theoretical maximum. More fertilizer will certainly be part of the answer, but inherent environmental constraints, especially water scarcity, as well as infrastructural and institutional shortcomings, are likely to prove a greater obstacle to the world-wide advent of "industrial" farming, with its dependence on external inputs.

5. How Much More Fertilizer Will the World Consume?

Analysts at the International Fertilizer Development Center (IFDC) have made detailed projections of future fertilizer demand, and come to a problematic conclusion. Their "real world" projection takes into account various economic and non-economic variables, such as foreign exchange availability, crop and fertilizer prices, the development of irrigation and other infrastructure, and the impact of policy reforms. On this basis, global consumption of fertilizer is projected to rise from 134 million tonnes today to 208 million tonnes in 2020 *(Figure 8*). The strongest growth is expected in Africa (2.4 percent annually), Latin America (2.2 percent annually), Asia (1.8 percent annually) and Central and Eastern Europe (2.2 percent annually). These rates of increase are far below those experienced between 1960 and 1990, reflecting a higher baseline, and changed economic and policy environments. Nitrogen consumption would rise from 82 million tonnes to 115 million tonnes, an increase of about 40 per cent. This projection is comparable with another recent estimate of 134 million tonnes, which assumes higher growth rates in Africa and Latin America.[42]

This substantial increase might not be enough, however. The IFDC's second projection is based on food production needs, that is, the amount of fertilizer needed to grow 2.5 billion tonnes of cereal or more. This leads to global fertilizer consumption in 2020 of 263 million tonnes, and nitrogen consumption of some 160 million tonnes (assuming today's NPK ratio does not change). The fertilizer "shortfall" in developing countries might be as much as 64 million tonnes. A third projection is based on "sustainable farming" needs, or the amount of fertilizer needed to maintain nutrient reserves in the soil at their initial levels. The projection is based on assumptions about nutrient uptake efficiency for various crops, expected improvements by the year 2020 in different world regions and the proportion of crop residues which are returned to the soil. Under this scenario, producing enough grain to feed the world, without mining the soil of its nutrients, would require application of 366 million tonnes of fertilizer; the proportion of nitrogen would probably decrease but would still be substantial. The fertilizer shortfall in developing countries is estimated at 130 million tonnes.[43]

6. Possible Solutions

Globally, fertilizer consumption must grow, but it must grow in a far more managed and thoughtful way than it has over the past 40 years. The objective of agriculture in coming decades must be to optimize soil productivity while preserving its capacity to function as a healthy, complex ecosystem. Fertilizer consumption will remain essential to food security in coming decades, but disruption of terrestrial and marine ecosystems could be greatly reduced if greater efforts are made to control the flows of nitrogen through the environment. On the production side, inorganic fertilizers should be priced and regulated more in accordance with their environmental impacts (removal of perverse incentives) and used more efficiently (innovative and integrated farming practices, new crops, nitrogen recycling). On the consumption side, the choices we make about diet and the sources of food we buy could, over time, help to reorient the world's food industry to a less nitrogen-intensive base.

Economic and Regulatory Incentives

Fertilizer use by farmers is too often typified by wasteful and careless practices, which are encouraged by artificially low product prices. Fertilizers receive heavy subsidies from governments worldwide, whether at the point of import, or manufacture, or supply to farmers. They are justified by governments on the grounds of protecting domestic producers, shielding manufacturing interests from competition, or ensuring national food security. Subsidies have often worked "too well." Many areas in the industrialized countries, and some parts of Asia, have already reached the point of diminishing returns on fertilizer application, where plants are unable to take up the additional nutrients they are given and ecosystems become saturated and degraded. Over-applying fertilizer represents both an economic and an environmental waste. Recent research has shown that using reduced amounts of fertilizer at just the right time can cut costs by up to 17 percent for farmers in developing countries, as well as reducing nutrient losses to the environment by up to 50 percent.[44] At the national level, subsidies constitute a heavy burden on the economy. For example, in India, fertilizer subsidies amounted to US$1.4 billion, or 3 percent of the national budget, in 1993-94.[45] Low fertilizer prices also tend to inhibit the development of production capacity and of competitive marketing and distribution systems, which works against the interests of farmers, and to reduce research interest and investment in alternative plant nutrient systems.

With the implementation of economic reform programs in the 1980s, the number of countries subsidizing fertilizers decreased significantly, but not uniformly. As of 1996, China, India, Indonesia, and Saudi Arabia still provided subsidies, for example, while Ghana, the Philippines, Thailand, and Venezuela did not.[46] Experience with energy policy has shown clearly that pricing policies which begin to incorporate environmental damage into the cost of fossil fuels are effective in encouraging more efficient use and the adoption of alternative energy sources. The same is true of fertilizers. The adjustment of distorted input prices to market level can be painful and politically sensitive, however, and high fertilizer prices can discourage fertilizer use altogether, with damaging consequences for food security. Rational pricing policy must aim to eliminate price distortions over the long term, while continuing to generate adequate incentives for fertilizer use by small farmers. Currently, however, policy in many countries seems to be directed towards increasing fertilizer application as fast as possible. The Chinese Academy of Agricultural Sciences, for example, has estimated that the country must raise average crop yields per hectare by 60 to 80 percent within the next 30 years, and that this will require a doubling of current nitrogen application rates.[47] Rather than pursuing unfettered growth, policies in countries which already tend to over-fertilize should be aiming to optimize agricultural production through incentives for responsible nitrogen management.

Direct regulation is increasingly being used to alter farmers' behavior in order to reduce environmental damage which has already occurred. It should be no surprise that nitrogen-related policy in the industrialized countries is beginning to develop along similar lines to carbon controls, involving emission ceilings, performance requirements, and incentives/penalties levied on users. Vigorous efforts are now being made in some countries in an attempt to reverse the nitrogen saturation afflicting intensively farmed land. The nitrogen fertilizer management plan of Minnesota, in the United States, recommends that a nitrogen budget based on the residual nitrogen in the soil, crop uptake, and supply of nitrogen from all sources should be prepared to develop more sustainable fertilizer recommendations.[48] In northwestern Europe, the problem, and controlling actions, are still more advanced. The European Union Nitrates Directive of 1991 (effective from 1999) is framed to control the net supply of nitrogen (supply minus uptake) to the soil. Planning authorities must take account of emissions from all sources, when recommending fertilizer application levels. It has become clear that the biggest adjustments must, in fact, come from the livestock sector; nitrogen emissions from animal manure exceed those from fertilizer by 14 to 91 percent in Belgium, Denmark, and the Netherlands.[49] Some individual countries in the region have gone further, introducing mandatory nutrient accounting schemes under which farmers must prepare fertilization plans, based on crop, nutrient input and output levels, and admissible losses. Fertilization above the agreed level is subject to heavy fines (Germany) or nutrient taxes (the Netherlands). In Denmark, the amount of fertilizer that may be applied to each crop is regulated, and 65 percent of the cultivated area must be covered by a green crop in winter to reduce leaching and run-off.

Efficient Nitrogen Management on the Farm

The efficiency of nitrogen fertilizer use today is very low. The proportion of nitrogen taken up by plants varies widely with crop, climate conditions, and agricultural practices, but field trials at experimental stations indicate plant uptake levels of 50 to 70 percent during the fertilizer application season.[50] On farms, nitrogen losses can be much greater. Numerous studies indicate that nitrogen loss rates of between 20 and 50 percent are still common in the industrialized countries, while nitrogen uptake by crops in Indian and Chinese rice paddies has been measured at 25 to 30 percent, principally because of rapid losses to run-off, erosion or gaseous emissions. Such wastage represent a substantial economic loss, as well as an environmental hazard. Given that over 80 million tonnes of nitrogen were applied to fields in 1996, a (conservative) 50 percent loss at a wholesale price of US$0.66 per kg of nitrogen in urea, amounts to US$26.4 billion.

Improved on-farm practices can significantly reduce nitrogen pollution. Fertilizer use efficiency has been improving in some developed countries, where farmers are being encouraged to plant cover crops in winter, avoid poor cropping practices, and plant "buffer" vegetation between fields and water courses to trap nitrogen run-off. In the United States, for example, corn production per kg of nitrogen applied increased from 18 kg in 1985 to 22 kg in 1995.[51] Precision "drilling" application of fertilizers is increasingly practised. Similar improvements have been achieved in western Europe, where agricultural production has continued to increase despite reductions in fertilizer use. Further improvements might be expected from more widespread adoption of slow-release fertilizers and urease inhibitors which can reduce the leaching of nitrate and/or emissions of nitrous oxide and losses of ammonia through volatilization. Currently, use of these products is inhibited by low prices for conventional fertilizers. Synthetic slow-release fertilizers are inherently more expensive to manufacture and only about half a million tonnes are applied annually world-wide, mostly to high-value crops and in non-agricultural sectors such as golf courses and gardens. Fiscal instruments which reduce the price differential between slow-release and conventional fertilizers could speed market penetration by the more efficient product.

In the longer-term, a significant contribution to improved nitrogen management would seem possible with new crop varieties and changes in the global balance of crops cultivated. Bio-engineered crops such as wheat and corn which can fix their own nitrogen could reduce the need for fertilizer application. More research is needed to understand the potential benefits and drawbacks of cultivating leguminous plants such as alfalfa and soybeans. Currently, legume planting world-wide adds about 40 million tonnes to the total amount of nitrogen fixed annually. Legumes are “free” natural fertilizers and their introduction into crop rotations, and ploughing of residues back into the soil, if more widespread, could assist in maintaining soil structure and fertility. Integrated farming practices, which seek to maximise soil fertility and stable yield gains through crop diversity and adaptability to local conditions will also have a role to play in reducing dependence on high levels of fertilizer application.

In many developing countries, fertilizer application levels at present are too low to cause significant eutrophication or acidification damage and a different policy approach is required. However, while nitrogen saturation might seem a far distant prospect in most of Africa and South America, tropical soils are fragile – often thin and light – and nitrogen is more readily lost to run-off or volatilization to the atmosphere. The potential for losses and environmental damage is therefore high and the agronomically optimum level of application may be lower than in temperate regions.

A priority area of attention should be the correction of unbalanced fertilization. Most fertilizers used in the developing world are nitrogen-based, because of their low cost per unit of nutrient and the quick and evident response of the plant. However, increased yields deplete the soil of other major and micro-nutrients which are removed with the harvested crop. These nutrients become deficient unless they are replenished. Excessive nitrogen applications, relative to potassium and phosphates, can lead to nutrient “mining” and loss of soil fertility. In many countries, especially in sub-Saharan Africa, nutrient removal already exceeds nutrient replacement by a factor of three or four.[52] Yields can also be reduced due to “lodging” (where the crop is unable to support its own weight), and greater competition from weeds and pest attacks. In much of Asia, rice yield losses of between 20 and 50 percent have been recorded as a result of disproportionate applications of nitrogen.[53] Significant yield increases could thus be achieved through the encouragement of inorganic fertilizers which provide a more balanced mix of nitrogen, phosphates, and potassium.

In many developing areas, however, lack of access to capital, lack of roads and rail links which could ensure timely delivery of fertilizers, and inadequate information, are likely to mean that soils continue to be gravely under-fertilized. The concept of managing a global nitrogen cycle helps to illuminate the fact that intensive agriculture and high protein diets are tending to concentrate nitrogen in some parts of the world, while impoverished farmers, without fertilizers, burning their crop residues and animal wastes for fuel, see their soil nutrients disappearing. The trend is accelerated by the growth of international trade in food, especially grains, which redistributes nitrogen from net producer to net consumer countries.

Economic development and poverty alleviation are the best long-term redress. In the shorter-term, internationally-funded research efforts into alternative methods of plant nutrition and support for traditional agricultural practices which help to maintain soil would be well repaid in terms of enhanced food security, reduced financial losses, and avoided environmental damage. Complementary measures include greater use of organic fertilizers (animal manure, human wastes, crop residues), applications of lime on the acid soils which are typical of tropical regions, alternating the growth of shallow-rooted and deep-rooted plants to hold nitrogen in the soil, and the use of crop rotations incorporating leguminous plants. Integrated plant nutrition systems (IPNSs) could prove important in effective management of plant nutrients as an element of broader agricultural development. IPNSs are designed to balance the nutrients available to the farmer from all available sources for their optimal productive use, and to minimize “leakage” of minerals into the wider environment.[54] Systems are tailored to meet the needs of specific farming types, yield targets, the physical resource base, and the farmer’s socio-economic background. Implementing such systems would involve a formidable improvement in average levels of service to low-income farmers, in terms of technical advice, inputs, credit, marketing facilities, and public investment in agriculture.

The Role of Consumers

The scope for consumer action initially appears limited in comparison with that of farmers. Nevertheless, three areas of behavior appear especially amenable to some change, and evidence of change is already underway in many industrialized countries. Dietary preferences in the wealthy countries are again shifting, as consumers’ concern with healthy eating encourages lower red meat consumption. In the United States, for example, per capita consumption of beef fell from a high of 89 pounds per year in 1976 to 65 pounds per year in 1996.[55] However, this was more than offset by increased poultry consumption. Interest in environmental and animal welfare issues is also encouraging vegetarianism, which is no longer the eccentric lifestyle choice it was a generation ago. According to a recent poll, 5 percent of Americans eat no red meat and about 1 percent eat no meat, poultry or fish at all.[56] Some European figures are higher: over 6 percent of British consumers claim to be vegetarian, as do over 4 percent of the Dutch.[57] Evidence that the trend is strengthening can be found in the increased range of vegetarian foods stocked by mainstream supermarkets and the wider choice of vegetarian meals offered in non-vegetarian restaurants. The minority trends towards reduced meat consumption, and the selection of meat produced under extensive conditions, could be reinforced with information highlighting the environmental impacts associated with intensive livestock farming. Perhaps more effectively, higher prices for fertilizers, and emission charges on feedlot operations would translate into higher meat prices and encourage still greater selectivity.

Consumers can also contribute substantially to “closing the open loop” which currently allows nitrogen to be deposited on the land, washed into water courses and flushed out to sea. A number of governments, at the local and national levels, have now introduced voluntary or mandatory recycling schemes for organic (kitchen and garden) wastes, whereby organic material is composted and returned as fertilizer to agricultural land rather than being landfilled. Households should also be encouraged to compost their own waste where feasible. Finally, the use of fertilizers on household lawns represents a small but significant contribution to nitrogen in urban run-off, which could be discouraged by information campaigns and product taxes.

Notes

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5. Food and Agriculture Organization of the United Nations, "Food, Agriculture and Food Security: Developments Since the World Food Conference and Prospects," World Food Summit: *Technical Background Documents*, Vol. 1, Paper 1 (FAO, Rome, 1996). p. viii.

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