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Agricultural Productivity, Sustainability, and Fertilizer Use

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Agricultural Productivity, Sustainability, and Fertilizer Use

Introduction

The "bountiful earth," "fruitful land," "rich soil,"—such terms must have been used from prehistoric times as farmers sought to grow sufficient food for their families through describing patches of land which they could crop.

Cropping, by its very nature, means getting more from the land than is put into it.

Most of the substance of plants comes from the sun, the atmosphere, and water, but a small percentage, the essential mineral content of plants, comes from the soil. Unless the mineral matter is returned to the cropped soil, agricultural production is not sustainable.

This latter fact has led to the development of the world's fertilizer industry, which now plays an essential role in feeding the world—unfortunately, some people would say that fertilizer is also poisoning the world, while many others are disquieted by their intensive use. A good world citizen is an informed citizen—this paper is intended to act as an initial source of information on the benefits and problems associated with fertilizer use.

Definitions

The following definitions are given because in discussions on currently emotive issues such as the use of fertilizers it is essential that technical and nontechnical people understand exactly what each is saying.

Agricultural Inputs

The productivity of settled agriculture is based on overcoming the diverse and often serious constraints to crop establishment and growth imposed by the soil and climate. The growth-reducing effects of pests and diseases (animals, weeds, insects, and microorganisms) must also be controlled and the final harvest preserved. All of these activities take energy in the form of physical, chemical, and biological inputs as follows:

Physical Inputs

Physical inputs (manual, animals, and machines) are used primarily to improve soil tilth needed to seed and establish the crop, manage soil water levels, suppress weed growth, and harvest the crop. Mechanized agriculture is heavily dependent on fossil fuel.

Chemical Inputs

Chemical inputs include fertilizers and a whole range of biocides (herbicides, insecticides, etc.).[1] Current production technologies are largely based on fossil fuels; in this class, nitrogenous fertilizers are the major user of natural gas energy.

Biological Inputs

Biological inputs are essentially based on the manipulation of existing biological resources to increase and stabilize yields by crop and cultivar selection, integrated pest management, and use of biological nitrogen fixation (BNF) to provide nutrient nitrogen for crop growth. The recycling of crop and animal residues to improve soil structure and increase soil organic matter levels also falls into the category of biological inputs as do modern biotechnological advances.

Soil Fertility

A fertile soil is defined as one capable of producing abundant vegetation (Oxford English Dictionary) or as one capable of sustaining abundant and vigorous vegetation (Webster's Dictionary).

1. *Fertilizers* supplement the soil levels of those inorganic ions that already exist naturally in soils and that are needed by plants for healthy growth. *Biocides* are often selective poisons based on complex and unique organic molecules. The very different role and nature of these two classes of chemical inputs must be clearly understood when the term chemical inputs is used.

In contrast, soil scientists have defined soil fertility only on the basis of plant nutrient levels in the soil and have reserved the term *soil productivity* for the dictionary definition of soil fertility (Brady, 1984).

Fertilizers

Fertilizers have traditionally been defined as any organic or inorganic material of natural or synthetic origin added to a soil to supply certain elements essential to the growth of plants (Brady, 1984). With this broad definition, it is usual to refer to the commercial fertilizer products of industry as "fertilizer" and the remainder as organic fertilizers. For the purist, urea is an industrially produced organic material; in practice, however, urea is classified along with ammonium nitrate, anhydrous ammonia, etc., as a fertilizer. Many of the so-called organic fertilizers of commerce are organic materials reinforced with commercial fertilizers.

This article discusses specifically the role of commercial industrial fertilizers and uses the term fertilizer to describe those materials; the term organic fertilizers is used for the nonmineral waste products used by farmers.

Sustainable Agriculture

In its broadest sense, *sustainable agriculture* means just that, an agriculture which will maintain its level of productivity for long periods. However, the term is currently used variously to cover a whole spectrum of ideas from, at the one end, an agriculture based solely on organic matter recycling and the natural control of pests and disease, through low-input farming (fertilizers, pesticides, and energy), to modern intensive farming using careful environmental monitoring to eliminate or at least reduce environmental effects, particularly as they relate to the nitrate contamination of groundwater, the use of biocides, and the health of the food consumer.

Low-Input Sustainable Agriculture (LISA)

The term "low-input sustainable agriculture" has gained wide, public recognition from its acronym LISA, a program launched by USDA, with the goal of reducing the level of inputs used in intensive agricultural production to a level that would sustain production without causing environmental damage.

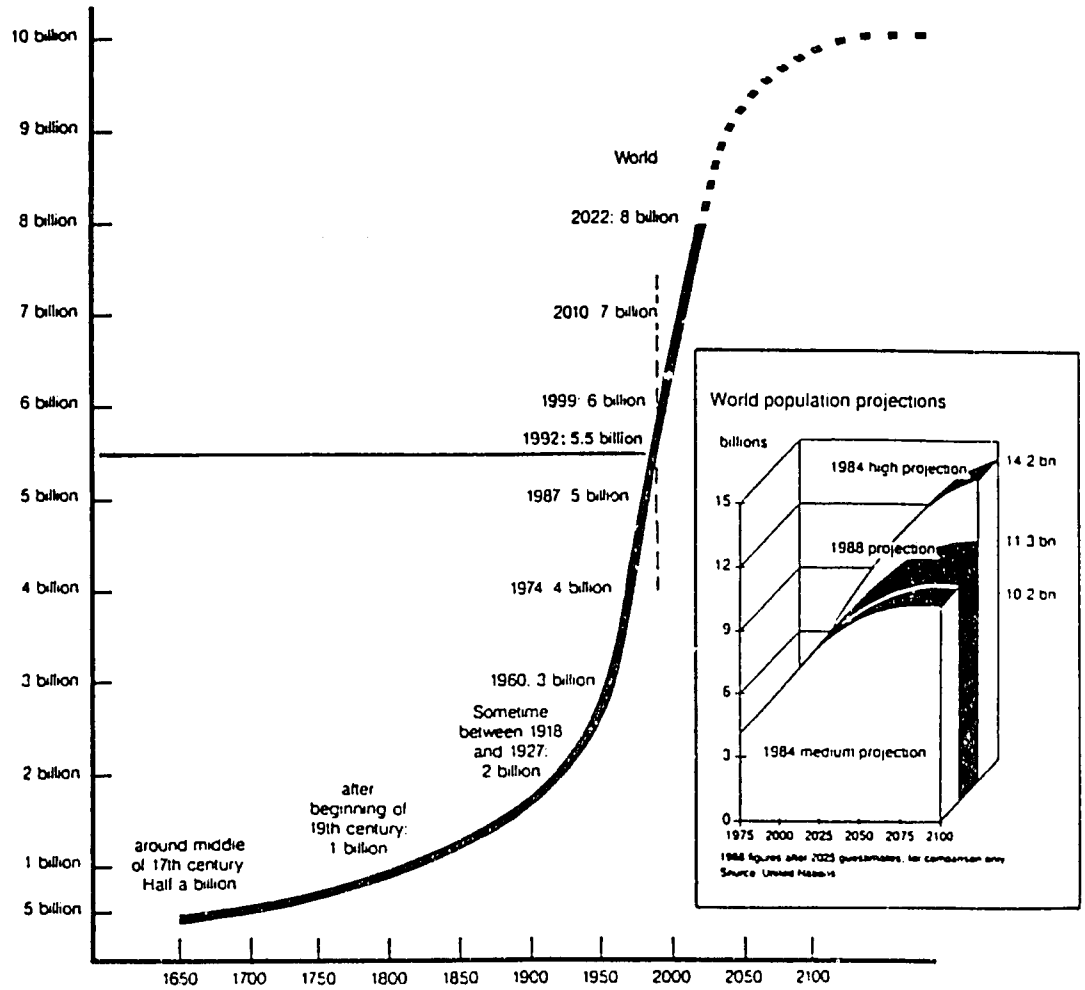
Needs Versus Resources

Historically, the small farmers of the world have taken amazing steps in selecting crops and varieties and cropping systems to fit their particular ecosystems. A good example is the existence of cropping systems using traditional varieties of rice that are season and period fixed and that, in the case of deep water rice, exhibit facultative elongation: Selection of such characteristics would have meant a Nobel Prize for a modern scientist.

The relatively rapid spread of maize and cassava in Africa and of the potato in Europe, all of which were imported from Latin America, illustrates the constant search for newer and better crops and cropping practices and the ready adoption of useful technologies by the farming community even in the absence of formalized research and extension activities. The search for means of safeguarding and improving the soil resource base has also been the historical goal of many farmers. Well-developed crop residue recycling systems, with or without an animal component, were developed in Europe and Asia in areas of high population density, and on all the continents long-term rotations and the use of wood ash, cattle manure, and leguminous crops were features of farming in many areas. All these systems, which are rich in their variability, developed as a response of the farmer to the decline in soil fertility caused by cropping and also because of the farmer's sense of stewardship (intergenerational responsibility).

The world has a finite land surface of which only about one-fifth is suitable for agricultural production. Unfortunately, population pressure has caused and continues to cause the collapse of many agricultural production systems that were sustainable when population pressures were low, with consequent severe damage to the soil resource base. Until the age of enlightenment, world population had grown only very slowly, with the average woman bringing only two to three children to adulthood. This all changed dramatically in the 19th and 20th centuries as population growth rates, due to improved survival, became geometrical (Figure 1). This situation was seen by Malthus as a portent of disaster, whereas Liebig (1840) took it as a scientific challenge to increase crop yields.

Each seed, plant, root, leaf, and piece of meat eaten by human beings contains mineral nutrients removed from the soil. Liebig demonstrated that these mineral nutrients were the key to plant growth and that unless these mineral nutrients are returned to the soil from which they



Source: United Nations Population Fund, 1992.

Figure 1. Growth of World Population.

came, that soil is in negative nutrient balance and agricultural production is not sustainable thereon. Liebig measured the amounts of plant nutrients removed from the soil by various crops and devised mixtures of salts to return to the soil both for replenishment of its fertility and to make up for already existing plant nutrient deficiencies. This idea of Liebig's led directly to modern soil fertility management techniques using fertilizer. Liebig was in error in some of his thinking, but his work in association with the relatively recent developments in plant breeding has postponed Malthus' apocalypse, albeit on a temporary basis.

The quantities of plant nutrients removed from a unit area of soil by modern agricultural systems, as indicated in Table 1, underscore the correctness of Liebig's general thesis.

Wheeler (1990) has pointed out that the most important single action that can be taken to reduce hunger is to support strategies in developing countries to increase agricultural production and increase incomes in rural areas. Both of these strategies are dependent on the rational use of fertilizer inputs for their success because the time is too short and the fertile land resources too scarce for other technologies to be used.

The energy components of agricultural production, including nitrogen fertilizer manufacture, are currently based on fossil fuel; although these components are amenable to major technological advances, the ability to exploit this potential is strictly limited at the present time. Global deposits of phosphate, potassium, and the other mineral nutrients needed for crop production are certainly adequate; however, the increasing need to use low-grade deposits will increase costs.

The Soil Resource

It is generally perceived that the soil, through its various physical, chemical, and biological processes,

Table 1. Approximate Nutrient Content in Portion of Crop of the Size Shown (U.S. Data)[a]

Crop	Yield	Nitrogen	Phosphorus as P_2O_5	Potassium as K_2O	Calcium	Magnesium	Sulfur
	(kg/ha)						
Maize (grain)	9,416	151	59	45	2	9	11
Maize (stover)	10,089	112	41	163	29	22	16
Rice (rough)	4,036	56	22	11	3	4	3
Rice (straw)	5,605	34	11	78	10	6	-
Sorghum (grain)	3,767	56	28	17	4	6	6
Sorghum (stover)	6,726	73	22	106	33	20	-
Wheat (grain)	2,690	56	28	17	1	7	3
Wheat (straw)	3,363	22	6	39	7	3	6

a. Many farmers in developing countries achieve or even surpass these yields.

plays an essential role in the growth of plants. This is incorrect, however, in that, given water, air, and mineral salts, plants grow perfectly well without soil. In intensive commercial vegetable production systems essentially based on hydroponics, the soil provides mainly physical support for the plant. This being said, most crop production will continue to rely on the soil as a physical, biological, and chemical environment for the plant roots with all three of these elements interacting, often in a complex way, to affect root growth and health and thereby dictating the final yield of the crop.

Soils are dynamic materials; i.e., they are constantly being added to and/or depleted in terms of their constituent soil minerals and organic matter and the chemical and physical makeup of these components.

The extremes that develop from this dynamism are illustrated in the fertile delta soils of the Nile, which were replenished each year by the silt carried down from Ethiopia, and in the barren Sphagnum bog lands of North America and Europe. In between these two extremes, soils range from, for example, the fertile prairies of North America to the acid, low-fertility soils of the Amazon basin.

The Interaction of Fertilizers With the Basic Components of Soil Productivity

Sustainable land use as defined by Young (1990) is that which achieves production while conserving the resources on which that production depends. Young recognizes *that the most direct and primary requirement for sustainability is to maintain soil fertility as defined in terms of total plant nutrient content of the soil profile*, but he stresses that in practice soil conservation should in fact be the maintenance of total soil productivity and therefore requires five actions on behalf of the farmer. These, somewhat modified from Young's originals, are as follows:

1. Control of soil erosion and the composition of runoff and drainage waters.
2. Maintenance of soil organic matter.
3. Maintenance of soil physical properties.
4. Economic optimization of the supply of nutrients to farmland in terms of agronomic and environmental needs.
5. Reduction or elimination of soil toxicities through biological, physical, and chemical means.

There is a degree of interaction between any and all of the five items listed, and therefore a change in any one of them affects the overall "productivity" of the soil. This is a particularly important point because it means that the role of fertilizer is clearly not restricted to just that of a "fertility" input directly affecting crop yields. Fertilizer also plays a key role as a soil conservation input that, when used correctly, improves the whole soil in terms of each of the items listed and, of course, when used abusively or inadequately can lead to degradation or loss of the soil and contamination of the environment.

Sustainable Agriculture and Fertilizers: Balancing the Plant Nutrient Budget

Although malnutrition and famine are the lot of many people, the current vogue for the use of the term *sustainable agriculture* arises because many well-informed (and coincidentally well-fed) people feel that agriculture as generally practiced is not sustainable but that strategies exist or can be developed to make it so.

This point of view raises two questions which must be answered:

- Are there sustainable agricultural practices for all the diverse farming systems that exist in the world?
- If globally applied, can these sustainable agricultural practices produce the food and fiber needed by the growing population at prices that most of that population can afford?

These questions in turn raise two policy issues—What will be done in areas where agriculture is unsustainable, and how can yields be increased to meet the needs of the burgeoning population living off an area of diminishing agricultural productivity?

Harwood (1990) in his review of sustainable agriculture highlights three points on which there is universal consensus: (1) agriculture must be increasingly productive and efficient in resource use, (2) biological processes within agricultural systems must be much more controlled from within (rather than by external inputs of pesticides), and (3) nutrient cycles within the farm must be much more closed. The first point is a truism; the second point clearly anticipates that pesticide use must be and will be increasingly based on integrated pest management; and the third point highlights the whole problem of sustainable soil fertility—nutrient cycles at the field, the farm, and even at the agroecological zone level *are not closed* and *cannot be fully closed.*

Little imagination is needed to understand how individuals, family groups, villages, towns, and cities are responsible for the removal of millions of tonnes of plant nutrients from the soil each year, nutrients which are not, and in most cases cannot be, returned to the fields from which they came.

Organic farming, which is essentially the recycling of organic waste at the farm level, does not replace plant nutrients removed from the farm in the produce sold, be it as grain, vegetables, fruit, fodder, or animal products, and it is therefore unsustainable. What are essentially low-output farming systems, based on biologically fixed nitrogen (leguminous crops), can restitute nitrogen to the soil and so become sustainable from that point of view, but the phosphate, potash, and other mineral nutrients removed with the harvests must still be replaced.

The conclusion must therefore be that there can be no sustainable agriculture without an infusion of plant nutrients into the various farming systems and that these nutrients (with the exception of nitrogen) must come from outside the agricultural production system, i.e., fertilizer is an essential input into a globally sustainable agricultural system.

A balanced approach to fertilizer use must therefore be established, on the one hand to ensure that soils are not depleted of nutrients by "soil mining" cropping practices and on the other hand to restrict or control intensive agricultural practices in clearly defined sensitive areas. The former will certainly help the economic development of many developing country farmers and lead to better conservation of their natural resource bases, whereas the latter is bound to adversely affect farmers in eco-regions incapable of absorbing the negative effects of such farming. An example of the latter is given by Tinker (1991) who states, "It is almost impossible to envisage an intensive agriculture, in the lower rainfall parts of *England*, which would ensure the drainage water contains less than 50 mg nitrate/liter of water at all times."

Very hard decisions will have to be made; irrespective of technological developments, however, fertilizer will remain an essential component of sustainable agricultural production.

Fertilizer Use

The Evolution of Fertilizer Use

Chemical fertilizers have revolutionized agricultural production on a global scale only since the 1960s. However, they had already proved to be indispensable to many farm production systems of the industrialized nations for almost a century before their global role developed.

The fertilizer industry began essentially in northern Europe during the industrial revolution—a revolution which saw the beginning of massive movements of a burgeoning population from the countryside to the cities and a consequent rapid growth in the market demand for food. The history of fertilizer use is therefore closely

linked to the production of cereal crops, and wheat, rice, and maize still account for most of the fertilizer consumed in the world. Developments in both industrial production technologies and the farm management of these three crops have had an impact on not only the quantities of fertilizer used but also the composition of those products.

Before the advent of high-yielding varieties of wheat and rice and of hybrid maize, major sources of plant nutrients were legume crops and farm and domestic manures. With these early farming systems, the major constraint on cereal production was the low level of soil phosphate, which spurred the early development of the commercial phosphatic fertilizer industry (1842) based on cheap phosphate rock.

The exploitation of potash deposits in Germany (1860) followed, and potassium chloride became an important fertilizer. Thereafter, the need for nitrogen became the key constraint to cereal production, particularly in northern Europe where the legume crops represented a lost opportunity to grow a cereal crop. Even so the advent of synthetic nitrogen fertilizers in the early 20th century led to only a slow replacement of legumes as sources of nitrogen. This slow growth in demand was due to economic factors (high cost of nitrogeneous fertilizers and low cereal prices) and to the genetically unimproved nature of the cereal varieties used. At this stage of agricultural development, the bane of farmers around the world trying to grow higher yields of cereals was crop lodging, an affliction particularly associated with high-fertility soils. For this reason, emphasis in fertilizer use was on phosphate and potash, and nitrogen was used only sparingly compared with today's practices. The dramatic global changes in fertilizer use and the pattern of nutrient use from 1960 onwards (Figure 2) reflect both the decline in legume-based rotations and pastures and the advent of fertilizer-responsive cereal crops. These changes are illustrated at the national level in Figure 3, where the major increase in the use of nitrogen in the United Kingdom arose from the replacement of clover-based ley farming by nitrogen-fertilized grass pastures. Figure 4 shows that the decline of the legume component of the maize cropping rotation in the United States is clearly linked to increased fertilizer nitrogen use on the maize crop, which was increasingly grown as a monoculture. The yield potential of the improved varieties combined with the increased use of fertilizers led to yield breakthroughs over a very short period. Historical rice yields in Japan and wheat yields in the United

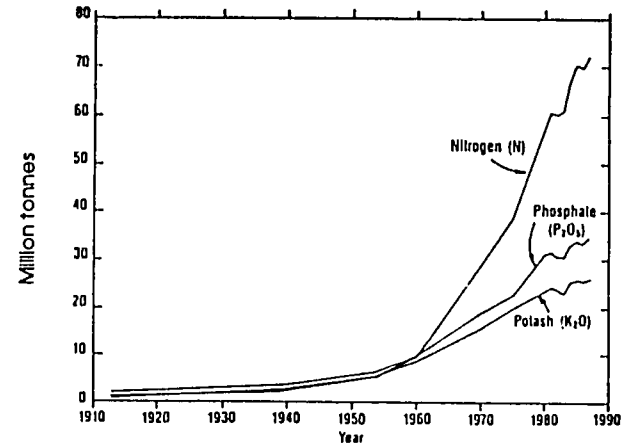


Figure 2. Nutrient Consumption in the World, 1913-1987.

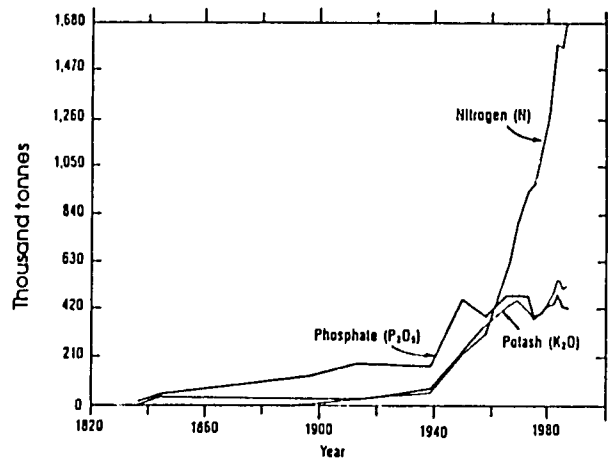
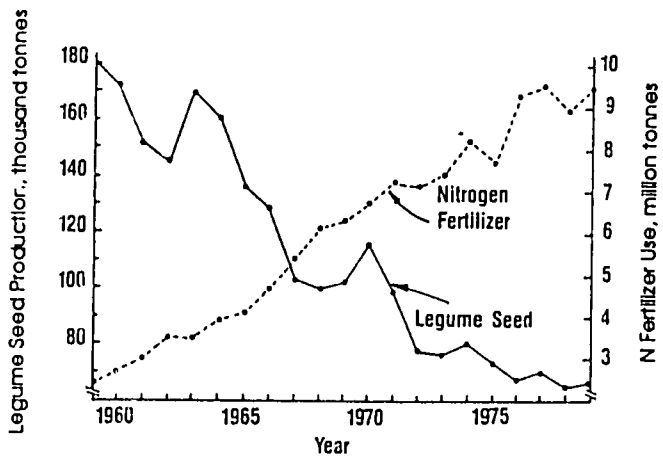
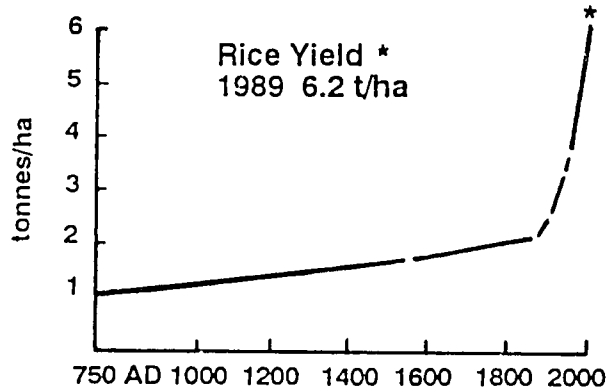


Figure 3. Nutrient Consumption in the United Kingdom, 1837-1987.

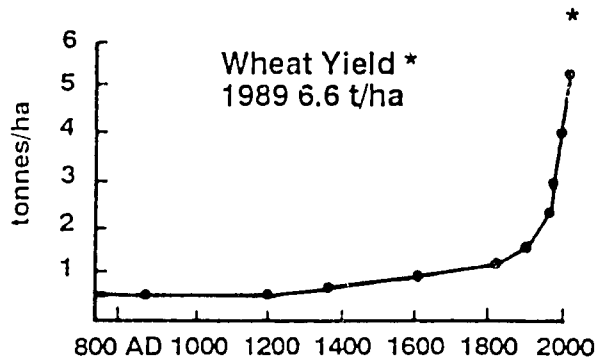


Source: Power (1981).

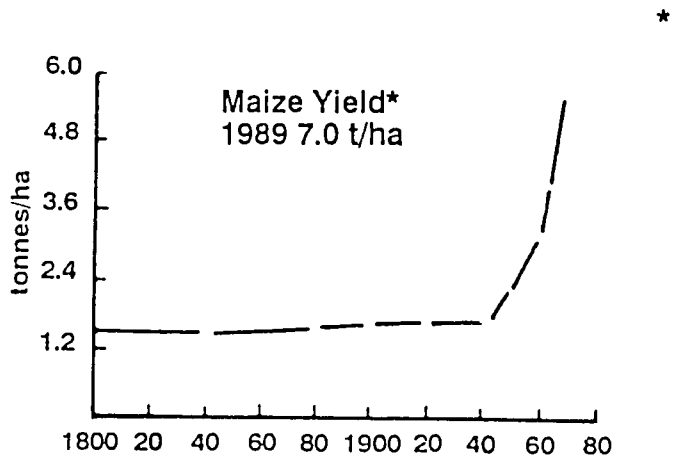
Figure 4. Legume Seed Production and Nitrogen Fertilizer Use in the United States, 1959-1979.



(a) Rice yields in Japan. Adapted from L.T. Evans (1973) and Jack R. Harlan (1975).



(b) Wheat yields in England. Adapted from L.T. Evans (1973).



(c) Maize yields in the U.S. Adapted from Jack R. Harlan (1975).

*Yields of 10 t/ha are now common for all three crops with a theoretical potential of about 20 tonnes.

Figure 5. The Interaction of Science and Farm Management Skills With Crop Yields.

Kingdom are given in Figures 5a and 5b. In the United States, the major crop with potential for rapid intensification was maize—an open-pollinated crop; it was not until the widespread use of hybrid maize in the 1950s that yields, and concurrently the demand for fertilizer, soared (Figure 5c). The plant breeder in the developing world also radically changed the agronomic efficiency of fertilizers by doubling and tripling the grain production per unit of nitrogen applied to wheat and rice.

There is no doubt that the Japanese rice farmer, the English wheat farmer, and the farmer of the U.S. Corn Belt were excellent farmers who managed their soils and crops well. Yet, historically, as the graphs show, yields were increasing only painfully slowly until the 20th century and the advent of scientific farming practices with fertilizer use as a key component. Figures 1 and 5 show that population growth and fertilizer-based yields are highly correlated, and it can be concluded that without fertilizer use the horror of mass starvation would by now have fallen upon many nations. Correctly used, fertilizer is land sparing (through increased yields) and can be an environmentally safe technology. Therefore, given current environmental goals and population growth rates, fertilizer is an essential ingredient of sustainable agricultural production.

Fertilizer and Crop Production

The contribution of fertilizer to land productivity is indicated by the yield increases brought about by the plant nutrients (nitrogen, potassium, and phosphorus) applied as fertilizers. Ratios of increased crop production per unit of nutrient applied vary with agroclimatic conditions, crops and varieties, application rates, and management practices. Experimental and farm data show that for cereals these ratios are between 3 and 25, and average ratios of 5-10 are usually adopted to calculate the contribution of fertilizers to the production of cereals and land productivity.

As shown in Table 2, the increase in grain production between 1970-74 and 1980-84 in Africa, Asia, and Latin America was clearly related to the increased use of fertilizers. Conservative estimates of increased grain production per unit of nutrient applied, calculated by assuming that the total increase in fertilizer use was applied to grain production, were 5.4, 10.4, and 7.4 in Africa, Asia, and Latin America, respectively. On the basis of these ratios and amounts of fertilizers used, the estimated contribution of fertilizers to agricultural production in Africa, Asia, and Latin America represents the equivalent of 475 million tonnes of cereal in 1985 (Table 3), which is sufficient to provide food for several hundred million people for a year.

Table 2. Increase in Average Grain Production and Fertilizer Use, by Region, Between 1970-74 and 1980-84

Region	Grain Production		Fertilizer Use		Ratio of Increased Grain Production per Unit of Nutrient Applied[a]
	Total Increase	Share of World Increase	Total Nutrient Increase	Share of World Increase	
	(million t)	(%)	(million t)	(%)	
Africa	8.2	2	1.5	3	5.4
Asia	200.3	55	19.2	45	10.4
Latin America	23.9	7	3.2	8	7.4
Total	**232.4**	**64**	**23.9**	**56**	**9.7**

a. Calculated by assuming that the total fertilizer increase was used only in grain production. Hence, these ratios should be considered as conservative estimates of the increased grain production per unit of nutrient applied.

Source: U.S. Department of Agriculture, Economic Resource Service. 1986. World Indices of Agricultural and Food Production 1950-85 (unpublished printout), USDA, Washington, D.C.; FAO Fertilizer Yearbooks for 1982 and 1984.

Table 3. Contribution of Fertilizer to Agricultural Production Expressed in Cereal Production Equivalents, 1985

	Total Nutrient ($N + P_2O_5 + K_2O$) Consumption	Increased Production per Tonne of Nutrient	Increased Production Due to Fertilizer, in Cereal Equivalents
	(million t)	(t)	(million t)
Africa	3.44	5	17.2
Asia	40.69	10	406.9
Latin America	7.38	7	51.6
Total	**51.51**		**475.7**

Source: Derived from data in FAO Production and Fertilizer Yearbooks.

During the past 20 years, the joint benefits of improved varieties, fertilizers, and irrigation in developing countries have been extraordinary. The yields from irrigated crop areas are frequently two or more times greater than on nonirrigated land. However, such increments in yields reflect the joint benefits of improved water supply to crops (irrigation) and fertilizers and, in the case of cereals, the use of improved varieties. Because the interaction between improved water supplies and additional supplies of plant nutrients is very large, one cannot separate the benefits of each of these important sources of agricultural production. However, it must be recognized that the benefits of irrigation cannot be fully realized without the use of fertilizers and that many irrigation investments in developing countries would not have been economically feasible without adequate fertilizer use.

The International Irrigation Management Institute has suggested that irrigated areas in developing countries are producing at far less than their potential and that most of the benefits of irrigation, to date, have occurred as a result of the magnitude of irrigation investments rather than the efficiency and productivity of systems. Sound water and fertilizer use programs are the basis of economic returns on investments in irrigation projects.

Conclusion

The elimination or even the reduction of fertilizer use in developing countries would result not only in the starvation and malnutrition of millions but also in an increased degradation of the environment through deforestation, soil erosion, and desertification, as has occurred worldwide in past centuries. In the vast majority of agricultural areas of developing countries, the certain benefits of fertilizer use to the environment overwhelmingly outweigh any of the possible but uncertain detrimental effects. Sound soil fertility management is the key to human survival. So far as the small-scale farmers of the developing countries are concerned, time is too short for the polemics of organic farming or low-input farming to constrain the development of an agriculture based on scientifically proven techniques of soil-nutrient management, which balance need with natural resource conservation. These scientific techniques will exploit the native fertility of the soil and the plant nutrients contained in the available biomass, as well as those biological factors that can enhance crop-nutrient supplies; they will also effectively use those fertilizer nutrients needed to maintain the fertility of the soil in an economically and environmentally sound way. For the developing countries, only an integrated, multidisciplinary approach to all aspects of fertilizer use research will ensure that maximum benefits are obtained from what is the most powerful yield-increasing technology available to man.

Because fertilizer use has complex ramifications, a series of briefs covering the most important points follow. Each of these briefs is based on the latest facts available: Some show the value of fertilizers, and others illustrate the problems associated with their production and use; none are emotive.

Brief 1

Major Issues Concerning the Need for and Use of Fertilizers

1. World population growth is rapid, and in many countries of the developing world, production of the staple foods expressed on a per capita basis is declining.
2. There is a finite amount of good arable land on which to grow food, and as the danger of inadequate food supplies is increasing, yield per unit area and per unit time must be substantially increased.
3. Agriculture is the principal user of water globally; inefficient use of this water is widespread.
4. Poor soil and water management in both rainfed and irrigated agriculture can cause severe and irreversible land degradation.
5. Soil is the most important resource for ensuring sustainable crop production; the reduction of soil fertility by the failure to replace nutrients depletes the soil resource base, often in an irreversible way.
6. The combination of sound water-management practices and correct soil-fertility management maximizes crop yields and minimizes environmental damage.
7. The energy inputs (mainly power and fertilizers) required by high-yielding production systems use nonrenewable fossil fuels. Energy is an emotional issue. All consumable energy on this earth is derived from the sun via photosynthesis. The sun's source of energy is nuclear and is sustainable. Phosphate,

potash, calcium, magnesium, and sulfur deposits (themselves the end product of geological nutrient recycling) are so enormous that their supply is assured, although the technologies of their production and use will have to change. Biological nitrogen fixation (BNF) will be an essential component of some sustainable agricultural systems, but currently BNF is not a land-sparing technology. Environmentally, biologically fixed nitrogen behaves no differently from synthetic nitrogenous fertilizers.

8. Correct soil fertility management programs integrating the use of organic manures, crop residues, and fertilizers can only be established where there is an adequate enabling environment of sound policies and infrastructure.

The use of chemical fertilizer integrated with sound crop nutrient management practices is the key to increased yields per unit area and the maintenance of these yields in a sustainable manner. Increased yields in themselves reduce the pressure for extension of cultivated areas and thus the encroachment of agriculture into marginal areas and fragile environments; in this light, fertilizer is not only essential but also environmentally beneficial. Careful use of fertilizer based on sound soil and crop-production knowledge can reduce any adverse environmental effects these products may have.

The efficient use of fertilizers has production, distribution, marketing, and use components, and thus the fertilizer subsector cuts across several key sectors including energy, industry, agriculture, infrastructure, and environment.

Developing the effectiveness and integration of the components of the fertilizer sector requires a multidisciplinary research base, such as that used by fertilizer sectors in competitive markets. The impact of conducive policy environments and a heightened sensitivity to environmental, equity, and development issues must also be studied.

Brief 2

Equity and Fertilizer Use

Increased rice production through increased use of fertilizer has been a major achievement of Bangladesh; however, many people felt that only the larger farmers had benefited economically from this development. Key findings on the issue of the equity of fertilizer use come from a study funded by the United States Agency for International Development (USAID) for the Bangladesh Agricultural Development Corporation (BADC) and conducted by IFDC.

The following equity implications of the direct benefits of fertilizer use were derived from this study.

1. The sample distribution of net benefits of fertilizer use among the farmers by season shows that in the 1979 Aman season, 81% of the net benefits of fertilizer used accrued to farmers who owned no more than 2.5 acres of land. This figure was 67.2% during the 1979/80 Boro season and only 40.7% and 39.9% during the 1980 Aus and Aman seasons, respectively.

2. Farmers who own smaller farms (low-income farmers) obtain higher net benefits of fertilizer use per acre of cropped land; i.e., their income, in percentage terms, increases more than that of the farmers who own larger farms. However, because of larger cropped areas per farm, the absolute amounts of net benefits of fertilizer use obtained by farmers who own larger farms are higher.

3. The income distribution effects of fertilizer use vary substantially according to the areas cropped by each farmer. The higher net benefits per acre of cropped land obtained by farmers who own and crop relatively small areas only partially offset the larger net benefits obtained by farmers who own and crop larger areas.

4. Fertilizer use does increase the income of all farmers but does not improve the farmers' income distribution. It does increase in a greater *proportion* the income of farmers who own small farms but in a greater *absolute amount* the income of farmers who own larger farms. The conclusion of the study was that, because of its effect on the income of small-scale farmers, fertilizer use alleviates poverty and enhances food security in an equitable fashion.

Brief 3

Biomass and Fertilizers

The accessible biomass (the portion of plant growth that can be harvested) is used for human and animal food, fiber, building materials, and fuel.

The importance of food and fiber and the indirect effects of intensive crop production on the environment

are widely recognized. Less well recognized is the fact that the use of biomass for fuel[2] has led not only to an increasing rate of deforestation and desertification, due to the removal of trees and shrubs, but also to the increasing use of crop residues and animal dung as substitutes for wood fuel. There is therefore a major and increasing drain on soil fertility in many cereal-growing areas of the developing world.

The problem to be faced, therefore, is to increase biomass production per unit area on a planned and sustainable basis. Because all plants (trees, shrubs, grasses, and crops) require plant nutrients for growth, and because low soil fertility is a major constraint to plant growth, the need for research and development activities to maximize biomass production by alleviating soil fertility constraints must receive the same priority as does research on increased food and fiber production.

Brief 4

Soil, Water, and Fertilizers

The water relationships of a soil can be changed by drainage, irrigation, and rainfall-harvesting techniques. Each stage of improvement of the water regime in relation to crop moisture requirements leads to an increase in crop production potential which, in order to be realized, needs an increased level of plant nutrient supply. For this reason, the irrigated areas of the developing world are among the highest users of fertilizers in the world; conversely, those areas of low and erratic rainfall are among the lowest users.

High-technology irrigation practices that use water and fertilizer efficiently are increasingly in demand and being adopted in many developing countries producing high-value crops. There is, however, a great need for improved water management combined with sound fertilizer practices under the marginal technology systems available to large areas of most developing countries. Research in this area is needed to ensure the maximum efficiency of both water and fertilizer nutrient use and thereby the reduction of the environmental damage to surface and groundwaters.

2. Biomass fuel accounts for almost all the fuel used in Ethiopia and Nepal and for three-fourths of the total supply in Kenya, one-half in India, and one-third in China.

Brief 5

Soil Organic Matter and Fertilizers

Crops need only sunlight, air, water, and inorganic salts (fertilizers) to give maximum yields.

Hydroponics, the technique of soilless culture, is often used to produce high yields of high-value crops. Skilled management of the levels of fertilizers supplied in the water is needed, but otherwise the technique is simple. Although neither organic matter nor humus plays a role in hydroponics, they are a foundation of conventional soil-based agriculture.

In their natural condition, soils are a result of what is added to them each year from plant roots, dead leaves, stalks, etc., and what is removed through the leaching of the soil profile by rainfall and the decomposition of plant residues into carbon dioxide and humus.

Under uncultivated conditions, the regular addition of organic matter and its incorporation into the soil by soil organisms lead to the development of higher levels of soil organic matter (humus), which, in turn, leads to improved soil structure and improved plant-nutrient and water-holding properties and greatly increased storage of soil nitrogen. The final equilibrium level of organic matter in a soil is a characteristic of a particular soil; generally, higher rainfall increases the level, and higher temperatures decrease the level.

Once a soil is cultivated, the level of the soil organic matter declines. Large quantities of N are initially liberated, the physical stability of the soil is reduced and its capacity to act as a reservoir for plant nutrients and soil moisture diminished, and, of course, large quantities of nutrients are removed in the harvest.

These facts account for the serious destruction of structurally fragile soils; however, for most of the productive soils of the world, these negative changes have been of little interest to the farmer because improved cultivation techniques combined with improved crop varieties and fertilizer use have achieved major increases in yield despite some soil and organic matter losses.

Almost coincidentally, the improvements in the practice of crop residue recycling in high-yielding areas due to improved machinery have led to the situation where, with maize, for example, up to 10 tonnes of dry crop residue—trash, stover, cobs, and roots—is returned to

each hectare harvested. Even these high levels of organic matter return, however, have only a small positive impact on soil organic matter levels. Barber (1979) showed for a high-yielding maize plot that at least 6 tonnes/ha of residues was required to maintain organic matter levels.

Of particular interest in this study was the fact that roots and root exudates were shown to contribute significantly to the maintenance of organic matter levels; however, although fertilizers greatly increase the aboveground biomass of crops, their effect on roots is complex. Highly fertile soils often tend to have lower root:top growth ratios than do the less fertile soils. Much research is needed to maximize the contribution of roots to soil productivity, particularly in areas where farmers remove almost the entire aerial portion of the crop, a common practice in many of the poorer areas of the world.

The conclusion therefore must be that high soil fertility resulting in higher production of crop residues that are correctly handled in the field will help to maintain soil organic matter but often at levels below those of the soil in its natural uncultivated state.

Brief 6

Soil Erosion, Crop Production, and Fertilizers

Assessment of the impact of erosion on crop yields is complex in that the shifting of land out of cropping and the impact of improved yield-increasing techniques on the land remaining under cultivation confound the situation. In many cases, crop yields have not fallen because soil fertility has been built up by the use of fertilizers and by the better management of crop residues. It must be said, however, that soil erosion often removes the most fertile soil and thereby decreases the sustainability of the system.

All the available techniques for controlling soil losses have been applied for many years, even hundreds of years, often in a very successful way and often alongside practices that are examples of what not to do. Sound stewardship of the soil, however, is not a universal goal; the needy and the greedy often have no interest in long-term and often low-payoff investments.

Traditional moldboard plowing, the basic step of crop production, is an effective means of controlling weed, insect, and disease problems; unfortunately, it leaves the soil exposed over very large areas and therefore vulnerable to erosion damage. Major efforts have been made to spread technologies that would permit intensive crop production while reducing or eliminating soil erosion, with contour planting and grassed waterways being the basic steps.

Plant residues left on the soil surface protect the soil from the beating action of raindrops, which can destroy the surface structure and thereby seal the soil surface, causing water to run off the soil rather than gently entering the soil profile and ensuring replenishment of the soil-moisture reservoir. No-till agriculture is a deliberate attempt to increase plant litter on the soil surface.

The U.S. system of crop residue recycling (CRR) relies heavily on the use of machinery. Unfortunately, under small-farm conditions of the tropics, the farmer just cannot handle the major physical effort needed for this work; in any case, much of the straw and stems are removed for use elsewhere. This removal of crop residues for off-farm use is, therefore, a serious drain on both soil stability and fertility. Increasing crop yields and crop-residue production through improved plant-nutrient management is an essential component of corrective measures, and fertilizers are an essential input to this management.

One of the key components of erosion control is the rapid establishment of ground cover in order to reduce rainfall impact on the soil surface; thus, the selective encouragement of weed growth combined with a sound herbicide application program is a practical proposition in some areas. The shift to reduced tillage practices also tends to necessitate the use of more chemical pesticides. Additionally, fertilizer placement becomes more critical and thus leads to an increased demand for innovations in product and application equipment.

Most farmers in the world are aware of the need for and methods of soil fertility maintenance including CRR but are often unable to apply these principles for operational or economic reasons.

Brief 7

Plant Nutrient Recycling and the Need for Fertilizers

The pedogenic processes are such that soils in their natural state vary from highly fertile soils to soils that are almost entirely depleted of plant nutrients. Historically,

farmers were quick to recognize the areas of fertile soils and took from those soils what crops they would grow and then moved on to virgin lands, or at least to rested land, for their next crops. Even now, over large areas of Africa, Asia, and Latin America this system of shifting cultivation, or the use of long fallow periods, sustains a low level of crop production on a permanent basis. Unfortunately, as the population grows, resting periods become shorter until the stage of continuous cropping is reached. Before this last stage is reached, management of soil to maintain productivity becomes critical to survival and yield-increasing technologies based on improved soil fertility are increasingly needed. Fertilizer use is usually an important component of such technologies.

There are historical examples of settled farming that maintained and even improved the productive power of the soil without the use of fertilizer, but—and this is a crucial but—only where plant and animal wastes were not only fully recycled on the farm but also supplemented by plant and animal products and wastes originating outside the farm. Good examples of well-managed nutrient-recycling systems were the animal waste and leguminous crop system of mixed farming in England and the human waste-management system of the Japanese rice farmer, both of which reached their peak before the introduction of commercial fertilizers.

Unless plant nutrients are brought in from outside the farm, all farming systems that sell crops off the farm have a negative plant nutrient supply balance for major elements, phosphorus, potash, sulfur, calcium, and magnesium; the N balance can be positive or negative, depending on the amount and type of leguminous crops (alfalfa, etc.) grown.

Phosphate deficiency stands out as a major constraint to food crop production in low-input systems. Large areas of the developing world are chronically deficient in phosphate; legumes, the key to low-input agriculture, are particularly sensitive to phosphorus deficiency. Unless phosphate fertilizers are used in these areas, even the best managed nutrient farm recycling system will not achieve the minimum soil phosphate levels needed for good yields. The need for correct phosphate nutrition of crops has proven to be the major constraint to organic farming and has led to the sleight-of-hand use of *natural* phosphate rock as a nonindustrial source of phosphate, which in reality is a totally inorganic source of phosphate.

Sulfur, although not a constituent of modern fertilizers, is similar to phosphate in terms of its status and usefulness. Organic manures are good sources of sulfur, but so also are elemental sulfur and inorganic sulfates.

Potash deficiency is increasingly a constraint to food crop production in the developing world because the continual removal of crop residues (stalks, straw, and leaves) for use as fuel and also for building materials and animal feed and litter represents a serious and increasing drain on soil resources and particularly on soil potash reserves.

Brief 8

Recovery of Fertilizer Nutrients by Crops

Nitrogen

The range of crops, along with the amounts and types of nitrogenous fertilizers used to grow them, is so wide that reports on fertilizer nitrogen recovery by the crop vary greatly. A general figure of around 50% recovery seems to be an average.

General figures from the United States for fertilizer N uptake of some of the more important crops are given in Table 4. These are fairly depressing figures if it is considered that the unused nitrogen could eventually end up in the groundwater.

Table 4. Percent Uptake of Fertilizer N by Some Important Crops

Crop	N Rate (kg/ha/year)	Total Crop Uptake (%)
Corn	50-168	23-32
Corn	90-360	24-60
Wheat	50-100	21-44
Rice	100	38-44
Barley	50	14-25
Sugarbeet[a]	56-280	12-40

a. Sugarbeet, *Beta vulgaris* L.

Source: Gilliam, Logan, and Broadbent (1985).

Phosphorus

The uptake of fertilizer phosphorus is generally below 10% in the first crop and even less in the following crops. Most phosphate research efforts have been aimed at maximizing the phosphate response of the crops being grown. Much emphasis has been given to promoting strong early growth of young plants. This has tended to emphasize the value of water-soluble phosphate in farm fertilizer programs. The buildup of high levels of

phosphate in the soil profile has occurred as a residual benefit from the use of this soluble phosphate.

Potassium

Unlike nitrogen and phosphorus, which exist in diverse forms in the soils, plant potassium remains as the cation K^+. The degree of movement of potash in the soil profile depends on soil properties, but as its mobility is generally greater than that of phosphate and much less than that of nitrate, efficiency of uptake is usually intermediate between N and P.

Plant Nutrient Dynamics

Much research is needed to maximize the efficiency of fertilizers. Form, timing, placement, and rate of application of crop nutrients, both organic and inorganic, affect their use. There can be no efficient use of plant nutrients without sound management of the soil, water, and crop. The basis of such research will be a better understanding of plant nutrient dynamics.

The major components of fertilizers are phosphorus, potassium, and of course nitrogen. In older terminology, phosphorus and potassium were "feed the soil" nutrients while nitrogen was a "feed the plant" nutrient. This was quite a good concept; unless there is soil erosion, phosphate and, to a lesser degree, potassium remain stored in the soil, and therefore fertilization with these nutrients can be regarded as being generally beneficial to soil fertility and sustainable agriculture.

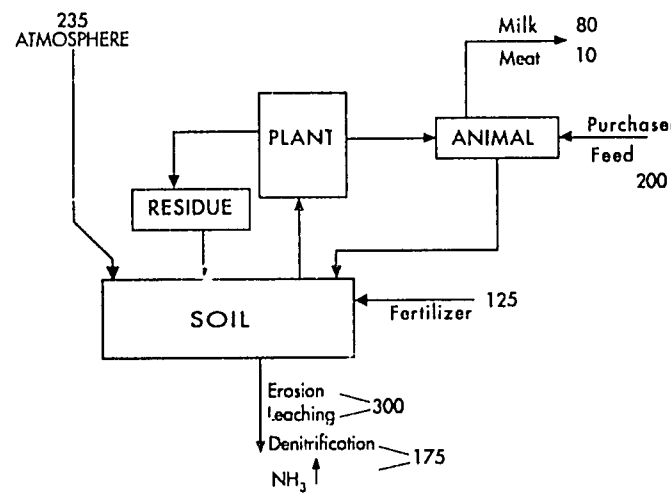
The eutrophication of surface waters has given phosphates a very negative image environmentally. The culpability is indirect, however, because correctly managed fields and correctly applied phosphate are not an environmental problem although the sheet erosion of soil from highly fertilized fields is. The problem of eutrophication of surface waters is that of land and water development planning, management, and monitoring.

Nitrogen as a natural or added soil component is the key both to crop yields and to plant nutrient-related environmental problems. The ammonia component of the soil and of the manures and fertilizers added can lose ammonia gas directly to the atmosphere, be taken up by the plant, or be converted to nitrate by soil microorganisms. Nitrate, derived from organic manure, crop residues, and fertilizer, is very soluble and will move with the soil water entering the plant with the transpiration stream, or move through and out of the soil with drainage or runoff water.

Soil nitrate can also, if there is a shortage of air in the soil, be reduced and released to the atmosphere in gaseous forms.

Whole farm nutrient balance sheets for nitrogen have been developed. Figure 6 is a good example of a dairy farm, showing the following important points:

1. Recycling of plant and animal waste does not add nitrogen to the whole system.
2. The atmospheric contribution to the nitrogen balance comes essentially from biologically fixed nitrogen.
3. The farmer is bringing more nitrogen onto the farm in the form of cattle feed than he is in terms of fertilizer.
4. Losses of nitrogen from the system are high, and the biologically fixed nitrogen contributes to this loss.



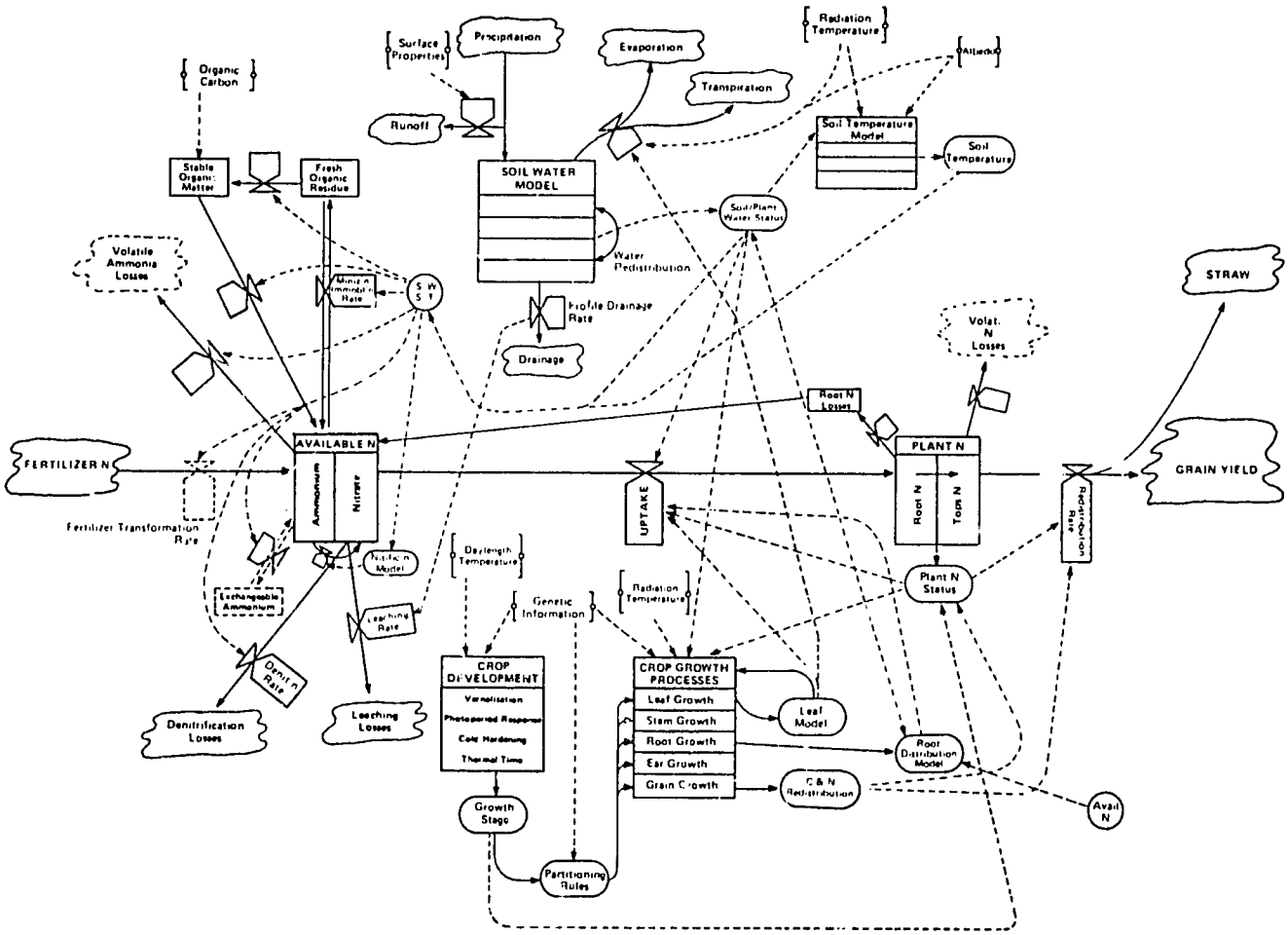
Source: Frink (1969).

Figure 6. Nutrient Cycling on a Farm. Numbers Are Nitrogen Inputs and Outputs (Kilograms Per Cow Per Year) From a Connecticut Dairy Farm.

Such farm nutrient balance studies are useful guides to the fate of plant nutrients, but more sophisticated approaches are needed if the goal of sustainable agriculture is to be achieved.

For example, with nitrogen, the situation is particularly complex because many factors affect its fate, including the nature and period of growth of the crop. The best illustration of this complexity is the flow diagram used by crop modelers to study nitrogen supply to cereal crops (Figure 7).

For phosphate, which is deficient in most developing country crop production systems, the picture is far simpler because essentially only soil-based changes are involved. Even so, a soil phosphorus balance must take



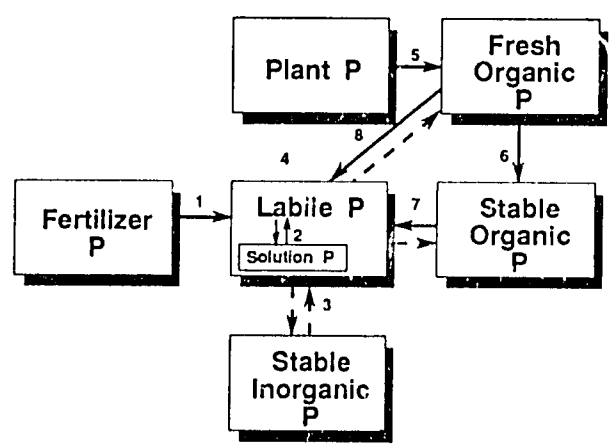
Source: Godwin and Vlek (1984).

Figure 7. Systems Diagram of Upland Nitrogen Model: Solid Lines Are Material Flows; Dotted Lines Indicate Information Lines.

into account the degree of availability of soil phosphate to the crop in both the short and the long term (Figure 8).

Because of the large amounts of potassium in the leaves and stalks of plants, studies of potassium dynamics are very much needed in areas where biomass is removed for burning or building purposes.

The dynamics of plant nutrient sulfur are complicated by atmospheric sulfur deposition, a major environmental concern over large areas of North America and Europe.



Source: Singh and Godwin (1989).

Figure 8. Phosphorus Pools and Their Relationship in the CERES Model. (Erosion Losses Are Not Included.)

Brief 9

Nitrogen—The Key Plant Nutrient

Because nitrogen compounds are present in all living organisms, they are also present in all plant and animal

wastes and in the soil organic matter formed from these wastes.

Traditional agriculture uses the nitrogen from decomposed plant and animal waste to provide nitrogen to the growing crop. Modern crop production systems have increasingly used nitrogenous fertilizers to supplement or even replace the traditional system, and in areas of high crop productivity fertilizer nitrogen is now the major source of crop nitrogen.

Under moist and warm conditions, various components of the soil microbial population convert soil organic matter first to ammonium and then to nitrate (nitrification). Ammonium-based nitrogen fertilizers are also nitrified to nitrate. Once organic matter nitrogen is converted into ammonia and to nitrate nitrogen, it becomes identical to industrial fertilizer nitrogen.

The amount of nitrate entering the groundwater reserves from agricultural land will vary greatly over different sites and cropping systems but will be directly linked to the amount of nitrate produced from organic matter, manures, and fertilizers.

Several factors are well established. Where high-value cash crops are grown, nitrogenous fertilizers represent only a small proportion of the total crop-production costs and even indeed the actual cash costs, and most farmers prefer to give that extra bag of fertilizer to ensure maximum yields. This leads to excessive use of fertilizer. Both policies and technologies must match to reduce this temptation.

Recovery of fertilizer nitrogen declines as the level of fertilizer use passes beyond the optimum application rate. Excessive additions of nitrogen (either as organic manure or fertilizers) will lead to the temporary accumulation of nitrogen in the soil and a later loss either to the groundwater as nitrate or to the atmosphere as nitrous oxides.

For a given weight of fertilizer nitrogen, recovery increases as the aboveground weight of the crop increases. Therefore, plants with a long growing season recover fertilizer nitrogen more effectively than do plants with a short growing season, and well-managed crops also will recover nitrogen more efficiently than a poorly managed crop.

The various commercial nitrogen fertilizers available show no difference in the efficiency of their nitrogen use under upland or irrigated field conditions. For flooded rice production, the efficiency of use of nitrogen fertilizers varies; deep-placed ammoniacal-N sources are the most effective.

The mineralized nitrogen derived from organic materials, such as animal manure or leguminous crop residues, will behave in exactly the same way as the nitrogen from fertilizers.

The inefficient use of nitrogen from both organic manure and fertilizer sources is a major reason for IFDC's heavy commitment to nitrogen use-efficiency research.

Brief 10

Soil Acidity and Fertilizers

The effects of soil acidity on plant growth are complex and range, for different crops and cultivars, from complete suppression of growth to a complete absence of any effect whatsoever. The adverse effects on growth are due both to the low levels of calcium, an essential plant nutrient, and to high levels of metal ions, mainly manganese and aluminum.

Soil acidity is related to the degree of loss of soil calcium from the soil profile caused by the acidification of drainage waters that have absorbed carbon dioxide. Soils in high-rainfall areas can therefore become extremely acid. The adverse effects of soil acidity on plants can be corrected by the very ancient practice of adding limestone to the soil. The production of agricultural limestone today is the basis of a major industry.

Unfortunately, in large areas of the tropics particularly, acid and aluminum toxic soils occur far from any source of limestone. Much progress is being made by the International Agricultural Research Centers (IARCs) in selecting and developing aluminum-resistant cultivars; however, such materials are a palliative only, in that eventually some limestone will have to be added to the soils if production is to be sustainable.

The first major synthetic nitrogenous fertilizer was ammonium sulfate. This fertilizer acidifies the soil due to the change of the ammonium content to nitrate, which produces the acidic hydrogen ions, and to the sulfate ion itself, which carries with it a basic ion—calcium mainly—when it is leached from the soil.

In the early days of fertilizer use, ammonium sulfate was competing with neutral fertilizers such as calcium and sodium nitrate and quickly earned a bad reputation in some areas as a soil acidifier. As can be seen in Table 5, anhydrous ammonia, urea, ammonium nitrate, and ammonium chloride, as well as ammonium sulfate, can cause acidity problems.

Table 5. Potential Acidity of Nitrogen Fertilizers

Fertilizer	N	Potential Acidity[a] kg $CaCO_3$/ kg Fertilizer	kg $CaCO_3$/kg N
	(%)		
Anhydrous ammonia	82	1.48	1.8
Urea	46	0.84	1.8
Ammonium nitrate	33.5	0.59	1.8
Ammonium sulfate	21	1.10	5.2
Ammonium chloride	25	1.28	5.1
Ammonium nitrate limestone[b]	20.5	0	0
Calcium nitrate	15	-0.20	-1.3
Sodium nitrate	16	-0.29	-1.8

a. Amount of pure $CaCO_3$ required to neutralize acidity produced by fertilizer in the soil.
b. Other similar products are calcium ammonium nitrate, nitro-lime, and nitro-chalk. Various means of production result in variations in grade and potential acidity.

Source: IFDC.

The increasing use of soil-acidifying nitrogenous fertilizers has, however, always concerned agronomists who have developed sound liming programs for most farm situations. It should be noted that attempts to develop the use of neutral or less acidifying fertilizers have been overtaken by the development of low-cost technologies for urea production. It is appropriate here to draw attention to the fact that soil acidification can be a serious problem even where nitrogenous fertilizers are not used. The acidification of ley pastures in Australia caused by the mineralization of biologically fixed nitrogen in the soil is well documented.

Brief 11

Biological Nitrogen Fixation and Fertilizers

The capability of a legume to add nitrogen to an agricultural system has long been recognized. The need to develop cropping systems for the tropics and subtropics which incorporate legumes has probably received too little attention. The "alley farming" system, in which rows of *Leucaena leucocephalla* alternate with several meters of arable land and the prunings from the legumes are used as a mulch, offers one system for accomplishing this. Wider use of grain legumes in the cropping system along with the return of crop residues to the soil offers another. As improved varieties of grain legumes such as soybean, mung bean, cowpea, and pigeon pea become available, we may expect a continuing expansion of their use. Their efficiency will, of course, depend on proper nutrition, and phosphate, sulfur, and other nutrients will need to be supplied to ensure that they yield adequately in terms of both grain and nitrogen fixed.

Additionally, there is evidence that starter amounts of fertilizer N are required to support legume growth before nodules develop. Also, the rate of N_2 fixation by the nodules does not seem to be able to change rapidly in response to rapid changes in the N demand of the plant. Thus, at the end of a period of environmental stress, e.g., high or low temperature or water stress, the addition of fertilizer N can be beneficial. However, this use of small booster doses of nitrogenous fertilizers must be very carefully managed because the more fertilizer applied, the less nitrogen that is fixed symbiotically.

Given the opportunity of growing a pasture legume crop, the farmer will either have to feed it to an animal or plow it down. In either case, gross inefficiencies are involved in the conversion of the legume crop into protein N suitable for the human diet or to soil N to fertilize the following cereal crop.

It should also not be forgotten that the land-sparing technology of the intensive cereal-growing systems—in terms of their high productivity linked to the effective use of applied industrial fertilizer nutrients, including N—makes these systems essential to the general well-being of most of the world's population.

Brief 12

Soil-Borne Diseases and Fertilizers

Huber (1990) encapsulated very clearly the interactions of plant nutrition and disease management as follows:

> Nutrient manipulation through fertilization or modification of the soil environment to influence nutrient availability is an important cultural control for plant disease and an integral component of production agriculture. Fertilization decreases soil-borne diseases by maximizing the inherent disease resistance of plants by facilitating disease escape through increased nutrient availability or stimulated plant growth, and by altering the external environment to influence the survival, germination, and penetration of pathogens. The flexibility in most disease-nutrient interactions permits a much broader utilization of this cultural control in decreasing disease severity

than is presently practiced. It is clear that the severity of most diseases can be decreased and the chemical, biological, or genetic control of many plant pathogens enhanced by proper fertilization. Breeding nutrient-efficient or disease-tolerant crops and establishing cultivar requirements should further improve production efficiency (D. M. Huber, 1990).

Brief 13

The Environment and Fertilizers

The effects of fertilizer on the environment need to be kept in perspective, particularly by ensuring that the adverse environmental effects of industry, the massive urbanization of good agricultural lands, and the expansion of low-production systems into forest areas and marginal lands are separated from specific fertilizer-use effects on the environment. Additionally, agricultural activities, such as simple cultivation of the soil, decomposition of leguminous crop residues, and use of animal manures, can all have environmental impact; thus, these effects also must be quantified.

Pollution of Surface Waters

Agriculture contributes to pollution from nonpoint sources (NPS). In the United States, the Association of State and Interstate Water Pollution Control Administrators (ASIWPCA) compared the 1972 water-quality assessment with 1982 assessments. Agricultural activities were found to be the main contributors of NPS pollution in both lakes and rivers. The predominant river NPS pollution is sediment, and the predominant lake and estuary NPS pollutants are plant nutrients.

Soil erosion control combined with the use of best crop-management practices is needed. Manure and soil analyses will enable the farmer to match nutrient application with crop requirements and thus help to prevent excessive use of both manures and fertilizers.

Pollution of Groundwaters

Nitrogen is the nutrient around which interest in groundwater pollution by agriculture revolves. The Royal Society (1983) showed that, despite almost 1 million tonnes of fertilizer nitrogen being added to United Kingdom grassland each year, little was leached out of the rooting zone. In contrast, of the 440,000 tonnes of fertilizer nitrogen added to arable soils annually, perhaps as much as 150,000 tonnes of nitrate nitrogen was lost by leaching. It is important to note that the quantities of nitrogen leached varied greatly from year to year and from soil to soil.

Attention is drawn in this report to the fact that plowing new land often releases more nitrogen than can be taken up by the crops; further, because the store of soil nitrogen in the United Kingdom is about 150 times greater than that added annually as fertilizer, decomposition of organic matter can lead to major nitrate losses from the soil profile. Indeed, a significant part of the present nitrate burden of certain aquifers in the United Kingdom is attributed to the plowing up of old grasslands in the period 1939-50.

The general conclusions of this report are that the contributions of soil organic matter, crop residues, animal manures, and fertilizers to increased crop yields must be more fully researched in order to develop nitrogen fertilizer practices that will maximize the efficiency of use of nitrogen by the crop and, at the same time, reduce the risk of nitrate contamination of groundwater.

Research in the United States on fertilizer nitrogen movement in percolating waters shows that the amount of fertilizer-derived N that leaches below an active rooting zone can be minimized by prudent fertilizer and/or irrigation practices. Correlation of well-water nitrate-nitrogen (NO_3—N) concentrations with fertilizer consumption data is inconsistent among states and regions; positive correlations are found mostly in the midwestern (Corn Belt) region and in irrigated areas of western states. There is clearly a need to monitor much more intensively nitrogen flux and the movement of nitrate into groundwater and to examine the effects of cultivation and cropping systems, along with animal manure and fertilizer applications, on these fluxes.

Fertilizers and Greenhouse Gases

Table 6 shows the relative contribution of the three naturally occurring gases that are suspected of contributing to global warming.

Carbon Dioxide (CO_2)

Fertilizers are relatively benign in terms of their impact on the CO_2 content of the atmosphere.

Table 6. Atmospheric Concentrations, Increase, Residence Time, and Relative Contribution to Warming for the Three Major Greenhouse Gases

	CO_2	CH_4	N_2O
Concentration (ppm)	350	1.7	0.3
Increase (ppb y^{-1})	1,750	19	0.75
Relative potential for thermal absorption (CO_2=1)	1	30	150
Relative contribution of 1 year's increase to increased thermal absorption	15	5	1
% biotic	30	70	90
Residence time (y)	300	8-12	100-200

Source: Bouwman (1989).

The production and use of 1 tonne of fertilizer nitrogen releases about 1 tonne of CO_2 to the atmosphere. Even with the production of fertilizer nitrogen approaching 100 million tonnes, the CO_2 evolved is only about 0.5% of the CO_2 evolved by burning fossil fuels.

Fertilizer N increases the biomass of crops, and therefore CO_2 is removed from the atmosphere to be returned later through oxidation either by burning or by metabolic action.

A major source of atmospheric CO_2 is deforestation, as the C stored in the wood is released on burning. Agriculture also generates CO_2 because soil organic matter levels fall when the land is cleared and cultivated. Fertilizer use would help to reduce these losses by reducing the rate of deforestation and by helping to maintain soil organic matter levels.

Methane (CH_4)

The biotic source of methane is the anaerobic metabolism of carbon compounds, which can occur when soils are waterlogged; therefore, flooded rice is a major anthropogenic source. Fertilizer is indirectly responsible for methane evolution through its stimulation of the biomass of the rice crop, part of which is in turn reduced in the soil to methane. The problem here, however, is due not so much to the use of fertilizer but rather to the necessity to intensify rice production for human needs.

Nitrous Oxide (N_2O)

This gas is important because it has a long residence time and absorbs 150 times more heat than does CO_2 As N_2O is essentially derived from the vegetated areas of the world, the contribution of agricultural production, and of fertilizer nitrogen in particular, to the world's N_2O budget needs to be clearly identified.

The source of N_2O is obviously those oxidized nitrogenous materials present in the soil (NO_2^- and NO_3^- salts) that are derived from fertilizers or biologically fixed nitrogen (legume plants) or from the soil organic matter itself.

Estimates of N_2O evolution due to nitrogenous fertilizers are apparently not more than 3% of the fertilizer N used or about 2 million tonnes of N_2O in 1990; the evolution of N_2O from cultivated legumes, however, is estimated to be at least ten times this amount. Additionally, tropical and subtropical woodland are major sources accounting for about one-half of all N_2O production.

Ammonia

The loss of nitrogen to the atmosphere through the volatilization of ammonia from surface-applied nitrogenous fertilizers and organic manures can be very high, but United Kingdom data indicate that ammonia losses from fertilizer, although significant, represent only a fraction of the ammonia losses from both pastured and housed livestock waste. Ammonia does have effects on the atmosphere, but these are minor relative to other atmospheric pollutants.

Conclusions

The impact of fertilizers on CO_2 evolution is insignificant compared with other sources such as the energy industry, tropical forest destruction, and the losses from soil organic matter due to cultivation.

Fertilizers do contribute to an increase in methane production; however, this is an indirect effect due to their role in increasing the biomass of rice paddies.

N_2O production from nitrogenous fertilizers, although significant, is small in comparison with N_2O production from crop legumes and tropical forests.

Brief 14

Fertilizer Production

The current structure of the fertilizer industry contrasts sharply with the industry of 1950 when world population was 2.5 billion and annual fertilizer consumption amounted to 14 million tonnes of nutrients, used mainly in Europe and North America. Today, 150 million tonnes of fertilizer nutrients, with Asia as a

major producer and consumer, provide food and fiber for more than 6 billion people. Until about the mid-1950s in North America and Europe, farmyard manures and crop rotation supplemented by small doses of nitrogen and phosphate provided enough plant nutrients for modest but acceptable yields. Low-analysis fertilizer products were the norm; nitrate of soda (16% N), ammonium sulfate (21% N), and ammonium nitrate (33% N) were the primary nitrogen fertilizers while single superphosphate containing 16%-20% P_2O_5 was the premium phosphate fertilizer.

Because the economics of crop production favored large-scale monocropping, the post-World War II industrial and agricultural boom, which coincided with the development and wide deployment of fertilizer-responsive HYVs of wheat, rice, and hybrid maize, fueled increased fertilizer use, especially the use of nitrogen.

Because sound crop fertilization needed not only nitrogen but also phosphate and potash, local and regional NPK (compound) granulation plants flourished in the United States and Europe. Thus, in 1960 in the United States, there were about 280 of these NPK plants, each producing between 25,000 and 50,000 tonnes of product annually. These factories produced high-quality but low-analysis products, such as 8-8-6, 3-9-18, and 3-12-12. The required nitrogen fertilizer was applied initially as ammonium nitrate; anhydrous ammonia and later urea then became the key nitrogen fertilizers.

In Europe, NPK technology was highly developed, and high-analysis materials, such as 15-15-15 or 20-20-0, supplied a large segment of the European market and were also exported.

In North America, long transport distances encouraged the production and use of concentrated nutrient fertilizers, and diammonium phosphate (DAP), potassium chloride (KCl), and urea production grew. Because these three products were manufactured by large integrated fertilizer plants located near the source of supply of the key raw materials, they were cheap. The difficulty was to get the farmer to use them.

In the United States, particularly in the Corn Belt, the practice of dry bulk blending of high-quality DAP, KCl, and urea fertilizer suited a small-scale operation (5,000 tonnes/year) and required little capital investment. Because the fertilizer raw materials were also cheap, thousands of these small operators were established; most of the granulation plants, unable to compete, went out of business.

In Asia, which is now the world's largest consumer and producer of fertilizer, farm use of the straight fertilizers, urea, DAP, and triple superphosphate (TSP), dominates the scene.

With the increasing complexity of crop-production systems and the refinement and increasing complexity of fertilizer recommendations, there is great potential for the use of blended fertilizers. However, caution is needed when moving from straight products or granulated products because the development of a fertilizer supply strategy based on prescription-type blending assumes the existence of the following elements:

1. A good knowledge of the nutrient needs of the crops.
2. The availability of high-quality granular ingredients for preparing uniform blends.
3. A marketing system that can effectively manage the distribution and use of a large number of fertilizer products.

Unless these essential elements are in place, the economics of blending as an alternative to traditional straight or compound products needs to be carefully evaluated.

Research on the most effective fertilizer sources and their production, marketing, and use is the basis of an effective supply system. Current fertilizer products are marketed essentially on the basis of lowest delivered cost of nutrient content; the agronomic efficiency and the industrial pollution aspects of the production and use of these products have been and largely remain secondary considerations.

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