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Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture:
Current Issues and Future Challenges

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Foreword

The challenge for agriculture over the coming decades will be to meet the world's increasing demand for food in a sustainable way. Declining soil fertility and mismanagement of plant nutrients have made this task more difficult. In their 2020 Vision discussion paper, *Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture: Current Issues and Future Challenges*, Peter Gruhn, Francesco Goletti, and Montague Yudelman point out that as long as agriculture remains a soil-based industry, major increases in productivity are unlikely to be attained without ensuring that plants have an adequate and balanced supply of nutrients. They call for an Integrated Nutrient Management approach to the management of plant nutrients for maintaning and enhancing soil, where both natural and man-made sources of plant nutrients are used. The key components of this approach are described; the roles and responsibilities of various actors, including farmers and institutions, are delineated; and recommendations for improving the management of plant nutrients and soil fertility are presented.

The genesis for this paper was a joint International Food Policy Research Institute/Food and Agriculture Organization of the United Nations workshop on "Plant Nutrient Management, Food Security, and Sustainable Agriculture: The Future to 2020" held in Viterbo, Italy, in 1995. It brought together experts from various fields and institutions including fertilizer industry groups, universities, nongovernmental organizations, and governmental agencies to examine the contributions fertilizers and other sources of plant nutrients can make to the food security of developing countries. The workshop's main conclusions and recommendations are reported in the Appendix.

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Director General

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1. Introduction

Can agriculture provide for the food needs of a world population projected to exceed 7.5 billion by the year 2020? Concern is growing that it may not. There are indications that the highly productive fertilizer and seed technologies introduced over the past three decades may be reaching a point of diminishing returns (Bouis 1993; Cassman et al. 1995; Flinn and De Datta 1984). Prospects for expanding low-cost irrigation, one of the driving forces behind yield increases, are also becoming more limited (Rosegrant and Svendsen 1993; Rosegrant 1997; Carruthers, Rosegrant, and Seckler 1997), as are the prospects for converting marginal lands into productive arable land (Bockman et al. 1990; Crosson and Anderson 1992). Furthermore, new technologies such as genetically engineered, yield-increasing plants are not expected to be major factors in food production increases in developing countries during the next two decades (Hazell 1995; Peng, Khush, and Cassman 1994). Consequently, keeping pace with population growth and increasing land scarcity will be more difficult than in the recent past.

Concerns also are growing about the long-term sustainability of agriculture. Both the over- and underapplication of fertilizer and the poor management of resources have damaged the environment. In developed countries, for example, overapplication of inorganic and organic fertilizer[1] has led to environmental contamination of water supplies and soils (Conway and Pretty 1991; Bumb and Baanante 1996; NRC 1989). In developing countries, harsh climatic conditions, population pressure, land constraints, and the decline of traditional soil management practices have often reduced soil fertility (Stoorvogel and Smaling 1990; Tandon 1998; Henao and Baanante 1999; Bumb and Baanante 1996). Because agriculture is a soil-based industry that extracts nutrients from the soil, effective and efficient approaches to slowing that removal and returning nutrients to the soil will be required in order to maintain and increase crop productivity and sustain agriculture for the long term.

The overall strategy for increasing crop yields and sustaining them at a high level must include an integrated approach to the management of soil nutrients, along with other complementary measures. An integrated approach recognizes that soils are the storehouse of most of the plant nutrients essential for plant growth and that the way in which nutrients are managed will have a major impact on plant growth, soil fertility, and agricultural sustainability. Farmers, researchers, institutions, and government all have an important role to play in sustaining agricultural productivity.

To better understand the processes at work in retaining soil fertility, the next chapter discusses the role of nutrients in creating an enabling environment for plants to grow. Chapter 3 reviews some current issues in plant nutrient use. Chapter 4 examines the decline in soil fertility, particularly in Sub-Saharan Africa, where pressures on agriculture are particularly severe. Chapter 5 discusses many of the challenges and possible responses to the decline in soil fertility at the farm level, with particular reference to the role that an integrated

[1] In this paper plant nutrients refer to all types of nutrients, whether organic or inorganic, that combine with energy from the sun to result in plant growth. The word "fertilizer" will usually refer to chemical or inorganic fertilizer unless it is explicitly qualified with the adjective "organic." Therefore, plant nutrients include both organic and inorganic fertilizers.

approach to the management of plant nutrients can play in maintaining and enhancing soil fertility. The sixth chapter looks at the contributions that institutions can make to ensure that agriculture will remain sustainable. The last chapter presents some recommendations for improving the management of plant nutrients and soil fertility in the years ahead. Several of these recommendations are based on a joint International Food Policy Research Institute/Food and Agriculture Organization of the United Nations workshop held in 1995 (Gruhn, Goletti, and Roy 1998). The workshop's main conclusions and recommendations are reported in the Appendix.

2. *Plant Nutrients and Soil Fertility*

Essential Nutrients

Plant growth is the result of a complex process whereby the plant synthesizes solar energy, carbon dioxide, water, and nutrients from the soil. In all, between 21 and 24 elements are necessary for plant growth. The primary nutrients for plant growth are nitrogen, phosphorus, and potassium (known collectively as NPK). When insufficient, these primary nutrients are most often responsible for limiting crop growth. Nitrogen, the most intensively used element, is available in virtually unlimited quantities in the atmosphere and is continually recycled among plants, soil, water, and air. However, it is often unavailable in the correct form for proper absorption and synthesis by the plant.

In addition to the primary nutrients, less intensively used secondary nutrients (sulfur, calcium, and magnesium) are necessary as well. A number of micronutrients such as chlorine, iron, manganese, zinc, copper, boron, and molybdenum also influence plant growth. These micronutrients are required in small amounts (ranging from a few grams to a few hundred grams per hectare) for the proper functioning of plant metabolism. The absolute or relative absence of any of these nutrients can hamper plant growth; alternatively, too high a concentration can be toxic to the plant or to humans.

Soil Characteristics

The capacity of soils to be productive depends on more than just plant nutrients. The physical, biological, and chemical characteristics of a soil—for example its organic matter content, acidity, texture, depth, and water-retention capacity—all influence fertility. Because these attributes differ among soils, soils differ in their quality. Some soils, because of their texture or depth, for example, are inherently productive because they can store and make available large amounts of water and nutrients to plants (Box 1). Conversely, other soils have such poor nutrient and organic matter content that they are virtually infertile.

Box 1

Soil Quality Affects Agricultural Productivity

A soil's potential for producing crops is largely determined by the environment that the soil provides for root growth. Roots need air, water, nutrients, and adequate space in which to develop. Soil attributes, such as the capacity to store water, acidity, depth, and density determine how well roots develop. Changes in these soil attributes directly affect the health of the plant. For example, bulk density, a measure of the compactness of a soil, affects agricultural productivity. When the bulk density of soil increases to a critical level, it becomes more difficult for roots to penetrate the soil, thereby impeding root growth. When bulk density has increased beyond the critical level, the soil becomes so dense that roots cannot penetrate the soil and root growth is prevented. Heavy farm equipment, erosion, and the loss of soil organic matter can lead to increases in bulk density. These changes in soil quality affect the health and producticity of the plant, and can lead to lower yields and/or higher costs of production.
Source: NRC 1993.

The way soils are managed can improve or degrade the natural quality of soils. Mismanagement has led to the degradation of millions of acres of land through erosion, compaction, salinization, acidification, and pollution by heavy metals. The process of reversing soil degradation is expensive and time consuming (Box 2); some heavily degraded soils may not be recoverable. On the other hand, good management can limit physical losses. Good management includes use of cover crops and soil conservation measures; addition of organic matter to the soil; and judicious use of chemical fertilizers, pesticides, and farm machinery.

Organic matter content is important for the proper management of soil fertility. Organic matter in soil helps plants grow by improving water-holding capacity and drought-resistance. Moreover, organic matter permits better aeration, enhances the absorption and release of nutrients, and makes the soil less susceptible to leaching and erosion (see Sekhon and Meelu 1994; Reijntjes, Haverkort, and Waters-Bayer 1992).

Plant Needs

Plants need a given quantity and mix of nutrients to flourish. The higher the yield, the greater the nutrient requirement. A shortage of one or more nutrients can inhibit or stunt plant growth. But excess nutrients, especially those provided by inorganic fertilizers, can be wasteful,[2] costly, and, in some instances, harmful to the environment. Effective and efficient management of the soil storehouse by the farmer is thus essential for maintaining soil fertility and sustaining high yields. To achieve healthy growth and optimal yield levels, nutrients must be available not only in the correct quantity and proportion, but in a usable form and at the right time. For the farmer, an economic optimum may differ from a physical optimum, depending on the added cost of inputs and the value of benefits derived from any increased output.

Nutrient Cycle

Soil nutrient availability changes over time. The continuous recycling of nutrients into and out of the soil is known as the nutrient cycle (NRC 1993). The cycle involves complex biological and chemical interactions, some of which are not yet fully understood. A simplified version of this cycle of plant growth, based on Smaling (1993), is shown in Figure 1. The simplified cycle has two parts: "inputs" that add plant nutrients to the soil and "outputs" that export them from the soil largely in the form of agricultural products. Important input sources include inorganic fertilizers; organic fertilizers such as manure, plant residues, and cover crops; nitrogen generated by leguminous plants;

Box 2

Reclaiming Acidic and Saline Soils

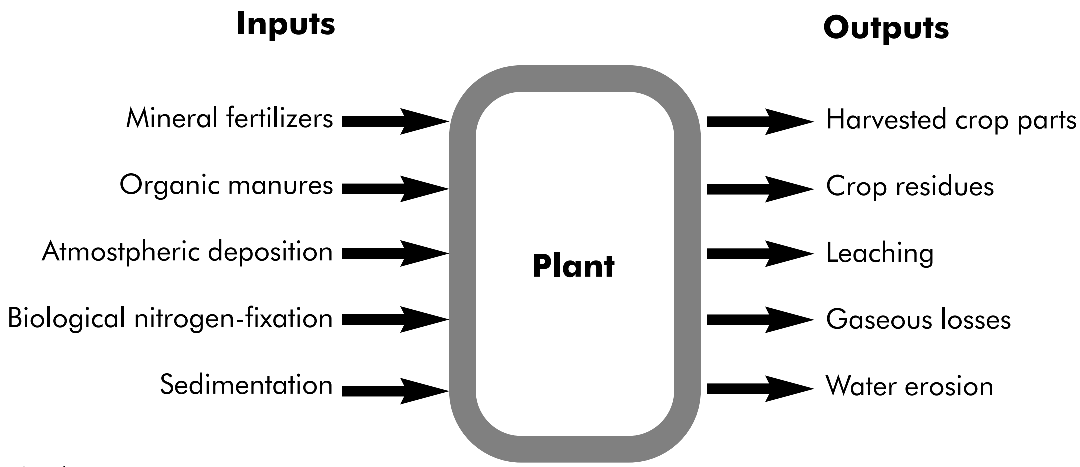
Two common features of degraded land are acidic and saline soils. Soils become acidic (low pH) through the leaching of bases by percolating water. Over time, application of most ammonia-based fertilizers will also lower pH. Lime, from limestone and dolomite, is frequently applied to raise soil pH. By improving the conditions for plant growth, liming increases nutrient removal and enhances organic matter decomposition. Concurrent application of lime and balanced nutrient replenishment is usually necessary to ensure continued long-term soil fertility.

Saline soils (high soluble salt content), sodic soils (high sodium content), saline-sodic soils (high soluble salt, high sodium), and high-lime soils are all types of alkaline soils. Drainage and nutrient application are usually sufficient to mitigate the effect of high-lime soils. Saline, sodic, and saline-sodic soils can usually be reclaimed over time through leaching. Low soil permeability and large amendment requirements make sodic soil reclamation a slow and expensive process.

Source: Thompson and Troeh 1973.

[2] See Liebig's Law of the Minimum in IFDC 1979.

Figure 1—The plant nutrient balance system



Source: Smaling 1993.

and atmospheric nitrogen deposition. Nutrients are exported from the field through harvested crops and crop residues, as well as through leaching, atmospheric volatilization, and erosion.

The difference between the volume of inputs and outputs constitutes the nutrient balance. Positive nutrient balances in the soils (occurring when nutrient additions to the soil are greater than the nutrients removed from the soil) could indicate that farming systems are inefficient and, in the extreme, that they may be polluting the environment. Negative balances could well indicate that soils are being mined and that farming systems are unsustainable over the long term. In the latter instance, nutrients have to be replenished to maintain agricultural output and soil fertility into the future. The inexpensive supply of nutrients in the form of inorganic fertilizers (Box 3) was a key factor, along with improved modern seed varieties and adequate supplies of water, in the substantial increase in yields that exemplified the Green Revolution of the 1960s and 1970s.

Box 3

Nitrogenous Fertilizer Production

By the beginning of the 20th century, natural supplies of nitrogen from atmospheric deposition, biological fixation by leguminous plants, and organic manures were inadequate for meeting agricultural needs resulting from population pressure. A plentiful, inexpensive source of nitrogenous fertilizer had to be developed. Fritz Haber was the first to develop a technique for the synthetic production of ammonia, for which he won the 1918 Nobel Prize in chemistry. Based on Haber's technique, Karl Bosch (chemistry Nobel prize winner of 1931) developed the production process that would make ammonia production economically viable. With the development of centrifugal compressors, the use of natural gas and naphtha as plentiful and inexpensive feedstocks, improvement in economies of scale, and other technological advances, the cost of ammonia production fell steadily from US $200 per ton in 1940 to US $30 per ton in 1972 (IFDC 1979). Along with the development of nutrient-responsive modern varieties, ammonia-based nitrogen and other inexpensive inorganic fertilizers provided the basis for the Green Revolution.

3. Some Issues in Plant Nutrient Use and Soil Fertility

Slowing Yield Growth

Despite the continued development of new and improved modern varieties and greater use of chemical fertilizers, yield growth began to slow in the latter part of the 20th century. The world's annual cereal yield growth rate has declined from an average of 2.2 percent in the 1970s to 1.1 percent in the 1990s (Table 1). Wheat yields in Asia grew at an average annual rate of 4.3 percent during the 1970s. But during 1990–1997, wheat yields dropped to the far slower growth rate of 0.7 percent per year. After rapid growth of almost 2.4 percent per year during the 1980s, Asian rice yield growth fell to 1.5 percent per year in the 1990s. This global slowdown has raised concerns that yield growth may have reached a plateau or begun to decline in many of the world's most fertile areas. In Sub-Saharan Africa, the situation is even more dramatic, with cereal yield growth decreasing steadily from 1.9 percent during the 1970s to 0.7 percent in the 1990s. These declines in Sub-Saharan Africa are partly attributable to poor soil management, which in turn has been accentuated by a number of other factors, including inappropriate policies, insufficient commitment to investment in agricultural research, falling agricultural prices, demographic pressures, land availability constraints, and ill-defined property rights. The cumulative effect of all these factors has led to increased soil mining. The remainder of this chapter will examine some of these factors as they apply the world over. The next chapter will focus specifically on Sub-Saharan Africa.

Slowdown in Investment

During the 1970s, governments and intergovernmental organizations gave investment in agricultural research a relatively high priority. In Asia, for example, real expenditure on public agricultural research and development grew at an average annual rate of 8.7 percent. During the 1980s, however, real expenditure growth in Asia slowed to 6.2 percent per year. Spending in Sub-Saharan Africa slowed even further, from 2.5 percent per year during the 1970s to 0.8 percent during the 1980s. For developed countries, investment growth slowed as well from 2.7 percent per year in the 1970s to 1.7 percent in the 1980s (Alston, Pardey, and Smith 1998). Without continued investment in research to propel the development of yield-enhancing technologies and sustainable agricultural management practices, crop yield growth could eventually stagnate and soil fertility could degrade to irrecoverable levels.

Investment in new irrigation infrastructure has also declined from its peak during the late 1970s and early 1980s. Both average annual public expenditures and annual lending and assistance for irrigation systems from international development agencies have fallen. Numerous factors have contributed to the reduction in irrigation investment, including the poor performance of some past investments, fewer low-cost irrigation sites for potential development, increased real capital costs for construction of new irrigation systems, and environmental concerns such as the spread of salinization (Rosegrant and Pingali 1994; Rosegrant and

Table 1—Annual cereal crop yield growth rates, 1970s -1990s

Crop	Region	1970s	1980s	1990s
			(percent)	
Wheat	Asia	4.33	3.71	0.72
	Latin America	0.60	3.40	2.36
	Sub-Saharan Africa	3.54	0.92	−0.81
	World	2.10	2.78	0.42
Rice	Asia	1.61	2.42	1.55
	Latin America	0.70	2.97	3.71
	Sub-Saharan Africa	0.02	2.51	−0.56
	World	1.49	2.37	1.54
Maize	Asia	3.43	2.75	1.55
	Latin America	1.49	0.61	3.82
	Sub-Saharan Africa	2.26	1.72	2.09
	World	3.19	0.60	1.76
Cereals	Asia	2.90	2.79	1.46
	Latin America	1.69	1.28	3.12
	Sub-Saharan Africa	1.90	0.56	0.66
	World	2.18	1.79	1.12

Source: Computed by the authors using data from FAO 1998.
Note: The 1990s refer to the period 1990–97.

Svendsen 1993). In Sub-Saharan Africa, lack of water is a serious restriction as well. Currently only 4 percent of cultivated land in Sub-Saharan Africa (5.3 million hectares) is irrigated, of which 70 percent is in Madagascar, Nigeria, and Sudan. Insufficient water retards nutrient availability and plant growth. Although the potential exists to bring an additional 20 million hectares of land under irrigation in Sub-Saharan Africa, technical, financial and socioeconomic constraints have slowed this expansion (Vlek 1993; World Bank 1989).

Declining commodity prices during the 1980s also reduced governmental and intergovernmental incentives to make agriculture-related investments. Prices for coffee and cocoa during the 1990-92 period fell to 39 percent of their nominal price in 1980-82. Similarly, the prices of wheat, maize, and rice in 1990-92 declined to 60, 61, and 50 percent of the prices, respectively, in 1980-82 (OECD 1993). In addition to reducing investment incentives, declining prices reduced farmers' incomes, often forcing them to mine soils more intensively. If crop yields are to increase and if agriculture is to be sustainable over the long term, a renewed commitment to agricultural research and infrastructure will be necessary.

Nutrient Overapplication and Environmental Contamination

Concern has also grown in recent years that the use of fertilizers, particularly inorganic fertilizers, can lead to serious environmental consequences. Environmental contamination of this type, however, is largely a problem in the developed world and a few regions of the developing world. As fertilizers make up a small share of the total production costs in many developed countries, farmers often apply fertilizer in excess of recommended levels in order to ensure high yields. Overapplication of inorganic and organic fertilizers is estimated to have boosted nutrient capacity in the soil by about 2,000 kilograms of nitrogen, 700 kilograms of phosphorus, and 1,000 kilograms of potassium per hectare of arable land in Europe and North America during the past 30 years (World Bank 1996). Such oversupply of nutrients can lead to environmental contamination, which often has negative consequences for humans and animals. Overapplication of nitrogen, for example, allows the nutrient to be carried away in groundwater and to contaminate surface water and underground aquifers. Ingestion of nitrate can be toxic to humans and animals when it is transformed within the body into nitrite, which affects the oxygen-carrying ability of red blood cells. Evidence also suggests that nitrite and the carcinogenic compounds it can create may also lead to goiter, birth defects, heart disease, and stomach, liver, and esophagus cancers (Conway and Pretty 1991).

Leaching and run-off of surplus nitrogen and phosphorus into rivers, lakes, and inlets can cause eutrophication—an excess accumulation of nutrients in water that promotes the overproduction of algae. Excess surface algae deprive underwater plants of sunlight, which in turn alters the aquatic food cycle. The decomposition of dead algae by bacteria reduces the amount of oxygen in the water available for fish.

Nitrogen also escapes into the atmosphere in the form of nitrogen gas and various nitrous oxides. In the upper atmosphere, nitrous oxides react to form acid rain, which can harm crops, acidify soil and water, and damage property. Cumulative application of acidifying ammonia-based fertilizers, together with acid rain, also contributes to soil acidification.

Evidence is mounting that excessive fertilization can damage the environment. In the United Kingdom, some 1.6 million people get water with nitrate levels that exceed guidelines, and Danish, Dutch, and German coastal regions show signs of eutrophication (Bockman et al. 1990). Furthermore, USDA (U.S. Department of Agriculture) estimates that agriculture causes nearly two-thirds of the pollution in U.S. rivers and that runoff from excess plant nutrient application causes close to 60 percent of the pollution in lakes (NRC 1993).

4. Soil Fertility Problems: Focus on Sub-Saharan Africa

While the overapplication of inorganic and organic fertilizers has led to environmental contamination in a number of areas in the developed world, insufficient application of nutrients and poor soil management, along with harsh climatic conditions and other factors, have contributed to the degradation of soils in Sub-Saharan Africa.

Climatic Conditions and Soil Management

Harsh climatic conditions contribute to soil erosion in several parts of Sub-Saharan Africa. Rapid water evaporation and inadequate and highly variable rainfall, for instance, deprive plants of the water necessary for growth. High atmospheric temperatures, strong light, and heat-retentive, sandy soils can combine to make the local environment too hot for proper plant growth. Powerful, dry wind gusts may also damage plants through both lodging (which causes plants to fall over and die before harvest) and evaporation (Lawson and Sivakumar 1991). Together, these harsh climatic factors, coupled with poor soil management, have reduced soil fertility by contributing to soil and water erosion. Slight to moderate erosion slowly strips the land of the soil, organic matter, and nutrients necessary for plant growth. This degradation increases the opportunity for drought and further erosion because it reduces the water-infiltration and water-holding capacity of the soil (Crosson 1986). Severe erosion may create gullies that interfere with farm machinery use. It may also lead to the conversion of land to lower-value uses, or its temporary or permanent abandonment. Off-farm erosion can lead to siltation in watersheds and a decline in water quality (Scherr and Yadav 1996). In such an environment, effective soil, water, pest, and crop management becomes absolutely essential. But economic and other pressures often make it difficult for farmers and their families to efficiently manage the soil for long-term profitability and sustainability.

Property Rights, Land Constraints, and Demographic Pressures on Soil Fertility

Insecure and crumbling tenure arrangements also contribute to declining soil fertility. Communal rights to graze land without any effort to maximize long-term returns has led to serious overgrazing, which is reported to be the main cause of human-induced degradation in Africa (Box 4). Ill-defined property rights and insecure tenure rights have also reduced the incentive for farmers to undertake soil fertility-enhancing investments. Secure tenure arrangements can help induce investment in soil fertility to reap the long-term reward of sustained high crop yields and greater profits. In Niger, for example, secure land for growing millet accounts for 90 percent of manured fields. These fields received an average of 307 kilograms per hectare of manure, while unsecured millet fields received only 186 kilograms per hectare (Hopkins, Berry, and Gruhn 1995). Sharecropping may contribute to land degradation as well. In Ghana, for example, sharecroppers have put enormous pressure on soil fertility to realize immediate high yields in order to pay land rents (Benneh 1997). Farmers in such situations discount the future at very high rates, thereby reducing the incentive for long-term investments in improved soil fertility.

Demographic pressures and land availability constraints have also contributed to the decline in yield growth and soil fertility. With increasing populations, the traditional techniques for renewing soil fertility, such as slash-and-burn and long-term fallowing, are not as feasible as they once were. The need for subsistence production and income are such that land can no longer be taken out of production for substantial periods to allow for natural nutrient replenishment. Nor are animal manures and crop residues usually sufficient for replacing lost nutrients. In addition, the promotion of rural nonagricultural development has increased the demand for crop residues as a source of fodder, fuel, and raw materials for artisanal activities, thereby limiting their availability as soil amendments.

Other traditional soil fertility management techniques also generally fall short of the nutrient requirements of today's intensive agricultural practices. For example, in order to provide 150 kg of plant nutrients to fertilize one hectare of land, a farmer could apply either 300 kg of inorganic NPK fertilizer, or 20 to 25 metric tons of crop residue grown on 6 to 10 hectares of land, or 18 metric tons of animal manure generated from crop residue grown on 10 to 15 hectares of land (Ange 1992). Under normal circumstances, farmers generally do not have the resources to produce sufficient organic fertilizers to replace all the nutrients removed at harvest time. Indeed, it has been estimated that without the improved input technologies developed during the 20th century, the planet would feed no more than 2.6 billion people, less than half its present population (Buringh and van Heemst 1977).

The Cumulative Effect of Negative Nutrient Balances

Cumulative negative nutrient balances heighten the impact of climatic factors, insecure tenure arrangements, and land and demographic pressures on soil fertility. In 1993 7 million metric tons of nitrogen, phosphorus, potassium, magnesium, and calcium were depleted from soils in the low-income countries of Bangladesh, Indonesia, Myanmar, Philippines,

Box 4

Extent and Causes of Human-Induced Soil Degradation

Soils in many countries suffer from declining fertility. Their physical and chemical structure are deteriorating and the vital nutrients for plant growth are slowly being depleted. By some estimates, the annual cost of environmental degradation in some countries ranges from 4 to 17 percent of gross national product. Three-quarters of the area degraded by inappropriate agricultural practices, overgrazing, and deforestation is in the developing world. The tables below illustrate the extent and human-induced causes of degradation in Africa, Asia, and South America (WRI, UNEP, and UNDP 1992; Oldeman 1992).

Extent of human-induced, nutrient-related soil degradation in selected regions (million hectares)

Region	Light Degradation	Moderate Degradation	Severe Degradation
Africa	20.4	18.8	6.6
Asia	4.6	9.0	1.0
South America	24.5	31.1	12.6

Source: Oldeman, Makkeling, and Sombroek 1992.

Human-induced causes of soil-degradation (percent)

Region	Deforestation	Overexploitation	Overgrazing	Agricultural activities	Industrial activities
Africa	13.6	12.8	49.2	24.5	---
Asia	39.9	6.2	26.4	27.3	0.1
South America	41.0	4.9	27.9	26.2	---
World	29.5	6.8	34.5	28.1	1.2

Source: Oldeman 1992.

Thailand, and Vietnam (Mutert 1996). In Sub-Saharan Africa net annual nutrient depletion was estimated at 22 kilograms of nitrogen, 2.5 kilograms of phosphorus, and 15 kilograms of potassium per hectare during 1982-84 (Stoorvogel, Smaling, and Janssen 1993). Estimates in Sub-Saharan Africa indicate a net loss of about 700 kilograms of nitrogen, 100 kilograms of phosphorus, and 450 kilograms of potassium per hectare in about 100 million hectares of cultivated land over the last 30 years (World Bank 1996). In addition, recent work by Henao and Baanante (1999) suggests that nutrient mining may be accelerating. In the more densely populated, semiarid, and Sudano-Sahelian area of Sub-Saharan Africa, net NPK losses have been estimated at between 60 and 100 kilograms per hectare per year. About 86 percent of the countries in Africa lose more than 30 kilograms of NPK per hectare per year (Henao and Baanante 1999).

The cumulative effect of yearly negative nutrient balances on crop yields is often seen through the impact of soil erosion on productivity. In the United States, for example, if present erosion rates continue and inputs are managed effectively, productivity could decrease by 5 to 8 percent over the next 100 years (Crosson 1986; Hagen and Dyke 1980), with regional variations ranging from 0.7 to 7.1 percent (USDA 1989) or 3 to 10 percent (Crosson and Anderson 1992). Modern integrated management and conservation practices could lower projected erosion-related productivity losses to about 2 percent over the next 100 years (USDA 1989). But this is a largely insignificant decrease when considered against annual productivity gains in the U.S. of about 1 percent per year from new technology and improved management (NRC 1989).

In many parts of the developing world where poor soil conservation and management methods prevail, however, long-term productivity is projected to decline substantially unless soil management practices improve. In Africa (Dregne 1990; Lal 1991) and Asia (Dregne 1992), past erosion has reportedly reduced average yields by 10 to 20 percent over the past 100 years. In especially fragile areas, such as in southeastern Tunisia, erosion has reduced long-term productivity by more than 50 percent (Dregne 1990). If erosion at this rate continues unabated, yields may decrease by another 16.5 percent in Asia and 14.5 percent in Sub-Saharan Africa by 2020 (Scherr and Yadav 1996).

Despite the cumulative effect of negative nutrient balances, overall yields in Africa have increased. From 1960 to the mid-1990s, wheat yields more than doubled from 0.7 to 1.8 metric tons per hectare, while maize yields rose from 1.0 to 1.7 metric tons (FAO various years). Together with the limited adoption of new technologies, the mobility of the Sub-Saharan Africa farmer has been a major factor in the improvement of yields, albeit at the cost of soil degradation. Between 1973 and 1988, arable and cropped land increased by 14 million hectares, forest and woodland area fell by 40 million hectares, and pasture land remained stable. Thus 26 million hectares (the difference in total land use) have been lost to desertification or abandoned. The effect of reduced soil fertility remains generally hidden because farmers abandon nutrient-depleted land to clear and farm uncultivated, marginal land. Once the land constraint becomes binding, however, as in the case of the Mossi plateau region in Burkina Faso, yields and production decline, thereby also contributing to migration to urban areas (Vlek 1993).

Declining Soil Fertility

The effects of declining soil fertility on yield growth are particularly visible in Africa, where the most serious food security challenges exist and lie ahead (Badiane and Delgado 1995; Rosegrant, Agcaoili-Sombilla, and Perez 1995). The low level of chemical fertilizer use, decline in soil organic matter, and insufficient attention to crop nutrient studies contribute the most to the loss of soil fertility in the region (Kumwenda et al. 1996).

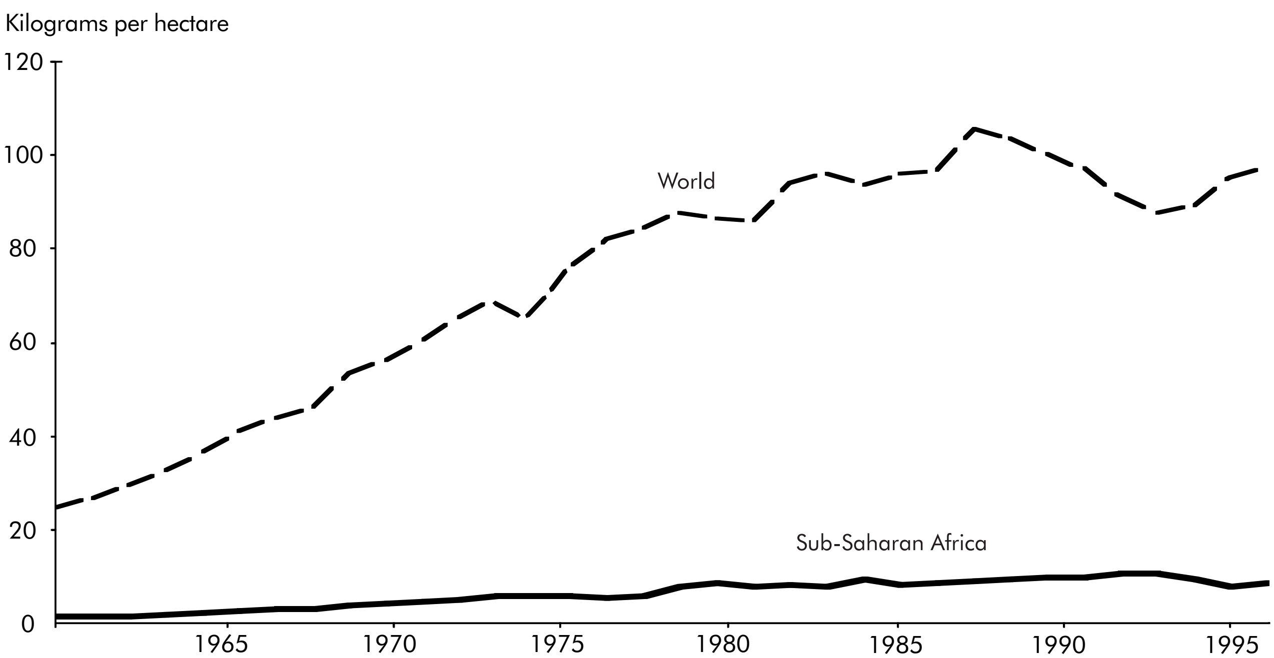
In comparison to the rest of the world, fertilizer use in Sub-Saharan Africa is low and declining. In 1996, Sub-Saharan Africa consumed only 1.2 million tons of fertilizer, (equivalent to 8.9 kilograms per hectare of arable land) (Figure 2). By comparison, global fertilizer use reached approximately

135 million tons in 1996, equivalent to 97.7 kilograms per hectare (FAO 1998 and 1999). While fertilizer use per hectare in developing countries continued to increase at a rate of 3.1 percent per year during the 1990s, in Sub-Saharan Africa it declined (Table 2). The fall in consumption has been most dramatic in West Africa and the developing countries of Southern Africa. Fertilizer use would probably be even lower if foreign aid were not available. More than half of the nitrogenous, phosphate, and potash fertilizer consumed in developing Africa is imported in the form of aid. In 1990, 22 of 40 Sub-Saharan Africa countries received all their fertilizer imports as aid (FERTECON 1993).

High import prices contribute to the low level of fertilizer use in Sub-Saharan Africa. High fertilizer prices arise from small procurement orders (tenders for less than 5,000 metric tons are common), weak bargaining power, and high freight and international marketing costs. Special mixes tailored for African needs, and other micronutrient additions, such as sulfur or boron, may add an additional US$35 per ton or about 20 percent to the price (Coster 1991). When coupled with high transportation costs due to poor infrastructure, the domestic prices of chemical fertilizer are such that one kilogram of nitrogenous fertilizer can cost the typical African farmer between 6 and 11 kilograms of grain, compared with 2 to 3 kilograms of grain in Asia (Isherwood 1996; Heiney and Mwangi 1997).

Most African farmers practice low-input agriculture that depends on organic matter in the soil to sustain production. Soil organic matter plays an important part in establishing the intrinsic properties of a soil, which make plant growth possible. Soil organic matter helps sustain soil fertility by improving retention of mineral nutrients, increasing the water-holding capacity of soils, and increasing the amount of soil flora and fauna (Woomer et al. 1994). Continuous cropping and erosion reduce the level of soil organic matter. Low-input systems can maintain and enhance soil organic matter though crop rotation and intercropping, the application of animal and green manures, fallowing, and reduced tillage (Kumwenda et al. 1996). But as pressure on land and crop intensification increase, these options do not remain practical. The adoption of intercropping and crop rotation techniques is often constrained by the extent of land and technology available and by the lack of knowledge

Figure 2—Fertilizer consumption in Sub-Saharan Africa and the world, 1961-96



Source: Computed by the authors using data from FAO 1998 and 1999.

Table 2—Annual growth rates in fertilizer use per hectare, 1960s -1990s

	West Africa	East Africa	Southern Africa	Sub-Saharan Africa	Developing world	World
			(percent)			
1960s	14.2	10.2	5.7	11.8	15.4	9.4
1970s	17.6	1.3	10.4	4.8	9.9	5.2
1980s	4.0	1.5	−3.9	1.9	4.6	2.2
1990s	−8.8	0.7	−3.4	−3.2	3.1	−0.5
1960s-1990s	9.7	4.2	3.6	5.4	8.3	3.7

Source: Computed by the authors using data from FAO 1998 and 1999.
Note: The 1990s refer to the period 1990 – 1996.

about optimal management techniques. Farmers need to know how to combine organic fertilizers with chemical fertilizers, apply improved pest and weed management techniques, and adopt high-yielding crop varieties (Kumwenda et al. 1996). Insufficient attention to effective crop nutrition and soil fertility management studies has also made it difficult to improve yields in Africa, even when improved germplasm has been made available. More research, expanded extension, and greater integration of knowledge could provide farmers with a stronger incentive to improve yields, maintain soil fertility, and sustain agriculture.

Government Commitment to Agriculture and Structural Adjustment

Although agriculture is increasingly recognized as the engine of economic growth in Sub-Saharan Africa, the level of government commitment to it is low. In the past governments often have penalized agriculture through a variety of mechanisms, including export and import taxes, foreign exchange controls, export licensing requirements and controls, and bureaucratic marketing boards. Food subsidies have allowed governments to keep food prices low, often to appease vocal urban constituents, but at the expense of rural producers. Such policies and practices have reduced farmers' incentives to increase local foodgrain production and use modern inputs to improve productivity. The lack of competition and heavy government regulation, along with structural factors such as inadequate institutional and physical infrastructure and underdeveloped research and extension systems, have often made fertilizer distribution systems inefficient and ineffective in meeting farmers' needs (World Bank 1993; Lele 1994; Bumb and Baanante 1996).

Structural adjustment programs (SAPs) have been instituted in many countries partly in response to these and other market failures. SAPs seek to reallocate resource use in order to improve economic efficiency and social welfare. Among other things, the programs have devalued exchange rates, the immediate effect of which has made imports such as fertilizers more expensive, which in turn has often increased farmers' costs markedly. Nitrogen-to-maize price ratios in Ghana, Tanzania, and Zambia, for example, were substantially higher during the 1990s, after the SAPs were instituted, than during the 1980s, when price controls and subsidies were in effect (Heiney and Mwangi 1997). The SAPs and higher input prices consequently have reduced the profitability of using fertilizer to increase the production of foodgrains for domestic consumption. Farmers growing export crops, though, have benefited from the restructuring of currencies and increased their fertilizer use. But, given the vast acreage devoted to food crops compared with the modest area under export crops, the devaluation of currencies and the reduction of fertilizer subsidies on balance have militated against increased application of imported fertilizers. Regardless of the type of crop produced, and despite the cost of fertilizer, three factors appear to be key in determining whether farmers use fertilizers. First, fertilizers should help farmers obtain sufficiently high yields. Second, farmers should be near major towns, where agricultural input distributors are located, in order to benefit from lower prices for inputs and higher prices and lower marketing costs for outputs. Third, farmers should be able to store at least part of their output, so that they can take advantage of higher out-of-season prices (Donovan and Casey 1998).When these three factors are in place, farmers are more willing and able to use fertilizer to increase income and sustain soils for the long term.

5. Challenges and Responses at the Farmer's Level

The Need for Concerted Action

Declining soil fertility and mismanagement of plant nutrients have made the task of providing food for the world's population in 2020 and beyond more difficult. The negative consequences of environmental damage, land constraints, population pressure, and institutional deficiencies have been reinforced by a limited understanding of the biological processes necessary to optimize nutrient cycling, minimize use of external inputs, and maximize input use efficiency, particularly in tropical agriculture (Kumwenda et al. 1996). But some responses can ameliorate these difficulties. The responses highlighted here comprise the approach commonly known as integrated nutrient management (INM). Institutional needs are discussed in the next chapter. The implementation of INM responses will require a concerted and committed effort by actors from a variety of sectors, including the private and public sectors, scientific and policy organizations, and industrialized and developing countries.

Integrated Nutrient Management

Goal of INM

Sustainable agricultural production incorporates the idea that natural resources should be used to generate increased output and incomes, especially for low-income groups, without depleting the natural resource base. In this context, INM maintains soils as storehouses of plant nutrients that are essential for vegetative growth. INM's goal is to integrate the use of all natural and man-made sources of plant nutrients, so that crop productivity increases in an efficient and environmentally benign manner, without sacrificing soil productivity of future generations. INM relies on a number of factors, including appropriate nutrient application and conservation and the transfer of knowledge about INM practices to farmers and researchers.

Plant Nutrient Application

Balanced application of appropriate fertilizers is a major component of INM. Fertilizers need to be applied at the level required for optimal crop growth based on crop requirements and agroclimatic considerations. At the same time, negative externalities should be minimized. Overapplication of fertilizers, while inexpensive for some farmers in developed countries, induces neither substantially greater crop nutrient uptake nor significantly higher yields (Smaling and Braun 1996). Rather, excessive nutrient applications are economically wasteful and can damage the environment. Underapplication, on the other hand, can retard crop growth and lower yields in the short term, and in the long term jeopardize sustainability through soil mining and erosion. The wrong kind of nutrient application can be wasteful as well. In Ngados, East Java, for example, the application of more than 1,000 kilograms per hectare of chemical fertilizer could not prevent potato crop yields from declining. Yields on these fields decreased more than 50 percent in comparison with yields on fields where improved soil management techniques were used and green manure was applied (Conway and Barbier 1990). The correction of nutrient imbalances can have a dramatic effect on yields. In Kenya the application of nitrogenous fertilizer on nitrogen-poor soils increased maize yields from 4.5 to 6.3 tons per hectare, while application of less appropriate phosphate fertilizers increased yields to only 4.7 tons per hectare (Smaling and Braun 1996). Balanced fertilization should also include secondary nutrients and micronutrients, both of which are often most readily available from organic fertilizers such as animal and green manures.

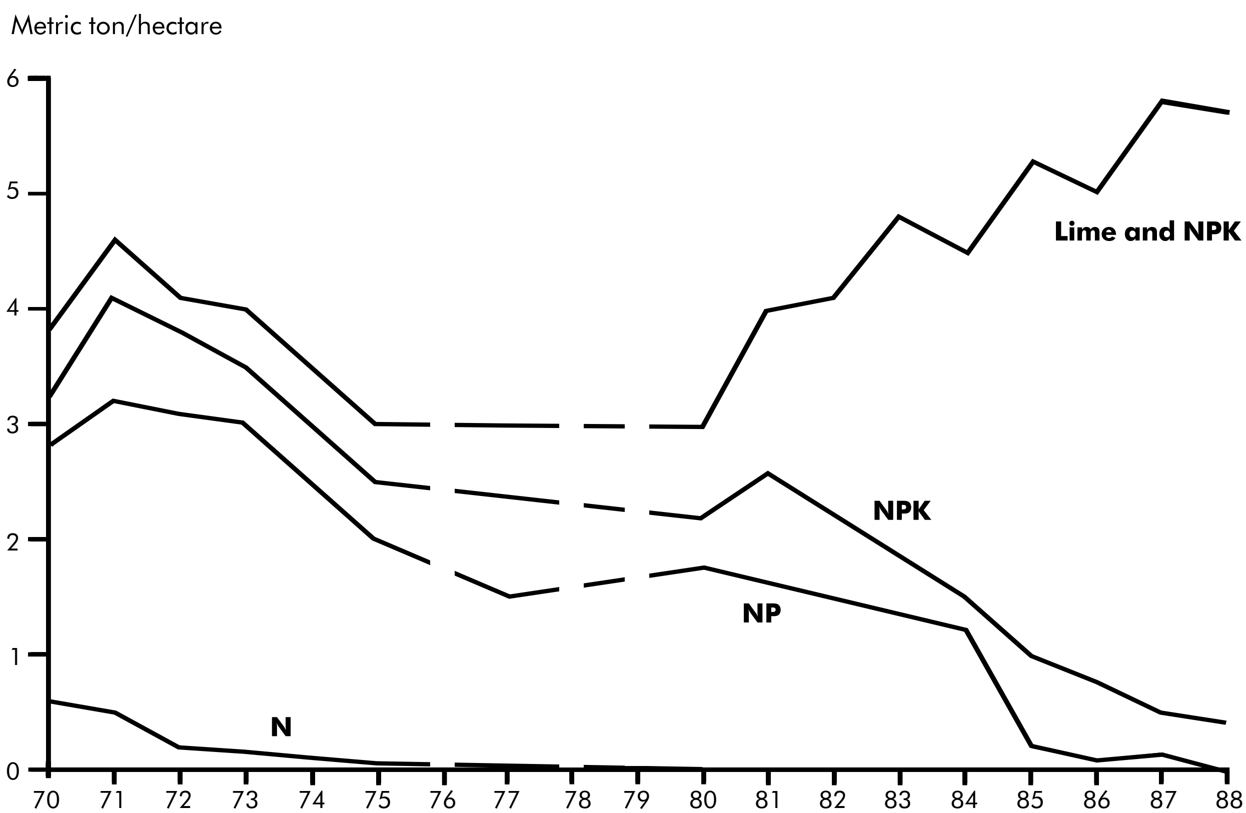
Lastly, balance is necessary for sustainability over time. Figure 3 shows that wheat yields become uneconomical after 5 years when only N fertilizer is applied. Even annual field applications of NP and NPK fertilizers were insufficient to sustain yields over the long term. Only when both lime and NPK fertilizer were applied did yields increase and fields remain productive despite continuous cultivation (Saxena 1995).

Coupled with other complementary measures, effective nutrient and soil management can help to reclaim degraded lands for long-term use in some cases. Heavy fertilizer applications on moderately degraded soil can not only replenish nutrients, but can produce about 7 tons per hectare of maize and about 6 tons per hectare of grain straw, which long-term studies in Iowa have shown can increase organic matter content in the soil (Ange 1993). Experiments in Ghana and Niger have demonstrated that by increasing the longevity and productivity of suitable agricultural land, the application of inorganic and organic fertilizer reduces the need to cultivate unsustainable and fragile marginal lands (Vlek 1990).

Nutrient Conservation and Uptake

Nutrient conservation in the soil is another critical component of INM. Soil conservation technologies prevent the physical loss of soil and nutrients through leaching and erosion and fall into three general categories. First, practices such as terracing, alley cropping, and low-till farming alter the local physical environment of the field and thereby prevent soil and nutrients from being carried away. Second, mulch application, cover crops, intercrop-

Figure 3—Long-term effect of balanced fertilization on wheat yield, 1970-88



Source: Saxena 1995.
Note: Data are missing for 1976, 1978, and 1979.

ping, and biological nitrogen fixation act as physical barriers to wind and water erosion and help to improve soil characteristics and structure. Lastly, organic manures such as animal and green manures also aid soil conservation by improving soil structure and replenishing secondary nutrients and micronutrients (Kumwenda et al. 1996).

Improved application and targeting of inorganic and organic fertilizer not only conserves nutrients in the soil, but makes nutrient uptake more efficient. Most crops make inefficient use of nitrogen. Often less than 50 percent of applied nitrogen is found in the harvest crop. In a particular case in Niger, only 20 percent of applied nitrogen remained in the harvest crop (Christianson and Vlek 1991). Volatilization of ammonia into the atmosphere can account for a large share of the lost nitrogen. In flooded rice, for example, volatilization can cause 20 to 80 percent of nitrogen to be lost from fertilizer sources (Freney 1996). These losses can be reduced, however. Deep placement of fertilizers in soil provides a physical barrier that traps ammonia. The use of inhibitors or urea coatings that slow the conversion of urea to ammonium can reduce the nutrient loss that occurs through leaching, runoff, and volatilization. With innovations of these kinds, better timing, and more concentrated fertilizers, nutrient uptake efficiency can be expected to improve by as much as 30 percent in the developed world and 20 percent in developing countries by the year 2020 (Bumb and Baanante 1996).

Untapped Nutrient Sources

If used appropriately, the recycling of organic waste from urban to rural areas is a potential, largely untapped, source of nutrients for farm and crop needs, especially on agricultural lands near urban centers. For example, environmentally undesirable wastewater has been used to irrigate fields and return nutrients and organic matter to the soil (Tandon 1992). Like organic manure, urban waste sludge is a source of primary nutrients, albeit a relatively poor source in comparison with commercial fertilizers. Stabilized municipal waste sludge typically contains about 3.3 percent nitrogen, 2.3 percent phosphorus, and 0.3 percent potassium, although some concentrations can reach as high as 10 percent nitrogen and 8 percent phosphorus on a dry weight basis (EPA 1984). Actual nutrient content, however, varies widely and depends on the source of the waste. Urban waste also has a number of other benefits. Like other organic manures, it helps improve soil structure by adding organic matter to the soil. It is also a source of the secondary nutrients and micronutrients that are necessary in small quantities for proper plant growth. In addition, urban waste transforms material that would otherwise be slated for costly disposal into a useful farm product.

Urban waste needs to be treated carefully because it may contain heavy metals, parasites, and other pathogens. The buildup of heavy metal concentrations in the soil can be cause for concern. While trace amounts of some heavy metals play a critical role in plant metabolism, excessive amounts have reduced crop yields and could be dangerous to public and grazing livestock (Conway and Pretty 1991). To minimize these risks the continuous application of urban waste needs to be monitored in order to ensure that heavy metal and overall nutrient concentrations do not reach toxic levels and do not damage the environment through leaching and eutrophication.

Urban waste also contains organic compounds such as dyes, inks, pesticides, and solvents that are often found in commercial and industrial sludge. These pathogens have been shown to cause genetic damage, while others, such as bacteria, protozoa, and viruses can cause salmonellosis, amoebic dysentery, and infectious hepatitis (Conway and Pretty 1991). Untreated urban waste can put these pathogens in contact with fruits and vegetables. One option is to compost the sludge. Composting concentrates nutrients and helps to kill disease-causing organisms, slow the release of nitrogen that might otherwise percolate into groundwater, and eliminate aesthetically objectionable odors (Kurihara 1984). Another option is to use ionizing radiation to kill pathogens in and on food without affecting taste. Despite some public concern about the safety of food irradiation, the technique is likely to be adopted more fully in the future in order to protect public health, improve the shelf-life of food, and make it more feasible to apply treated, nutrient-rich urban waste to farmland.

Currently, effective use of urban waste is hampered by its high water content, bulkiness, distance from rural areas, contamination with nondecomposable household items, and high handling, storage, transport, and application costs. However, given the cost and the lack of availability of inorganic fertilizers in some areas, the relative abundance and benefit of urban waste as a soil amendment, and the rising cost of environmentally safe waste disposal, economies may make urban waste an appropriate fertilizer choice in areas where agricultural lands are near urban centers.

Alternative sources of inorganic fertilizers will also be required in the future, particularly in those parts of Africa where the fertility of the soil needs to be rebuilt and high costs and supply constraints limit the application of fertilizer. Soil infertility (particularly phosphorus deficiency) in parts of semiarid West Africa, for example, limits crop production more than the lack of moisture. Phosphorus application of 15-20 kilograms per hectare can substantially improve crop yields. Medium-reactive and partially acidulated, less-reactive phosphate rock found in Mali, Niger, and Senegal are as agronomically effective as commercial superphosphate fertilizers (Bationo and Mokwunye 1991). Low-cost technology needs to be developed so that phosphate fertilizer can be locally produced from these and other untouched or currently uneconomical phosphate rock reserves. Where phosphate deficiency is severe in Sub-Saharan Africa, government assistance in developing low-cost technology and in applying phosphate fertilizer should be evaluated. Because phosphorus and phosphorus rock bind to the soil and thereby reduce the opportunity for leaching, and because these fertilizers release nutrients slowly over time, their use to preserve the long-term productive capacity of the land should be considered more of a capital investment than a subsidy or an environmentally undesirable government intervention (Mokwunye 1995; Gerner and Baanante 1995; Teboh 1995).

Internal Nutrient Sources

Although new sources of nutrients can be developed, genetic engineering offers the potential for plants themselves to generate some of the nutrients they require through nitrogen fixation. In this process, rhizobium bacteria infect, invade, and draw energy from leguminous plants, and in return the bacteria convert and store atmospheric nitrogen in a form that the plant can use for growth (Rao 1993). Besides helping the plants themselves, cereals grown in rotation with leguminous plants can absorb the nitrates released from the decaying roots and nodules of the leguminous plants. Experiments have shown that rice-legume rotations can result in a 30 percent reduction in chemical fertilizer use (Pingali and Rosegrant 1994).

Genetic research has begun to identify the genes responsible for such nitrogen fixation and assimilation. Further research offers the opportunity of altering or developing microorganisms that can fix nitrogen in nonleguminous plants, such as cereals. As with leguminous plants, plant nitrogen needs could be partially met by the plant itself, such that farmers would then simply need to top-up crops with inorganic nitrogen fertilizers (Rao 1993). The task is considerable. Some 17 genes code the enzymes involved in nitrogen fixation. Since these genes, as well as the genes necessary for nodule formation, need to be transferred, the process is complex and its realization will be costly. Furthermore, because the amount of energy required to fix 150 kilograms of nitrogen per hectare could reduce wheat yields by 20-30 percent, an appropriate balance needs to be found between the nutrient-supply-enhancing benefits of nitrogen fixation and the potential reduction in yields (Greenley and Farrington 1989; Lipton and Longhurst1989).

6. Challenges and Responses at the Institutional Level

The promotion of integrated nutrient management in different parts of the world, and particularly in rural areas of developing countries where most of the poor live, will require a concerted effort by a multitude of actors. The following sections discuss the key components of a strategy for building appropriate institutions involved in research, extension, and participatory work on INM.

Research

The means to improve nutrient and soil fertility management may well differ in many parts of the world. Whatever steps can be taken will depend, in the first instance, on having adequate information on a wide range of topics dealing with the nutrient cycle. Even though some valuable agricultural research has been conducted in temperate regions (Box 5), the research in tropical regions presents enormous challenges that will require the cooperation of both national and international agricultural research centers. For example, much more needs to be known about the role of micronutrients in many parts of Asia, where rice yields in irrigated areas appear to have leveled off despite increasing rates of NPK application (Gill 1995). Similarly, more needs to be known about whether constraints arising from a shortage of micronutrients are affecting production in the potentially rich soils of areas such as the Llanos Orientales in Latin America. Deriving such information may require a reorientation of ongoing research and trials as well as the initiation of research and monitoring efforts specifically intended to learn more about soil management under different conditions. A study in the Brazilian sertao illustrates the nutrient management research currently underway in some developing countries. The high aluminum toxicity of sertao soils has limited crop production in these areas. Sustained research has led to the development of a package of inputs of new plant varieties, crop rotations, and soil additives that could well transform large areas of previously unproductive sertao lands into a source of millions

Box 5

Benefits of Integrated Nutrient Management

Sufficient and balanced application of organic and inorganic fertilizers is a major component of INM. Classical field experiments at the Rothamsted Experimental Station in England have provided a wealth of INM-related information on crops grown continuously and in rotation under a variety of soil fertility amendments. A number of lessons can be learned about appropriate and balanced fertilization from these experiments. Continuously cropped wheat, without the benefit of organic and inorganic fertilizers, typically has low yields, on the order of 1.2 tons per hectare. Short fallow rotations of one to three years have little effect on yields. The application of organic and inorganic fertilizers can increase average wheat yields to 6-7 tons per hectare. Wheat yields are highest (9.4 tons per hectare) when farmyard manure is applied, wheat is grown in rotation, and inorganic fertilizers are used to top-up nitrogen availability.

Source: Rothamsted Experimental Station 1991; IFA 1995.

of tons of grain (Borlaug and Dowswell 1994). For Africa, the research challenge is even more demanding in view of the severe climatic and soil conditions and the diversity of smallholder farmers. The research conducted by CIMMYT (the International Maize and Wheat Improvement Center) on soil fertility management for the maize cropping system of smallholders in Southern Africa is promising. It suggests that several options exist for increasing the availability and use of organic sources of nutrients, improving maize genotypes for soils with low fertility, and overcoming micronutrient deficiencies (Kumwenda et al. 1996). Such research continues and needs to be further promoted through regional and national collaboration.

Extension

No single set of recommendations on plant nutrient application are appropriate for the diverse agricultural environments and economic conditions that exist in the world. Rather, farmers, with the aid of extension services, have to be given access to and choose the most appropriate and cost-effective technologies for their particular circumstances. Farmers also need to participate in the development of these technologies and become knowledgeable about managing soil fertility and capturing the opportunities offered by their diverse environments. Successful INM adoption programs thus must enhance farmers' capacity to learn and break free from the conventional fix of one-way technology transfer from researcher to farmer (Deugd, Roling, and Smaling 1997).

Successful INM extension will also require greater monitoring and testing of plants and soils. Monitoring will help ensure that an environment conducive for optimal plant growth and crop yield can be established through nutrient application and soil reclamation. Where practical and available, testing techniques such as plant-nutrient-

Box 6

Plant Symptom Analysis, Tissue Analysis, and Soil Testing

A variety of testing procedures are used to determine nutrient availability and deficiencies in plants and soils. The most common on-field test for nutrient deficiencies is plant symptom analysis. Visual clues can alert farmers and others to nutrient deficiencies in plants. In comparison with healthy plants, nitrogen-deficient plants appear spindly, stunted, and pale. Purplish spots or streaks and brown dead spots are symptoms of phosphorus and potassium deficiencies, respectively. Premature ripening is often a sign of a low N:P ratio, whereas delayed ripening and increased water content is an indication of too high an N:P ratio. If identified and caught early enough, corrective measures can be taken during the growing season to mitigate the negative impact of such deficiencies.

A crop could also suffer from hidden hunger, a condition in which a nutrient is deficient yet no symptoms appear. Postharvest tissue and soil testing, or field experimentation with different nutrients at different concentrations, can help forestall hidden hunger.

Tissue analysis and "quick" sap tests also help indicate plant nutrient status. In this process, a tissue/sap sample is taken from the plant and compared with a reference standard for each plant's stage of maturity. For this technique to be used effectively over a wide area, different soil types, slope percentages, soil drainage conditions, and cropping and fertilizing histories have to be taken into account. Only then can the appropriate fertilizer application and soil remediation steps be taken.

Although it is less useful during the cropping season, soil testing is a relatively easy and inexpensive method for evaluating the nutrient content available to plants. Based on soil samples reflecting different soil types, geographic conditions, and production histories for each part of a farmer's field, recommendations are made to the farmer for applying the appropriate quantity and type of fertilizer. Generally, each sample should represent no more than 4 hectares, and less for intensively cultivated areas.

Sources: Tisdale and Nelson 1975; Thompson and Troeh 1973; Bockman et al. 1990.

deficiency diagnosis, plant tissue analysis, biological comparison tests across soils, and chemical soil analysis are needed to help the farmer improve crop and soil management (Box 6). Together, monitoring, testing, and nutrient application recommendations that reflect crop needs and soil nutrient levels can enable extension agents to help farmers overcome the limitations arising from harsh agroclimatic and soil conditions.

Participation

Participation is another key to more effective INM. The interaction of farmers, researchers, extension services, nongovernmental organizations (NGOs), and the private sector involved in the distribution system is vital to the proper evaluation and wider dissemination of traditional technologies and the development and adoption of new ones. Farmers need to play a more important role in technology development. Plant breeders, for example, often focus narrowly on increasing yields and disease resistance. But farmers have other concerns as well. In particular, farmers want modern varieties that generate high yields for crops with high consumer demand, save labor and reduce costs, and produce plants that resist drought, pests, and disease (Franzel and Van Houten 1992). New technologies should also take into account the diversity, food security, and other risk concerns of smallholder farmers.

Government has an important role to play in promoting policies that contribute to sustainable nutrient and soil fertility management. This role involves committing resources to national research and extension programs and creating an environment conducive to the adoption of sustainable and yield-improving technologies. In effect the government's role will continue to change from one of supplying and distributing chemical fertilizers to one of regulating the market for plants and nutrients, both organic and inorganic. The policy environment needed for the development of efficient markets will require investment in transport and communication infrastructure. Only when remote areas are sufficiently connected to markets can farmers have access to the critical inputs and technology necessary for augmenting and sustaining production and have the ability to sell their goods and services. In the meantime, less-developed regions should be supported temporarily with programs that help to conserve and recapitalize nutrient reserves and sustain soil fertility.

7. Conclusions and Recommendations

Recent agricultural trends indicate that yields for many cereals are not rising as quickly as they did during the 1960s and 1970s. Part of the explanation for such a decline in yield growth is the mismanagement of nutrients and soil fertility. Future strategies will have to redress this poor management in order to create synergies with other yield-increasing technologies. Boosting food supplies to meet projected demand by 2020 will require substantial increases in yields in Africa, Latin America, and Asia. The integrated management of nutrients and soil fertility, along with continuous technological change, farmer participation, technology transfer, and a conducive policy environment, are key components for attaining these increases.

So long as agriculture remains a soil-based industry, there is no way that required yield increases of the major crops can be attained without ensuring that plants have an adequate and balanced supply of nutrients. The appropriate environment must exist for nutrients to be available to a particular crop in the right form, in the correct absolute and relative amounts, and at the right time for high yields to be realized in the short and long term.

In this regard it is important that governments encourage analysis of "nutrient cycles" to have a better basis for determining the flow of plant nutrients in and out of soils. Governments should establish adequate testing and monitoring systems to gather data on the nutrient cycle and nutrient balances in representative areas throughout their rural economies. Further, governments should support research for developing modern varieties and appropriate integrated nutrient systems for harsh climatic environments, such as those in Sub-Saharan Africa. Research should also be promoted on biological nitrogen-fixation as a low-cost "organic" approach to increasing nitrogen availability and organic matter content in soils. Government and extension services will initially need to stimulate the adoption of nitrogen-fixing species and innoculants by farmers.

The application of targeted, sufficient, and balanced quantities of inorganic fertilizers will be necessary to make nutrients available for high yields without polluting the environment. Governments should take the necessary steps to facilitate the widespread and responsible use of chemical fertilizers. At the same time, every effort should be made to improve the availability and use of secondary nutrients and micronutrients, organic fertilizers, and soil-conservation practices. Farmers will need government assistance to establish an environment in which they will be able to choose the appropriate technologies for their particular circumstances.

At present, the environmental drawbacks of heavy fertilizer use are confined to some developed countries and a few regions in developing countries. Appropriate and responsible application of fertilizers will help to maintain yields and minimize pollution. By contrast, levels of fertilizer use in most developing countries are so low that there is little likelihood of major environmental problems from their application. In fact, greater application of organic and inorganic fertilizers in these areas could benefit the environment and increase yields.

Special efforts are needed to overcome the serious problems of mining soils in many parts of Africa. The ongoing reduction of plant nutrients may well lead to irreversible degradation and soil infertility unless steps are taken to improve soil management. These steps include (1) widespread soil testing, (2) closer cooperation and coordination between farmers and researchers to exchange information and disseminate technologies that take into account immediate farmer survival needs along with longer-term soil fertility and agricultural sustainability requirements, (3) encouragement of extension services and NGOs to pay attention to soil-related issues, (4) promotion of more productive use of organic nutrients, and (5) promotion of vegetative-cover methods to conserve soil moisture and nutrients.

The difficulties arising from poor management of plant nutrients and soil fertility are related mostly to environmental problems, declining yield, and unsustainable agriculture. The poor, primarily smallholder farmers in developing countries, pay the consequences in terms of reduced food security. The challenges are enormous and the responses are complex.

Successful integrated nutrient and soil fertility management depends on a concerted effort by a multitude of actors. Similar complexity will characterize the response of research and extension organizations and the building of institutions that stress the participation of smallholder farmers, the private sector, the public sector, and NGOs.

Success will ultimately depend on how well these complex actions and socioeconomic factors can increase crop yields in a sustainable manner and improve the food security of millions of smallholder farmers currently struggling with declining soil fertility and poor management of plant nutrients.

Appendix

Conclusions and Recommendations of the IFPRI/FAO Workshop on Plant Nutrition Management, Food Security, and Sustainable Agriculture: the Future to 2020, May 16-17, 1995, Viterbo, Italy*

Conclusions

1. There will have to be a very substantial increase in the use of mineral fertilizers to meet the food needs of human populations by the year 2020, especially in the developing countries, even though organic sources can and should make a larger contribution to supply plant nutrients.

2. There is a lack of prioritized and strategic problem-solving agricultural research that is related to plant nutrition management and the incorporation of mineral and organic sources of plant nutrients into the soil.

3. There is a need for participatory and farmer-adapted approaches to technology development.

4. There is a need to emphasize to donors and national governments that in most developing-country situations, attention to the future of their agricultural sectors is of paramount importance, including macroeconomic considerations and other related sectoral policies affecting transport and energy.

5. In view of current forecasts of production capacity, fertilizer prices are likely to increase after the year 2000, especially those of phosphates.

6. Fertilizer use in Sub-Saharan Africa is too low. While in some local situations increased recycling of organic materials is possible and desirable, increased fertilizer use is essential to break out of the constraint of low biomass production in the region. Although farmers often appreciate the need for fertilizer inputs, this is not yet translated into an effective demand because of high prices, insecure supplies, and in some cases because farmers have a high aversion to the risks associated with food production in marginal agroclimatic and socioeconomic conditions. Fertilizer prices at the farm gate are also excessively high because of thin markets, lack of domestic production capacity, poorly developed infrastructure, and inefficient production systems.

7. The notion of declining efficiency of fertilizer use in Asia is overly simplistic. Possible reasons for apparent diminished returns from increased fertilizer applications in this region include: (i) more fertilizers are being used on lands with poorer soils or uncertain water supply; (ii) the increased intensity of cropping, especially changes in crop sequences, makes current management practices, including fertilizer use, less effective; (iii) there is an imbalance in the supply of N, P, and K, with applications of the latter two nutrients often being too low; (iv) deficiencies of secondary nutrients and micronutrients are beginning to appear; (v) there is an overall decrease of soil organic matter and an increase in soil degradation in general; and (vi) adverse effects from pests and diseases are increasing in the region.

*More information on the workshop, as well as the workshop papers themselves, are available in Gruhn, Goletti, and Roy 1998.

8. There is a future strategic problem of procurement of raw materials for P and K fertilizers, especially in Asia, and of the pricing of natural gas for local N-fertilizer production compared with its use for energy.

9. Environmental considerations, such as pollution and degradation of natural resources, are important but need not necessarily involve costly trade-offs between environmental and agricultural production concerns. Environmental priorities will differ between countries and regions. Agricultural intensification can be sustainable, provided that there is effective management of all plant nutrients.

10. Nongovernment and private sector involvement is essential for the effective stimulation of the use of plant nutrient inputs, with appropriate monitoring by governments of effective, equitable, and pollution-free distribution of these inputs.

Recommendations

A. *Promote effective and environmentally sound management of plant nutrients.*

A1. The balanced and efficient use of plant nutrients from both organic and inorganic sources, at the farm and community levels, should be emphasized; the use of local sources of organic matter and other soil amendments should be promoted; and successful cases of integrated plant nutrient management should be analyzed, documented, and disseminated.

A2. Innovative approaches to support and promote integrated plant nutrient management should be pursued.

A3. The joint UN Inter-Agency and Fertilizer Industry Working Group on Fertilizers should be revitalized, and should henceforward give attention to the wider topic of Plant Nutrient Management.

A4. Encouragement should be given to FAO to develop further, in cooperation with all relevant organizations, a Code-of-Conduct on the effective and environmentally sound management of plant nutrients, for dissemination at both international and national levels.

B. *Improve database, research, monitoring, and extension of effective plant nutrient management.*

B1. Participatory forms of design, testing, and extension of improved plant nutrient management strategies that build upon local institutions and social organizations, including trained farmer groups, should be promoted.

B2. A network of benchmark sites on representative farmers' fields in major farming systems should be developed to monitor the stocks and especially the flows of plant nutrients.

B3. A comprehensive data base needs to be developed for all mineral and organic sources of nutrients, including their amount, composition, processing techniques, their economic value, and their availability.

B4. The impact of micro- and macro-economic policies on plant nutrient management should be evaluated.

C. *Support complementary measures to lower costs, recycle urban waste, secure land tenure, and increase production capacity.*

C1. Ways and means should be sought to lower the price of fertilizers at farmgate and to reduce the farmers' perception of the risk in the use of fertilizers by: (i) investing in distribution infrastructure; (ii) researching innovative ways to share risks and to provide finance; (iii) encouraging subregional cooperation for country-level fertilizer production facilities and/or procurement; and (iv) improving dialogue between different sectors and agencies to arrive at a common approach to improved plant nutrition.

C2. Improvement of security of access to land is essential for the intensification of fertilizer use and the successful promotion of integrated plant nutrient management systems.

C3. The recycling of pollutant-free organic urban waste into the wider peri-urban agricultural sector should be promoted, considering that such waste constitutes an increasingly significant and so far largely untapped source of plant nutrients.

C4. Investment in production capacity for mineral and organic fertilizers should be increased and facilitating the procurement of raw materials and energy for their processing enhanced.

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