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Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa

Proceedings of a symposium, held in Lome, Togo, March 25 – 28, 1985

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MANAGEMENT OF NITROGEN AND PHOSPHORUS FERTILIZERS

Preface

Food security, one of the basic human rights, seems to be ever eluding the people of sub-Saharan Africa. With each occurrence of crop failure, agriculturalists around the world reawaken to the challenge of ensuring stable, adequate food production in the tropical African environments.

The International Fertilizer Development Center (IFDC), with its mandate of alleviating food shortages through judicial use of fertilizers, formulated a program to study fertilizer use strategies for sub-Saharan Africa. With generous financial assistance from the International Fund for Agricultural Development (IFAD), IFDC, in collaboration with the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) and the International Institute for Tropical Agriculture (IITA), initiated a research project aimed at assessing means to remedy soil nutrient deficiencies that constrain food production in the humid, subhumid, and semiarid tropics of Africa. The results of this project were summarized during a workshop held in Togo, March 25-28, 1985; the proceedings of that meetings are found in this volume.

The project established collaboration with numerous national programs that were responsible for much of the data collection. The data presented in Chapters 6 and 9 include much of this information. We wish to acknowledge the contribution of the individual scientists, J.T. Ambe, F. Ganry, M. Gaoh, M. Issaka, J. Kiazolu, J. Kikafunde-Twine, K. Kpomblekou, F. Lompo, H. Maduakor, O. Mandiringana, E. Melebou, K. Munyinda, H. Mwandemere, L. Nnadi, F. Nweke, O. Osiname, A. Pinto-Toyi, E.R. Rhodes, M. Sedogo, H. Ssali, and S.O. Taal. Their dedication to the research has played an essential role in the success of this project.

Food problems in tropical Africa will not be solved easily. Introduction of fertilizer in those regions where it has a chance to profitably increase food production will be part of the solution to this problem. While we recognize that a single, short-term project to study the use of fertilizers may not sub-

stantially affect the pace of fertilizer adoption, we hope that this research wi find its place alongside that of other research groups and will be the cause fc continuation and escalation of this effort. IFDC is committed to its researc involvement in Africa and will continue to support this program.

December 1985

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Fertilizer problems and policies in sub-Saharan Africa

Mohinder S. Mudahar

Introduction

Sub-Saharan Africa consists of over 40 low-income tropical countries. Many of these countries are facing serious food, hunger, and nutrition problems. The food problem in sub-Saharan Africa is as serious today as it was in Asia in the 1960s, at least in the relative sense. Although the food crisis in sub-Saharan Africa is not irreversible, the potential long-term agricultural development strategy to solve this food problem is more difficult to formulate and more expensive to implement.

Agriculture dominates the national economies in most of the countries in sub-Saharan Africa. However, the performance of the agricultural sector has been very poor, as has been reflected by declining crop yields and low per capita food production. The agricultural sector needs to become more productive and dynamic if it is to significantly contribute to economic development in sub-Saharan Africa.

Fertilizer use, along with other complementary agricultural inputs, is expected to play a vital role in transforming traditional agriculture and accelerating agricultural growth. However, the present level of and growth in fertilizer use are extremely low and fluctuating. In many cases the growth in fertilizer use is even negative. Accelerating the economic use of fertilizer would require appropriate technology and major policy reforms.

Most countries in sub-Saharan Africa depend on fertilizer imports to meet part or all of their domestic requirements. Countries with negative growth in fertilizer use are generally those that depend exclusively on imports. Foreign exchange allocation to import fertilizer does not seem to receive a priority commensurate with its contribution to agricultural growth.

The raw materials for nitrogen, potash, and sulfur fertilizers are limited and unevenly distributed. However, many countries in sub-Saharan Africa are known to have phosphate resources. Consequently, most of these coun-

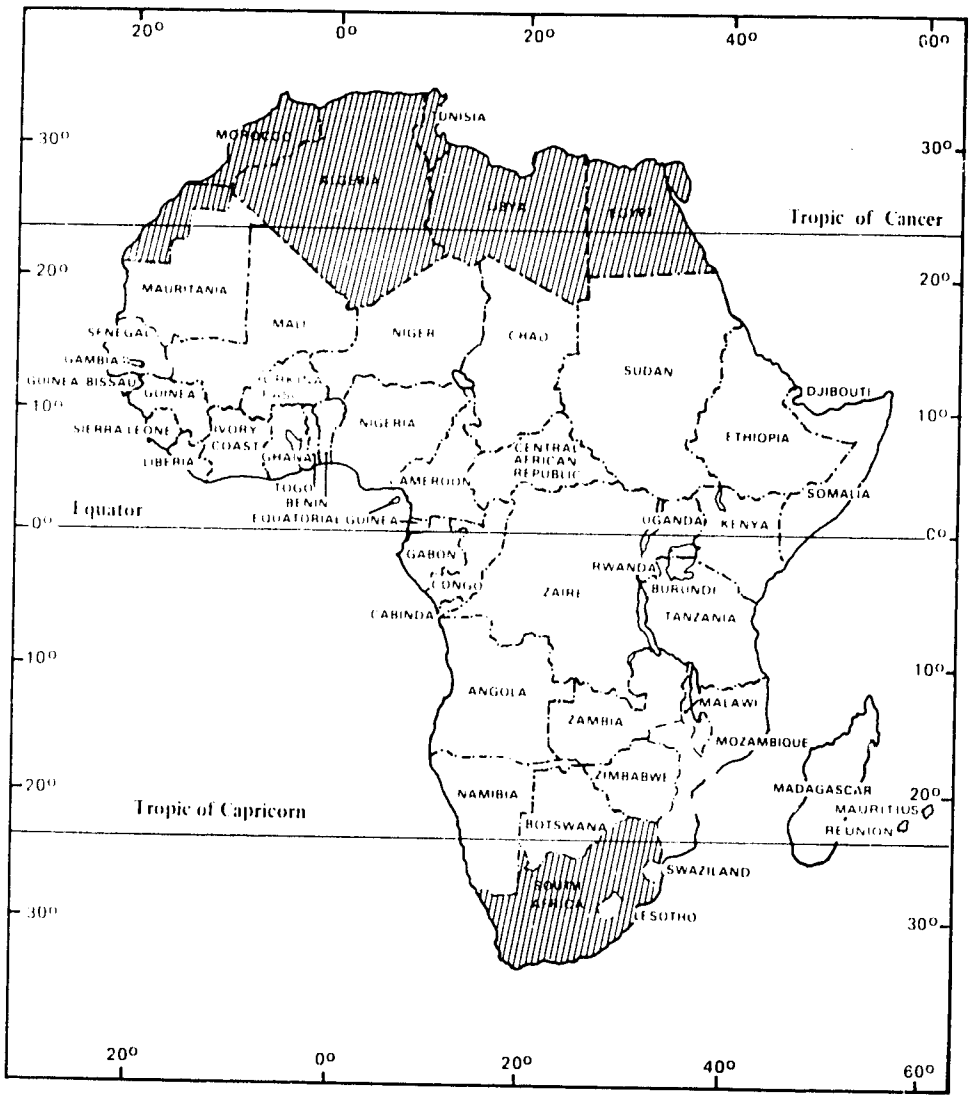

Figure 1. Sub-Saharan Africa.

tries would prefer to make economic use of their indigenous phosphate resources in the form of modified phosphate fertilizers.

The purpose of this paper is to analyze the fertilizer problems and policies in sub-Saharan Africa. More specifically, the objectives are:

1. To assess the role of agriculture in economic development.
2. To determine the role of fertilizer in agricultural development.
3. To analyze the growth and patterns in fertilizer consumption.
4. To identify and analyze the policies needed to expand fertilizer demand.

5. To evaluate the implications of an import subsitution policy for phosphate fertilizer.

Agriculture in economic development

Contribution of agriculture

According to the World Bank [37], 20 of 34 low-income countries (with per capita gross national product [GNP] less than $410/year) are in sub-Saharan Africa. The per capita GNP varies from a low of $80/year in Chad to a high of $4,000/year in oil-exporting Gabon (Table 1). Agriculture contributes to the economic development of these countries in many ways.

First, approximately 78% of the population (380 million in 1982) of sub-Saharan Africa is in the rural areas and depends on agriculture for its livelihood. Second, with the exception of oil- and mineral-producing countries, agriculture contributes from one-third to one-half of the gross domestic product (GDP). Third, the agricultural sector provides wage goods and raw material to the urban-industrial sector. Fourth, with the exception of oil- and mineral-exporting countries, agricultural exports account for the major share of foreign exchange earnings. Fifth, the direct and indirect agricultural taxation also contributes a large share of government revenue.

Agriculture-led economic growth

The cross-country experience of high-income countries indicates that the relative contribution of the agricultural sector declines as per capita GNP increases. However, in sub-Saharan Africa, the agricultural sector still dominates national economies. As shown in Table 1, the overall economic performance (growth in GDP) of a particular country is determined by the performance of the agricultural sector (growth in agriculture). Those countries that have neglected the agricultural sector are experiencing negative or low growth in GDP. In other words, premature emphasis on the industrial sector at the expense of the agricultural sector has resulted in stagnant agricultural growth. This is more evident in sub-Saharan Africa than anywhere else.

Most sub-Saharan African countries are among the world's poorest countries. Within each of these countries the poorest segment of the population is in the rural areas and depends on agriculture for its livelihood. The average per capita income differential between the rural and urban areas varies from

Table 1 Indicators for economic and agricultural growth in sub-Saharan Africa

Country	GNP per capita (1982) $	Growth in GNP per capita, 1960-82	Contribution of agriculture to GDP (1982)	Growth in GDP, 1970-82	Growth in agriculture, 1970-82
		(%)			
Benin	310	0.6	44	3.3	–
Botswana	900	6.8	12	–	–
Burkina Faso	210	1.1	41	3.4[c]	1.4[c]
Burundi	280	2.5	56	3.5	2.3
Cameroon	890	2.6	27	7.0	3.4
Central African Republic	310	0.6	35	1.4	2.3[c]
Chad	80	-2.8	64[b]	-2.6[c]	-1.0[c]
Congo	1,180	2.7	6	6.8	1.9
Ethiopia	140	1.4	49	2.2	0.9
Gabon	4,000	4.4	–	–	–
Gambia	360	2.5	26	–	–
Ghana	360	-1.3	51	-0.5	-0.2
Guinea	310	1.5	41	3.8	–
Guinea-Bissau	170	-1.7	–	–	–
Ivory Coast	950	2.1	26	5.7	4.5
Kenya	390	2.8	33	5.5	4.1
Lesotho	510	6.5	23	6.6	0.3[c]
Liberia	490	0.9	36	0.0	3.5
Madagascar	320	-0.5	41[b]	0.2	0.3
Malawi	210	2.6	–	5.1	4.1
Mali	180	1.6	43	4.3	3.8
Mauritania	470	1.4	29	2.0	3.4
Mauritius	1,240	2.1	14	–	–
Niger	310	-1.5	31	3.4	-2.4
Nigeria	860	3.3	22	3.8	-0.6
Rwanda	260	1.7	46[b]	5.3	–
Senegal	490	0.0	22	2.9	2.3
Sierra Leone	390	0.9	32	2.0	2.5
Somalia	290	-0.1	–	3.8	–
Sudan	440	-0.4	36	6.3	4.1
Swaziland	940	4.2	–	–	–
Tanzania	280	1.9	52	4.0	2.8
Togo	340	2.3	23	3.0	1.7
Uganda	230	-1.1	82[b]	-1.5	-0.6
Zaire	190	-0.3	32[b]	-0.2[c]	1.5[c]
Zambia	640	-0.1	14	0.9	1.9
Zimbabwe	850	[illegible].5	15	2.2	1.8

– = Not available.

[a] Derived from the World Bank [37]. Information was not available for those sub-Saharan countries that are not included.

[b] Refers to 1981.

[c] Refers to 1970-81.

1:4 to 1:9 in most African countries compared with ratios of 1:2 and 1:2.5 in Asian countries [17]. Clearly, any effort to reduce poverty and accelerate economic growth must give agriculture the highest priority in resource allocation, technology generation, and policy reforms.

Food problem and prospects

Sub-Saharan Africa is facing a serious food crisis.[2] According to the World Food Council, 25 of the 43 food-priority countries are in sub-Saharan Africa. Some of the clearly emerging trends in food-related indicators are as follows: (1) food consumption is rising, (2) per capita food production is declining, (3) food deficits are growing, (4) food exports are declining, (5) food imports are increasing, (6) consumption of wheat and rice is increasing and partly replacing consumption of coarse grains, and (7) average per capita daily calorie intake is below minimum nutritional standards.

The projected gross food deficits during 1990 in sub-Saharan Africa are estimated to be between 27 million tonnes and 34 million tonnes [14].[3] These food deficits are approximately 26%-30% of projected food demand during 1990. According to FAO [5], the estimated net cereal deficits are expected to increase from 24 million tonnes in 1990 to 44 million tonnes in year 2000 based on a trend-growth scenario and from 16 to 28 million tonnes in the respective years based on a best-growth scenario.

There are several reasons for the present food crisis in sub-Saharan Africa, including drought, outbreaks of pests and diseases, and other natural and environmental disasters. However, the present food crisis has been developing for several years. First, food consumption requirements have been increasing rapidly in the last decade in response to high population growth. Second, food consumption requirements in the urban areas have been increasing even faster in response to rapid growth in urban population, which in many cases was twice the growth in population (Table 2). Third, and the most important, per capita food production has been declining. As reported in Table 3, growth in per capita food production from 1971-73 to 1981-83 was negative in 31 of 40 sub-Saharan countries.

The long-term solution to the food problem is neither food aid nor food imports. Food aid does not generally go to the needy population. In addition, it depresses crop prices, decreases incentives for expanding domestic production, and discourages governments from making commitments to developing the agricultural sector. Food imports, on the other hand, are expensive and require scarce foreign exchange which many countries in sub-Saharan Africa cannot afford. Food imports also provide disincentives to farmers by depressing crop prices. Furthermore, very expensive imported food requires

Table 2 Population growth and urbanization in sub-Saharan Africa[a]

Country	Population Mid-1982 (millions)	Total population growth rate, 1970-82	Urban population growth rate, 1970-82	Population in urban sector, 1982
		(%)		
Angola	8.0	2.5	5.8	22
Benin	3.7	2.7	4.4	15
Botswana	0.9	–	–	–
Burkina Faso	6.5	2.0	6.0	11
Burundi	4.3	2.2	2.5	2
Cameroon	9.3	3.0	8.0	37
Central African Republic	2.4	2.1	3.5	37
Chad	4.6	2.0	6.4	19
Congo	1.7	3.0	4.4	46
Eq. Guinea	0.4	–	–	–
Ethiopia	32.9	2.0	5.6	15
Gabon	0.7	–	–	–
Gambia	0.7	–	–	–
Ghana	12.2	3.0	5.0	37
Guinea	5.7	2.0	5.2	20
Guinea-Bissau	0.8	–	–	–
Ivory Coast	8.9	4.9	8.2	42
Kenya	18.1	4.0	7.3	15
Lesotho	1.4	2.4	15.4	13
Liberia	2.0	3.5	5.7	34
Madagascar	9.2	2.6	5.2	20
Malawi	6.5	3.0	6.4	10
Mali	7.1	2.7	4.7	19
Mauritania	1.6	2.3	8.1	26
Mauritius	0.9	–	–	–
Mozambique	12.9	4.3	8.1	9
Niger	5.9	3.3	7.2	14
Nigeria	90.6	2.6	4.9	21
Rwanda	5.5	3.4	6.4	5
Senegal	6.0	2.7	3.7	34
Sierra Leone	3.2	2.0	3.9	23
Somalia	4.5	2.8	5.4	32
Sudan	20.2	3.2	5.8	23
Swaziland	0.7	–	–	–
Tanzania	19.8	3.4	8.5	13
Togo	2.8	2.6	6.6	21
Uganda	13.5	2.7	3.4	9
Zaire	30.7	3.0	7.6	38
Zambia	6.0	3.1	6.5	45
Zimbabwe	7.5	3.2	6.0	24

– = Not available.

[a] Derived from World Bank [37].

Table 3 Growth in total and per capita food production in sub-Saharan Africa[a]

Country	Population growth, 1970-82	Growth in food production indices, 1971-73 to 1981-83[b]	
		Total	Per capita
		(%)	
Angola	2.5	0.5	-2.0
Benin	2.7	2.2	-0.9
Botswana	2.7	-1.6	-4.4
Burkina Faso	2.0	2.3	-0.2
Burundi	2.2	1.6	-0.5
Cameroon	3.0	1.5	-0.8
Central African Republic	2.1	1.7	-0.5
Chad	2.0	2.2	0.2
Congo	3.0	2.2	-0.4
Eq. Guinea	2.3	-	-
Ethiopia	2.0	2.3	0.1
Gabon	1.0	0.8	-0.2
Gambia	2.9	0.1	-2.7
Ghana	3.0	-1.6	-4.6
Guinea	2.0	1.4	-1.2
Guinea-Bissau	1.7	0.8	-0.9
Ivory Coast	4.9	5.5	1.6
Kenya	4.0	2.2	-1.8
Lesotho	2.4	0.0	-2.4
Liberia	3.5	2.8	-0.7
Madagascar	2.6	1.8	-0.7
Malawi	3.0	2.4	-0.8
Mali	2.7	2.7	0.0
Mauritania	2.3	1.6	-1.4
Mauritius	1.5	0.1	-1.5
Mozambique	4.3	-1.7	-4.2
Namibia	2.8	0.5	-2.4
Niger	3.3	3.9	1.0
Nigeria	2.6	2.9	-0.3
Rwanda	3.4	4.4	1.3
Senegal	2.7	2.2	-0.5
Sierra Leone	2.0	1.7	-1.0
Somalia	2.8	1.1	-4.4
Sudan	3.2	3.2	0.4
Swaziland	2.7	4.5	1.6
Tanzania	3.4	3.1	0.0
Togo	2.6	1.8	-1.0
Uganda	2.7	2.1	-0.9
Zaire	3.0	2.2	-0.6
Zambia	3.1	0.8	-2.3
Zimbabwe	3.2	1.0	-2.2

- = Not available.

[a] Derived from data reported in FAO [7], FAO [9], and World Bank [37].

[b] Base years for indices are 1974-76 = 100.

food subsidies for the consumers, which not only drain scarce financial resources but transfer income to the urban consumers. The only long-term solution to the food problem in sub-Saharan Africa is through an increase in domestic food production, along with a decrease in population growth and urbanization rate. This will not only provide a solution to the food problem but will also raise the income levels of the rural poor and, hence, may reduce poverty.

Fertilizer in agricultural development

Sources of agricultural growth

Needed growth in food production to meet the 1990 projected consumption target in sub-Saharan Africa is between 4.0 and 4.4%/annum, depending upon the income growth scenario [14]. This is 0.4% to 0.5%/annum higher than what is needed to meet Asia's food consumption target during 1990. The historical performance of growth in food production, even though it varies from one region to another and from one country to another, has not been very impressive in sub-Saharan Africa.

The estimated annual growth in food production in sub-Saharan Africa was 1.91% during 1962-72, and 1.88% during 1972-82 [20]. During the 1960s, all of the growth in food production was from area expansion, and crop yields either remained constant or declined. However, during the 1970s only 57% of the growth in food production was attributed to area expansion, and the remaining 43% was due to an increase in crop yields. These results indicate that there has been a slowdown in area expansion as a potential source of agricultural growth.

The estimated annual trend growth in cereal production in sub-Saharan Africa is projected to decline from 2.10% during 1969/71-1979/80 to 1.70% during 1979/80-2000 [31]. The contribution of area expansion in cereal growth is projected to decline from 56% in the 1970s to 41% in the 1980s and 1990s.

According to FAO [5], the relative contribution of area expansion to additional crop production in developing market economy (DgME) Africa is estimated to be only 27% during 1980-2000.

Land-surplus myth

In the common man's concept of sub-Saharan Africa there is abundant land

suitable for crop production and waiting to be brought under cultivation. In relation to Asia, there is some truth in this perception. Sub-Saharan Africa is vast and sparsely populated. However, a major share of land mass is not really suitable for crop production. Most of what is suitable and easily accessible has already been brought under cultivation.

There are significant differences of opinion among experts with respect to the potentially arable land in sub-Saharan Africa. The available estimates indicate that the potentially arable land in sub-Saharan Africa is between 304 and 733 million ha [27]. Depending upon which of these estimates is most appropriate, actual arable land is between 25% and 60% of the potentially arable land.

The concept that all the land is potentially arable, without any considerations for cost, crops, and agroclimatic factors, is at best dubious. The soils in Africa are highly weathered, fragile, low in organic matter, highly leached, and low in soil fertility; they experience widespread deficiencies in essential plant nutrients. Consequently, soils in Africa are quite different from soils in Asia with respect to their suitability for crop production, and the nutrient needs for tropical agriculture are quite different from the needs for agriculture in the temperate zone [19,16,34].

According to FAO [4], only 16% of soil resources in Africa have no serious limitation for crop production. The remaining 84% of the soils experience serious limitations for production, including (a) excess water, 9%; (b) shallow depth, 13%; (c) mineral stress, 18%; and (d) drought stress, 44%. It is extremely expensive to develop these soils and make them productive for crop cultivation. Furthermore, already productive soils are being lost through mismanagement, erosion, desertification, and deforestation.

How good are the soils for crop production without adequate soil moisture and water supply? Most of the crop production in Africa is rainfed, based on uncertain, inadequate, or too much rainfall. Sometimes there is plenty of rainfall but not at the time that crops need it. Approximately 4 million ha is under irrigation, which is about 2% of the arable land. The development of irrigation systems is expensive and slow, and the prospects for irrigation development in sub-Saharan Africa are limited.

Green revolution myth

The dwarf and fertilizer-responsive modern varieties developed at the International Maize and Wheat Improvement Center for wheat and at the International Rice Research Institute for rice have made it possible for Asia to make spectacular strides in agricultural and food production. It is often asked, Why can't the African farmers increase their crop yields and food

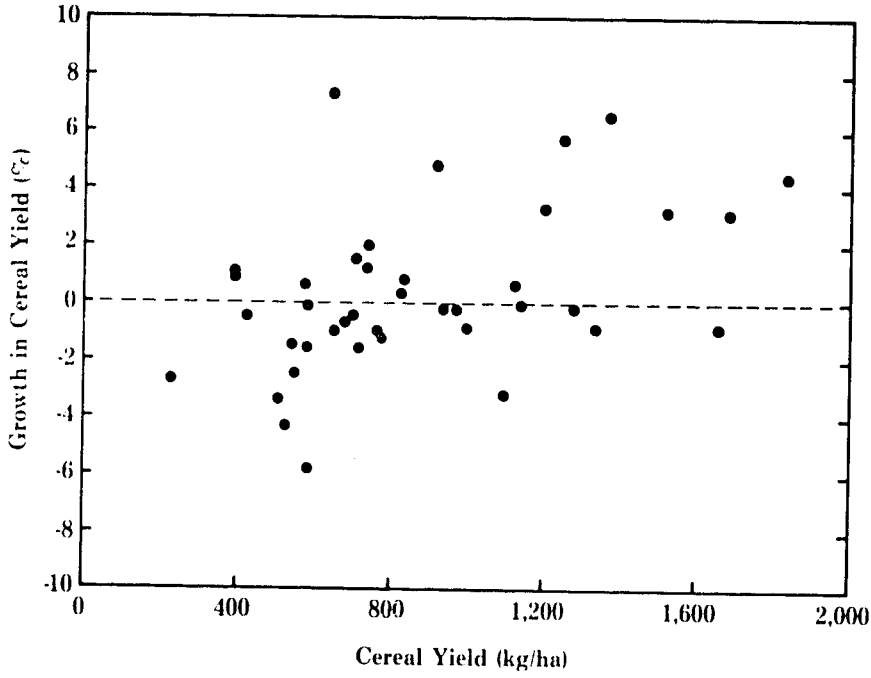

Figure 2. Estimated average level and annual growth in cereal yields in sub-Saharan Africa, 1980-82.

production, as has been done by the Asian farmers? The simple fact is that wheat and rice, the two Green Revolution crops, are not major crops in sub-Saharan Africa. The food staples in the semiarid tropical region of sub-Saharan Africa are millet and sorghum, whereas in humid and subhumid tropical regions of sub-Saharan Africa the food crops are maize, cassava, and yams. Some rice is grown on river deltas and in coastal countries where an adequate water supply is assured.

None of the food crops grown in sub-Saharan Africa has experienced the kind of technological breakthroughs that wheat and rice have in other areas. Consequently, sub-Saharan Africa has not been bypassed by the Green Revolution; there has never been a Green Revolution in this area. There is little or no improved crop technology on the shelf waiting to be transferred. Most of the technological changes are marginal. Both the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the International Institute of Tropical Agriculture are making gains in developing crop technology suitable for sub-Saharan Africa. However, there are enormous economic, policy, institutional, infrastructural, and environmental barriers to the transfer and dissemination of the available improved crop technology and management practices.

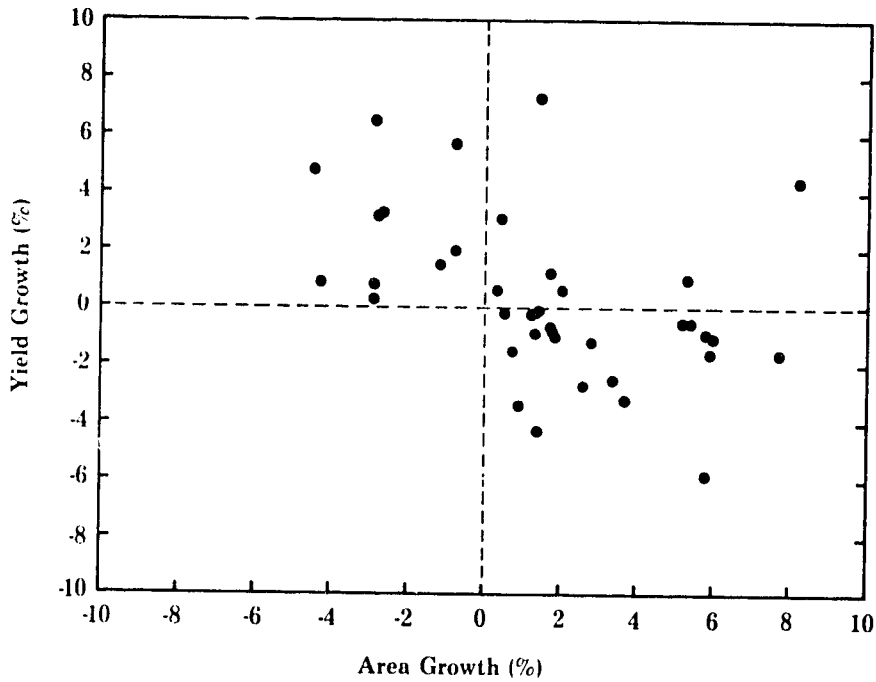

Figure 3. Estimated annual growth in cereal yields and area in sub-Saharan Africa from 1966-68 to 1980-82.

The cereal yields in most of the sub-Saharan African countries are very low (Figure 2). During 1980-82, the average cereal yield was less than 1 tonne/ha in 26 of 39 countries in sub-Saharan Africa. Furthermore, in 22 of 39 sub-Saharan countries the average cereal yields declined from 1966-68 to 1980-82. A large number of countries with negative growth in cereal yields also had low cereal yield levels. As reported in Figure 3, the source of growth in cereal production varied from one country to another. Of 39 sub-Saharan African countries (a) 7 countries experienced positive growth in cereal yields and area, (b) 10 countries experienced positive growth in cereal yields but negative growth in area under cereals, and (c) 22 countries experienced positive growth in area but negative growth in cereal yields. Lack of appropriate and economical agricultural technology appears to be a major constraint for increasing crop yields and accelerating agricultural growth.

Contribution of fertilizer

Crops cannot experience healthy growth in the absence of proper plant nutrition. Higher crop yields, multiple cropping, and an increase in productivity

of marginal lands will not be possible without an increase in fertilizer use. Organic manures and plant residues are important sources of nutrients, but they cannot supply all the nutrients needed to grow food in order to feed the expanding population. The biological fixation of nitrogen is possible but only for legume crops. Consequently, there is no substitute for chemical fertilizers in order to meet the expanding requirements for plant nutrition. We must also remember that the modern crop varieties cannot achieve their genetic potential yields in the absence of fertilizer. The interaction effect between modern crop varieties, water supply, and fertilizer use is not only positive but very large.

The contribution of fertilizer to incremental cereal production and to yields in DgME Africa has been estimated to be about 20% and 36%, respectively, from 1948/52 to 1972/73 [29]. This contribution is expected to increase over time, as it has in other developing and developed countries of the world. Fertilizer is a vital component of an improved crop technology package (modern varieties, water, insecticides, and fertilizer). Improved and appropriate farm technology is necessary and is expected to play a dominant role in any strategy of agricultural development in sub-Saharan Africa.

Fertilizer consumption growth and patterns

Aggregate fertilizer consumption

The historical growth in aggregate fertilizer (N, P_2O_5, K_2O) consumption in continental Africa during a 30-year period from 1950/51 to 1982/83 is reported in Figure 4. The total nutrient consumption has increased from 0.25 million tonne in 1950/51 to 3.5 million tonnes during 1982/83, implying a 14-fold increase over 30 years.

The sources of nutrients have been shifting from low-analysis to high-analysis single or multinutrient fertilizers. Although the sources of nutrients vary from one country to another and over time in a particular country, the most popular fertilizers at present include urea, ammonium sulfate (AS), calcium ammonium nitrate (CAN), single superphosphate (SSP), triple superphosphate (TSP), muriate of potash (MOP), and some selected speciality or compound fertilizers. In addition to NPK, a large amount of sulfur (often more than K_2O) is supplied through AS and SSP. However, the sulfur-containing fertilizers are gradually being replaced by sulfur-free high-analysis fertilizers, and this is resulting in sulfur deficiencies [16].

The pattern of growth in fertilizer consumption in sub-Saharan Africa is not much different from that in continental Africa. However, the amount of

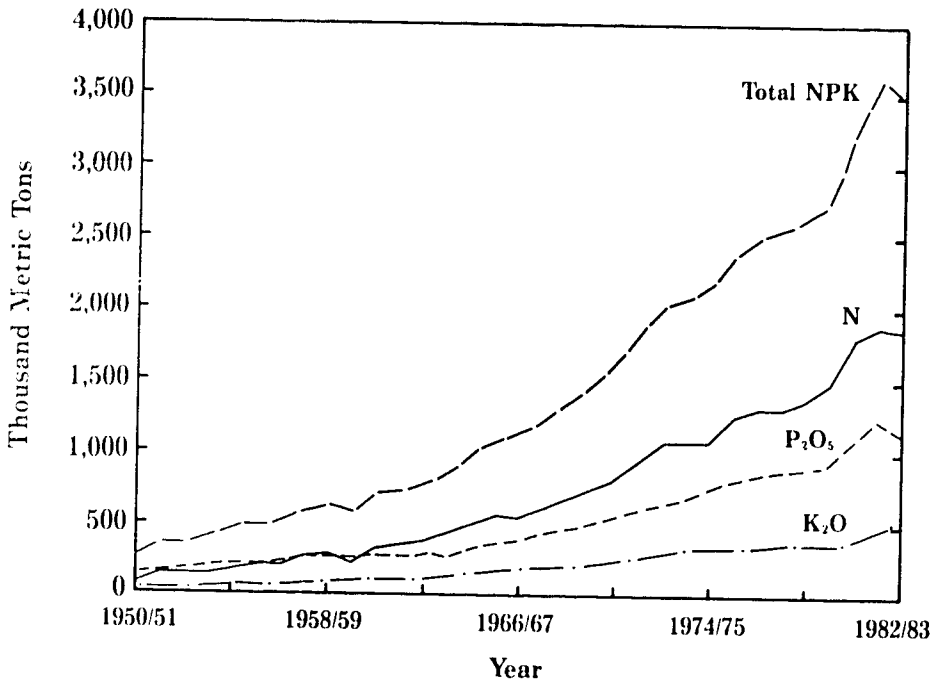

Figure 4. The dynamics of nutrient fertilizer consumption in Africa, 1950/51 to 1982/83.

aggregate fertilizer consumption in sub-Saharan Africa is very small, about 1 million tonnes (3-year average, 1980/81 to 1982/83) which is about 30% of the corresponding consumption in continental Africa and 70% of that in DgME Africa. The share of sub-Saharan Africa in world fertilizer consumption is 0.9%, whereas its share in world population is about 8%. India, with twice the population of sub-Saharan Africa, consumes six times more fertilizer. According to FAO [5], the nutrient requirements in DgME Africa are estimated to be 2.3 million tonnes during 1990 and 5.3 million tonnes during the year 2000, implying an annual growth rate of 8.9%.

The aggregate consumption in sub-Saharan Africa varies from one country to another (Table 4). Nigeria, Zambia, and Zimbabwe account for 50% of the total consumption in sub-Saharan Africa. In most of these countries fertilizer consumption is very small. For example, 20 of 40 sub-Saharan African countries consume less than 5,000 tonnes of nutrients annually. The growth in fertilizer consumption varied from one country to another, and one-third of sub-Saharan African countries experienced negative growth in the 1970s.

Table 4 Average level of and growth in fertilizer consumption in sub-Saharan Africa[a]

Country	Fertilizer use		Fertilizer consumption	
	1979-81 average (kg/ha)	Growth[b] (%)	1980/81-1982/83 ('000 tonne)	Growth[c] (%)
Angola	4.1	-0.9	11.3	-3.1
Benin	1.3	-8.9	2.2	-7.2
Botswana	0.9	-4.3	1.4	-3.2
Burkina Faso	2.9	25.5	8.4	21.3
Burundi	0.8	4.8	1.2	1.7
Cameroon	5.3	6.6	38.6	7.7
Central African Republic	0.4	-9.6	1.1	-5.3
Chad	0.5	-3.3	3.6	5.5
Congo	0.6	-25.4	0.8	-17.9
Eq. Guinea	0.2	-29.8	0.03	-31.7
Ethiopia	3.3	23.5	41.6	21.2
Gabon	1.6	[a]	0.7	[d]
Gambia	15.2	27.9	2.0	[d]
Ghana	7.4	23.5	22.7	24.7
Guinea	1.1	-4.8	1.9	-4.1
Guinea-Bissau	2.1	[d]	0.9	[d]
Ivory Coast	13.3	6.5	45.3	7.7
Kenya	25.8	1.4	71.1	4.0
Lesotho	15.0	24.3	4.5	14.7
Liberia	11.1	7.3	3.2	4.4
Madagascar	2.6	-7.4	10.5	-1.9
Malawi	11.9	8.6	33.2	10.6
Mali	5.7	7.0	11.2	7.6
Mauritania	7.2	28.2	0.5	[d]
Mauritius	238.1	1.4	24.9	1.1
Mozambique	9.5	13.4	36.3	14.7
Niger	0.8	23.1	3.7	[d]
Nigeria	5.4	33.5	195.4	32.3
Rwanda	0.2	-4.0	0.5	[d]
Senegal	4.6	8.7	20.7	6.8
Sierra Leone	1.5	1.4	2.1	0.4
Somalia	1.2	-9.1	1.2	-8.0
Sudan	5.1	5.1	70.4	6.0
Swaziland	72.1	5.8	16.9	9.9
Tanzania	6.1	7.4	29.1	6.9
Togo	2.5	23.6	2.5	[d]
Uganda	0.1	-22.6	0.5	-21.3
Zaire	1.2	4.1	6.8	4.9
Zambia	14.5	7.4	92.4	9.2
Zimbabwe	59.3	2.4	165.0	3.7

[a] Derived from data reported in FAO [7,8,9].
[b] Annual compound growth rate from 1969-71 to 1979-81.
[c] Annual compound growth rate from 1969/70-1971/72 average to 1980/81-1982/83 average.
[d] 1969-71 average = 0 or not available.

Fertilizer consumption per unit of land

Average fertilizer consumption per unit of land (in kilograms per hectare of arable land and land under permanent crops) is extremely low. During 1979-81, the average nutrient consumption in sub-Saharan Africa was 6.4 kg/ha, which was 71% of DgME Africa, 36% of continental Africa, 20% of developing market economies, 14% of developing countries, 6% of developed countries, and 8% of world average. One must be careful in interpreting these results. In most sub-Saharan African countries, only a small percentage of cropped area is actually fertilized. As a result the actual fertilizer use on fertilized land is much higher than indicated by the average use levels.

Since the average fertilizer use in sub-Saharan Africa is so low, one would expect rather high growth rate. However, the annual growth in fertilizer use from 1969-71 to 1979-81 was about 7%, which is approximately two-thirds of the growth in developing countries. Both fertilizer use levels and growth vary from one country to another in sub-Saharan Africa. For example, in 20 of 40 countries, the average nutrient consumption was less than 5 kg/ha.

Annual average growth in fertilizer use from 1969-71 to 1979-81 varied from 34% in Nigeria to -30% in Equatorial Guinea. However, for countries with fertilizer use less than 1 kg/ha, very high positive or negative growth rates may be misleading and may simply reflect changes in supply situation. However, it is important to note that countries with local production facilities (no matter how small) had positive growth in fertilizer use, and all the countries with negative growth rate met their requirements through fertilizer imports.

Fertilizer use by crops

The estimated share of fertilizer consumption by crops in selected countries of sub-Saharan Africa is reported in Table 5. The information is not the most recent, but it broadly reflects the pattern of fertilizer use among different crops. The results indicate that, with the exception of Niger and Nigeria, one-half to two-thirds of fertilizer is used on export crops. This is partly a reflection of the fact that fertilizer use is relatively more profitable on export crops than on food crops.

As far as individual crops are concerned, fertilizer use varies from one food or export crop to another. During 1983, for example, 49% and 19% of all the fertilizer consumed in Niger was used on millet and rice, respectively. Sorghum, millet, and maize accounted for 24%, 16%, and 12% of the total fertilizer consumed in Nigeria. The situation also varies across different nutrients. For example, millet accounted for 50% of the N, 51% of the P_2O_5, and 54%

Table 5 Estimated share of fertilizer consumption by crops in selected countries of sub-Saharan Africa[a]

Country	Year	Percent share of NPK consumption for									
		Millet	Sorghum	Maize	Rice	Cotton	Groundnuts	Sugarcane	Coffee/ tea/cocoa	Others	Total
Burkina Faso	1975	–	28	–	7	40	7	18	–	–	100
Cameroon	1977	–	–	–	4	–	–	41	3	52	100
Chad	1978	–	–	–	2	97	–	–	–	1	100
Gambia	1976	6	4	20	4	–	66	–	–	–	100
Ivory Coast	1973	–	–	2	3	24	–	23	1	47[b]	100
Malawi	1976	–	–	11	7	2	–	8	19	53[c]	100
Mali	1976	–	–	6	15	51	6	–	–	22	100
Niger	1983	49	5	–	19	2	13	–	–	12	100
Nigeria	1979	16	24	12	11	7	2	6	3	19[d]	100
Senegal	1975	36	–	–	20	13	31	–	–	–	100
Sudan	1975	–	–	–	2	46	–	6	–	46[e]	100
Tanzania	1975	–	–	21	–	19	–	5	27	28[f]	100

[a] Derived from FAO [6], IFDC [11], Martinez and Diamond [18], Ministere du Developpment Rural [21], and van Dierendonck, Krishnaswami and Verghese [33].

[b] 31% for banana/pineapple and 16% for rubber/oil palm/coconut.

[c] 33% for tobacco.

[d] 13% for yams, cassava, and potatoes.

[e] 27% for wheat.

[f] 24% for tobacco.

of the S: rice accounted for 30% of the N, 8% of the P_2O_5, 55% of the K_2O, and 1% of the S; and groundnuts accounted for 22% of the P_2O_5 and 34% of the S in all the individual nutrients consumed in Niger during 1983.

Policies needed to expand fertilizer demand

Fertilizer demand-related problems

The specific fertilizer problems faced by farmers, dealers, importers, producers, and government vary from one country to another. However, the general principles in identifying the problems and in finding appropriate solutions through policy measures are essentially the same. The fertilizer problems can be divided into two broad categories: (1) fertilizer demand, at both the farm and national levels, is low and fluctuating even when fertilizer is available at the right time and place and (2) fertilizer is not available at the right time and place, and many countries are unable to meet even low fertilizer demand and reduce fluctuations in supply over time.

Most countries in sub-Saharan Africa are facing both demand- and supply-related problems [24,39]. Since in many of these countries the level of and growth in fertilizer use are extremely low, it is important to identify and analyze fertilizer demand-related problems and policy measures, which is the focus of this paper. The factors contributing to low fertilizer demand include (1) low fertilizer response, (2) high fertilizer cost, (3) low crop prices, (4) high risk of losing money as a result of the variability in fertilizer response and prices, (5) lack of cash or credit, (6) lack of knowledge, and (7) lack of complementary farm inputs such as fertilizer-responsive crop varieties, water, and insecticides.

Fertilizer use economics

The farmer is the ultimate decisionmaker with respect to fertilizer use and the target of most fertilizer policies. Consequently, it is important to understand the farmers' decisionmaking process regarding fertilizer use and to evaluate the economic implications of alternative fertilizer policies. The knowledge about fertilizer response forms the basis for the economic analysis of fertilizer use which, in turn, forms the basis for fertilizer policy formulation. Given the fertilizer response function, the optimum level of fertilizer use is determined by economic factors, including constraints and risk associated with fertilizer use.

Farmers in sub-Saharan Africa are no different from farmers anywhere else in the world, except that they more frequently face serious environmental constraints. Furthermore, the desire to meet household food consumption needs and to minimize the risk of losing money is extremely important. Most African farmers also tend to face a serious labor constraint, especially during the peak season. Given these considerations farmers will use fertilizer only if its use is economical.

The profit-maximizing level of fertilizer use is determined by the behavioral rule implied by the equality between marginal value of the product and marginal cost of fertilizer. In other words, profit will be maximum when the fertilizer price line is tangent to the response curve or when the marginal product of fertilizer use is equal to the price ratio of fertilizer and crop output (Figure 5). The magnitude of all these variables, hence the economics of fertilizer use, can be manipulated through fertilizer policy [23].

Fertilizer response and technology policy

Fertilizer response is determined by numerous factors such as crop, crop variety, irrigation, rainfall, soil moisture, soil quality, fertilizer source, fertilizer management, cropping pattern, and various agroclimatic factors. FAO has conducted a large number of trials and demonstrations in many countries of sub-Saharan Africa as part of the Freedom from Hunger Campaign.

The selected fertilizer response coefficients from FAO demonstrations are summarized in Table 6. The average fertilizer response based on selected fertilizer response studies in Nigeria are reported in Table 7. These results indicate that yield response to applied fertilizer is positive and significant, and it varies from one crop to another and from one location to another. The fertilizer response is generally higher for export crops, root crops, and those using improved farm practices than for cereals (except possibly for rice) and other crops using traditional farm practices.

As fertilizer use goes up, the additional yield from additional fertilizer use declines according to the law of diminishing returns. As a result, it is important to continuously increase and sustain the response to applied fertilizer through a stream of technological improvements that would shift the fertilizer response function upward. This would require improved fertilizer technology, fertilizer-responsive crop varieties, irrigation, and improved farm management practices. In addition, it is extremely important to prepare soil maps that indicate the nature and magnitude of nutrient deficiences in relation to different crops and farming systems.

The results from the joint International Fertilizer Development Center and ICRISAT research trials in Niger indicate that soils are generally deficient in

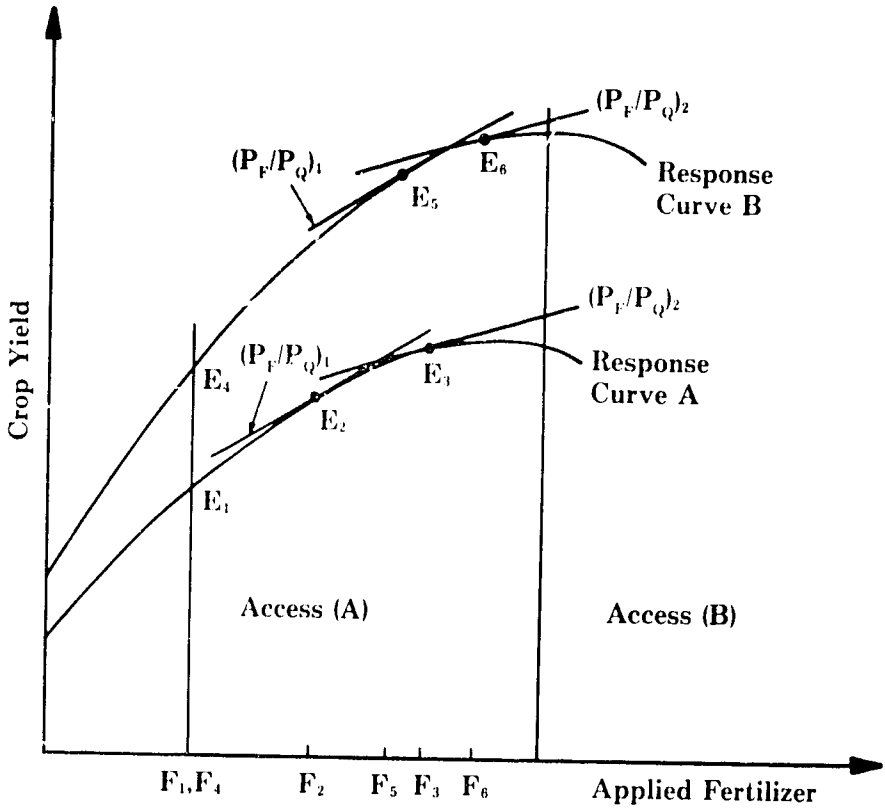

Figure 5. Implications of alternative fertilizer policies on the economics of fertilizer use.

phosphorus. The average response to applied phosphate was much higher than to applied nitrogen or potash for millet and sorghum. One should keep in mind, however, that most of the fertilizer trials and demonstrations dealt with sole cropping systems, whereas mixed cropping systems dominate the agricultural sector in most sub-Saharan countries. Finally, the variability in fertilizer response for a particular crop is extremely high from one location to another and from one year to another on the same location. There is a need to reduce this variability, and hence the risk factor, through appropriate fertilizer technology and management practices.

Fertilizer profitability and price policy

Farmers will not use fertilizer if it is not profitable. The profitability of fertilizers use can be determined by evaluating value/cost ratios. According to FAO, farmers will not use fertilizer if the average value/cost ratios are lower than 2. For sub-Saharan Africa the minimum acceptable value/cost ratios

have to be even higher. In addition to the fertilizer response coefficient, value/cost ratios are determined by three important variables: fertilizer price paid by the farmer, crop price received by the farmer, and associated fertilizer costs (such as labor cost and credit cost) borne by the farmer.

The average value/cost ratios based on selected fertilizer response studies in sub-Saharan Africa are reported in Tables 8 and 9. The results indicate that the average value/cost ratios vary from one nutrient to another, from one crop to another, and from one location to another but are generally higher than 2. The value/cost ratios are higher for export crops than for food crops, higher for improved farm practices than for traditional practices, and higher for subsidized fertilizer prices than for unsubsidized fertilizer prices.

The estimated value/cost ratios indicate that fertilizer use is profitable. However, one must keep in mind that the value/cost ratios are generally based on fertilizer response coefficients from experiment stations and official fertilizer and crop prices; they do not incorporate associated fertilizer cost. Fertilizer response on farmers' fields is lower than that on experiment stations. The fertilizer price paid by the farmer is generally higher than the official price, and the crop price received by the farmer is generally lower than the official price. In addition, the farmer also bears other costs associated with fertilizer use. Consequently, under farmer circumstances the average value/cost ratios may not be as attractive as they appear.

The possibilities for improving fertilizer use incentives through price policy do not appear very good. Fertilizer subsidies are very common in most

Table 6 Fertilizer response coefficients based on fertilizer demonstrations in sub-Saharan Africa[a]

Country	Kilogram of crop yield per kilogram of applied nutrients for[b]					
	Sorghum	Maize	Rice	Wheat	Yams	Groundnuts
Botswana	3.8	4.9	–	–	–	–
Cameroon	–	9.8	–	–	49.4	9.1
Ethiopia	16.3	15.1	–	7.3	–	–
Gambia	–	–	6.6	–	–	14.7
Ghana	7.9	11.9	9.4	–	69.0	7.5
Ivory Coast	–	10.3	6.2	–	26.4	–
Kenya	–	14.6	–	–	–	5.0
Nigeria	–	9.5	7.1	–	6.8	15.5
Senegal	–	–	3.7	–	–	6.3
Sierra Leone	–	–	10.3	–	–	7.9
Togo	7.0	6.5	15.2	–	26.8	4.6

[a] Mudahar [24]. The coefficients are based on data reported in FAO [2].

[b] The fertilizer productivity is based on average best NPK treatments between 1961 and 1971.

Table 7 Estimated average response based on selected fertilizer response studies in Nigeria[a]

Crop	Farm practice	Area	Year	Nutrient source	Treatment $N:P_2O_5:K_2O$	Additional yield (kg/ha)	Average response over control (kg/kg of nutrient)
Millet	Improved	Sokoto	1976	CAN, SSP	17-12-0	338	11.7
Sorghum	Farmer	Sokoto and Niger	1976	CAN, SSP	35-24-0	299	5.1
	Improved	Sokoto and Niger	1976	CAN, SSP	70-48-0	700	5.9
Maize	NA	Kwara	1970/72	AS, SSP	73-40-0	1,288	11.4
	NA	Bendel	1976	AS, SSP, MOP	75-34-34	836	5.8
Rice	Farmer	Niger	1976	AS, SSP	84-36-0	591	4.9
	Improved	Niger	1976	AS, SSP	126-36-0	1,234	7.6
	NA	Nigeria	1961/71	AS, SSP, MOP	22-22-22	470	7.1
Wheat	Indus variety	Kano	1973/75	AS, SSP	80-40-0	1,442	12.0
Yams	NA	Nigeria	1961/71	AS, SSP, MOP	22.4-22.4-22.4	2,232	33.4
Cassava	NA	Nigeria	1961/71	AS, SSP, MOP	34-28-34	4,300	44.8
Groundnuts	Farmer	Niger and Sokoto	1976	SSP	0-18-0	269	14.9
	Improved	Niger and Sokoto	1976	SSP	0-36-0	602	16.7
Cotton	Improved	Niger and Sokoto	1976	CAN, SSP	35-24-0	460	7.8

NA = Not Available

[a] Derived from Joly [15], Poulson [30], NAFPP [26], FAO [30], and Pandey [28].

sub-Saharan African countries. The stated primary purpose is to lower the fertilizer price paid by the farmer. However, the financial burden of fertilizer subsidies is rather high and increasing over time. Most governments are in the process of reducing fertilizer subsidies by increasing fertilizer prices (Figure 6). In the absence of any significant improvements in fertilizer production, procurement, and marketing efficiences, the prices paid by the farmers are expected to increase.

Despite temporary slowdown, the energy prices will continue to put an upward pressure on fertilizer prices through an increase in production, marketing, and freight costs [25]. The crop prices, on the other hand, are not expected to increase as rapidly as the fertilizer prices. This is due to inefficient crop marketing systems and the continuous desire of national governments to keep a lid on food prices through so-called cheap food pricing policy. The net result of these pricing policies will be to stop or reverse the declining trend in fertilizer/crop price ratios (Figure 6). This will lower incentives to expand fertilizer use and may dampen fertilizer demand.

In addition, many countries in sub-Saharan Africa (Niger, for example) are reducing or eliminating provision of fertilizer credit because of the high cost of subsidized and poorly implemented credit policies. There is a need for fertilizer credit, but it should be given at a market rate of interest to reduce its inefficient use. Alternatively, fertilizer sales could be linked with crop marketing.

Table 8 Average value cost ratios based on fertilizer trials in sub-Saharan Africa[a]

Country	Crop	Average value cost ratios for[b]			
		N	P_2O_5	K_2O	NPK
Cameroon	Maize	2.2	0.9	2.6	1.9
Ghana	Maize	2.1	2.3	5.8	3.4
Ivory Coast	Maize	1.6	1.2	1.2	1.3
Nigeria	Maize	0.9	0.8	2.2	1.3
Ghana	Rice	5.1	4.8	9.2	6.4
Ivory Coast	Rice	1.8	1.4	2.5	1.9
Nigeria	Rice	2.5	3.1	3.8	3.1
Senegal	Rice	2.8	1.6	5.5	3.3

[a] Mudahar [24]. The value/cost ratios are derived from summary results reported in FAO [2] which are based on average best NPK treatments between 1961 and 1971.

[b] The average value/cost ratios are based on the official fertilizer and crop prices.

Table 9. Average value cost ratios based on selected fertilizer response studies in Nigeria[a]

Crop	Farmer practice	Cost of fertilizer		Value of incremental output[d]	Value/cost ratio	
		Subsidized[b]	Unsubsidized[c]		Subsidized	Unsubsidized
		₦				
Millet	Improved	4.8	18.3	57.9	12.1	3.2
Sorghum	Farmer	9.8	37.3	51.8	5.3	1.4
	Improved	19.7	74.5	121.3	6.2	1.6
Maize	NA	20.5	75.6	219.6	10.7	2.9
	NA	21.7	80.5	142.5	6.6	1.8
Rice	Farmer	21.6	80.2	106.1	4.9	1.3
	Improved	28.8	108.2	221.6	7.7	2.0
	NA	9.5	34.6	84.4	8.9	2.4
Wheat	Indus variety	21.7	80.2	403.8	18.6	5.0
Yams	NA	9.7	35.2	626.5	64.6	17.8
Cassava	NA	13.5	49.4	684.5	50.7	13.9
Groundnuts	Farmer	3.6	12.1	78.0	21.7	6.4
	Improved	7.2	24.2	174.6	24.3	7.2
Cotton	Improved	9.8	37.3	151.8	15.5	4.1

NA = not available.

[a] The fertilizer response coefficients used in estimating average value/cost ratios were obtained from Table 7.

[b] Based on 1979/80 subsidized prices which were 0.171, 0.144, 0.200, and 0.060 ₦/kg of N from AS, N from CAN, P_2O_5 from SSP, and K_2O from MOP, respectively.

[c] Based on 1979/80 unsubsidized prices which were 0.667, 0.604, 0.672, and 0.233 ₦/kg of N from AS, N from CAN, P_2O_5 from SSP, and K_2O from MOP, respectively.

[d] Based on 1978/79 average farm-gate prices.

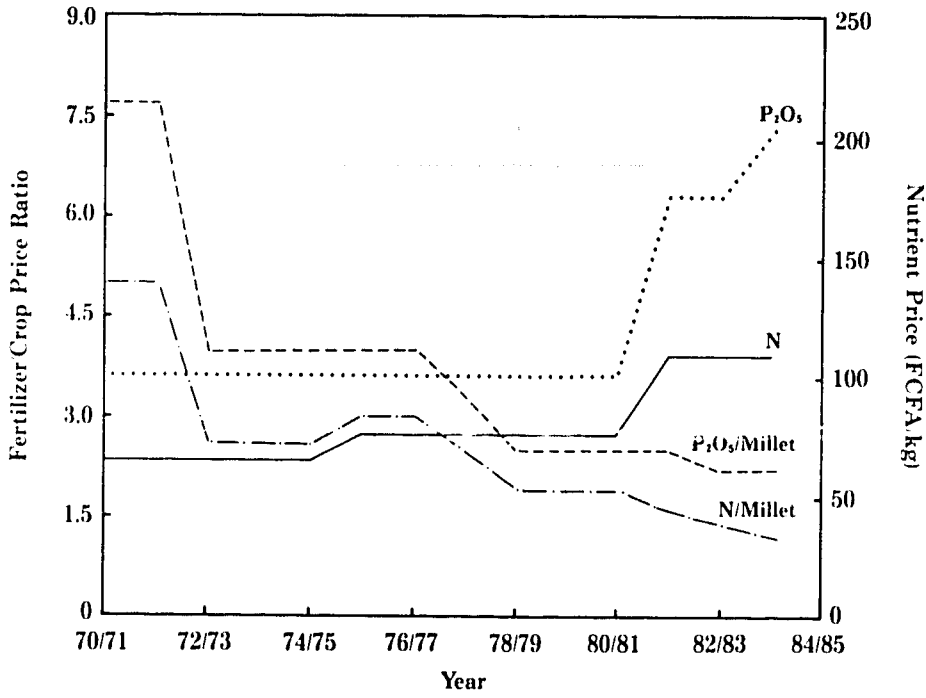

Figure 6. The dynamics of nutrient prices and nutrient/millet price ratios in Niger.

Fertilizer recommendations and promotion policy

The productivity of fertilizer use is heavily influenced by fertilizer management. Many countries in sub-Saharan Africa do have agricultural extension agencies of some sort that are assigned the job of fertilizer promotion and its efficient use. In many countries, the total expenditure on agricultural extension is larger than the expenditure on agricultural research, clearly indicating misplaced priorities. There is a need not to reduce the expenditure on agricultural extension but rather to substantially increase the expenditure on agricultural research.

The farmers in sub-Saharan Africa are most likely aware of the potential contribution of fertilizer to crop production; however, they may not have sufficient knowledge about fertilizer recommendations and improved management practices. In many cases, although such information does exist, it is not made available to the farmers; consequently, it is of little use to the farmer and even to the nation. On the other hand, fertilizer recommendations for specific agroclimatic conditions, crops, crop technology, and soil conditions just do not exist. The blanket recommendations for the whole country are not only inappropriate but could in fact be counterproductive.

Fertilizer promotion must be based on scientific information developed through fertilizer-related agronomic and soil fertility research and sound economic and policy analyses. The fertilizer promotion policy should include development of soil fertility maps, establishment of soil testing laboratories, formulation of soil and crop-specific fertilizer recommendations, and initiation of well-designed fertilizer demonstrations under farmers' field conditions.

However, it is important to keep in mind that a vigorous fertilizer promotion policy will improve the knowledge base of the farmers but will not achieve the desired outcome in the absence of fertilizer availability at the farm level.

Complementary inputs and investment policy

One of the major problems facing sub-Saharan Africa is the pursuit of economic policies that discriminate against the agricultural sector. This includes agricultural price policy, taxation policy, trade policy, technology policy, marketing policy, and policies designed to provide basic amenities to the rural population. With the exception of oil- and mineral-exporting countries, the agriculatural sector contributes a major share to the GDP. Yet the share of national public expenditure allocated to the agricultural sector is extremely small (Table 10). Such a strategy reflects government's lack of commitment to develop the agricultural sector and raise the income levels of the rural poor.

In addition to developing the necessary infrastructure and institutions that serve the agricultural sector, there is a need to increase resources for agricultural research and development of irrigation systems. The experience around the world indicates that returns to investment in agricultural research are very high. Agricultural research in sub-Saharan Africa needs to be directed toward crop improvement in the context of both existing and improved farming systems. The objective of crop improvement research must be to develop crop varieties that are high yielding, fertilizer responsive, disease resistant, pest resistant, drought resistant, and suitable for local environmental conditions. In this context, very limited progress has been made in sub-Saharan Africa.

Modern crop varieties in the absence of fertilizer use may not yield any more than do the existing crop varieties. On the other hand, fertilizer cannot be applied in the absence of an assured water supply (from rainfall or irrigation) even if fertilizer-responsive crop varieties are available. An assured supply of water through irrigation is essential for the use of modern farm technology; equally important, irrigation is essential for the use of modern farm technology; equally important, irrigation facilitates multiple cropping

and reduces yield risk with or without modern farm technology.

Many countries in sub-Saharan Africa have no irrigation systems or only poorly developed ones. For example, in 20 of 34 sub-Saharan African countries less than 2% of the arable land is equipped for irrigation, regardless of the quality. The development of an irrigation system is very expensive and requires a long time. Consequently, the prospects of a rapid expansion in irrigated area in the next decade are rather limited in sub-Saharan Africa.

The long-term solution to the food and poverty problem in is the transformation of the agricultural sector through development, transfer, and use of appropriate agricultural technology. This will not only increase rural income

Table 10 Share of agriculture in national government expenditure in sub-Saharan Africa

Country	Contribution of agriculture to GDP (1982)[a]	Share of agriculture in total expenditure (1981)[b]
	(%)	
Botswana	12[b,c]	9.7[d]
Burkina Faso	41	3.9[e]
Burundi	56	12.0[f]
Cameroon	27	2.2[d]
Chad	64[c]	20.9[g]
Congo	6	3.2[h]
Ethiopia	49	8.5[i]
Gambia	26[b,c]	22.0[j]
Ghana	51	12.2[d]
Ivory Coast	26	3.4[d]
Kenya	33	11.2
Lesotho	23	18.5
Liberia	36	4.6
Mali	43	7.6
Mauritania	29	7.1[e]
Mauritius	14[b,c]	6.2
Niger	31	6.8[d]
Nigeria	22	2.6[f]
Rwanda	46[c]	13.0[d]
Senegal	22	5.2[k]
Sierra Leone	32	4.1[e]
Sudan	36	9.4[d]
Tanzania	52	7.0[e]
Togo	23	8.9[e]
Zambia	14	23.0[d]

[a] Derived from the World Bank [37].
[b] Derived from the World Bank [36].
[c] Refers to 1981.
[d] Refers to 1980.
[e] Refers to 1979.
[f] Refers to 1977.
[g] Refers to 1976.
[h] Refers to 1970.
[i] Refers to 1978.
[j] Refers to 1975.

and employment but will also stimulate industrial growth through growth linkages and multiplier effects.

Phosphate resources and import substitution

Indigenous phosphate resources

Only about 10 countries in sub-Saharan Africa have facilities to produce limited quantities of nitrogen and/or phosphate fertilizers. Almost all of the fertilizer requirements are met through imports. With the exception of a few countries, sub-Saharan Africa has limited or no known resources to produce nitrogen and potassium fertilizers. However, most of these countries are known to have phosphate rock. Togo and Senegal are among the current exporters of phosphate rock.

Appropriate phosphate technology

The known reserves of phosphate rock (at current prices and technology) in most sub-Saharan countries are small by world standards. However, these reserves are large enough to meet their own phosphate fertilizer requirements for decades. The phosphate resources vary in chemical composition, and many are known to have impurities. As a result, the small quantity along with poor quality precludes the use of many of these phosphate resources for manufacturing known commercial phosphate fertilizers. However, many of these resources have been found suitable either for direct application or for manufacturing modified phosphate fertilizers such as partially acidulated phosphate rock (PAPR).

It is relatively cheaper to produce PAPR since it uses much less sulfuric acid than is needed for producing SSP. Furthermore, the available evidence based on fertilizer trials for millet and other crops in Niger and Nigeria indicates that 50% PAPR (50% of the sulfuric acid used for SSP) is as economical a source of phosphorus as is SSP [12,10,22]. Furthermore, PAPR, like SSP but unlike TSP, also contains sulfur, the supply of which is essential for increasing crop yields and improving its quality for human nutrition [16].

Economic consequences of a PAPR plant

The economic consequences of a PAPR plant were estimated for Niger, as part of a feasibility study [13]. Niger is a land-locked country. Since transportation costs are rather high, fertilizers imported from the international market are very expensive. Several schemes to produce PAPR in Niger were evaluated in comparison with imported SSP. The internal rate of return (IRR), though it varied from one scheme to another, was always positive and reasonably high, assuming plant capacity was fully utilized.

Since PAPR is considered to be a substitute for SSP, domestic production of PAPR is viewed as a policy of import substitution. Consequently, the PAPR plant has many other potential economic benefits for the country as compared with imported SSP. These economic benefits are estimated for a run-of-pile PAPR plant (100 mtpd of product) based on rock from Parc-W phosphate deposit and a sulfuric acid plant based on imported sulfur.

First, even at 15% IRR, the unsubsidized retail price of PAPR is almost 15% lower than the unsubsidized retail price of imported SSP.

Second, the annual financial saving through PAPR production (at minimum acceptable IRR of 12.5%) over SSP imports could be $0.9 million in the first year (50% capacity utilization) and $1.6 million in the third year (90% capacity utilization) of plant operation.

Third, for a country like Niger, even a small PAPR plant could be a great asset not only through annual additions to national income but also through a favorable impact on balance-of-trade.

Fourth, the foreign exchange component of PAPR production is about one-half the corresponding foreign exchange component of SSP imports.

Fifth, the PAPR plant is estimated to create 151 jobs (a total of 4,100 persons were employed in Niger in the manufacturing industry during 1981) with an initial annual wage bill of apporoximately $0.5 million. Additional indirect employment through growth linkages and multiplier effects could be at least two to three times that of direct employment at the PAPR plant.

Sixth, and very important for a land-locked country like Niger, indigenous PAPR production can provide phosphate fertilizer security. In this context, the PAPR plant can contribute toward providing food security and accelerating and stabilizing growth in agricultural production.

Summary and conclusions

The objective of this paper was to analyze fertilizer problems and policies in sub-Saharan Africa, with particular reference to raising fertilizer productivity, accelerating fertilizer demand, and using indigenous phosphate resources.

Sub-Saharan Africa consists of over 40 low-income tropical countries, with a combined population of 380 million. Several of these countries face serious food and foreign exchange problems. The agricultural sector dominates their national economies, even for those countries that are rich in oil and mineral resources. However, the performance of the agricultural sector, as reflected by the declining crop yields and per-capita food production, has been rather dismal. Accelerating agricultural growth is essential for solving food problems and achieving long-term sustained economic growth.

Fertilizer use, along with other complementary inputs, has played and will play an even greater role in the future in transforming the traditional agriculture and accelerating agricultural growth. However, the present level of and growth in fertilizer use are extremely low and fluctuating. In many cases fertilizer growth was found to be negative. The average fertilizer use in sub-Saharan Africa is 6.9 kg/ha, which is 14% of the average in developing countries. The aggregate fertilizer consumption is about 1 million tonnes of nutrients which is 30% of the consumption in continental Africa.

There is a need for appropriate technology and major policy reforms to expand fertilizer demand, assuming that fertilizer is available to the farmer at the right time and price. In addition to creating the necessary institutions and infrastructure to serve agriculture, there is a need for major reforms and commitment in at least four areas: (1) raise fertilizer efficiency, productivity, and response through development of appropriate fertilizer technology and management; (2) improve incentives, increase profitability, and reduce risk from fertilizer use through appropriate price, subsidy, and credit policies; (3) transfer and disseminate fertilizer technology and management practices through appropriate fertilizer recommendations and promotion policy; and (4) improve crop response to applied fertilizer through the development and transfer of fertilizer-responsive crop varieties, expansion in irrigation, and investment in agricultural research.

Most countries in sub-Saharan Africa depend on imports to meet part or all of their domestic fertilizer requirements. Fertilizer imports generally do not receive the priority or timely allocation of foreign exchange which is rather scarce. However, most countries do have phosphate resources that could be used to produce modified phosphate fertilizers, especially PAPR which has been found to be as economical a source of P_2O_5 as SSP. Furthermore, the use of indigenous phosphate resources through PAPR or other modified phosphate fertilizers not only saves foreign exchange and provides phosphate fertilizer security but also has many other direct and indirect potential economic benefits for the country over imported SSP.

The long-term solution to the food and poverty problems in sub-Saharan Africa is accelerating agricultural growth through development, transfer and use of appropriate agricultural and fertilizer technologies. This will not only

increase rural income and employment but will also stimulate industrial growth.

Notes

[1] Countries included in sub-Saharan Africa, with the exception of some off-shore islands, are shown in Figure 1. Egypt, Libya, Tunisia, Algeria, Morocco, and South Africa are not part of sub-Saharan Africa. On the other hand, the definition of developing market economy Africa, according to the Food and Agriculture Organization of the United Nations (FAO), excludes only Egypt, Libya, Sudan, and South Africa from continental Africa.

[2] The literature on food problems and prospects in Africa is large and growing. A few of the selected studies that deal with food problems are USDA [32], IFPRI [14], Mellor and Paulino [26], Sanderson [31], FAO [5], World Bank [35], World Bank [38], and Eicher [1].

[3] These food deficits are in terms of cereal equivalents. The noncereal food staples are converted into cereal equivalents by using appropriate conversion factors.

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Constraints to fertilizer use in sub-Saharan Africa

John McIntire

Introduction

Sub-Saharan Africa has some of the lowest rates of fertilizer consumption in the world. Between 1979 and 1982 its share of world nitrogen consumption was about 1.0% and its share of the developing countries' nitrogen consumption about 2.5%. Its share of P_2O_5 use was between 1% and 2% of the world total and between 4% and 8% of the total for the developing countries [7].

The tendency in many countries has been for fertilizer growth to be roughly equal to population growth. Rates in 1974-76 were about 4.2 kg/arable ha; the average in 1978-82 was about 5.7 kg/arable ha. Most of that growth was in Nigeria, which increased consumption per hectare by 171% [7].

Why is use so low in sub-Saharan Africa? What has made it rise, and what could make it rise more? This paper seeks to answer these questions by considering factors that influence fertilizer demand in sub-Saharan Africa. It does so in a limited way. First, most of the analysis is limited to the principal cereals of the subcontinent: maize, pearl millet, rice, and sorghum.[1] Although there are constraints to fertilizer use on cash crops, such as cotton and groundnuts, or on root crops, such as yams and cassava, it would require a longer paper to review them adequately.

Second, much of the analysis is limited to two fundamental constraints: the low fertilizer response of the principal rainfed cereals and the insufficient supplies of fertilizers to much of the subcontinent.

Third, fertilizer is not an end in itself. It is a means to higher incomes for farmers and to lower prices for consumers. As such, its use as an agricultural input must always be compared with alternative inputs and production strategies. Because sub-Saharan Africa has low population density in general, farmers will prefer extensive strategies – those raising cultivating area – to intensive ones – those raising yield per unit area. Fertilizer use is an intensive strategy, a fact which has been insufficiently recognized when discussing constraints.

Fourth, nothing is said about risk because this factor was reviewed recently by Shalit and Binswanger [29]. They concluded that risk explained no more than 10%-20% of the shortfall in fertilizer consumption from the economic optimum and that this shortfall was small compared with the shortfall from the risk-averse optimum. It is not that risk is never a constraint, but rather that it is much less important than simple lack of profitability.

Fifth, nothing is said about credit, i.e., financing investment by borrowing, as a constraint. There are good reasons why credit supply is weak in areas with low population density [2]. There are also enough unhappy experiences with public credit to make one wary of concluding that governments can supply credit where it is now absent. Again, it is not that credit is never a constraint, but rather that farmers are more able to finance profitable investments out of savings than is generally recognized.

Fertilizer use in sub-Saharan Africa

Use per hectare and per caput

Fertilizer production, consumption, and trade data from the Food and Agriculture Organization of the United States (FAO) were used to produce the summaries in Table 1 [7]. Mean use of NPK per arable hectare was about 5.7 kg in 1978-82. The largest use was in Zimbabwe, and only five other countries used more than 10 kg/ha. By comparison, the 1982 average was 77.9 kg/ha for the world, 26.3 kg/ha for Latin America, and 72.5 kg/ha for Asia [7].

Since sub-Saharan Africa has lower population density than the developing countries of Asia, nutrient use per hectare is not necessarily the best comparison; that is, one expects greater use in areas of high population density because of greater land pressure. More densely populated areas usually have more irrigation, which is associated with greater fertilizer use (see, for example, Desai [5], Jha [14], and Jha and Sarin [15] for India).

Table 1 also presents nutrient use per caput in the 35 countries. The mean in 1978-82 was 2.3 kg/caput, the maximum was 19.5 (Zimbabwe), and the minimum was 0.03 (Uganda). The average was 25.5 for the world as a whole, 18.3 for Latin America, and 11.5 for Asia. Compared with the situation in Latin America, Africa's relative gap, when use is expressed per caput, changes little; however, when compared with that in Asian countries of similar income levels but with greater population density, the gap decreases.

Table 1 Characteristics of fertilizer use in 35 sub-Saharan African countries, 1961-65 to 1978-82

Country	Nutrient, kg/caput		Nutrient, kg/Arable ha		1978-82 as % of 1961-65	% Share of total use, 1978/82		
	1974/76	1978/82	1974/76	1978/82		N	P	K
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Angola	1.10	2.17	2.00	4.30	430.0	48.8	27.1	25.6
Benin	1.10	0.53	1.70	1.10	550.0	51.5	27.3	21.2
Botswana	3.00	2.00	1.60	1.17	83.3	42.9	57.1	0.0
Burkina Faso	0.50	1.23	1.00	3.27	NA	32.7	41.8	23.5
Burundi	0.20	0.33	0.60	0.90	NA	51.9	29.6	22.2
Cameroon	1.80	4.40	2.20	5.37	670.8	52.2	17.4	31.1
Central African Republic	1.00	0.50	1.10	0.63	633.3	89.5	5.3	10.5
Chad	1.80	1.00	2.50	1.40	NA	42.9	21.4	31.0
Congo	2.30	0.37	4.70	0.90	47.4	59.3	11.1	33.3
Ethiopia	1.00	1.13	1.90	2.60	2,600.0	38.5	61.5	0.0
Gabon	0.90	0.53	1.10	0.60	NA	44.4	11.1	33.3
Gambia	2.20	4.30	7.70	16.43	4,108.3	31.6	62.1	5.9
Ghana	1.90	1.40	6.80	7.03	1,172.2	48.3	19.9	30.8
Guinea	0.30	0.27	1.00	0.87	144.4	23.1	42.3	30.8
Ivory Coast	5.20	5.33	10.10	11.00	1,100.0	33.9	19.1	47.3
Kenya	3.80	3.63	22.50	26.17	272.6	47.4	40.3	12.4
Liberia	2.80	1.53	12.80	7.70	1,925.0	55.8	28.1	16.0
Madagascar	1.00	1.33	3.00	3.93	262.2	43.2	18.6	38.1
Malawi	3.30	5.10	7.70	13.57	589.9	70.5	17.7	11.5
Mali	1.20	1.67	3.70	5.63	NA	50.9	21.3	29.0
Mauritania	0.50	0.67	3.70	5.83	NA	67.4	25.1	7.4
Mozambique	0.80	2.77	2.60	9.57	503.5	56.8	32.4	10.8
Niger	0.20	0.40	0.30	0.70	NA	42.9	42.9	9.5
Nigeria	0.80	1.87	1.80	4.87	4,866.7	52.1	30.8	17.1
Rwanda	0.00	0.13	0.40	0.47	NA	42.9	28.6	28.6
Senegal	8.40	4.33	8.40	4.70	106.8	28.4	42.6	30.5
Sierra Leone	0.70	0.30	1.10	0.77	766.7	34.8	34.8	34.8
Somalia	0.70	0.17	2.10	0.73	91.7	86.4	4.5	9.1
Sudan	4.90	2.63	6.40	3.93	106.3	99.2	0.8	0.0
Tanzania	1.90	1.70	6.10	5.67	515.2	59.4	25.3	14.7
Togo	1.10	0.90	1.70	1.70	NA	35.3	35.3	27.5
Uganda	0.30	0.03	0.40	0.07	9.5	50.0	50.0	0.0
Zaire	0.50	0.30	1.70	1.20	600.0	47.2	25.0	22.2
Zambia	12.20	12.93	11.90	14.87	707.9	68.6	22.4	9.2
Zimbabwe	22.70	19.50	56.00	55.33	199.8	51.0	28.6	20.5
Mean	2.12	2.33	4.17	5.73	347.7	51.3	30.3	18.4
Minimum	0.00	0.03	0.30	0.07	9.5	23.1	0.8	0.0
Maximum	22.70	19.50	56.00	55.33	4,866.7	99.2	62.1	47.3

Notes: The means of columns (2) and (3) are weighted by country populations; the means of columns (4), (5), and (6) are weighted by country arable areas. The sums of columns (7), (8), and (9) for a given country may not add to 100% because of rounding errors. Sources of data are FAO Fertilizer Yearbooks, various years [7].

Trends in use over time

Of the 35 countries shown in Table 1, 16 increased use per caput between 1974-76 and 1978-82, and 17 increased use per hectare. The absolute changes were small. The percentage changes were large because the base for the comparisons was low.

There have been larger changes since independence. The results in column [6] of Table 1 were attained by taking 1961-65 as a base and expressing consumption per hectare in 1978-82 as a percentage of the base. This suggests that there has been some growth in consumption per arable hectare.

Nutrient composition of use

Columns (7), (8), and (9) of Table 1 present the shares of N, P_2O_5, and K_2O in the 1978-82 totals. There were no major changes between that period and 1974-76. The mean share of N for sub-Saharan Africa was 48.9% in 1974-76 and 51.8% in 1978-82; for P_2O_5, the corresponding shares were 30.7% and 30.3%.

Self-sufficiency in fertilizer consumption

Fertilizer consumption in sub-Saharan Africa depends on imports. Of the 35 countries in Table 1, only 8 produce fertilizers. Of the producers, none are self-sufficient; the nonproducers are, of course, entirely dependent on imports. Import policies are therefore crucial for consumption growth.

Fertilizer response and economic returns

Monetary return is the basic determinant of fertilizer demand. Physical response – kilogram of product per kilogram of nutrient – is one of the main determinants of monetary return. To describe the effects of response on fertilizer demand, this section reviews some fertilizer experiments from rainfed areas of semiarid West Africa.

Physical responses to nutrients

Published results of experiments were reviewed for maize, millet, paddy, and sorghum. These results give a good idea of response and form a basis for a discussion of constraints.

Table 2 presents estimates of N and P_2O_5 responses in sub-Saharan Africa,[2] based on results from the FAO fertilizer program as cited by Zalla, Diamond, and Mudahar (henceforth ZDM) [33]. In the ranges cited from trials of nitrogenous fertilizers, paddy had the highest response. The same was true of demonstrations. Maize had the second highest response and millet/sorghum the lowest. These results suggest that, for a given output/input price ratio, rice provides the strongest incentives for use of fertilizers, followed by maize, followed by millet/sorghum. Trials with phosphatic fertilizers showed roughly the same rankings as trials with nitrogen.

Data were assembled from experiments in Burkina Faso, Mali, and Niger. Marginal and average products of N and P_2O_5 were calculated and are reported in Table 2. For nitrogen, the mean average physical products (APP) were at the low end of the response range from FAO trials for millet and at the high end for sorghum. For maize and paddy, the mean APPs of nitrogen were above the maxima. The mean marginal physical products (MPP) of nitrogen were less than the mean APPs for each crop and accorded better with the ranges from the FAO trials.

For P_2O_5, it was possible to calculate mean MPPs and APPs only for maize and sorghum. For maize, the mean APP was near the maximum of the ZDM trial range. For sorghum, the mean APP was in the middle of the ZDM range. For both crops, the mean MPPs were less than the mean APPs.

Regression analysis

– In order to estimate MPPs across sites, regression analysis was done with the data used to produce Table 2. Results are in Table 3. A first specification was done with N, P_2O_5, and K_2O, with their squares and full interactions ($N*P_2O_5$, $N*K_2O$, and $P_2O_5*K_2O$). In the millet and sorghum regressions, dummy variables were included for experiments in farmers' fields.

There are two problems in this approach. One is that many trials have little or no variation in nutrients other than the main one tested. This allows an estimate of the main effect when other nutrients are not limiting. Pooling data across sites introduces variation in other nutrients, but it does so at the risk of confounding site variation with nutrient variation.

Second, when pooling data from rainfed experiments in maize, millet, and sorghum there is the risk of confounding yield variation caused by nutrients with yield variation caused by rainfall at different sites. Because nutrient responses interact with moisture, the nutrient regression coefficients will be biased unless moisture is included as a regressor.

Maize results

– Nitrogen and nitrogen squared were not significant. This is perhaps because most of the maize observations were taken from one set of trials [30]

in which the nitrogen treatment varied little. P_2O_5 was significant at the 5% level, though P_2O_5 squared was not significant at the 10% level.

Millet results

– The linear term for nitrogen was 4.9 and was significant at the 1% level. The linear term for P_2O_5 was 9.3 and was also significant at the 1% level. The

Table 2 Fertilizer responses for maize, millet, paddy, and sorghum as calculated from literature review and from FAO results

	Maize	Millet	Paddy	Sorghum
Nitrogen applications				
Mean nutrient level, kg N/ha	107	79	99	50
MPPs, kg grain/kg nutrient				
Number of observations	6	30	63	36
Mean	16.2	4.3	18.3	5.7
Standard deviation	8.2	4.1	10.9	4.9
APPs, kg grain/kg nutrient				
Number of observations	6	20	63	19
Mean	20.4	5.9	21.4	9.9
Standard deviation	4.7	3.3	8.1	5.5
Results from FAO fertilizer trials				
Mean nutrient level, kg N/ha	40	20	45	20
Response range, kg/kg	6-14	5-10	10-20	5-10
Results from FAO fertilizer demonstrations				
Mean nutrient level, kg N/ha	20	20	30	20
Response range, kg/kg	10-20	6-14	10-20	6-14
Phosphorus applications				
Mean nutrient level, kg P_2O_5/ha	150	NA	NA	52
MPPs, kg grain/kg nutrient				
Number of observations	22	NA	NA	9
Mean	10.7	NA	NA	6.7
Standard deviation	12.6	NA	NA	5.3
APPs, kg grain/kg nutrient				
Number of observations	22	NA	NA	9
Mean	12.6	NA	NA	7.0
Standard deviation	7.8	NA	NA	5.7
Results from FAO fertilizer trials				
Mean nutrient level, kg P_2O_5/ha	20	20	20	20
Response range, kg/kg	5-12	4-8	8-15	4-8
Results from FAO fertilizer demonstrations				
Mean nutrient level, kg P_2O_5/ha	20	20	20	20
Response range, kg/kg	2-8	6-15	4-12	6-15

Notes: Data sources are [31], [27], [17], [19], [4], [3], and [30]. Data from FAO fertilizer trials and demonstrations are from 'various FAO Fertilizer Program Reports and country research station reports' as cited in [33]. MPPs = mean marginal physical products, and APPs = mean average physical products.

Table 3 Fertilizer response functions for maize, millet, rice, and sorghum (dependent variable is grain yield/ha)

	Maize	Millet	Rice	Sorghum
Independent variables				
Nitrogen	5.709	4.372	26.771	20.943
	0.290	4.932[c]	5.303[c]	2.974[c]
P_2O_5	19.392	11.413	1.261	27.756
	2.550[b]	5.702[c]	1.487	2.720[c]
K_2O	NA	-8.544	-2.942	NA
	NA	1.931[a]	1.086	NA
Nitrogen squared	0.007	NA	-0.065	-0.090
	0.055	NA	2.132[b]	2.035[a]
P_2O_5 squared	-0.046	NA	NA	-0.088
	1.415	NA	NA	0.883
K_2O squared	NA	NA	NA	NA
	NA	NA	NA	NA
$N*P_2O_5$	NA	NA	NA	-0.005
	NA	NA	NA	0.077
$N*K_2O$	NA	NA	NA	NA
	NA	NA	NA	NA
$P_2O_5*K_2O$	NA	NA	NA	NA
	NA	NA	NA	NA
Adjusted R-squared	0.302	0.779	0.549	0.702
Number of observations	38	71	70	54
F-statistic	5.004[c]	83.354[c]	22.004[c]	21.779[c]
Mean fertilizer rates, kg/ha				
N	112.6	40.6	60.6	33.4
P	105.8	44.8	121.8	38.8
Marginal physical products at mean fertilizer rates, kg/kg				
N	7.2	4.4	18.9	14.9
P	9.7	11.4	1.3	20.9
Marginal physical products at 50 kg/ha of nutrient, kg/kg				
N	6.4	4.4	20.3	11.9
P	14.8	11.4	1.3	18.9

Notes: Regression specification was ordinary least squares. T-statistics are shown as absolute values on the line below the regression coefficients:
[c] means significant at 1% level, [b] at 5% level, and [a] at 10% level. Maize data are from [30] and [31]. Millet data are from [17], [19], and [31]. Rice data are from [3] and [31]. Sorghum data are from [17], [27], and [31].

millet estimates had no significant quadratic or interaction terms.

The International Fertilizer Development Center (IFDC) [12] estimated millet's response to nitrogen as yield = 11.41 N – 0.0777 N^2. This implies an MPP of 3.6 kg/kg at an N rate of 50 kg/ha. Montgomery [21] estimated the MPP to be 3.4 kg/kg at an N rate of 50 kg/ha. He estimated the linear response to P_2O_5 to be 9.17 kg of millet. He reported the squared term for P_2O_5 to be nonsignificant and the interaction of P_2O_5*K_2O to be –0.155. At a K_2O rate of 50 kg/ha, this gave an MPP for P_2O_5 of 1.4 kg/kg.

Paddy results

– The MPP of nitrogen calculated at the mean rate of 60.6 kg/ha, was 18.9 kg/kg, which corresponded to the tabulated experiments. This value was close to Montgomery's [21] estimate of 16.2 kg/kg and to the ZDM [33] estimate of 17.0 kg/kg. P_2O_5 was not significant in any specification, although Montgomery found it to be so. Using Montgomery's coefficients (cited in [18]) gave a marginal product of P_2O_5 of 4.25 kg/kg at a P_2O_5 rate of 50 kg/ha.

Sorghum results

– The linear term for P_2O_5 was significant at the 5% level, but the squared term was not significant at the 10% level. The calculated MPP of P_2O_5 (5.5 kg/kg at a P_2O_5 rate of 50 kg/ha) in sorghum is similar to those derived from the literature review. The linear term for nitrogen was significant, as was the squared term. The calculated MPP of nitrogen in sorghum is 0.7 kg/kg at an N rate of 50 kg/ha, which is due to the negative interaction between N and the farmers' tests in Burkina Faso. Montgomery's function showed the marginal product of N to be 8.1 kg of sorghum at N and P_2O_5 rates of 50 kg/ha. The same function showed the marginal product of P_2O_5 to be 4.9 kg of sorghum at an N rate of 50 kg/ha.

Experiment results and fertilizer profitability

A review [6] of FAO trials and demonstrations found that fertilizer applications would generally have been profitable in Ethiopia and in seven West African countries. The incremental value to cost ratios (VCRs) in rice ranged from 2.6 to 6.5; in maize, from 1.8 to 3.7; in millet, from 1.8 to 4.3; in sorghum, there was one observation of 1.8. High VCRs were observed in yam and groundnut in West Africa and in teff and wheat in Ethiopia. These results are based on thousands of observations, and they appear to establish fertilizer profitability in many situations on several major food crops.

The results of the FAO trials not only showed that fertilizer could be profit-

able, but also confirmed two general trends. First, rice gave the best VCRs, followed by maize, followed by sorghum. The West African results showed rice giving higher VCRs than maize in three of four countries [6].
In Kenya, Lesotho, and Botswana, the average VCR was 2.05 for maize (c.v. of 37.4%) and 0.89 for sorghum (c.v. of 54.2%) [6]. Second, profitable fertilizer responses were found with local cultivars.

Working in Northern Nigeria, Goldsworthy [10] found N and P_2O_5 applications to be profitable on sorghum; for example, at an N rate of 26.3 kg/ha, 16.2 kg/ha of P_2O_5 would have been profitable in a relatively dry area, and 21.2 kg/ha would have been optimal in a wetter area. For maize, Goldsworthy [11] found profitable fertilizer responses in the same two areas at rates of 66.1 kg N/ha and 39.7 kg P_2O_5/ha. This work was done with local cultivars or with test cultivars derived from local parents.

Evidence about fertilizer profitability on millet and sorghum in farmers' fields

In spite of relatively unfavorable fertilizer responses in millet and sorghum, the evidence just cited suggests that those crops can be fertilized profitably. To examine this suggestion in farmers' conditions, the International Crops Research Institute for the Semi-Arid Tropics undertook experiments with farmers in Burkina Faso and in Niger to determine the farm-level economic returns to fertilizers.

Table 4 reviews results for the two countries. In Burkina Faso, Matlon [17] worked with local and test sorghum in areas with 700, 650, and 460 mm of rainfall. For the test sorghum in the two areas with higher rainfall in 1983, four estimates of the APP of all nutrients were from −3.5 kg/kg to 19.6 kg/kg when 50 kg/ha of product NPK (14-23-15) was applied. The mean of the four observations was 9.1 kg/kg, and one of the four was negative. Unsubsidized NPK was most profitable in the range of 50 kg/ha of product. Subsidized NPK was most profitable in the same range – from 83% to 100% of farmers would have had positive returns to subsidized fertilizers.

For the local sorghum, four estimates of the APP of all nutrients were from −0.3 to 19.8 kg/kg when 50 kg/ha of product NPK was applied. The mean of the four estimates was 7.2, and one of the four was negative. Unsubsidized NPK and subsidized NPK were again most profitable in the 50 kg/ha dose; at that dose, with fertilizer subsidies, from 50% to 89% would have had positive returns.

Matlon's reported data show APPs of between 2.4 and 8.7 kg/kg for 50 kg/ha of product NPK on millet, with a mean of 6.6 and no negative values. He found unsubsidized NPK to be profitable in the range of 50 kg/ha on millet in the area with 650 mm of rainfall. Unsubsidized fertilizer was not

profitable on average on millet in an area with 460 mm. In spite of negative *average* profitability in the latter area, at least 33% of farmers would have profited by applying 50 kg/ha of subsidized NPK to local millet.

McIntire [19] tested a fertilizer package of 30 units of N as urea and 18 units of P_2O_5 as simple phosphate on a local cultivar of millet in Niger. In 1982, in a village with 540 mm of rainfall, 54% of farmers would have profited from unsubsidized fertilizer and 69% from subsidized fertilizer; the APP of nutrients was 4.6 kg/kg. In a village with 240 mm, 17% would have profited from unsubsidized fertilizer and 63% from subsidized fertilizer; the APP was 2.3 kg/kg. In 1983, in a village with 360 mm, 50% would have profited from unsubsidized fertilizer and 69% from subsidized fertilizer; the APP was 3.9 kg/kg. In a village with 390 mm, 57% of all farmers would have profited without subsidies and 71% with; the mean APP was 4.9 kg/kg.

One characteristic of these results was the lower responses achieved on farm than on station. Comparing the responses from Matlon's work on sorghum to those in Table 2, one sees that the range of responses in farmers' fields (mean APPs of 7.2 on local sorghum and 9.1 for test sorghum) was similar to the FAO ranges but at lower nutrient levels. The APPs from Niger on millet (a range of 2.3 to 4.9 kg/kg) were also less than those shown in Table 2.

Table 4 Value: cost ratios (VCRs) for sorghum and millet fertilization in farmers' fields, Burkina Faso and Niger, 1982 and 1983

	Unsubsidized fertilizer, % of VCRs > 1.0		Subsidized fertilizer, % of VCRs > 1.0	
	Local cultivar	Test cultivar	Local cultivar	Test cultivar
Burkina Faso, 1983 sorghum				
700 mm rainfall	NA	NA	89.0	83.0
650 mm	NA	NA	50.0	100.0
460 mm	NA	NA	20.0	20.0
Niger, 1982 millet				
540 mm	53.8	40.7	69.2	70.4
240 mm	16.7	52.0	62.5	68.0
Niger, 1983 millet				
390 mm	57.1	60.7	71.4	78.6
360 mm	50.0	80.8	69.2	92.3

Notes: Burkina Faso data are from [17, Table 3]; fertilizer rate is 50 kg/ha of product NPK (14-23-15). Niger data are from [19]; fertilizer rates are 30 kg/ha of N and 18 kg/ha of P_2O_5.

A second characteristic was the high variability in yields at the farm level, even with fertilizer applications. For example, the coefficient of variation of both fertilized and unfertilized millet yields in Niger was always greater than 40% in 1982 and in 1983 [20].

A third characteristic was the absence of a dramatic effect on fertilizer returns from test cultivars of sorghum or millet. Although 8 of 11 comparisons between test and local cultivars in Table 4 showed more farmers having higher VCRs with the test cultivars, in 4 of the 8 the difference was less than 10%. There is some evidence, therefore, that the test cultivars give better fertilizer responses in rainfed semiarid conditions, but the differential is not yet very great. The evidence that local cultivars can be fertilized profitably, on the other hand, means that there is no reason to postpone fertilizer extension until better cultivars are developed.

A fourth characteristic was that higher fertilizer responses were achieved in wetter areas. Although there exists some potential for profitable fertilizer use, even without subsidies, in the driest areas, it ought to be apparent that some areas are more promising than others. The variability in responses caused by the agroclimate does *not* mean that risk is a constraint to fertilizer use. Negative financial and economic returns, caused by low physical response to nutrients, are sufficient constraints without introducing risk.

Fertilizer subsidies with government budget constraints

Many African governments subsidize fertilizers. In Table 5, where subsidies are expressed as percentages of prices paid by farmers, the range of rates in 1976-80 was 2%-510% for N and 7%-620% for P_2O_5. Comparing Table 5 to Table 1, one notes that both Nigeria, with high subsidies, and Kenya, with low ones, had good fertilizer consumption growth rates.

Basic relations in the economic analysis of fertilizer use are:

$$R = p_o{*}y_o - p_n{*}q_n \qquad (1)$$

and

$$y_o = f(q_n) \qquad (2)$$

where:

R is revenue, p is price, q is quantity, y is crop yield, o is output, and n is a fertilizer nutrient. In Equation (1), revenue is equal to output value less fertilizer cost. In Equation (2), yield is a function of fertilizer nutrient quantity. The optimal fertilizer rate, as shown in Equation (3), is that at which the marginal revenue product of fertilizer is equal to the marginal cost of fertilizer:

$$p_n = (dy/dn)*p_o. \quad (3)$$

The term (dy/dn) is the MPP of nutrient in terms of grain. Equation (3) says that the optimal fertilizer rate is a function of response, nutrient price, and grain price. If the prices of output and fertilizers were equal for maize, millet, rice, and sorghum, then rice would have the highest use, followed by maize, sorghum, and millet. Because crop and input prices vary significantly in national and international markets, the actual pattern of fertilizer use does not necessarily follow that suggested by physical responses alone.

The low fertilizer rates in sub-Saharan Africa can be explained in large part by the fact that millet and sorghum, which have low nutrient responses, occupy a greater share of sub-Saharan Africa's cropped area than do rice and maize. Even without such 'constraints' as risk, credit, and marketing, one expects to see less fertilizer used on millet and sorghum than on rice and maize. Although there are other constraints, which might be costly in some cases, their existence is unnecessary to explain low fertilizer use in many rainfed areas of sub-Saharan Africa.

Table 5 Calculated fertilizer subsidy rates for 1976-80, selected countries of sub-Saharan Africa, as % of reported official prices paid by farmers

	Nitrogenous fertilizers					Phosphatic fertilizers				
	1976	1977	1978	1979	1980	1976	1977	1978	1979	1980
	(%)									
Burkina Faso	NA	NA	NA	NA	75.0	NA	NA	NA	NA	NA
Burundi	27.3	59.1	59.1	52.0	NA	41.2	146.9	65.0	NA	NA
Ethiopia	NA	NA	37.6	NA	NA	NA	NA	NA	NA	NA
Gambia	NA	NA	222.9	222.6	226.0	245.3	NA	282.9	245.9	165.7
Kenya	1.8	NA	NA	NA	NA	7.2	NA	NA	NA	NA
Niger	131.5	NA	NA	28.5	62.2	149.8	NA	NA	89.1	242.1
Nigeria	421.4	100.0	300.6	296.9	300.0	524.8	100.3	257.7	294.9	300.0
Senegal	NA	8.5	NA	NA	NA	NA	NA	NA	NA	NA
Sudan	NA	NA	60.1	NA	NA	NA	NA	59.8	NA	NA
Tanzania	56.1	NA	NA	NA	NA	115.7	80.4	NA	NA	NA
Togo	394.9	509.8	306.3	320.9	492.9	358.8	570.7	341.0	337.9	619.5
Uganda	67.4	NA	NA	NA	NA	112.7	NA	NA	NA	NA

Notes: Data are from [7]. The rate of subsidy is equal to the reported subsidy, in current $/tonne, divided by the reported official price in current $/tonne. Data for four countries not shown here (Mali, Ivory Coast, Sierra Leone, and Liberia) show that fertilizers for rice production were subsidized in the 1970s [25].

The effects of subsidies on optimal fertilization rates

Equation (3) was used to estimate the effects of fertilizer subsidies on optimal rates. Optimal fertilizer rates were calculated at subsidies of 0%, 25%, and 50%, as shown in Table 6. A 50% subsidy would have little effect on the optimal N rate in rice or in maize. A 50% subsidy would increase optimal N rates by 18% in sorghum and by 25% in millet. For P_2O_5 applications to sorghum or to millet, a 50% subsidy has a slightly smaller effect than it has on N applied to those crops.

Though these results are sensitive to the response function, they establish that high subsidies would not dramatically increase fertilizer use on millet or on sorghum. They would have had almost no effect, absolutely or relatively, on maize or rice. It therefore appears that high subsidies might incur heavy budgetary costs with only a small effect on nutrient use.

A graphic model or fertilizer subsidies with government budgetary constraints

If fertilizer subsidies are available to all potential users, they will increase

Table 6 Effects of fertilizer subsidies on optimal N and P_2O_5 rates assuming international prices of fertilizers and crops

	Maize	Millet	Paddy	Sorghum
Optimal N levels, kg/ha				
With base prices	134.9	54.4	197.6	110.2
With 25% subsidy	137.9	61.3	199.7	120.2
With 50% subsidy	141.0	68.1	201.8	130.3
Optimal P_2O_5 levels, kg/ha				
With base prices	185.7	59.6	NA	117.8
With 25% subsidy	192.0	65.1	NA	125.9
With 50% subsidy	198.2	70.7	NA	134.0
Effects of 50% subsidies on optimal rates, as % of base rate				
N	4.6	25.2	2.1	18.2
P_2O_5	6.8	18.7	NA	13.8

Notes: Millet and sorghum response functions are from [21]. Paddy response functions are from Table 3. Maize response to P_2O_5 is from Table 3, and N response is from [28]. Urea price is for 1976-80 from [32], adjusted for sea transport costs by adding $30/tonne and converted to N by dividing by 0.46.

The price of triple superphosphate is for 1976-80 from [32], similarly adjusted for sea transport and converted to P_2O_5 by dividing by 0.46. The price of U.S. maize, Thai rice, and U.S. sorghum for 1976-90 are from [32]; the price of sorghum is used for the price of millet. All prices are in 1980 dollars. The last rows of the table may contain rounding errors.

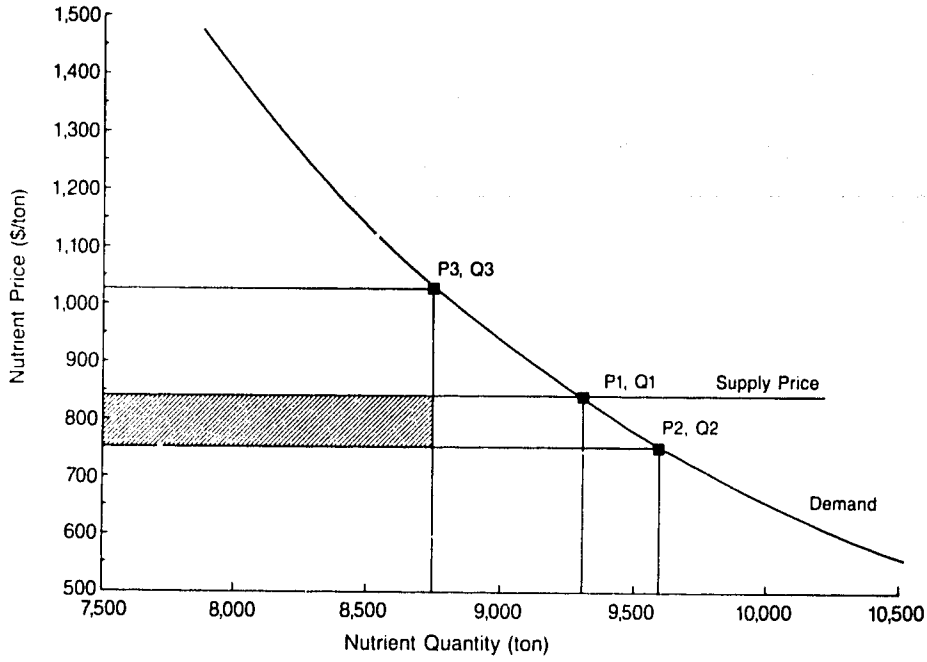

Figure 1. Market structure for subsidized fertilizers.

nutrient demand. If the subsidies are not available to all users – i.e., if they are rationed – then they might reduce fertilizer demand. This argument is illustrated in a graphic model of the market structure for imported fertilizers.

Figure 1 shows a market structure for fertilizers. The line labeled demand is the downward sloping isoelastic demand curve for fertilizers as a function of price. The line labeled supply is the supply curve of imported fertilizers facing African importers. Without trade restrictions on imported fertilizers, market equilibrium occurs at price P_1 and quantity Q_1.

A reasonable representation of government decisions is one in which an agricultural bureaucracy decides a target price for fertilizers, based on estimates of what farmers can pay. If this target price is below the import price, then fertilizers are subsidized. In Figure 1, the target price is P_3. The difference between the import price and the target price (i.e., P_1-P_3 in Figure 1) is the subsidy per unit. At P_3, Q_2 would be demanded by farmers and imported by the country.

A second financial bureaucracy decides the total amount of subsidy the country can pay. Suppose that, because of budgetary constraints, the country can only afford a total subsidy in the amount of G, shown as the shaded area in Figure 1; that is, not all of Q_2 can be subsidized. The amount imported, Q_3, is then equal to $G/(P_1-P_3)$, that is, to the total amount of subsidy divided

by the subsidy per unit. If the total subsidy is fixed, then a larger subsidy per unit implies a smaller total quantity of imported fertilizer because of the government's financial constraint.

If the government imports Q_3 then equilibrium occurs at P_3, which, in the market shown, is greater than P_1. In this market structure, the imported quantity Q_3 must be rationed because Q_3 is not available to satisfy market demand at P_2. The difference between P_3 and P_2 is defined here as the black market premium. It is the difference between the price (P_3) that farmers would pay if Q_3 were imported and there were no subsidy and the official subsidized price (P_2). P_3 does not *have* to be greater than P_1; obviously if Q_3 were nearly equal to Q_2, then price P_3 would be nearly equal to P_2. The difference between P_3 and P_2 depends on the price elasticity of fertilizer demand and on the difference between Q_3 and Q_2. The smaller the price elasticity, the larger the difference between P_3 and P_2.

If the black market premium is large, then one can infer that subsidies actually do reduce fertilizer consumption.[3] There is no convenient way to estimate the size of the black market premium because thee are no data on fertilizer quotas in Africa. However, as will be shown in the following section, there is strong evidence from fertilizer import demand functions that several important countries (in particular, Nigeria, Madagascar, and Zaire) had significantly lower fertilizer imports than they should have had at the time that they subsidized fertilizers heavily. This provides some support for the model sketched in this section.

The model in Figure 1 could be extended to include a foreign exchange constraint. It is not necessary to assume that fertilizer subsidies exist for imported fertilizers to be rationed; if there are foreign exchange shortages, then the effect on domestic prices could be the same as that of government budgetary constraints.

Estimating fertilizer import demand

The preceding discussion assumes that the main microeconomic determinant of fertilizer demand is financial returns as defined by response functions and prices. The discussion also assumes that fertilizer is available to all users. If, however, supplies are rationed because of import constraints, then not every farmer can buy all he wants at the going price. Because fertilizer supply is largely determined by the availability of imports, discussion of constraints must consider what determines import demand.

Before describing the import demand estimates, reference is made to the work of Gunvant Desai [5] on Indian fertilizer consumption. Desai argues that the response functions are more important than relative prices in deter-

mining the growth rate of fertilizer consumption. We have seen that responses of millet and sorghum are less favorable to fertilizer use than those of maize and rice. That application rates are lower on millet and sorghum than on maize and rice is consistent with Desai's argument.

Desai next argues that fertilizer supplies are crucial for growth. He asserts that demand estimates, as functions of prices and other variables, are biased because they do not consider that fertilizer supply stimulates fertilizer demand. Although price policy has been a central theme in the debate about fertilizer use in Africa [29], Desai argues that the emphasis on price and profitability issues is misplaced.

Though Desai does not agree with this interpretation of his argument, it can be summarized in three propositions. First, the shadow price of fertilizer is higher than the market price in the short run. Either because of import or domestic production shortages, there is not enough fertilizer to supply existing demand at the market price. Therefore, fertilizer is rationed in the short run. Second, fertilizer is rationed in the long run – i.e., its long-run shadow price stays above its long-run market price – because of the same shortfalls even if supplies are growing. This results from the stimulative effect of supplies on demand.

Third, Desai argues that while irrigation is vital to widespread use of fertilizer, there is untapped demand in the rainfed areas. He argues that this demand can be tapped by increasing supplies at given prices – that is, without adding to fertilizer subsidies or to crop price supports and without changing the response functions. Evidence about fertilizer profitability at the farm level [17,19] supports this argument. If the argument is true, it places more emphasis on supply and extension policies and less on research policies.

Regression models of fertilizer import demand

To define some of the causative effects in fertilizer supply in sub-Saharan Africa, an import demand function was estimated for N and P_2O_5 by using pooled cross-section and time-series data with dummy variables for countries and for years over the period 1971-80.

The model is used only to show which factors determine fertilizer import demand. Its results do not show which factors determine *farmers'* fertilizer demand. Import prices often differ significantly from domestic prices; therefore, import prices are not always relevant for modeling farmers' decisionmaking. Because of such price disparities, fertilizer imports are probably rationed, and rationing affects demand estimates.

Model specification

Two equations were specified. In the first, the dependent variable was annual imports of nitrogen in tonnes for 1971-80. In the second, the dependent variable was annual imports of P_2O_5, also in tonnes for 1971-80. The independent variables are described below with data sources indicated in brackets.

Export earnings, millions of 1980 dollars [13]
– Total export earnings were hypothesized to increase fertilizer imports. One- and two-year lag transformations were also specified.

Gross domestic product per caput, 1980 dollars [13]
– National income was hypothesized to increase fertilizer imports. One- and two-year lag transformations were also specified.

Net official development assistance per caput, 1980 dollars [23,24]
– Official development assistance (ODA) was, following Desai's arguments, hypothesized to increase fertilizer demand. One- and two-year lag transformations were also specified.

Irrigated area, 1,000 hectares [8]
– Irrigated area was hypothesized to increase fertilizer demand.

Wheat area and rice area, 1,000 hectares [8]
– These were hypothesized to increase fertilizer demand.

Roots and tubers area, 1,000 hectares [8]
– This area was hypothesized to *decrease* fertilizer demand because of the lack of improved cultivars.

Import prices, 1980 $/tonne [32]
– This was hypothesized to decrease fertilizer demand. The price variable for nitrogen was constructed by taking the international urea price in each year from 1971 to 1980 in 1980 dollars. Sea transport costs were added to each annual price, and the resulting sum was then multiplied by the ratio of c.i.f. to f.o.b. prices to account for internal transport and handling, as shown in [13]. The resulting urea price was divided by 0.46 to arrive at a nitrogen price. The price variable for P_2O_5 was constructed similarly.

Country dummy variables
– The Sahel countries (Gambia, Burkina Faso, Mali, Mauritania, Niger, and

Senegal) and Sudan were set equal to zero in the analysis of covariance.

Year dummy variables
– The year 1975 was set equal to zero in the analysis of covariance.

Domestic fertilizer production [7]
– Domestic production of N and P_2O_5 was hypothesized to reduce fertilizer imports.

Regression results for N import demand

Table 7 shows the results. The equation was highly significant overall. Export earnings and irrigated area were significant and contributed two-thirds of the equation's explanatory power. Official development assistance and rice area were positive but were not significant at the 10% level. Nitrogen price was positive – i.e., it had the wrong sign – but was not significant at the 10% level. Wheat area was negative and significant at the 10% level.[6] Domestic nitrogen production was negative but was not significant at the 10% level. Seven of the country dummies were significantly different from zero at the 5% level, but none of the year dummies was significant at the 10% level. None of the interaction variables was significant at the 10% level.

An increase of 1,000 ha in rice would only have raised N imports by 26.7 tonnes, whereas increasing wheat area by the same amount would have reduced it by 21.4 tonnes. While there is reason to suspect bias in the sign of the wheat coefficient, it is apparent from these results that, as yet, there are no large positive effects of wheat area or of rice area on nitrogen import demand. This is consistent with the Indian situation in the 1950s before the introduction of high-yielding varieties of rice and wheat [5].

Not only was import demand insignificantly related to price but there was also a positive relation between the two. This does not mean that prices have no effect on fertilizer demand.[7] It does suggest that governments establish target import quantities as functions of other variables and that prices, while they may have some role, are less important than other variables in determining those targets. What was estimated here is partly an administrative process and not one that depends on microeconomic profitability criteria.

These results suggest that the two forces driving demand for imported nitrogen are irrigation and export earnings, with a lesser role for rice cultivation and official development assistance. However, even though those variables explain much of the variation in import demand, they have little impact on the amounts imported. For example, an increase of $1,000,000 in export earnings would only result in 3.2 tonnes more nitrogen being imported. At

Table 7 Regression results for imported nitrogen (dependent variable is tonnes of nutrient)

Independent variables	Regression coefficient	t-statistic
Wheat area, '000 ha	-21.417	1.857[c]
Rice area, '000 ha	26.655	1.434
Irrigated area, '000 ha	37.873	12.689[a]
ODA/caput, 1980 $	23.282	0.686
Export, million 1980 $	3.201	7.184[a]
Price of N, 1980 $/t	17.303	0.843
Production of N, t	-0.034	0.122
Country dummies		
Benin	3,077.821	0.853
Botswana	2,004.854	0.395
Burundi	3,427.249	0.935
Cameroon	9,544.345	2.677[a]
Congo	630.638	0.187
Ethiopia	35,504.170	3.653[a]
Ivory Coast	-9,271.867	1.521
Kenya	19,664.020	4.893[a]
Liberia	-1,297.452	0.344
Madagascar	-37,851.840	1.987[b]
Malawi	14,767.840	4.283[a]
Nigeria	-26,776.780	3.238[a]
Rwanda	2,392.750	0.683
Sierra Leone	-6,314.104	0.964
Tanzania	6,000.531	1.602
Togo	1,878.298	0.546
Zaire	-7,335.755	1.496
Zambia	26,327.000	6.534[a]
Zimbabwe	6,870.402	0.401
Year dummies		
1971	6,633.698	0.606
1972	5,623.527	0.598
1973	1,310.333	0.230
1974	-12,741.620	0.857
1976	6,336.027	0.768
1977	1,862.642	0.239
1978	1,509.097	0.202
1979	2,527.344	0.359
1980	4,592.734	0.822
Adjusted R-squared	0.675	
n of observations	258	
F-statistic	16.255[a]	

Note: The country dummies are set equal to zero for the Sudan and the Sahel countries (Gambia, Mali, Mauritania, Niger, Senegal, Burkina). The year dummies are set equal to zero for 1975. [a] indicates significantly different from zero at the 1% level, [b] at the 5% level, and [c] at the 10% level.

an N price of $750/tonne, the marginal propensity to import N with earnings from exports is 0.0024 (i.e., (750*3.2)/1,000,000). An increase of 1,000 ha of irrigated area would only increase imports by 37.9 tonnes.

The effects of national policies not captured by such variables as export earnings, cropping pattern, irrigation, fertilizer production, or development assistance were measured by the country dummies. Of those country dummies, seven were signifcant at the 10% level. Their magnitudes were much greater (e.g., Ethiopia, Madagascar, Nigeria, Zambia, Kenya) than those of the other variables. The relative magnitudes of the country dummies and the coefficients of the continuous variables suggest that, for at least seven countries, national policies were more important in determining import demand than were such things as cropping pattern or prices.

Regression results for P_2O_5 import demand

Table 8 shows the demand function for imported phosphorus. Exports were again important although their coefficient was smaller than in the nitrogen regression. The calculated marginal propensity to import P_2O_5 from $1,000,000 export earnings was 0.0012. Irrigated area was not significant. Rice area and roots and tubers area were significantly positive at the 5% level. The coefficients mean that an additional 1,000 ha of roots and tubers would only add 4.4 tonnes to the annual P_2O_5 import demand, while an additional 1,000 ha of rice would add 13.3 tonnes to annual demand. The P_2O_5 price coefficient had the expected negative sign, though the coefficient was not significant at the 10% level. Domestic production of P_2O_5 was significantly negative at the 5% level; the coefficient means that every tonne of P_2O_5 produced domestically reduced imports by 133 kg.

Nine of the country dummies were significantly different from zero at the 5% level. The dummies for Zaire, Nigeria, and Madagascar were negative, whereas those for Kenya and Zambia were positive. The positive signs for Kenya and Zambia might be due to hybrid maize, as well as to fertilization of coffee and tea in Kenya. The negative signs for the former three have different causes. In Madagascar and Zaire, they were probably due to severe foreign exchange shortages. In Nigeria (and also in the Ivory Coast) they were probably due to the failure to maintain growth in fertilizer imports commensurate with the rapid growth in export revenues in the late 1970s.

The year dummies for the P_2O_5 regression had generally higher t-values than did those in the N regression, though none was significant at the 5% level.

Table 8 Regression results for imported phosphorus (dependent variable is tonnes of P_2O_5)

Independent variables	Regression coefficient	t-statistic
Roots/tubers area, '000 ha	4.432	1.969[c]
Wheat area, '000 ha	−27.961	7.212[a]
Rice area, '000 ha	13.270	1.966[c]
ODA/caput, 1980 $	−2.980	0.239
Exports, million 1980 $	1.636	9.275[a]
Price of P_2O_5, 1980 $/t	−0.087	1.229
Production of P_2O_5, t	−0.133	2.173[b]
Country dummies		
Benin	−1,565.853	1.125
Botswana	−1,075.817	0.576
Burundi	−2,008.876	1.457
Cameroon	−1,925.145	1.155
Congo	−1,368.215	1.061
Ethiopia	36,616.960	11.512[a]
Ivory Coast	−8,701.047	3.250[a]
Kenya	21,664.850	15.415[a]
Liberia	−4,201.944	2.867[a]
Madagascar	−16,317.390	2.347[b]
Malawi	1,602.346	1.247
Nigeria	−25,318.310	3.950[a]
Rwanda	−1,565.972	1.148
Sierra Leone	−6,300.875	2.514[b]
Tanzania	−4,270.167	1.708[c]
Togo	−1,735.924	1.358
Zaire	−13,035.170	3.459[a]
Zambia	10,747.260	8.008[a]
Zimbabwe	6,368.131	1.758[c]
Year dummies		
1971	−6,639.745	1.482
1972	−4,637.477	1.434
1973	−3,422.667	1.656
1974	4,021'029	0.787
1976	−5,015.497	1.272
1977	−5,733.959	1.435
1978	−5,791.093	1.400
1979	−4,411.959	1.294
1980	−3,234.639	1.054
Adjusted R-squared	0.816	
n of observations	243	
F-statistic	31.604[a]	

Note: The country dummies are set equal to zero for Sudan, Gambia, Mali, Mauritania, Niger, Senegal, and Burkina. The year dummies are set equal to zero for 1975. [a] indicates significant at the 1% level, [b] at the 5% level, and [c] at the 10% level.

Conclusions

Most of sub-Saharan Africa has low population density when compared with tropical low-income Asia. This does not mean that all of sub-Saharan Africa is sparsely populated. It does mean that, as a general principle, the demand for intensifying agricultural technologies, such as chemical fertilizers, is relatively low in Africa. This is not a 'constraint' to widespread use of fertilizer: the refusal to adopt intensive technologies in sparsely populated areas is a rational choice, if it is possible to expand output by cultivating more land rather than by cultivating more intensively. It is simply a general prediction that use rates per hectare will be lower in sub-Saharan Africa than in more densely populated areas.

In the context of low population density, this paper has concentrated on two constraints to widespread use of fertilizer. The first is the low response rates of two major rainfed cereals, pearl millet and sorghum, compared with those of maize and rice. The Indian experience shows that irrigation and high-yielding varieties are crucial for extensive use of fertilizer. That experience, when combined with what we know about low response rates in two major rainfed cereals, explains part of low fertilizer use in the subcontinent. Sub-Saharan Africa's cropping pattern is dominated by rainfed production of two cereals that have low nutrient responses compared with the irrigated rice and wheat that have stimulated Indian fertilizer demand in the last 30 years [26,9]. (Though nothing has been said about root crops, it is doubtful whether their responses are so much greater than those of millet or sorghum that the general constraint would be loosened). This does not mean that there should be widescale efforts to develop fertilizer-responsive cultivars of millet and sorghum. It does mean that such efforts should be targeted for intensive millet and sorghum production systems – i.e., where those crops are major shares of the cropping pattern, where soil regeneration via fallow is becoming impossible because of land scarcity, and where irrigation is uneconomical.

The absence of fertilizer-responsive varieties of rice, maize, and wheat on a wide scale and the relative unimportance of irrigation in sub-Saharan Africa are now major constraints to widespread use of fertilizer [16]. This does not mean that general efforts should be put into developing African wheats or into large irrigation projects; such efforts would have to be judged on their benefits, and it is unlikely that they would be very profitable now. It does mean that rapid growth in fertilizer consumption is possible now probably only in some limited areas where irrigation and high-yielding varieties are found together or where responsive rainfed cultivars exist (e.g., hybrid maize in Eastern Africa). In such areas, the second constraint – supply restrictions – would be more important than lack of response.

The second constraint is that of possible fertilizer supply restrictions. In

spite of the insistence here on the relative unresponsiveness of two of the major crops, there is evidence from stations and farms that they can be fertilized profitably. Why do they not receive more fertilizer? Although it would take country studies to answer the question fully, it appears that there are supply restrictions. Many African countries subsidize fertilizers heavily, and many of them have heavy government budget deficits. Those facts, when combined in a simple market structure, provide a plausible explanation of how subsidies might constrain growth in fertilizer use. This model argues for a re-examination of the response trials and of the economic analyses based on them – which have been used to justify subsidies – in order to eliminate excessive subsidies.

Some support for the existence of a foreign exchange supply constraint is provided by two aspects of the import demand equations. First, some countries with severe foreign exchange shortages had significantly negative country dummy coefficients. Second, the marginal propensity to import fertilizer from export earnings was low for N (0.0024) and even lower for P_2O_5 (0.0012). This suggests that governments assign little priority to fertilizer imports when they have good export earnings. The scarcity of imported nutrients in countries that produce very little of their consumption would, if one accepts Desai's reasoning about the importance of supply factors, be a major constraint to widespread use of fertilizer.

Notes

[1] Millet means 'pearl millet' (*P. americanum*) and not 'finger millet' (*E. coracana*).

[2] Poulain [27] estimated the average responses of maize, sorghum, and millet to N. For the ranges 0-40, 40-80, 80-120, and 120-160 kg of N/ha, they were: maize, 27, 16, 13, 13; sorghum, 12, 16, 13, NA; millet, 12, NA, NA, NA. Traore [31] found millet responses to be 8 kg/kg of N in the N range of 80-120 kg/ha and 4 kg/kg in the N range of 120-160 kg/ha. The term 'NA' means no estimate is available. Most experimental work does not allow calculation of K_2O responses. Zalla, Diamond, and Mudahar [33] concluded that maize, millet/sorghum, rice, and groundnuts did not respond well to K_2O.

[3] The ZDM [33] and Montgomery [21] estimates for millet and rice might be based on the same data. Montgomery's rice work is probably with high-yielding varieties. Most of the trials for millet, maize, and sorghum used local varieties or improved cultivars based on local parents.

[4] There is some difficulty in interpreting the FAO subsidy and price data. One way to calculate the domestic N price is to take the international urea price [32] and to convert it to N prices by dividing by 0.46. By adding $30/t for sea transport costs, one gets an estimate of the c.i.f. price of N in a coastal African country. By taking the reported FAO prices for N for each country and adding the reported subsidies [7] for each coastal country, one should arrive, more or less, at the same estimate. In most cases, this was not possible.

[5] Black markets in fertilizer have been observed by Balcet and Candler [1] in Northern Nigeria and by Matlon [17] in Burkina Faso. There is also a black market in smuggled fertilizer in eastern Niger, where heavily subsidized Nigerian fertilizer is sold at a price above the Nigerian price but below the official price of Niger.

[6] The contrary sign of the wheat coefficient in the N estimate (and in the P_2O_5 estimate below) is probably due to the high correlation between wheat area and the dummy variable for Ethiopia. Estimates with Ethiopia set equal to zero in the analysis of covariance gave positive wheat area coefficients.

[7] Mudahar [22], in a review of price elasticities of demand for fertilizer, found many absolute values greater than 1.0.

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Fertility of soils of tropical Africa: a historical perspective

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Introduction

Because parent materials in tropical Africa are not uniformly distributed and the climate is diverse, inherent fertility of the soils varies considerably. Because of intensive leaching and the degree of weathering, many soils of tropical Africa have relatively low inherent fertility.

Tropical soils have been defined as those that lack significant summer-to-winter mean temperature variations; i.e., the difference between mean temperature in the summer and mean temperature in the winter at a depth of 50 cm in the soil is less than 5°C [38]. This is the only property common to all the soils of tropical Africa. For the purpose of this paper, however, other generalizations will have to be made to trace the historical profile of such a varied region. The paper is not intended as a documentation of all work that has been done on soil fertility in tropical Africa but will endeavor to show the inherent fertility of these soils and how management practices, past and present, have affected the fertility of such soils.

Parent materials and inherent fertility

Soils of tropical Africa have been formed from Pre-Cambrian parent materials, volcanic ashfalls, and materials that have been reworked by processes of erosion and deposition [1,15,37,38,44]. Since parent materials are not uniformly distributed and the conditions responsible for soil formation in tropical Africa are diverse, soils vary considerably in inherent fertility.

In general, basic parent materials (e.g., basalts and dolerites) weather basically so that the silica will tend to become soluble and to leach away with the production of an iron- and aluminum-rich clay. In acidic parent materials (e.g., granites and rhyolites), however, the iron and aluminum are mobilized

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and drain off, leaving behind soil rich in silica which is sandy if much quartz was originally present [15]. Inherent soil fertility is relatively high in soils developed over basic parent materials; soils developed over granites, however, are usually sandy, and they vary in chemical fertility depending on the content of dark minerals (e.g., olivine, pyroxenes, and amphiboles) in the granites and granitized (magmatites) rocks [1,15,44]. The poorest basement complex soils are those developed over quartzite and other quartzite rocks [1]. The inherent fertility of tropical soils developed from sediments will vary depending on the origin and composition of the materials: sandstones give rise to very poor sandy soils [1,32], and over mudstones poor clay soils are formed [1]. In alluvial plains, alluvium will be rich and fertile if it originates from relatively young materials and less fertile if it originates from highly weathered surfaces [37]. There are also pyrite-rich deposits in tropical plains and coastal areas resulting in infertile acid sulfate soils [1,44]. The amount of rainfall will determine whether the soils developed are acidic or basic in reaction and the nature of the predominant clay. In savanna areas with low rainfall (500-1,000 mm annually), bases are not easily leached; hence, soils will have a relatively high soil pH and base saturation and, in extreme cases, can be alkaline and/or saline. Substantial amounts of montmorillonite can be found in these soils [1]. In forest zones receiving relatively higher rainfall (over 1,500 mm annually), soils are fairly well leached of bases and are usually acidic in reaction. As a result of intensive leaching and weathering, the clay fraction will be dominated by kaolinite, halloysites, and/or iron and aluminum oxides. As data in Table 1 show, these clays have a low and variable cation exchange capacity (CEC). The soils have relatively low inherent

Table 1 Charge characteristics of some clay minerals separated from soils of Kenya (meq/100 g clay)

Material	Cation exchange capacity			Anion exchange capacity
	Permanent	Variable	Total	
Montmorillonite	112	6	118	1
Vermiculite	85	0	85	0
Illite	11	8	19	3
Halloysite	6	12	18	15
Kaolinite	1	3	4	2
Gibbsite	0	5	5	5
Goethite	0	4	4	4
Allophanic colloid	10	41	51	17
Peat	38	98	136	6

Source: Sanchez, 1976 [37].

fertility, and accumulated organic matter is the main source of CEC and nutrients, particularly nitrogen.

Climate, vegetation and their effects on soil organic matter accumulation

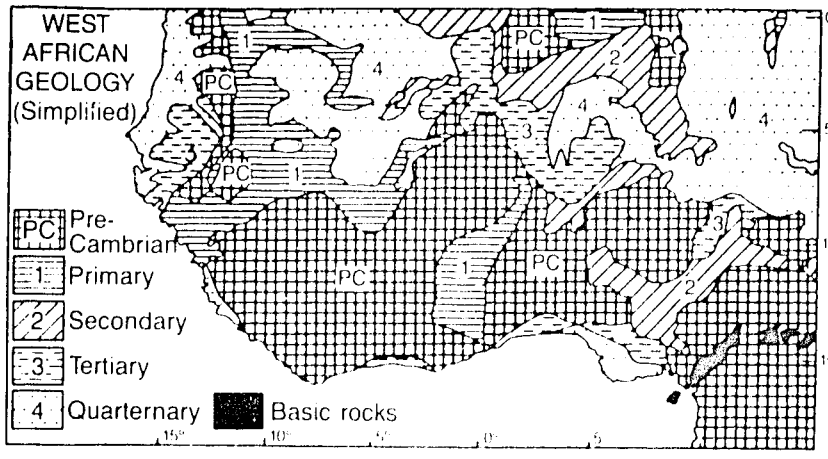
Often the extent of dense humid forests is viewed as an index of good soil fertility, but the presence of such vegetation rarely depends on soil condition [37]. In fact, many zones under tropical rain forests and forest/savanna mosaic are on soils with relatively low inherent fertility [12]. West Africa offers the best example (Figure 1) and emphasizes the influence of climate on vegetation. Vegetation changes in a north-south direction in West Africa depending on the amount of distribution of the annual rainfall.

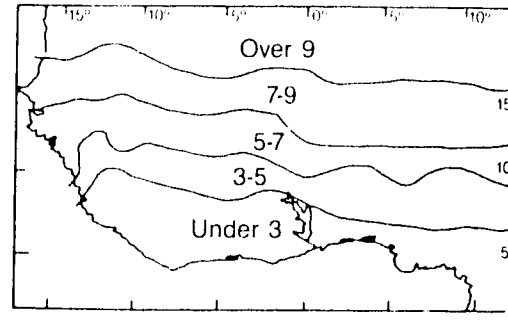
Data in Table 2 show that, although the inherent fertility of tropical soils in Africa varies a great deal, most soils can support plant growth provided moisture is not limiting and drainage is good. In a closed system, different plant species will ensure that nutrients are well recycled in the soil profile allowing both shallow- and deep-rooted plants to grow and accumulate organic matter in the soil. The inherent soil fertility, nevertheless, will influence the nutrient content of the vegetation and also the rate at which dry matter is accumulated, i.e., how soon, if ever, the potential dry matter production (calculated on the basis of rainfall regimes) will be achieved. The pattern of soil organic matter accumulation differs depending on the type of vegetation. Grassland (savanna) soils generally have less organic matter than

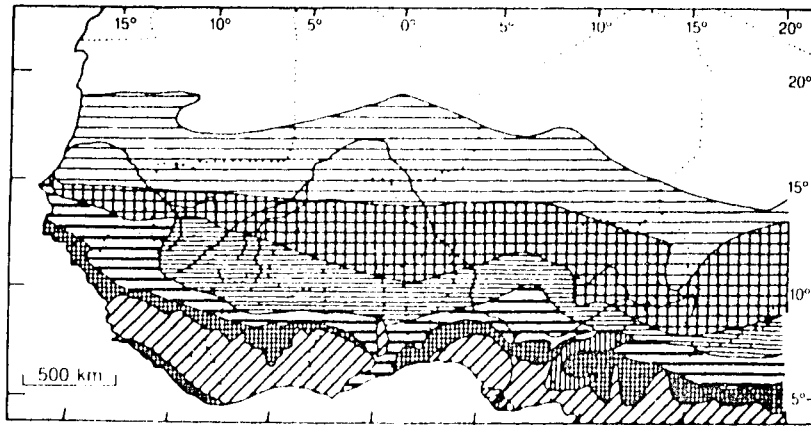
Table 2 Analytical data for some typical topsoils in Uganda, 0-15 or 0-20 cm horizon

Soil	pH	C	Truog's available P	Exchangeable cations (meq %)				
				Ca	Mg	K	Clay	Silt
	(%)						(%)	
Derived from volcanic ash	6.0	6.4	475	11.6	2.5	1.2	23	10
Derived from basic amphibolites	6.2	6.0	24	11.7	8.1	2.6	34	20
Deep, red, buganda loam	6.1	2.0	27	4.2	2.0	0.5	28	9
Deep, red, buganda clay loam	6.4	4.0	37	10.0	3.0	1.3	38	12
Dark, horizon loams	5.0	2.6	9	2.9	1.2	0.2	35	9
Deep sandy soils	5.5	1.6	10	2.0	0.9	0.1	23	5
Shallow, sandy soil over laterite	5.6	1.0	5	1.6	0.8	0.4	17	4
Reclaimed swamp soil	4.7	3.1	11	4.4	1.4	0.4	23	17
Levels below which deficiencies may be expected	4.5	1.0	5	2.0	0.5	0.2	–	–

Source: Adapted from Stephens, 1970 [44].







Sahel | Sudan | Northern Guinea | Southern Guinea
Forest/savanna mosaic | Forest | Montane communities

Figure 1a The geology of West Africa (source: Ahn [1]).

Figure 1b Number of months with less than 25 mm of rain (source: Ahn [1]).

Figure 1c Vegetation zones of West Africa (source: Jones and Wild [28]).

forest soils, and the distribution of the organic matter down the soil profile is also different (Figure 2). More of the organic matter in the grasslands soil moves down into the subsoil compared with that in the forest soils because much of the organic matter in the grasslands soil is derived from decomposi-

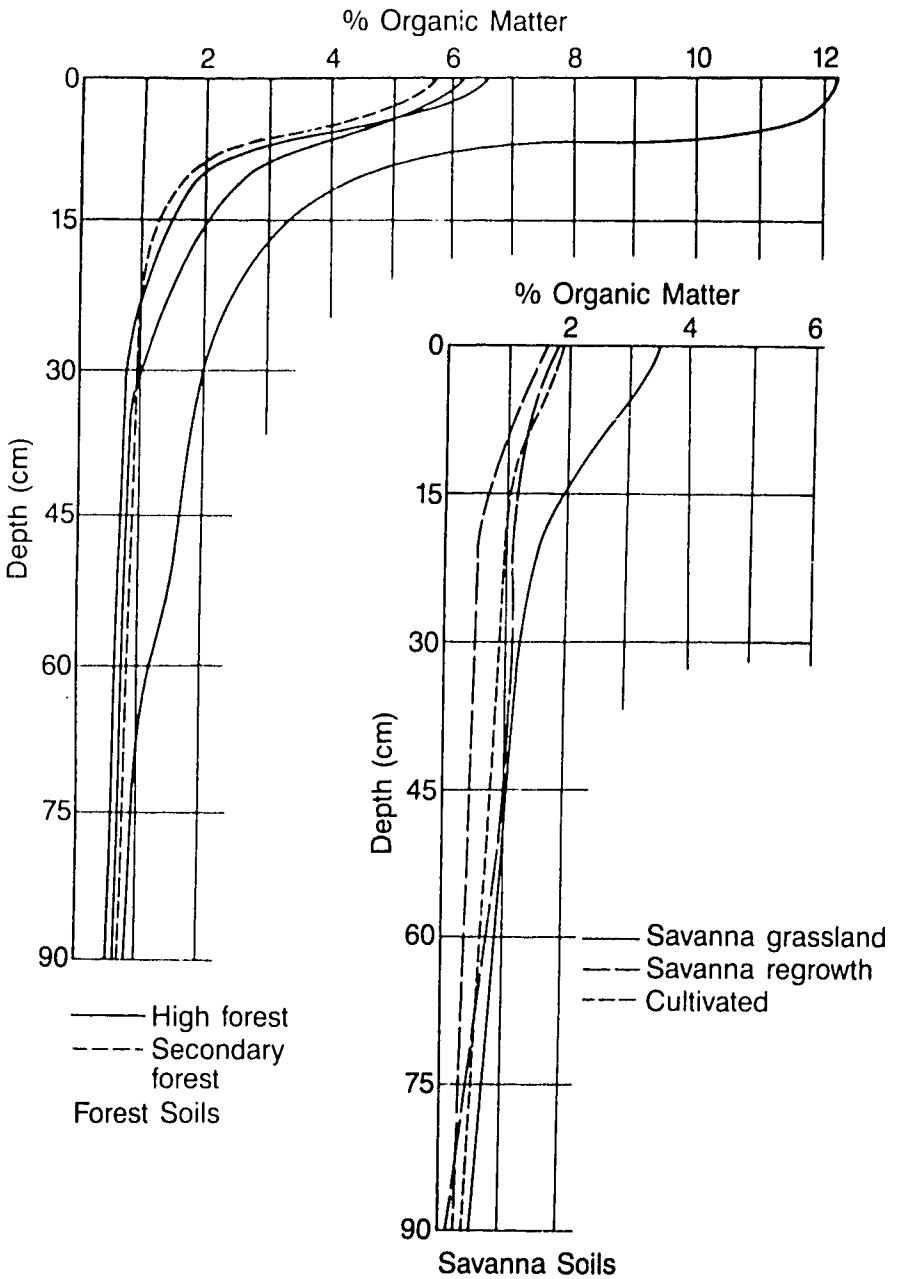


Figure 2. Organic-matter distribution in typical West African forest and Savanna profiles (source: Ahn [1]).

tion of the fibrous root systems and the grasslands are subject to annual burning [1].

The wet equatorial climates (where tropical rain forests are found) such as that found in the Congo River basin and some parts of West Africa lack marked seasons for agricultural operations and were not cultivated much until the introduction of perennial crops such as rubber, cocoa, coffee, and oil palm, which are suitable for these climates. Hence, earlier human settlements and agriculture were concentrated in zones that received enough rainfall but had adequate dry spells for harvesting and other field operations. These were mainly the deciduous and semideciduous forest and tall bush/savanna zones.

Soil fertility and its management

In traditional agriculture relatively small pieces of land were cleared because of the lack of adequate implements and labor (mainly family labor) available. Although the inherent soil fertility varied considerably and in some cases was very low, the soils would have years of nutritional accumulations mainly as soil organic matter.

Whether the fields were burned before clearing or after depended on the type of vegetation and the length and intensity of the dry spells preceding the field operations. In either case it was the only practical method of freeing the land of debris (the main objective of burning during land clearing). In savanna areas grass was burned annually to get rid of the dry, unpalatable old grass stands and to encourage regrowth of new grass shoots palatable to

Table 3 The change in nutrient content and pH of the 0-45 cm depth of soil following a rest phase and an arable phase on the same area of land in Uganda

	Measured after resting phase, 1963-66	Measured after arable phase, 1966-69
Organic carbon	+15,950	−19,700
Total nitrogen	+769	−968
Total phosphorus	+85	−88
Total sulfur	+45	−86
pH ($CaCl_2$)	+0.26	−0.31
Exchangeable K	+471	−461
Exchangeable Ca	+971	−1,897
Exchangeable Mg	+420	−420

All vegetation was incorporated into soil with Rototiller after the rest period; units – kg/ha.
Source: Jones, 1972 [27].

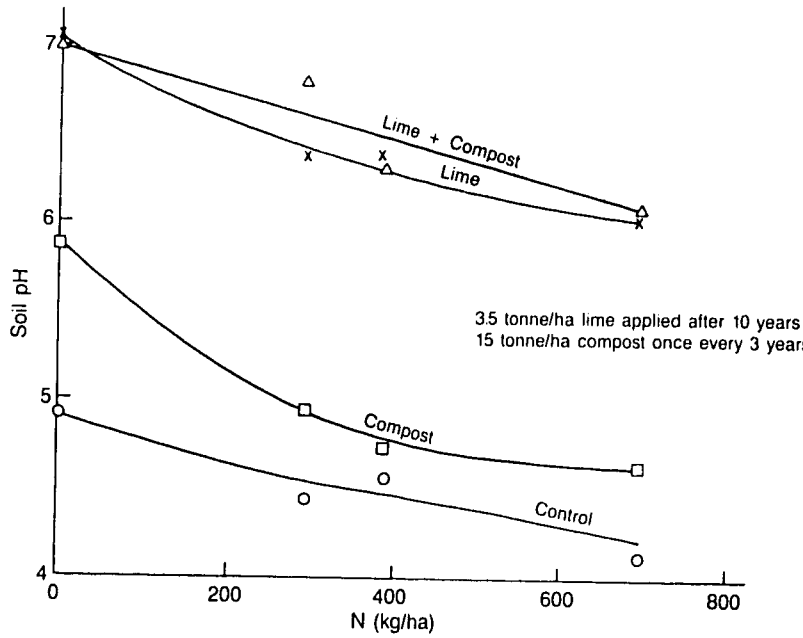


Figure 3. Soil pH related to total N applied ($[NH_4]_2SO_4$) during 14 years (source: P.H. LeMare [31]).

animals. In terms of crop nutrient requirements, burning concentrated basic nutrients (e.g., potassium, calcium, and phosphate) which remained in the ashes. These gains, however, were accompanied by losses of raw organic matter and nutrients like nitrogen and sulfur. In addition, the burning could hasten the release of organically bound nutrients [38]. If this burning were followed by periods of intensive rainfall, much of the nutrients in the ash released from organic sources would be lost through leaching and runoff before any crop uptake.

The fertility of the soil in the cleared pieces of land depended mainly on the organic matter in the soil. These pieces of land were then cropped until they could no longer support good crop yields. In most of these soils with low inherent fertility, the maintenance of fertility depends on how well the soil organic matter is preserved during cropping. During cropping, nutrients and soil organic matter are depleted (Table 3), soil pH decreases (Table 3 and Figure 3), and soil physical properties deteriorate, all of which are directly related to the amount of organic matter originally in the soil. The rate of decline in soil fertility with continuous cropping has been influenced by man's activities (e.g., clearing methods and soil conservation measures, particularly mulching), the intensity of cropping, and the inherent soil fertility. In traditional agriculture the crops grown had relatively low yield potentials, and, as data in Table 4 indicate, the dry matter yields and nutrient uptake

from the soil were also relatively low. Such yields could therefore be sustained for long periods under traditional agriculture. Since the fields under cultivation were small, the effects of soil erosion on soil fertility were minimal.

When crop yields declined to unacceptable levels, the overcropped pieces of land were abandoned and new ones opened (shifting cultivation), leaving the old pieces under natural fallows to restore their soil fertility. Thus traditional farming systems in tropical Africa relied on natural fallow to recycle leached nutrients and accumulate organic matter in the topsoil. Shifting cultivation therefore was, and still is wherever practicable, a stable, efficient soil fertility management system considering the resources farmers have at their disposal in sparsely populated areas [38].

In those early days there were very few perennial crops; where such crops were grown, however, farmers developed methods of maintaining soil fertility for relatively long periods. For example, bananas (plantains) are the staple food in southern Uganda. The banana fields in this area were usually small and always surrounded the homesteads. Thus, refuse and ashes were deposited in these fields. In addition, mulching of these fields was part of the culture. This minimized soil erosion and preserved soil organic matter and thus soil fertility for decades.

Introduction of cash crops (annuals like cotton and perennials like coffee,

Table 4a The removal of nutrients by the maize at Kitale, Kenya[a]

	Nutrients removed		
	N	P	K
	(%, Ranges)		
Grain	1.39-1.76	0.24-0.31	0.19-0.23
Cobs (without grain)	0.34-0.62	0.03-0.07	0.72-1.01
Stover	0.64-0.87	0.06-0.09	1.05-1.68

Table 4b Dry matter and range of nutrients removed by combined yield of grain, empty cobs, and stover (lb/acre) at Kitale, Kenya[a]

Yield range 200 lb Bag/acre	Dry matter	N	P_2O_5	K_2O
8-12 (modest crop)	3,840-5,760	35-62	12-20	31-58
20-25 (good crop)	9,600-12,000	117-126	40-49	119-147

[a] Adapted from Drysdale, 1965 [14].

cocoa, and tea) necessitated increases in land areas under cultivation per household, and the introduction of perennial crops necessitated development of different methods of maintaining and increasing the soil fertility. In addition, increasing population pressure has reduced the availability of land and resulted in reduced ratios of length of fallows to cropping years to the point that shifting cultivation is losing its effectiveness and, as a result, soil fertility is decreasing in many areas [38].

Rural population statistics in Kenya (Table 5) indicate that in some areas of high agricultural potential, a household has only about 1 ha to grow both food and cash crops. Situations like these exist in other African countries (e.g., Rwanda). Although these may represent the extreme, population pressure is increasing throughout all of tropical Africa. In situations like the one in Kenya, shifting cultivation as a soil fertility management system is out of the question. This high population pressure has also introduced other soil fertility dimensions. People have had to move from the highly populated zones with high agricultural potential to relatively drier areas and often without any knowledge of soil management under the new conditions. The drier areas are often susceptible to loss of soil fertility as a result of soil erosion under arable cultivation (Table 6).

Along with the introduction of cash crops and increased population pressure came urbanization, which necessitated increases in food production to feed those in urban areas. This extra production could only be met by either increasing the area of land under food crops or by increasing yield per unit of land through use of soil amendments or through use of high-yielding varieties. Improved or high-yielding varieties also have higher demands for nutri-

Table 5 Available agricultural land per household in some districts of Kenya

District	Agricultural land per household	Persons per household	Population density[a]		Agricultural/potential
			1969	1979	
	(ha)		(persons/km^2)		
Kiambu	1.13	4.80	194	280	High
Kakamega	1.33	5.18	222	294	High
Muranga	1.46	5.00	180	261	High
Kisii	1.50	5.82	307	395	High
Machakos	6.79	5.48	50	72	Medium to low
Kitui	23.94	5.33	12	15	Low
Laikipia	33.68	4.42	7	13	Low

[a] For the whole district: approximate annual population growth 3.9%.
Source: Adapted from Jaetzold and Schmidt, 1982 [25].

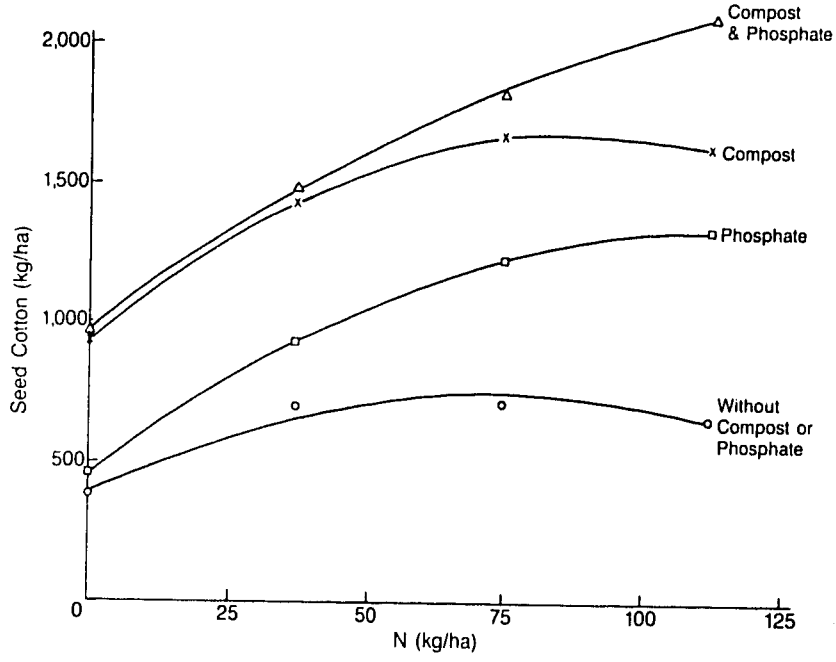


Figure 4. Effect of compost and phosphate, after liming, on response to nitrogen (means of 3 seasons after 14 years). (source: P.H. LeMare [31]).

ents from the soil (Table 4); where they were introduced into shifting cultivation systems, the arable phases had to be shorter because of the increased nutrient uptake per season.

In response to these problems, efforts were made to reduce the length of the fallows and find alternatives to shifting cultivation as a means of restoring and maintaining soil fertility. The former involved use of selected plant species that would improve soil productivity at a faster rate [2.35]. This approach was particularly appealing in farming systems that included livestock (mixed farming systems).

Table 6 Effect of cropping practice on soil loss and runoff on tatagra clay loam, Rhodesia

Crop	6½% Slope		4½%		3%	
	Maize[a]	Napier grass[b]	Maize	Napier grass	Maize	Napier grass
Soil loss (tons/acre)	4.2	0.9	1.5	0.9	1.0	0.3
Runoff (% total rain)	22	8	15	2	14	Nil

[a] Continuous cropping.
[b] Established and periodically cut for fodder.
Source: Compiled from Hudson, 1957 [24].

Other efforts to find alternatives to shifting cultivation as a means of restoring and maintaining soil fertility were concentrated on nitrogen inputs, manures, and composts. In many of these early experiments ammonium sulfate was used as a nitrogen source. Results indicated that yields could not be maintained for a long time by merely applying ammonium sulfate [11,18,31,36,43] unless other nutrients like phosphorus were also applied. In most of these experiments manures were superior to the chemical fertilizers added (Figure 4), but in a few others the fertilizers were superior or produced significant interactions with manures (Table 7 and Figure 5). These results indicated that manures were not always the best solution and that their nutrient content varies.

These early findings led to the type of research reported by Greenland and Nye [23] and Jones [27] who sought to understand how fallows in shifting cultivation system helped to restore soil fertility. It was found that a rest phase (fallow) increased nutrient content and pH of soil whereas cropping depleted soils of nutrients and decreased soil pH (Table 3, Figure 3). After such studies in Uganda, a fertilizer mixture was formulated which satisfactorily increased and maintained crop yields (Figure 6) for years. Other experiments like that in Nigeria (Figure 7) and that in Cameroon (Table 8) showed similar results and indicated that soil fertility can actually be increased and maintained through use of fertilizers (Table 8).

Current soil fertility problems

Use of chemical fertilizers

Although both the need for fertilizers and their effectiveness have been ade-

Table 7 Fertilizer responses (bags/acre) on maize under reserve conditions of Malawi on a repeatedly cropped granite sandveld

N Level	Level of manure				Mean
	0	5	10	15	
(lb urea/acre)	(tons/acre)				
0	0.2	2.5	1.3	2.3	1.6
85	7.5	7.4	10.0	8.0	8.3
170	10.2	15.7	13.2	16.4	13.9
255	10.5	14.1	15.7	19.0	14.8
Mean	7.1	9.9	10.1	11.5	9.6

LSD (5%) main effect means = 1.71; within treatments = 3.42.
Source: Johnson, 1962 [26].

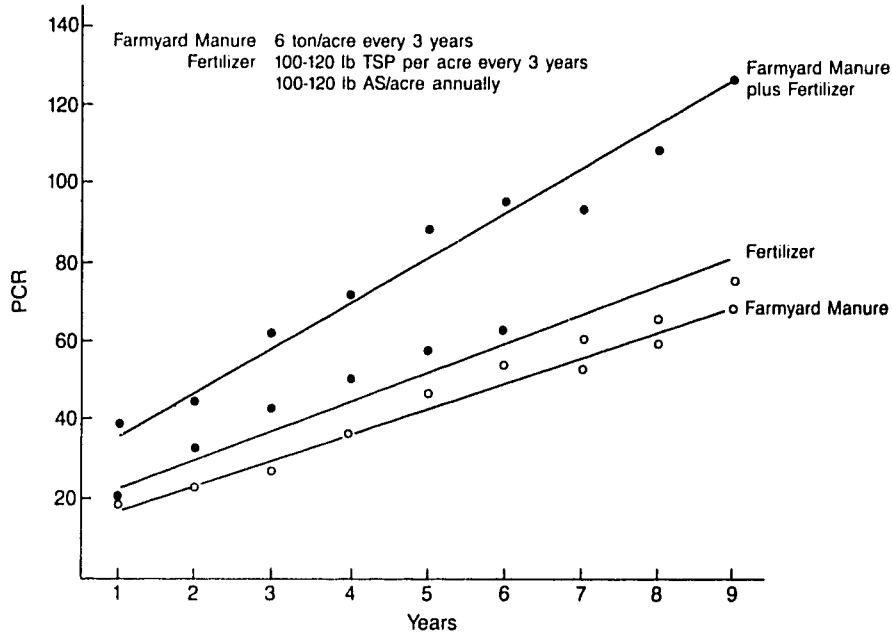


Figure 5. Relationship between percentage cumulative response (PCR) and time (1953-61) for cotton at Ukiriguru, Tanzania (source: Evans [18]).

quately demonstrated, there are still problems associated with fertilizer use. As has been pointed out, soil fertility in tropical Africa is not significantly different from that of similar climates [38]; for example, the low-base-status soils of Zaire, Sao Paulo (Brazil), and the southeastern United States have similar fertility problems [38]. The main difference in the productivity of these regions is that Sao Paulo and the United States use high levels of fertilizer and lime efficiently and they have adequate transportation, industry, and market infrastructure. In addition, the success with cash crops on both large- and small-scale farms in Africa is a clear indication that soil fertility can be increased and maintained through judicious use of fertilizers. Although tea growing was extended only recently to small-scale farmers in Kenya, they now produce more tea than the large-scale farmers. These farmers use fertilizers, and the Kenya Tea Development Authority has conducted fertilizer demonstrations on farmers' fields, provided the appropriate fertilizers and credit, and improved access roads so that the produce can be collected daily close to the farmers' fields. Similar successes have been recorded with other cash crops like cotton in Northern Ivory Coast. Unfortunately, increased yields of food crops through use of fertilizers in most African countries are limited to research centers and a few large-scale farms. Very few small-scale farmers, who produce the bulk of the food grown in Africa, use

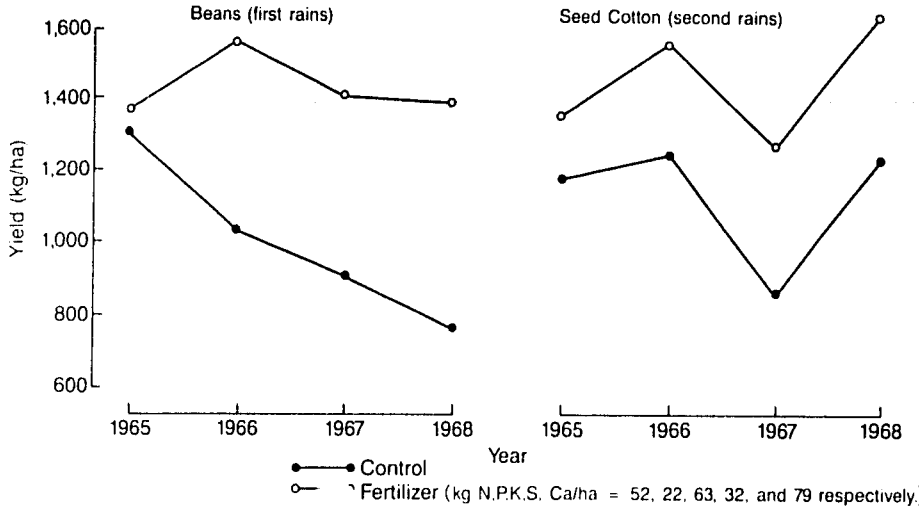


Figure 6. Effect of annual fertilizer additions on continuous rotations of bean and cotton grown on a red ferralitic soil in Uganda (source: Jones [27]).

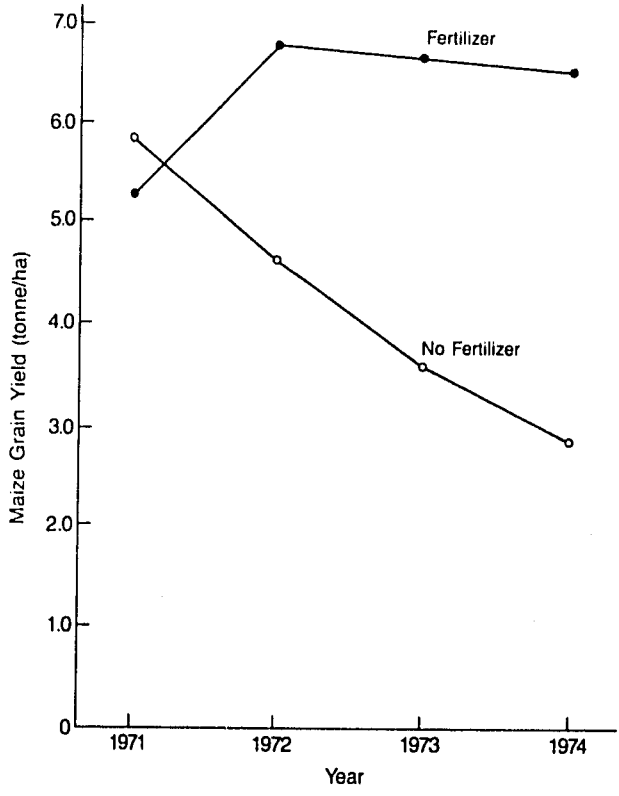


Figure 7. Long-term effect of fertilizer (120 N, 66 P, 30 K, kg/ha per crop) on maize grain yield grown on an Alfisol in the forest zone of Nigeria (source: Kang et al. [29]).

Table 8 Gains and losses of nutrients during 4 years of cotton sorghum rotation in Northern Cameroon on alluvial soil (0.7% C. 10% clay) (kg of nutrient/ha)

	N			P_2O_5			K_2O			CaO			MgO		
	F_2	F_3	F_5	F_2	F_3	F_5	F_2	F_3	F_5	F_2	F_3	F_5	F_2	F_3	F_5
Crop removal	−140	−268	−186	−91	−148	−112	−258	−499	−403	−76	−130	−102	−51	−87	−62
Leaching	−18	−27	−22	−Tr	−Tr	−Tr	−7	−7	−7	−103	−104	−131	−14	−29	−32
Fertilizer additions	+200	+400	+200	+270	+270	+270	+300	+300	+300	+150	+150	+150	0	0	0
Sorghum straw additions	0	0	+111	0	0	+45	0	0	+393	0	0	+74	0	0	+51
Balance	+42	+105	+103	+175	+122	+203	+35	−206	+283	−29	−84	−9	−65	−115	−43

F_2 = 50 kg urea/ha; F_3 = 100 kg urea/ha; F_5 = 50 kg urea/ha + 10 tonnes sorghum straw every 2 years.
All treatments for cotton received 45 kg TSP and 60 kg KCl/ha: those for sorghum received 90 kg TSP and 90 kg KCl/ha.
F_3 gave best yields each year followed by F_5.
Source: Gigou, 1982 [21].

fertilizers. The successes with cash crops clearly indicate that the issue is not small-scale farmers' technical capability of raising crop yields through use of fertilizers, but rather the profitability of using fertilizers on food crops. The infrastructure outlined above for the small-scale tea growers rarely applies to production of food crops; hence, farmers do not use fertilizers on food crops because of the high costs of inputs and marketing problems.

Some countries (e.g., Ivory Coast) have tried to overcome this problem by encouraging farmers to alternate annual cash crops with annual foods in the hope that food crops would benefit from the residual effects of fertilizers applied on the cash crops. In addition, there has been an increase in agronomic research aimed at developing technological packages that will produce reasonable crop yields with minimum inputs. Such research includes incorporating biological nitrogen fixation technologies in the farming systems, studying nutrient balances for efficient use of fertilizers, and use of fertilizer materials that are less capital intensive, such as phosphate rock and partially acidulated or heat-treated phosphate rock.

Soil acidity

Many soils in areas with good annual rainfall are acid in reaction, mainly because of intensive leaching. Continuous cropping also results in lower soil pH (Table 3 and Figure 3) as does use of fertilizers like ammonium sulfate. Soil acidity influences the availability of macronutrients like phosphorus and micronutrients like manganese and also affects the magnitude of the soil charges since in most tropical African soils the soil particle charges are pH dependent. Aluminum and manganese toxicity are the most common causes of acid soil infertility, but both can be corrected by increasing soil pH to about 5.5 [37]. There is evidence indicating that resting the land results in an increase in soil pH (Table 3) and that application of manures also increases the soil pH (Figure 3). These results imply that soil management practices that preserve or increase soil organic matter levels also help to increase and maintain the soil pH levels. Hence, shifting cultivation helps maintain and increase the soil pH to acceptable levels in traditional farming systems. In more recent times, lime and farmyard manure have been used to increase soil pH (Figure 3). The length of the fallow phase or the amount of lime and manures required to raise the soil pH to a given value varies depending on the buffering capacities of the soil (Figure 8). In some cases the capacity is so high that it is more advisable to grow acid-tolerant crops like tea than to apply the large quantities of lime required. There does not seem to be a good reason for liming the tropical soils in Africa beyond pH 6.0 [20,37,42] unless imported plant species not adapted to acid conditions are being grown.

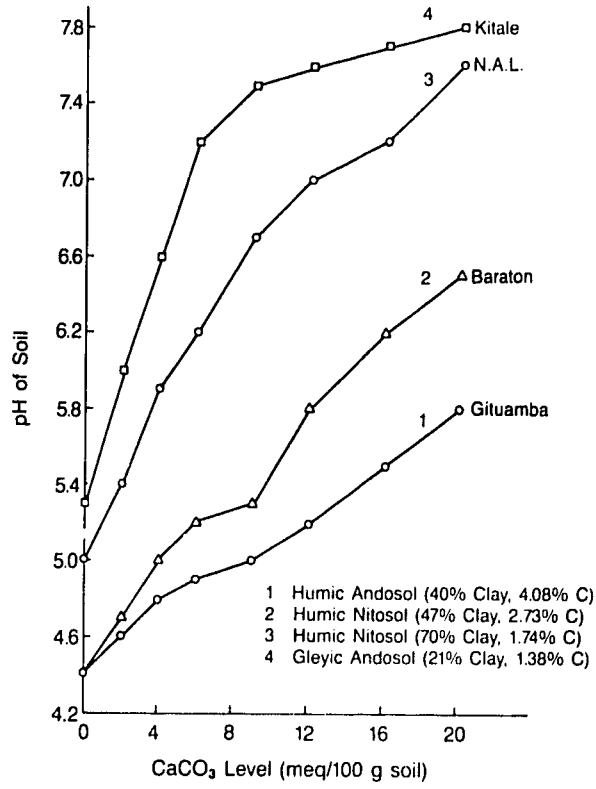


Figure 8. Effect of lime on soil pH [moist $CaCO_3$ incubation for 3.5 months) (source: Ssali and Nuwamanya [42]).

Nitrogen

Nitrogen is the nutrient element that most frequently limits yields in the tropics [37]. Soil nitrogen is derived from rain and dust, biological nitrogen fixation, animal and human wastes, and fertilizers. In natural systems and traditional agriculture, biological nitrogen fixation is the main source of nitrogen (Table 9). About 98% of the soil nitrogen is stabilized in the soil organic matter; the remainder is in mineral forms [40]. Thus, the total nitrogen in the soil and the amounts of nitrogen released for nutrient uptake will depend on the organic matter content of the soils [4,5]. It is not surprising, therefore, that fertility of tropical soils in Africa has been equated with their organic matter content [6,19].

At the beginning of the wet season there is a flush of nitrogen whose magnitude is directly proportional to the duration and intensity of the preceding dry season [39]. This flush may contribute 13 to 183 kg N/ha; whether this nitrogen released will be beneficial to the subsequent crop depends on the

intensity and frequency of the rains early in the season. Annual crops will not have developed well enough to utilize much of the flush nitrogen early in the season; hence, most of it is susceptible to losses through leaching.

In general, soils under forest are higher in nitrogen than soils under grass because of a greater accumulation of organic matter (Table 3 and Figure 2). In addition, many savanna soils have a high C:N ratio and often respond to nitrogen fertilizer even in the first season after a grass fallow. Nitrogen balance studies under arable farming indicate that to have a positive nitrogen balance, higher nitrogen inputs (fertilizer or manures) are required (Tables 8 and 9). Although manures have been used satisfactorily to supply nitrogen, in some cases the C:N ratio is too high and additional nitrogen is required (Table 7). Under continuous arable cropping, prudent use of nitrogen fertiliz-

Table 9 Balance sheet of nitrogen additions and removals in different grazing systems of the Nigerian savanna

Source	Annual addition or removal under			
	Natural savanna	Grass pasture	Legume pasture	Semi-inensive arable farming
	(kg/ha)			
Addition				
Rainfall	5.0	5.0	5.0	5.0
BNF[a]	35.0	15.0	40.0	30.0
Plant residues	10.0	10.0	10.0	10.0
Animal excreta	2.5	7.5	7.5	?
Human wastes	?	?	?	?
Fertilizer	0.0	75.0	20.0	30.0
Total Additions	52.5	112.5	82.5	75.0
Removal				
Burning	25.0	10.0	10.0	25.0
Erosion	6.0	6.0	6.0	6.0
Runoff	0.0	7.0	0.0	5.0
Leaching	0.0	20.0	5.0	7.5
Denitrification	0.0	?	?	0.0
Volatilization	1.0	3.5	3.5	1.0
Removal in feed	8.0	24.0	24.0	35.0
Total Removal	40.0	70.5	48.5	79.5
Balance	+12.5	+42.0	+34.0	−4.5

[a] BNF - Biological nitrogen fixation.

Source: Singh and Balasubramanian, 1980 [40].

ers has maintained and increased soil nitrogen for good crop yields [18,21,26,27,29,40].

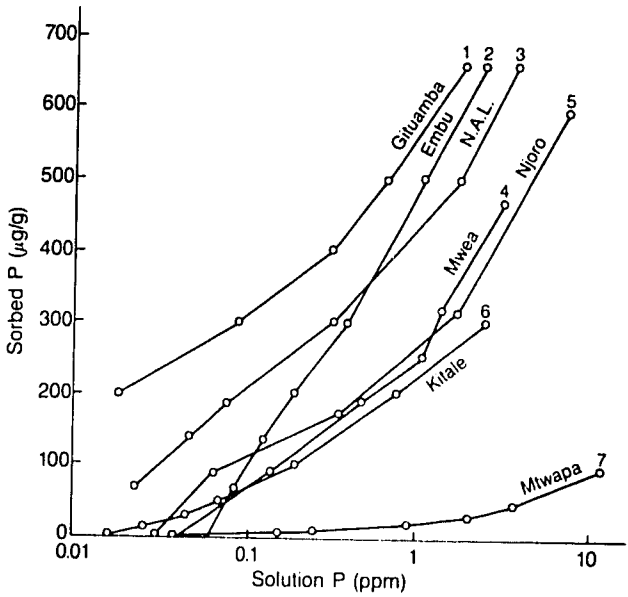
More recent research efforts have been geared toward efficient use of nitrogen fertilizers. The use of slow-release fertilizers like the urea supergranule is being investigated. The use of ^{15}N to study the nitrogen balance sheet in different ecological zones of tropical Africa will help to pinpoint the main routes through which nitrogen is lost from the soil. In addition, there is increasing awareness and use of biological nitrogen fixation technologies in the farming systems of Africa with an ultimate aim of increasing farmers' crop yields with minimum inputs. An African Association for Biological Nitrogen Fixation has been formed, and its first conference was held in 1984. The proceedings of this meeting [41] provide the most recent information on biological nitrogen fixation in farming systems of tropical Africa.

Agroforestry systems incorporating biological nitrogen fixation (e.g., alley cropping) have the potential to increase crop yields with little or no additional input of nitrogen fertilizers [46].

Phosphorus

After nitrogen, phosphorus is generally the most limiting nutrient element in tropical Africa. In many cases where soils had adequate soil organic matter levels (and hence, soil nitrogen), phosphorus was found to be the most limiting nutrient [16,44]. Although the total amount of phosphorus in tropical soils is variable, highly weathered soils generally have low total phosphorus [37]. In addition, many soils in the tropics sorb phosphorus from the soil solution and thus render it less available for plant uptake (phosphorus fixation). The magnitude of phosphorus fixation is generally related to the soil pH, the iron and aluminum oxides in the soil, and exchangeable aluminum. Thus, highly acid and weathered clayey soils will usually have high phosphorus fixation capacities (Figure 9). Andosols, however, tend to have higher phosphorous fixation capacities because of their high amorphous oxide (including allophane) contents. Since many tropical soils are inherently low in total phosphorus, shifting cultivation never really solved phosphorus problems in traditional agricultural systems; in some cases phosphorus deficiencies were observed immediately after clearing [22]. The traditional systems, therefore, relied on growing crop species with low phosphorus requirements and on efficient mycorrhiza associations to extract the small quantities of phosphorus in the soil.

There are conflicting views about management of phosphorus in high-fixing soils. Earlier studies recommend banding of phosphorus fertilizer to reduce fixation of the applied phosphorus. However, although banding may



1. Humic Andosol — 40% Clay (Allophane)
2. Dystric Nitosol — 64% Clay (Metahalloysite)
3. Humic Nitosol — 72% Clay (Metahalloysite)
4. Pellic Vertisol — 62% Clay (Montmorillonite)
5. Mollic Andosol — 44% Clay (Amorphous)
6. Orthic Ferralisol — 49% Clay (Kaolinite)
7. Orthic Ferralisol — 8% Clay (Kaolinite)

Figure 9. Phosphorus sorption isotherms for soils in Kenya (source: Ntuma and Ssali [34]).

be satisfactory in soils with moderate fixation capacities, in high-fixing soils requiring high rates of phosphorus fertilizer, the band can limit root development and subject the crop to serious moisture stress [37].

In more recent studies, sorption isotherms have been used to try to satisfy the phosphorus-fixing capacity of soils by incorporating high rates of phosphorus fertilizer in the surface soil. The fixed phosphorus is then released gradually over the years. This approach requires high initial investment and can only be used in situations where capital is not a problem; hence, it is beyond the financial capability of the small-scale farmer who is the main producer in tropical Africa. A combination of an initial broadcast of phosphorus fertilizer at relatively low rates followed by annual banded applications would be cheaper, and this practice has been successfully tried [37].

Other alternatives that have been tried with success include use of phosphate rocks, phosphate rock mixed with elemental sulfur, and partially acidulated or heat-treated phosphate rock [30]. Because of the high costs involved in transporting such low-analysis materials, however, these materials can only be used where countries (or neighboring countries) have their own phosphate deposits.

Other nutrient elements

With the exception of sandy savanna soils, most tropical African soils have adequate potassium levels [7,44]. Quantity/intensity relations indicate that soils of tropical Africa vary in their potassium 'potential buffering capacity' and reserve (Figure 10) [45]. They also indicate that in some soils with illite and amorphous clays, potassium fixation can occur. Besides crop uptake, the highest potassium losses are due to leaching under arable cultivation, and in some cases, potassium deficiencies have been reported after a few years (3 to 5) of continuous cropping [7]. Under traditional agriculture, potassium problems were solved by a few years of fallow; under continuous cropping, however, potassium has to be added either in manures or in the form of chemical fertilizers.

A number of responses to sulfur have been recorded in Africa since the first report of 'tea yellows' in Malawi [17]. Most of these responses have been in savanna soils where much of the sulfur is lost through annual burning [37]. Research in West and East Africa indicated that amounts of sulfur deposited with rain water and dust vary mainly according to the amount of dust in the air [8,10]. In East Africa annual deposits in rainfall were enough to replace sulfur removed by 750 kg/ha of tea pluckings or 500 kg/ha maize grain [10]. These findings indicate that under the less intensive traditional agricultural systems in tropical Africa sulfur may not have been a major problem. Further work in Kenya [17] indicated that the bulk of sulfur in the soil is in the top layer of the profile and that it is proportional to the organic matter content of soils. It also indicated that in soils with high clay content, mineralized sulfur is sorbed in the subsoil. Hence, sulfur problems are likely to be experienced in light-textured soils with low organic matter and no sulfur reserve in the subsoil. Other reports indicate a 'break response', which may be due not to an incipient soil sulfur deficiency [9] but rather to temporary shortage caused by small amounts of subsoil sulfur and a relatively slow sulfur release due to a high C:N ratio following clearing of grasses. In such cases small doses of sulfur are recommended for the first season.

Since many soils of the tropics have pH-dependent charges that preferentially hold monovalent cations, polyvalent cations like calcium and magnesium are easily lost through leaching in areas of high rainfall. In traditional agricultural resting the land under a fallow helped to recycle the leached cations (Table 3). Under systems of continuous cultivation, these cations have to be added either in fertilizers (e.g., use of calcium ammonium nitrate) or through use of appropriate liming materials (including dolomitic limestone where Mg is low).

As macronutrient problems are being solved and as cropping is becoming more intensive and diagnostic techniques are being improved, more and

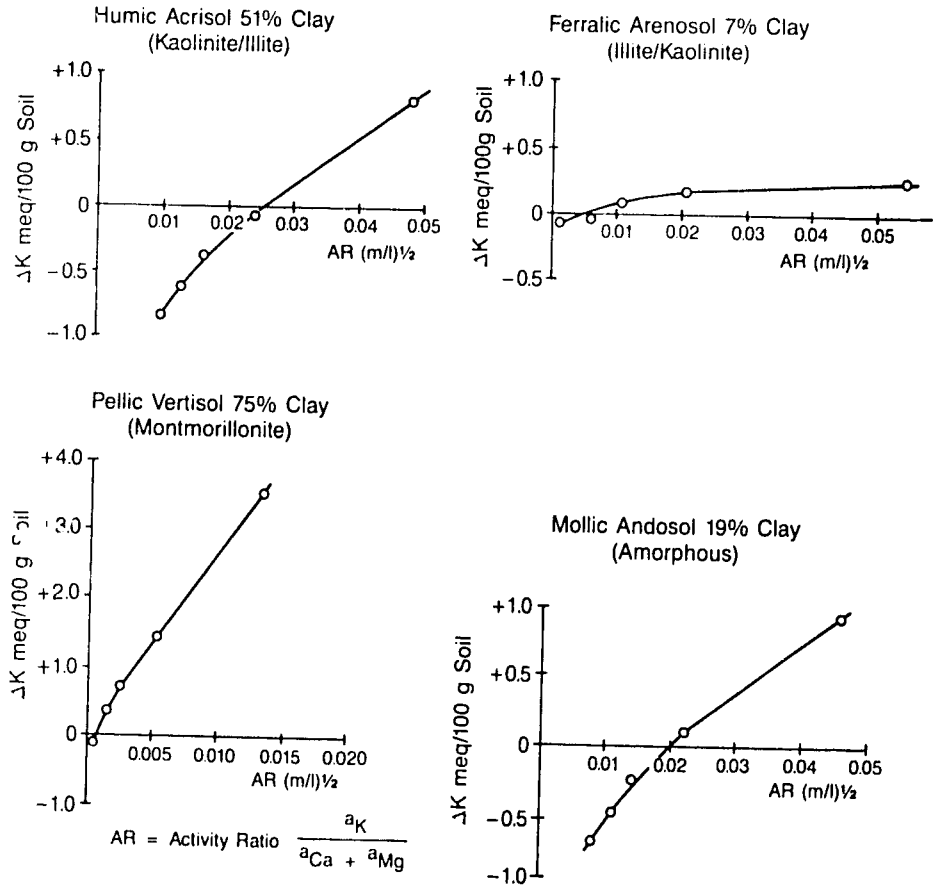


Figure 10. Potassium quantity/intensity (Q/I) relations for some soils in Kenya (source: Muchena [33]).

more micronutrient deficiencies are being discovered. The most common problems of this kind in tropical Africa are deficiencies of molybdenum, boron, and zinc, but occasionally copper, manganese, and iron deficiencies are mentioned [13]. The availability of micronutrients for crop uptake is influenced by soil reaction. Most micronutrients are less available at high soil pH levels; however, molybdenum is less available in acid soils. At very low soil pH levels, manganese toxicity can be a major soil fertility problem in tropical Africa [44]. Besides pH influences, parent materials differ in their micronutrient contents. For example, in a wheat-growing area of Kenya where soils were derived from very low copper volcanic ash, copper has to be applied for good wheat yields.

In the less intensive systems the macronutrients become a limiting factor well before micronutrient problems are recognized except in very acid soils

where manganese toxicity becomes a problem [44]. Under more intensive cropping, more and more micronutrient problems are bound to occur since the nutrient uptakes have increased and the cropping is continuous.

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Cropping systems and soil fertility management in the humid and subhumid tropics with special reference to West Africa

B.T. Kang

Introduction

Traditional cropping systems vary and have developed in response to prevailing soil and climatic conditions and socioeconomic and ethnological preferences. In the humid zone, traditional agriculture is dominated by tree components including plantain and bananas. These are the most stable production systems for the humid tropics.

Multiple cropping is a widely practiced arable cropping system. Although a large number of species may be encountered in intercropping systems, on the basis of the dominant crop(s), seven major crop-based systems can be distinguished in West Africa. These cropping systems strongly reflect the influence of climate and soils. The cassava-, plantain-, and rice-based systems are prevalent in the humid region with acid and low-base-status soils, whereas the maize-, yam-, sorghum- and millet-based systems are more common in the high-base-status soil.

Large areas of humid and subhumid tropical Africa are dominated by low-activity clay (LAC) soils consisting mainly of Alfisols and Ultisols. These soils have major constraints for intensive and continuous arable crop production. Traditional farmers rely on the fallow period for restoring the soil fertility which is exhausted during the short cropping cycle. Although information on fertilization practices for multiple cropping is scarce, there are some general concepts that can assist in more efficient fertilizer use. Reduced tillage systems combined with use of crop residue and in situ mulches from planted fallow play an important role in maintaining the level of soil organic matter and soil fertility. With judicious fertilizer use and liming, sustained crop yields can be attained on Alfisols and Ultisols. Integration of food and tree crop production as in alley cropping can be used as a low-input (nitrogen) soil fertility maintenance system for continuous food crop production in the tropics.

'Cropping system' refers to the kinds or combinations of sequences of arrangements in time and space in addition to practices and technologies used in production of crop(s) in a specified area [41]. Consequently, cropping systems differ depending on climatic and soil conditions and on socioeconomic, technological, and managerial factors of the agricultural production process. The farmer thus manages his crop(s) in such a way as to obtain maximization of outputs with the most efficient utilization of inputs.

The traditional cropping system, which has been the mainstay of agricultural production in tropical Africa, is undergoing rapid changes in response to increasing population and land use pressures and changes in socioeconomic conditions. The system, which relies on restoration of soil fertility by means of a long fallow period, is not well suited to these rapid changes. Shortening the fallow period because of land scarcity and prolonging the cropping cycle with no inputs have thus resulted in a rapid decline in soil fertility and crop yields as already observed in many areas in tropical Africa dominated by highly weathered and LAC soils.

Despite the considerable efforts made by various research institutions during the last two decades to describe, improve, and develop alternative methods to the traditional production systems, progress attained is still limited. Similarly, only some progress has been made in developing soil fertility management practices for sustained and viable crop production on the LAC upland soils [24]. Some of these developments will be discussed in this paper.

Crop production systems

Tree-based cropping systems

Traditional cropping systems are varied and flexible and are well adapted to the local environment, socioeconomic factors, and farmers' needs. In a recent survey on prevailing farming and cropping systems in the humid zone of southern Nigeria [16] it was observed that the traditional agriculture is predominantly upland and that it consists mainly of the following subsystems:

1. Bush fallow 'slash-and-burn' food crop production and land rotation system.
2. Permanent tree crop farming.
3. Taungya system.
4. Multistory cropping in compund farming.

The above systems are dominated by a tree component. Tree crops including plantain and bananas account for 67% of the land under cultivation, while arable crops account for only 25%.

The Taungya system is practiced in areas where the forestry department is establishing tree plantations. Food crop production is practiced only during the period between land clearing and the tree establishment phase [30]. The Taungya system is not attractive to farmers, and it persists only where there is population pressure.

Multistory cropping in compound farming is an intensive management system. Both trees and arable crops are found, usually in mixtures. Plantains and bananas are of special significance in this system. The high organic matter produced by the bananas and plantains serves as mulching materials and combines with the house refuse usually dumped on the soils to maintain the soil fertility and increase the productive life of the land.

Although trees and shrubs play an important role in nutrient recycling during the fallow period in the humid zone, their roles decrease in the subhumid and semiarid regions.

In the traditional agriculture, multiple cropping is the widely practiced system for arable cropping. Multiple cropping is defined as the growing of two or more crops on the same field in a year [6]. This may include intercropping (growing of two or more crops simultaneously on the same field per year) and sequential cropping (growing of two or more crops in sequence on the same field per year). Despite its popularity, it is only during the last two decades that serious research efforts have been made to better evaluate the merits of multiple cropping. Many of the studies have shown numerous advantages of intercropping systems including higher combined yields, higher yield stability from season to season, better spread of production over the growth period, improved quality of products reduced adverse effects of pests, higher returns, and better soil protection against erosion [5,9,39,41,49]. There are also several disadvantages related to intercropping, especially those difficulties related to the use of mechanized equipment, the use of fertilizer and pesticides, more serious drought stress, and the complexity of interactions.

Major food crop-based systems

Specific intercropping systems have developed over centuries in the different regions in response to the prevailing soil and climatic conditions and socioeconomic and ethnological preferences. Though a large number of species may be encountered in intercropping, there are usually two or three major crops that are dominant components [3,39]. Seven major systems based on the dominant crop can be distinguished in West Africa [47].

Cassava-based cropping systems
– These are mainly found in the poor sandy soils of the coastal belt, where other food crops perform less satisfactorily except for coconuts or oil palm. Cassava is mainly associated with maize.

Plantain-based cropping system
– This system is predominant in the forest areas from the Ivory Coast to Cameroon. Major food crops are plantains, cocoyams, maize, and cassava. Plantains and cocoyams are planted after the land is cleared at the beginning of the season. Maize is planted after the onset of regular rains. Cassava closes the rotation and is planted only in the second and third year and grows into the fallow period. Other important secondary crops are yams and groundnuts.

Rice-based cropping systems
– Rice-based cropping systems are common in the forest areas from Western Ivory Coast to Sierra Leone. Here the field is opened for rice, planted at the first rain, and intercropped later with maize and cassava as well as vegetables and spices. Cassava is not harvested until the second and third year. Rice is planted either as pluvial (upland) rice or as hydromorphic rice in valley bottoms (bas-fonds).

Yam-based cropping systems
– In the forest and derived savanna transition zone and in the southern Guinea savanna, cropping systems are traditionally based on yams. Yams are normally planted in the first year after bush clearing. Usually early and late yams are planted in the same field, either intercropped or in separate plots. Yams are often intercropped with cowpea or maize, cassava, vegetables, plantains, and often groundnuts. In the second year maize and/or pluvial rice will be intercropped with different minor crops and the first-year cassava crop.

Maize-based cropping system
– A maize-based system is dominant in the forest and derived savanna transitional zone and in the southern Guinea savanna. It is usually intercropped with cassava, yam, and cowpea. The maize-cassava intercrop is a very productive combination and is widely practiced in the zone. Maize is also well adapted to the tropical highlands where it has the highest production potential. In the highlands of Cameroon it is associated with cocoyams, yams, beans, and groundnuts.

Sorghum-based cropping systems

– These cropping systems are typical of the northern Guinea and the Sudan savannas. Major crops in the systems are millet, maize (only in the Guinea savanna), groundnut and cowpea. Another secondary crop is bambara nut that is mainly planted on soils too poor for groundnuts.

In this region cropping patterns are also changing with the position in the toposequence. Millet is often planted as a sole crop on the shallow soils on the top of the hills, sorghum and millet are intercropped on the slopes, while sorghum may be monocropped on the deeper, more fertile soils in the valley bottoms.

Millet-based cropping system

– With decreasing rainfall (less than 600 mm/year) millet becomes the predominant food crop in the northern Sudan savanna zone. The choice of crops is rather limited because of uncertain rainfall distribution and the short growing season. Millet/groundnut and millet/cowpea are most important combinations.

The above crop-based systems greatly reflect the influence of climate and soils. The cassava-, plantain-, and rice-based systems are predominant in the humid region dominated by acid and low-base-status soils, whereas the maize-, yam-, sorghum-, and millet-based systems are dominant in the high-base-status soils.

Fertility management for crop production

Major soil constraints for crop production

Large areas of humid and subhumid tropical Africa are dominated by low-activity clay soils consisting mainly of Alfisols, Ultisols, and Oxisols [7]. These soils have a humber of major physical and chemical constraints for arable crop production [23,33,36]. The humid region, dominated by the low-base-status and acid Ultisols and Oxisols, is more suitable for tree crop production than for food crop production. Tree- and shrub-based production systems are proving to be most stable in this region, as shown by the existence of highly successful tree crop plantations of rubber and oil palm. Traditional farmers have also successfully used trees and shrubs to maintain soil fertility during the fallow period.

The major soils also have specific problems for use in food crop production. The Alfisols and associated soils are extremely susceptible to soil erosion and compaction; they also have low water retention capacities, and thus

are subject to drought [26,32,33]. Deficiencies of nitrogen and phosphorus are common, while localized deficiencies of patassium, magnesium, iron, zinc, and sulfur occur under intensive cultivation [12,23]. The Ultisols and Oxisols have acidity and aluminum toxicity problems. Although phosphorus deficiency is widespread, the soils have only a moderate degree of phosphorus fixation [21]. Low nutrient reserves, nutrient imbalance, and multiple nutrient deficiencies of nitrogen, phosphorus, potassium, calcium, magnesium, and zinc are common problems [22,24]. Soil fertility management systems for intensive and continuous crop production on these soils have therefore to take into account these soil constraints. Failure to do so will lead in most cases to a rapid loss in soil fertility and result in soil degradation and decreasing yields.

Soil fertility maintenance in the traditional system

In the humid and subhumid zones, traditional farmers rely on the fallow period for restoring soil fertility, which is exhausted during the short cropping cycle. Deep-rooting trees and shrubs in the fallow play a very important role in pumping up plant nutrients from lower soil horizons and retaining most of them in the biomass. Though traditional burning of the biomass following land clearing is seldom complete, it assists in the release of the nutrients for the crop. The effect of burning on soil fertility is influenced by the type and age of fallow vegetation and soil properties. Results of observations in southern Nigeria showed that the effect of burning following a long fallow period is more pronounced on the acid and low-base-status Ultisols than on the high-base-status Alfisols [26]. The effect of burning on soil fertility, particularly on the acid Ultisols is only of short duration, i.e., for 1 to 2 seasons [42,48].

Although in the savanna zone, the grass fallow also plays an important role in improving soil fertility [46], it is less effective in nutrient recycling than are the deep-rooted trees and shrubs grown in the humid zone. Jaiyebo and Moore [20] showed that mixed bush in nutrient recycling was more effective than grass fallow (star grass) or annual leguminous cover crop (kudzu). Despite the effectiveness of the traditional fallow system in soil fertility regeneration, it has the disadvantage of requiring a long fallow period for soil fertility restoration. In some areas of humid West Africa a minimum fallow period of 5 or more years is required before crops can be successfully cultivated again [38]. The large requirement of land area for sustaining the system makes it unprofitable. Rapid population growth as observed in many parts of tropical Africa has also placed considerable pressure on the system, forcing a drastic shortening in the fallow period. The shortened fallow cycles usually

do not allow sufficient soil fertility regeneration for sustained agricultural productivity and result in rapid soil degradation and reduction in crop yields [17]. This necessitates the development of alternative soil fertility management techniques that can increase and sustain crop production.

Fertilizer use and soil fertility management in multiple cropping systems

Besides its many advantages for increasing production, another reason for multiple cropping is to utilize more efficiently native and applied nutrients [40]. Although multiple cropping is widely practiced in the humid and subhumid tropics, information on fertilization practices for this system is scarce and is concerned mainly with nitrogen fertilization and, to a limited extent, with phosphate fertilization. However, certain basic information from sole cropping can also be applied to multiple cropping situations. Based on the soil and particularly on characteristics of the crops to be grown in combination, some basic concepts can be formulated to assist in determining the most efficient fertilizer use for a particular multiple cropping pattern [40,43,45].

An intercropping system may not require additional fertilizer if only one component needs fertilizer and there is little competition between the component crops for the nutrients concerned [43]. For example, in a sorghum-pigeon pea intercropping, nitrogen needs to be applied only to the sorghum crop, which shows good response to nitrogen. Similar principles also apply to phosphorus. For sequential cropping and intercropping of cereal and pigeon pea, phosphorus needs to be applied only to the more responsive cereal crop.

Where both component crops in a multiple cropping system require the same amount of nutrients, an increase in fertilizer requirements can be expected. For cereal-legume intercrop the phosphorus and sulfur requirements may be greater than under sole cropping. Similarly, in a cereal-cereal intercrop, the nitrogen requirement may be greater.

Inclusion of legumes in multiple cropping systems or in crop rotation offers considerable benefits because of their ability to fix nitrogen biologically. There are two main types of mechanism postulated for the beneficial effects of legumes in multiple cropping systems [43]: (1) through immediate transfer, in which nitrogen travels from the legume directly to the associated crop, and (2) through residual effects in which nitrogen fixed by the legume is available to an associated sequentially cropped non-legume after senescence of the legume and decomposition of its organic residue. Although several research workers [15,44] reported some direct transfer of nitrogen in a maize-cowpea intercrop, most studies indicate a residual effect from the leguminous crop [2,27,43].

Soil fertility management with continuous cropping

Significant changes in soil properties occur on the upland soils following land clearing and cropping. Investigations on Alfisols and Ultisols showed a sharp decline in the soil organic matter level during the first few years following land clearing and cropping [1,10,14]. Continuous cropping on the Alfisols also results in a sharp decline in soil pH. The pH decline is more pronounced when moderate to heavy rates of acidifying fertilizers are used [8,26]. The decline in soil organic matter level combined with soil acidification with cropping will reduce the soil effective cation exchange capacity and increase losses of exchangeable calcium and magnesium [26]. It thus appears that after several years of continuous cropping liming may be needed, even on the high-base-status Alfisols.

Soil organic matter plays an important role in managing the fertility of these fragile soils. Reduced tillage systems, combined with use of crop residue mulches and in situ mulches from cover crops (such as *Mucuna utilis*) or from live mulches, play a very important role in maintaining the soil organic matter level and soil productivity [4,33,34]. The presence of mulch cover besides a high nutrient status and high biological activity, also maintains favorable soil physical conditions [31]. On the generally highly erosive Alfisols, the no-tillage production systems with crop residue mulching on newly cleared forest land have shown distinct advantages [13,31]. Higher maize yields can be maintained for 24 consecutive crops with no-tillage than with plowing on an Alfisol [19].

With good soil management combined with judicious fertilizer use and improved varieties, high crop yields can be maintained on the Alfisols and associated soils. In a field trial conducted at the International Institute of Tropical Agriculture (IITA) site in Ibadan on a kaolinitic Alfisol derived from banded gneiss, with moderate annual fertilizer application (60-120 kg N, 60 kg P, and 80 kg K/ha), the main-season maize yields for 12 years of cropping were sustained at over 4.5 tonnes/ha. Yields of minor-season cowpea relay cropped on residual fertilizers (applied to preceding maize crops) was maintained at about 1.0 tonne/ha. Important components for successful continuous cropping included crop rotation, provision of the nutritional needs of the crop in relation to changes in soil properties, and retention of crop residue.

Various institutions working in the humid tropics in recent years have also developed soil management technologies that will permit continuous crop production soil management technologies that will permit continuous crop production on low-base-status and acid Ultisols [18,35,37]. High combined yields of maize, upland rice, rice-beans, and cassava were maintained on fragile Ultisols in south Sumatra, Indonesia for a 5-year period, with initial

application per hectare of 80 kg N, 80-120 kg P, 50 kg K, 50 kg Mg, and 1,000 kg lime and annual applications per hectare of 125 kg N and 100 kg P [35]. On high-activity clay Ultisols in the upper Amazon of Peru, sustained and moderately high yields of upland rice, groundnuts, and soybeans (in rotation) of over 2.0 tonnes/ha were obtained for each of the crops with adequate fertilization and liming [37].

Recent investigations for managing the coarse-textured kaolinitic Ultisol (Typic Paleudult) for sustained crop production in the humid zone of southeastern Nigeria showed that sustained yields of maize and cowpea can be obtained over a period of 7 years on small farms with application of low rates of lime (200-400 kg/ha annually) in combination with an application of 120-50-30-5 kg/ha as N-P-K-Mg (plus S and Zn) applied to the first-season maize crop [19]. The cowpea crop planted in the second season received no fertilizer. At the low rate recommended, the lime can be regarded as a fertilizer rather than a major soil amendment.

With intensive and continuous cropping, crop yields can be sustained by the judicious use of fertilizers and small quantities of liming material on these soils. However, high prices for fertilizers and lime and their limited availability will curtail their use by farmers. In addition, as mentioned earlier soil acidification may also become a problem with continuous cropping and repeated use of acidifying fertilizers. There is therefore a need to develop an integrated approach to soil fertility management on these soils in order to better utilize native nutrient sources and biologically fixed nitrogen sources and thus reduce dependency on purchased inputs.

Low-input fertility management involving trees and shrubs

Integration of food crops with tree crops in agroforestry systems has received considerable attention in recent years as an alternative low-input soil fertility management possibility for the humid and subhumid tropics [11,28]. Integration of limited food production at the initial stage of forest regeneration, known as the Taungya system, has been successfully practiced with no inputs required [30].

The traditional cropping and bush fallow land rotation system relies on trees and shrubs for nutrient recycling and soil fertility regeneration. In an effort to improve this system and make it more productive, IITA has developed the alley cropping system [25], in which food crops are grown in the alleys formed by hedgerows of planted shrubs and trees. The hedgerows are periodically pruned during the cropping season to prevent shading and to provide mulch and green manure for the companion crop. Inclusion of leguminous trees and shrubs such as *Leucaena leucocephala* and *Gliricidia*

sepium in the hedgerows can contribute fixed nitrogen to the system. Results of 7 years of observations in southern Nigeria indicated that this system can contribute between 40-60 kg N/ha to the companion maize crop and be used successfully as a low-input (nitrogen) soil fertility maintenance system for food crop production on high-base-status Alfisols and related soils [28,29].

Since fertilizer use in improved farming systems will result in larger removal of nutrients in the crops, a correspondingly increased return of cations will be required to correct acidity and maintain high levels of production on these fragile soils. In many parts of the humid tropics where lime is not readily available, inclusion or integration of trees and shrubs in the crop production system as practiced in alley cropping can serve as an important solution to part of the acidity problem in LAC soils. The trees and shrubs with their deep rooting are able to gather cations leached from the surface and return them to the topsoil through leaf litter or prunings.

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Biological nitrogen fixation and soil fertility maintenance

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Introduction

Nitrogen compounds comprise from 40% to 50% of the dry matter of protoplasm, the living substance of plant cells. For this reason, N is required in large quantities by growing plants and is indeed the key to soil fertility. Non-N_2-fixing plants – for example, cereals – take all the N they need from the soil. In Senegalese conditions this uptake was estimated to be as follows: 79-132 kg N/ha/crop for pearl millet; 74-84 for rice; 134 for sorghum; and 121-138 for maize [3]. N_2-fixing plants, essentially legumes, take a part of the N they require from the atmosphere, but we shall see later that the N uptake from soil may be relatively high.

When N fertilizers are available, soil N levels are maintained or improved by applying these industrially fixed N sources. Such a technology, which allows continuous crop yields, is successfully used in intensive agricultural systems, but the following limitations have been progressively appearing: increasing cost especially in developing countries, low yields resulting from leaching and denitrification in many tropical soils, and pollution of underground water by nitrates. The other alternative for maintaining or improving the soil N status is to exploit biological N_2 fixation.

In the last decades a tremendous amount of work has been devoted to the study of this process. Very promising results have been achieved at the level of the molecular and genetic manipulations of N_2-fixing organisms, but agriculture and forestry have not yet benefited from these remarkable advances in our knowledge. Such a failure can be partly explained by the following attitudes of researchers: (1) most studies have been focused on the symbiont and have neglected the host; (2) the identification of the potential limiting factors acting in situ has been overlooked, probably because of the extreme difficulty of this task; (3) relatively few attempts have been carried out to precisely quantify the process of N_2 fixation, especially for trees; (4) finally,

the transfer of fixed N_2 to soil and non-N_2-fixing plants has not been systematically investigated.

Improving the soil N status by exploiting the biological process of N_2 fixation should be based not only on the use of highly active N_2-fixing systems but also on methods facilitating the transfer of fixed N_2 to soil. Consequently, this paper will be divided into two sections. The first section will be devoted to the potential of the different N_2-fixing systems and to the improvement of this potential. In the second section we shall briefly present the information we have on the transfer of fixed N_2 to soil and on the maintenance of fertility in relation to different types of soil management.

Nitrogen-fixing potential of agronomically important systems and their improvement

Main N_2-fixing systems involved in agriculture and forestry

All major groups of symbiotic N_2-fixing systems occur in agrosystems and forests. They can be simply classified as follows:

- Legumes - *Rhizobium* symbioses.
- Actinorhizal plants - *Frankia* symbioses.
- Azolla.
- Symbioses with Gymnosperms (especially cycads).

In some ecosystems, N_2 fixation can also be achieved by free-living microorganisms:

- N_2-fixing blue-green algae (especially abundant in wetlands).
- Heterotropic N_2-fixing bacteria, for instance, *Azospirillum* thriving in the rhizosphere or on plant residues (such as straw).

Validity of quantitative data of N_2 fixation estimated in the field

Methods for evaluating N_2 fixation in the field have been described recently in the excellent treatise edited by Bergersen [2]. The methods most generally used are as follows:

1. The difference on N balance studies [39].
2. The difference method (the quantity of N_2 fixed being measured by the difference between the total N content of N_2-fixing plants and the total N content of non-N_2-fixing plants growing in similar conditions) [67].
3. ^{15}N-based techniques, especially the direct isotope dilution method [4,51,64] and the A value method [21].
4. The acetylene reduction technique [2].

Other methods have been proposed: for example, with legumes and actinorhizal plants estimation of nodule numbers or weight has successfully been used to compare N_2-fixing potentials of clones or cultivars. It is not possible to discuss problems related to biological N_2 fixation in the field without checking the validity of the data that are reported. Unfortunately, a part of these data must be discarded because the authors did not take into account the limitations of the methods they used [69]. Some published, and often quoted, estimations have been calculated from wrong assumptions. Thus *Leucaena leucocephala* was credited with a very high N_2-fixing potential, ranging from 600 to 1,000 kg N_2 fixed/ha/year [10,30]. Such values, however, are not valid; they are related to the total N accumulation in the foliage fraction of the tree and thus cannot be attributed solely to N_2 fixation because soil also contributed to the plant N nutrition [31]. Quantification of N_2 fixation by trees is difficult indeed. The isotope methods, which are known for their reliability, may lead to insufficiently accurate estimations; with trees, it is difficult to label the total volume of soil explored by the roots and to get a stable soil enrichment throughout long-term experiments. Fortunately, relatively accurate estimations of N_2 fixation can probably be obtained by using the difference method, provided that the non-N_2-fixing and N_2-fixing systems exhibit equally efficient use of soil and/or fertilizer N [5].

It is probably even more difficult to quantify N_2 fixation by blue-green algae and azolla in wetland rice fields. Many figures that have been reported are liable to criticism, especially evaluations based on acetylene reduction assay [65]. With these N_2-fixing systems, the isotope dilution technique has not yet been used in the field or in field-simulating conditions, probably because of the difficulty of obtaining a non-N_2-fixing control.

Most studies on rhizosphere N_2 fixation have been carried out by using acetylene reduction assays. These proved that N_2 fixation actually occurs in the rhizosphere of non-nodulating plants, but they were incorrectly used in quantifying rhizospheric N_2 fixation, since they ignored the limitations of the method [61,68]. The claim that rhizospheric N_2 fixation could be agronomically significant and the fact that some inoculation trials had effectively increased the yield of some crops [58] generated an explosion of investigations on this N_2-fixing system up to the end of the seventies. Recent studies, however, have shown that rhizospheric N_2 fixation is only in the range of 1-18 kg N_2 fixed/ha/crop in wetland rice fields [53], and the rate of N_2 fixation is certainly much lower in drylands, which are known to be a much less favorable habitat for N_2-fixing free-living bacteria. Extensive field experiments performed in different countries, especially in India [62] and in the United States [59], have clearly shown that if increases of crop yields resulted from inoculation with *Azospirillum* in some conditions, this response probably should not be attributed to N_2 fixation but rather to other

mechanisms, namely, production of plant growth hormones, stimulation of nutrient uptake, or protection against diseases.

By contrast, free-living micro-organisms can probably fix N_2 actively when they have access to large amounts of energetic substrate, a situation that occurs when straw or other plant residues are generously incorporated into the soil. Estimations of the N input through this process are still scanty.

To summarize, one should always interpret with utmost caution N_2-fixation estimations, especially when they are related to systems that are difficult to explore, namely, perennial crops, trees, blue-green algae, azolla, and the rhizosphere of non-nodulating plants. By contrast, a number of correct estimations of N_2 fixation by annual legume crops are available [42], and these can be used with confidence. Most of the discussion in the following sections will be based on these last types of data.

Variations in the N_2-fixing activity of the different systems

The potential of N_2-fixing systems varies a great deal. Among legume crops, for example, it is well known that soybean fixes N_2 much more actively than does bean. Table 1 shows that among tropical N_2-fixing trees *Acacia mearnsii* and *Leucaena leucocephala* are very active in N_2 fixation, whereas *Acacia holosericea* is a poor fixer. However, such comparisons are often liable to criticism not only because of the lack of reliability of some estimations, as

Table 1 N_2 fixation by trees in the tropics

Species	Method of estimation[a]	N_2 fixed (kg/ha/yr)	Reference
Acacia mearnsii	B	200	[46]
Acacia holosericea	I	4-11	[8]
	A	6	[41]
Acacia pennatula	A	34	[54]
Gliricidia sepium	A	13	[54]
Inga jinicuil	A	35	[54]
Leucaena leucocephala	A	110	[34]
Prosopis glandulosa	C	25-36	[55]
Erythrina poeppigiana	D	57-66	[19]
Casuarina equisetifolia	B	58	[11]
Casuarina equisetifolia	I	40-60[b]	[23]

[a] A: acetylene reduction assay; B: nitrogen balance studies; C: ^{15}N abundance studies indicating that 50% of total plant N comes from nitrogen fixation; D: root nodule turnover; I: isotope method (A value).

[b] 11-month-old trees; 10,000 trees/ha.

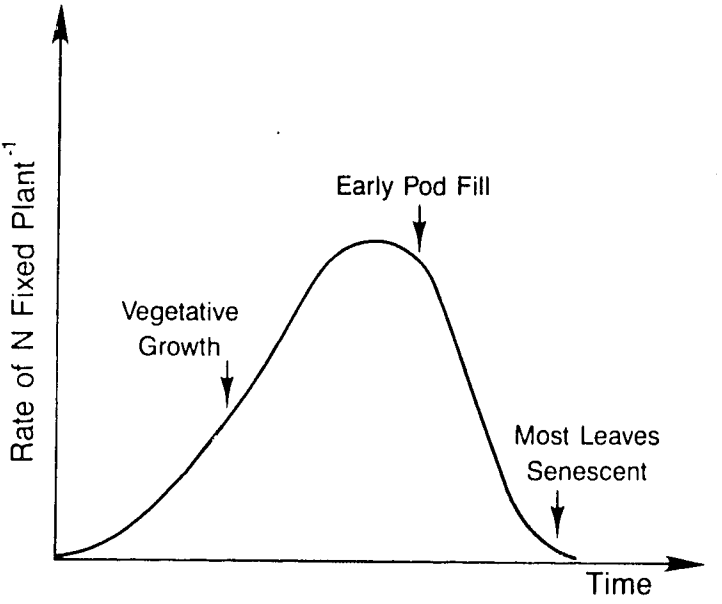

Figure 1. Generalized pattern of N_2-fixing activity for an annual legume.

mentioned earlier, but also because each individual N_2-fixing system may exhibit large variations in activity.

Variations in the N_2-fixing activity of a given system

The activity of a given N_2-fixing system varies greatly with the age of the system and with the environmental conditions.

Variations with age

The pattern of N_2-fixing activity of annual plants is usually characterized by a peak just after flowering (Figure 1); the magnitude of this peak varies with environmental conditions and planting density. The seasonal pattern of N_2 fixation for perennial plants is probably not very different from that of annual plants; they also exhibit a peak sometime during the growing season. The N_2 fixation pattern related to the whole life span of the perennial plants probably follows the curve represented in Figure 2. When the perennial plants are still young, N_2 fixation is negligible, but it increases rapidly with age. Thus during the first 4 months of its life, a seedling of *Casuarina* fixes less than 0.05 g of N_2, but during the following 6 months it can fix up to 3-6

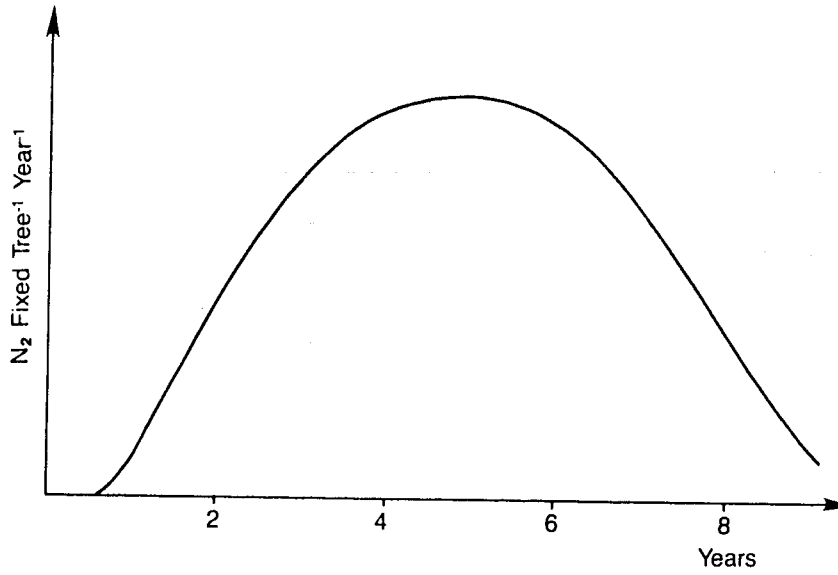

Figure 2. Hypothetical pattern of N_2 fixation during the first year of growth of a tree.

g of N_2. Such a surge in N_2-fixing activity probably lasts for 5-10 years. When the climax has been attained, the trees grow on the combined N accumulated in the soil through decomposition of leaf and root litter, and N_2 fixation is very low. During the growing season N_2 fixation of a perennial plant exhibits a seasonal pattern. The occurence of such variations should be kept in mind when comparing stands that differ especially in age and planting density.

Variations with environmental conditions

Large variations can be directly related to variations of the environmental conditions, which are chemical, physical, or biological in nature [12,25]. A consequence of the high sensitivity of the N_2-fixing systems to the environment is the need for caution in interpreting both short- and long-term estimates.

Technologies for improving N_2 fixation in the short term

Up to now these technologies have been mostly related to the improvement of the symbiont performance, a topic that we shall mention briefly. We shall focus our attention on the approaches based on the host plant studies and recall some of the elementary principles of agricultural management that are too often neglected. We shall not discuss here the technologies that are pres-

ently envisioned but not yet ready to be used. These include the generation of new N_2-fixing systems resulting from the transfer of *nif* genes (and other ancillary genes) to mycorrhiza [28], somatic hybridization of non-N_2-fixing and N_2-fixing plants, and introduction of expressible *nif* into the plant genome [48].

Improvement of the symbiotic micro-organism and inoculation

The recent advances in the molecular and genetic manipulation of micro-organisms offer the possibility of improving the strains of *Rhizobium* that are currently used. Broadening the host spectrum of specific strains has already been achieved by genetic manipulation [35]; competitiveness and/or effectiveness could probably also be improved by using the same technology. However, none of the strains of *Rhizobium* obtained by these means have yet been used in agronomic practice, and thus one must still rely upon strains that have been selected by the usual methods of screening [63]. *Frankia* was isolated and cultivated in vitro for the first time only in 1979 [7], which means that the genetics of this symbiont is still in its infancy. The isolation and culture in vitro of blue-green algae associated with azolla or cycads have not yet been achieved; thus, any attempt to initiate genetic studies is precluded.

Inoculating the host plant with its specific symbiont to increase N_2 fixation is often recommended as a general and unfailing method. In fact, the beneficial effect of inoculation can only be expected when the symbiont is absent or in very low numbers in the soil under study or when the strain to be introduced is both competitive and more effective than the native strains. A few illustrative examples follow.

Successful inoculations

– In most situations, including tropical soils, inoculating soybean with its specific *Rhizobium japonicum* significantly increases N_2 fixation and yields [1,6]. A less classical example is that of the inoculation of *Casuarina equisetifolia* with an effective strain of *Frankia*. Table 2 shows that inoculation increased the growth of the tree more than did the application of N fertilizer.

Unsuccessful inoculation

– In tropical soils, legumes of the cowpea cross-inoculation group show little or no response to inoculation. Thus in Nigeria little or no response has been obtained for cowpea, jack bean, lima bean, and pigeon pea [1]. Another example, related to trees, is that of an inoculation trial of *Acacia holosericea*

carried out in Senegal. Inoculation with the effective strain did not significantly improve the height of the trees after transplantation, and it slightly reduced the survival percentage (Table 3, second and third lines).

Improvement of the host plant

Enhancing N_2 fixation by plant breeding has been advocated for a long time [32,44,45], but this approach has not yet been really exploited by plant genet-

Table 2 Influence of inoculation with Frankia ORS021001 on height, dry weight, and N_2 fixation of 11-month-old Casuarina Equisetifolia

Treatments		Height (cm)	Dry weight (g/tree)	N_2 fixed	
Inoculation	N addition (g/tree)			% Ndfa[a]	g N_2/tree
0	0.5	170 a	295 a	0	0
0	2.5	192 a	409 a	0	0
+	0.5	216 b	525 b	39-53[b]	3.3-2.3[b]

[a] Nitrogen derived from atmosphere.
[b] First figure calculated from direct isotope dilution method, second figure from A value method.
Figures in same columns followed by same letter do not differ significantly, P = 0.05 (Duncan test).

Table 3 Influence of the treatment of acacia holosericea seedlings in the nursery on survival and growth after transplantating[a] Sangalkam, Senegal (unpublished)

Treatment in the nursery		11 months after transplantating		17 months after transplantating	
Sterilization[b]	Inoculation[c]	Survival (%)	Height (cm)	Survival (%)	Height (cm)
0	0	38.2 a	29.4 a	36.8 a	105.3 a
S	0	89.6 b	38.6 b	89.6 b	119.9 b
S	R	75.0 c	36.2 b	72.2 c	117.7 b
S	RM	84.7 bc	45.6 c	84.7 b	134.2 c

[a] Seedlings transplanted when 2 months old.
[b] S: soil sterilization with methylbromide (300 g/m^3).
[c] R: inoculation with *Rhizobium* strain ORS841; RM double inoculation with *Rhizobium* and *Glomus mosseae*.
Figures in same columns followed by same letter do not differ significantly, P = 0.05 (Duncan test).

Figure 3 Time course of nodule dry weight of peanut expressed as milligrams per plant (A: cv. 28-206 and GH 119-20; B: cv. 55-437. Field experiment carried out at Patar, Central Senegal in 1977).

icists. In addition to plant breeding, screening of spontaneous or artificially induced mutants or screening followed by cloning of individuals with superior ability to fix N_2 within a heterogeneous population would probably lead to interesting applications in the short term. A few examples follow.

Crop-legumes

– These legumes are knows to exhibit variations among cultivars. The variations affect nodulation (Figure 3) or the amount of N_2 fixed, and thus significantly change the soil N balance (Table 4). Using ethyl-methyl- alfonate mutagenesis and M2 family pot selection, Gresshoff et al. [29] recently obtained soybean mutants showing excessive nodulation (up to threefold to fourfold increases in nodule number or mass) above that of wild plants. This supernodulation was also expressed in the presence of otherwise inhibitory levels (5 mM) of combined N (up to tenfold increases in nodule numbers). At the same time the nitrogenase activity of the soybean mutants was not affected by these inhibitory levels of combined N.

N_2-fixing trees

– Many N_2-fixing trees are cross-pollinated so that the genetic heterogeneity of individuals is considerable. This characteristic complicates germplasm exploration and selection, but it can be exploited by screening the best clones, a technique that implies that clonal propagation methods ara available. In-

vestigations in the latter direction are under way at the Bureau for Overseas Scientific and Technical Research/National Center for Scientific Research laboratory in Dakar, and the preliminary results on *Acacia senegal* and *Casuarina* spp. are most promising.

Agricultural management

We have seen that the amount of N_2 fixed by a given N_2-fixing system is related to the potential of this system which, in turn, is determined both by the associated symbiont (*Rhizobium* or *Frankia*) and by the host plant. However, this potential is often limited by environmental, chemical, physical, and biological factors. In arid and semiarid conditions, water stress is a major limiting factor, as illustrated by Figure 4. The agronomist should attempt to minimize or eliminate the impact of these limiting factors. Since this topic has been adequately discussed already [13,26], we shall restrict our attention exclusively to the following two problems.

Phosphorus availability
– Any soil deficiency affects not only growth of the plant but also the functioning of the symbiotic system. A most common nutritional disorder is that

Table 4 Percent plant N derived from N_2 (% Ndfa) and N balances of cowpea and soybean cultivars when grown in a soil low in available N

Cultivars	N_2 fixed (kg N_2/ha)	% Ndfa	N balance (kg N/ha)
Cowpea[a]			
ER1	50	61	+2
TVu 1190	101	75	+52
Ife Brown	81	76	+24
TVu 4552	49	64	+3
Soybean[b]			
26/72	143	86	+7
22/72	126	80	+7
44/A/73	110	76	−1
Jupiter	108	75	−6
4/73	64	73	−6

[a] [18].
[b] (unpublished).
For each crop, comparisons between cultivars were carried out at the same time, in the same soil. Tops were returned to soil in both experiments.

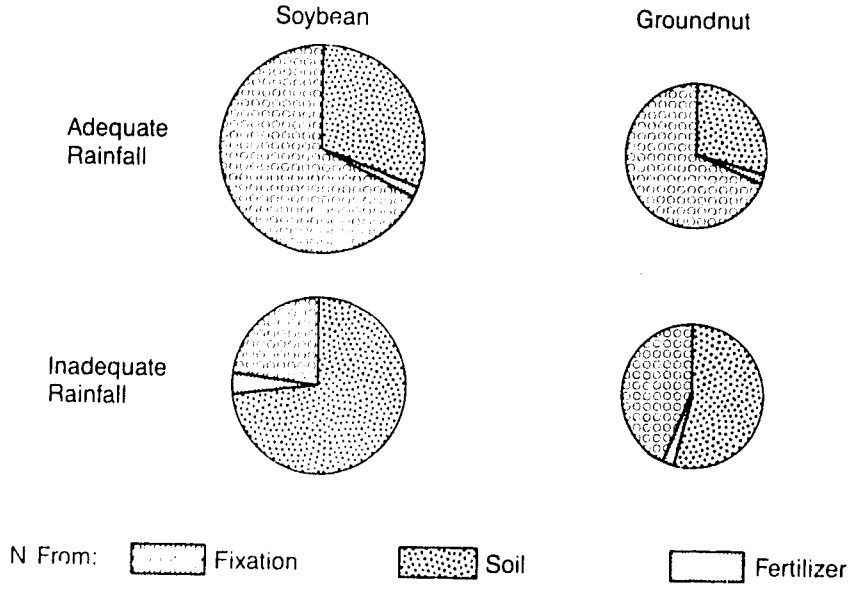

Figure 4. Left: N_2 fixation by soybeans inoculated with an effective strain of *Rhizobium* in a field experiment carried out in South Senegal (In 1982 [adequate rainfall] percentages of plant N derived from N_2 fixation [Ndfa] and N_2 fixed expressed as kg/ha were 70% and 109%, respectively, whereas in 1980 [inadequate rainfall] related figures were 24% and 34%).

Right: N_2 fixation by groundnut spontaneously nodulated by native *Rhizobium* in a field experiment carried out in central Senegal (In 1975 [adequate rainfall] Ndfa and N_2 fixed were 66% and 67%, respectively, whereas in 1974 [inadequate rainfall] related figures were 44% and 52%, respectively [unpublished]; diameter of circles is proportional to total N content of plants).

resulting from phosphorus deficiency. Alleviating this soil defect by applying appropriate amounts of soluble phosphorus dramatically restoes N_2 fixation. The example given in Table 5 is interesting because it shows that a modest application of P (22 kg/ha) combined with inoculation with *Glomus mosseae*, an endomycorrhizal fungus, significantly increased the percentage of N derived from atmospheric N_2 (% Ndfa) and the total amount of N_2 fixed (nearly a twofold increase) by field-grown soybean. Subsequently, the grain yield was significantly improved. The results of this inoculation trial with an endomycorrhizal fungus should not be extrapolated to other environmental conditions without caution. It should be emphasized that the successful effect of *Glomus mosseae* inoculation reported here was attributed mostly to the fact that the native endomycorrhizal populations were very low in the experimental site.

Inhibition of N_2-fixing systems by combined N

– It is well established that nitrate and, to a lesser extent, other forms of combined N retard nodulation and N_2 fixation. Such an inhibition is obviously responsible for the deficit in the N balance observed when the amount of N fertilizer applied to a given legume reaches inhibitory levels [18]. A first approach to circumventing this inhibition is to use plant-symbiont systems that are capable of continuing to fix N_2 even in the presence of large amounts of combined N. We have already given the example of mutant soybeans obtained by Gresshoff et al. [29]. *Sesbania rostrata*, a stem-nodulated legume, has been shown to have the unique ability to absorb combined N with roots and to fix N_2 with its stem nodules [15]. It has ben suggested that transferring the stem nodulation characteristic from this plant to other legumes would be a way to develop new, uninhibited N_2-fixing systems [13,14]. A second approach, which has not been seriously explored, is to use some forms of N fertilizers that do not inhibit N_2 fixation and yet provide the plants with the complementary N required for their growth. Hardy et al. [32] proposed designating such forms of fertilizers as compatible fertilizers. In a preliminary experiment they found that 'soybean meal' applied to soybean not only did not inhibit N_2 fixation but increased it by 12%. It would be unrealistic to propose the use of soybean meal as a compatible N fertilizer, but it would probably be possible to obtain new forms of N fertilizers with similar properties. To start with, it would be worthwile to study the effect of the existing slow-release N fertilizers on the N_2-fixing activity of symbiotic systems.

Fertility maintenance

The contribution of N_2-fixing systems to the soil N pool depends on their

Table 5 Effect of inoculation with glomus mosseae on N_2 fixation and grain yields of field-grown soybean with or without application of P fertilizer [22]

Treatments		N_2 fixed		Grain yield	
Inoculation	Superphosphate (kg P/ha)	% Ndfa	kg/ha	kg dry wt/ha	kg N/ha
Rhizobium	0	67 a	73 a	1,423 a	90 a
Rhizobium + Glomus	0	67 a	80 a	1,431 a	98 a
Rhizobium	22	70 a	109 b	2,017 b	134 b
Rhizobium + Glomus	22	76 b	139 c	2,290 c	155 b

Means followed by the same letter within columns do not differ significantly, P = 0.05.

N_2-fixing potential and on the amount of fixed N transferred to the soil. We have already discussed in detail the means of obtaining systems with the highest N_2-fixing potential. In this section we shall examine the problem of the transfer of fixed N_2 to soil and give examples related to different types of agricultural and forestry management.

Transfer of fixed N_2 to soil

J. Sprent [60] aptly recalled that 'legumes are not altruistic'. They fix N_2 for themselves, normally releasing little N into the soil during their growth. However, some N is transferred from the decomposition of dead tissues such as leaves, cladodes or phyllodes, fruit, roots, and nodules. A return of N in plant tops to the soil via leaching is likely to occur during rain, irrigation, dewfall, or spraying [66]. The amount of N transferred is usually low for grain annual crops, since much of the current research on improvement of grain legumes is aimed at improving the harvest index of grain and ensuring that it is indeed harvested [33]. In contrast, larger amounts of N are probably transferred when tops are incorporated into the soil or after being transformed into farmyard manure. N transfers are considerable for legumes that are ploughed in as green manure. The same is true for trees that shed large quantities of leaves and fruit.

Grain legumes

According to Henzell and Vallis [33], 60%-70% of the legume N may be harvested and residues may have a lower percentage of N than the material harvested. Consequently, it is not surprising to observe negative N balances in rotations comprising grain legumes. To improve the soil N status in such systems, the recommendation is to use cultivars that actively fix N_2 (Table 4), to ensure the return of tops, and to avoid or minimize the addition of N fertilizers, which are known to inhibit N_2 fixation. The main emphasis should be placed on rotations that ensure the replenishment of the N stock. Thus, maintenance of soil fertility in a soybean-maize rotation in Senegal has been achieved by returning the tops of both crops to the soil. Improvement of fertility was attributed not only to the increase in soil organic matter but also to the enhancement of N_2 fixation by soybean, as suggested by the increase of nodule numbers (Table 6). It is interesting to note that in this experiment a relatively high yield of maize (2,000 kg grain/ha) was obtained without the addition of N fertilizer in the framework of a 4-year rotation.

Wetland rice

Flooded soils appear to maintain higher N fertility than dryland soils. Moderate but fairly stable yields of rice (2 tonnes/ha) are maintained for many years without any addition of N fertilizer, a fact which is attributed to the input of N to the soil through spontaneous N_2 fixation. Four types of N-fixing systems can be involved: legumes used as green manure (and also, but only in China, a non-legume, *Coriaria sinica*); azolla, which is used in a similar way as legumes; blue-green algae; and heterotropic N-fixing microorganisms thriving on straw and, to a lesser extent, on living rice plants.

Green manuring based on the incorporation of N-fixing plants or azolla is certainly the most efficient technique, and it allows a substantial improvement of the N status of the soil. However, Roger and Watanabe [53] concluded their excellent review on the 'technologies for utilizing N_2 fixation in wetland rice' by stressing the socioeconomic limitations of green manuring: this management practice is labor intensive, and it can be used only where economics is not a major factor.

Since the ecology of blue-green algae is still poorly understood, Roger and Watanabe [53] would not confidently recommend algal inoculation in spite of the fact that this practice would probably require only little additional labor. According to these authors, the future for heterotrophic N_2 fixation is even less bright, except when it is associated with straw incorporation.

We are well aware that the practices based on the production and incorporation of a large biomass (legumes, azolla, and, to a lesser extent, straw) are limited by economic factors [33,53], but the use of stem-nodulated legumes

Table 6. Influence of the return of plant residues or addition of organic amendment (compost) on yields[a] of soybean and maize grown in a sequential rotation for 4 years (unpublished)

Treatments		Soybean		Maize
Return of maize straw	Addition of compost (t/ha)	Nodule number/plant (day 55)	Grain yield (kg dry wt/ha)	Grain yield[b] (kg dry wt/ha)
0	0	7 a	1,650 a	900 a
+	0	27 b	2,000 b	1,300 b
+	1.5-2.0	26 b	2,250 c	2,000 c

[a] Mean yield for 3 successive years.
[b] No N fertilizer was applied at any time.
Figures in same column followed by same letter do not differ significantly, P = 0.05.

with a high N_2-fixing potential will probably facilitate the revival of composting and green manuring, such as practiced now or in improved versions. In fact, *Sesbania rostrata*, a stem-nodulated legume whose remarkable characteristics were discovered in 1979 [15,16], appears to be a good candidate for green manuring or composting [52].

N_2-fixing trees in mixed stands or associated with annual crops

The contribution of trees to the N status of soil is a priori more important than that of annual crops because of two specific habits.

1. Except for young trees (less than 1-2 years old), part of the N that trees take through their roots returns to the soil with litter; thus, N is continuously circulating in the ecosystem. The N returned in litter may be a high proportion of N derived from N_2 fixation (% Ndfa) or from soil uptake. An interesting consequence of this fact is that 'in low soil N conditions, leaf drop may be used as a very rough estimator of N_2 fixation, but it neglects the N stored in the plant during growth and N turned over underground' [57].
2. Through their extensive root system trees act as a 'nutrient pump', redistributing the nutrients, especially N, in the profile and contributing to their accumulation at the surface or the soil [50]. Thus trees appear to be good candidates for mixed cropping systems. However, one should be aware of limitations to their ae resulting from competition for light and water and, with some species, the production of phytotoxic compounds (allelopathy) excreted by roots or accumulated in the litter [36].

Mixed stands

In temperate areas, growing mixed stands of N_2-fixing and non-N_2-fixing trees has been attempted, but not with much success except for the reclamation of waste areas [43,56]. Although this approach has not yet been seriously studied in tropical and subtropical conditions, it should not be overlooked since spontaneous mixed stands do exist. For example, in Australian *Eucalyptus* forests, species of *Acacia* are widespread as understory shrubs with members of the Papilionoid tribe or the cycad *Macrozamia* (a thermophilic plant with coral-like nodules resulting from the association with an N_2-fixing blue-green alga) [60]. Mixed stands of *Eucalyptus sieberi* and *Allocasuarina littoralis* are not uncommon in southeast Australia [17]. Mixed stands of *Casuarina* sp. and *Anacardium occidentale* have reportedly been used to fix sand dunes in Orissa [47].

Intercropping tree legumes with annual crops

Intercropping can be defined as growing two or more crops simultaneously in the same field. Ideally one of the associated plants should be able to fix N_2. Some examples show that this type of intercropping can result in improved soil fertility and often increased yields. The classical example is that of *Acacia albida* associated with millet, sorghum, or groundnut. *Acacia albida* is a tree legume that has the unusual habit of growing new foliage during the dry season and losing its leaves during the early part of the rainy season. Crops can be grown around and under the tree without suffering from light and water competition; thus, they derive benefit from the topsoil enrichment [9,20,27,38]. In this association it is not very clear whether the improved fertility of the soil under the trees is due mainly to N_2 fixation or to the redistribution of nutrients, especially N, in the profile (pumping effect). Intercropping *Leucaena leucocephala* with maize is probably an interesting method. Experiments carried out that a population of 10,000 to 20,000 plants/ha is adequate to provide sufficient foliage to cover the soil and supply substantial quantities of nutrients without significantly competing with maize. Table 7 shows that maize yields were only slightly reduced by the highest population of *Leucaena leucocephala* [49]. Except for a few clear-cut examples, such as that of *Acacia albida*, "we have as yet very little experimental evidence on tree-crop associations that tells us whether the species mixtures will interact mutual inhibition, cooperatively or through one form or

Table 7 Maize height reductions and grain yields when grown in association with leucaena at CIAT, Colombia [49]

Leucaena	Maize	Maize	
Population plants/ha	Population plants/ha	Height[a] reduction (%)	yield[b] (t/ha)
0	25,000	0	4.6
0	50,000	0	5.2
10,000	25,000	2	4.7
10,000	50,000	11	4.6
20,000	25,000	0	4.2
20,000	50,000	12	4.9
40,000	25,000	10	3.5
40,000	50,000	15	4.9

[a] Forty days after planting compared to check.
[b] Corrected to 15% moisture content.

another of compensation' [36]. This type of information is obviously required if a particular tree-crop association is to be encouraged.

N_2-fixing tree-annual crop or N_2-fixing-non-N_2-fixing tree rotations

In New Guinea the following shifting cultivation system is currently practiced with success. *Casuarina oligodon* is planted in wasted, N-deficient soils and grown for 5-10 years. It is then harvested for wood or charcoal, after which the land is planted with various crops [57]. The same system based on buildup of an N reserve by the N_2-fixing tree is used in India [40]. Soil-improving properties of casuarinas have also been exploited in alternating rotation with *Anacardium occidentale* for the production of cashew nuts in India (J.C.G. Ottow, personal communication).

Conclusion

Restoration, maintenance, and improvement of the N status in soils can be achieved through biological N_2 fixation provided that the N_2-fixing systems used exhibit a high N_2-fixing potential, that no environmental factor limits this activity, and that the largest portion of fixed N_2 is transferred to the soil. Most often these conditions are far from being fulfilled. Thus there is a tremendous need for research in three major fields.

1. Improving the N_2-fixing potential of existing systems or obtaining new systems is obviously a major requirement. There is a need for increased emphasis on the plant rather than on the associated symbiont. It is high time that we orient our efforts toward exploiting the genetic variability of the host plants. For trees, one should attempt to select the best 'soil improvers,' that is, trees that will fix the largest amounts of N_2 and also return N (and P absorbed together with N) to the soil via leaf fall or lopping [36,37]. The host plant and microbial approaches should be used to identify N_2-fixing systems that would not be too sensitive to combined N.
2. Identification of limiting factors, though often extremely difficult, should be carefully carried out at each site. This type of investigation is a prerequisite to any attempt to exploit biological N_2 fixation. It would be ineffectual to develop powerful N_2-fixing systems without first attempting to identify and eliminate potentially limiting factors.
3. The problem of improving the transfer of fixed N_2 to soil should probably be undertaken by agronomists and economists; however, plant ecologists should study some aspects, such as those related to the plant-to-plant interactions in agroforestry systems.

Biological N_2 fixation is probably the only alternative source of N in some specific situations: in countries where N fertilizer is unavailable or unaffordable[1] or where intensive labor is cheap and in agroforestry systems or rice fields where only moderate yields are expected. By contrast, intensive agriculture usually consumes large amounts of N fertilizer without attempting to benefit from the input of N from N_2 fixation. Such a situation should be corrected not only for the sake of saving N fertilizers but also to avoid the pollution hazards that are linked to their use. We have already noted that the combination of biological N_2 fixation and N fertilizers is not a utopian dream,since the possibility exists of processing compatible fertilizers or obtaining N_2-fixing systems that are not inhibited by combined N.

Notes

[1] In Casamance, 1 kg of urea costs 150 FCFA (0.33 US $) during the summer of 1984; this price was considered as prohibitive by the farmers

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Management of nitrogen fertilizers for tropical African soils

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Introduction

Nitrogen is a key element in food crop production in tropical Africa. To a large extent, stable food crop production in the tropics is a function of the degree to which the soil fertility is maintained. Nitrogen, the most mobile plant nutrient, is the most easily exhaustible nutrient element in the soil. This is particularly true in the fragile, poorly buffered soils commonly found in tropical Africa. Traditional farmers in Africa found adequate solutions to deal with this problem through shifting cultivation and use of leguminous crops to restore soil fertility. Return of crop residues and maintenance of a continuous crop stand were means of avoiding soil degradation. The increase in population pressure, coupled with the urbanization of the countryside, has led to farmland being continuously used with a resulting loss of productivity. Use of fertilizer is increasingly seen as a partial solution to the problem of restoring soil fertility and providing food for the African population.

Fertilizer experimentation in Africa so far has been limited in scope. Earliest research was focused on cash crops such as cotton and oil palm, for which recommendations were firmly established. Since 1961, the Food and Agriculture Organization of the United Nations (FAO) has conducted an extensive fertilizer program in Africa consisting basically of simple NPK trials and demonstration plots [14]. Although useful in determining the basic nutrient requirements for major food crops in various African environments, these studies did not adequately address the issues of fertilizer efficiency and soil fertility maintenance or restoration. Moreover, differences in uptake rates between traditional cereals and the modern, high-yielding alternatives necessitate a reassessment of fertilizer requirements as established by the FAO studies [20].

The studies outlined in this report were born of the need to develop and pursue a coordinated research program involving the food crops of sub-

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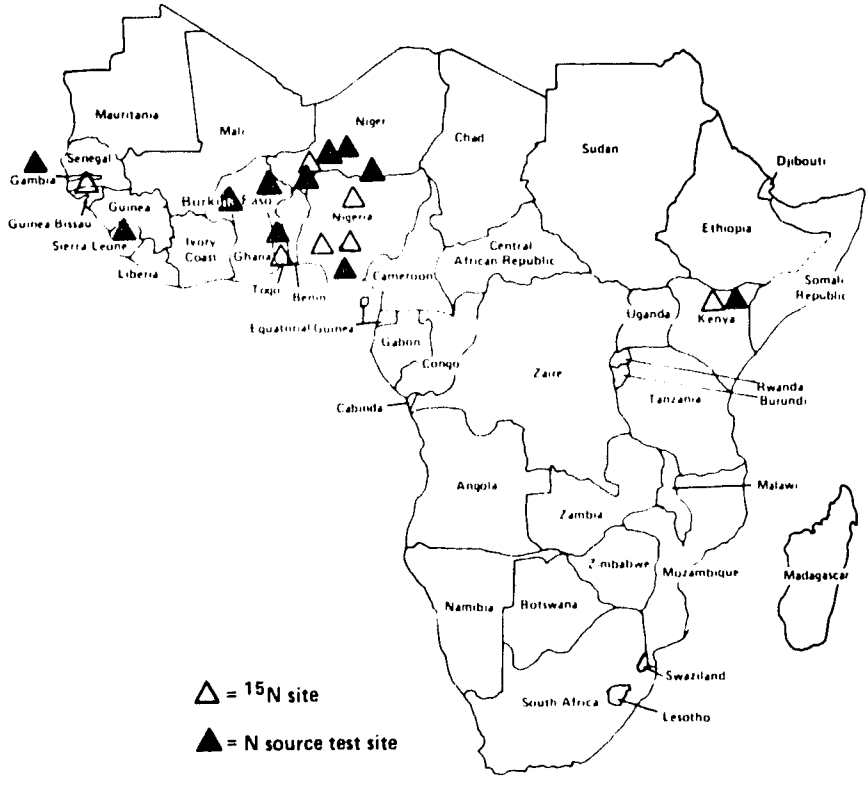


Figure 1. IFDC's nitrogen research program in sub-Saharan Africa.

Saharan Africa. Starting in 1982, the International Fertilizer Development Center (IFDC) and its collaborators established ^{15}N balance studies on an agroecological cross section of West Africa. In addition, studies were conducted on various subhumid sites on an east-west transect (Figure 1). Ultimately, nitrogen trials were conducted at 18 sites in 8 countries. The facilities at IFDC Headquarters were used in an attempt to identify the important mechanisms of N loss that may occur under field conditions. This information, combined with numerous traditional fertilizer screening experiments conducted at additional sites (Figure 1), provides a better understanding of the performance of various N sources and management techniques for the different agroecological zones. This information, in turn, may help policymakers and farmers select the most profitable package of N source and management for their region or farm.

Objectives of the nitrogen program

The primary objective of the nitrogen program within the Africa Fertilizer

Research Program sponsored by the International Fund for Agricultural Development (IFAD) was to assess fertilizer source and management factors that could realistically be used at the level of the peasant farmer to increase food production in Africa. The more specific goals were as follows:

1. To assess the performance in terms of grain yield of commonly available N sources such as calcium ammonium nitrate (CAN) and urea under appropriate management systems.
2. To assess the value of point-placed urea as compared with banding and broadcasting of urea prills.
3. To construct ^{15}N balances in order to determine the fertilizer-N uptake and losses that occur with different N sources under different management systems.
4. To determine the effect of various soil and agroclimatic factors on the performance of N fertilizers.

These trials were conducted at a number of sites in all three agroecological zones of sub-Saharan Africa (humid, subhumid, and semiarid). In order to achieve these goals, it was recognized that cooperation of national scientists and their supporting government agencies in sub-Saharan Africa was required. Thus, another goal of the IFAD-funded IFDC nitrogen program was to develop an effective international network for fertilizer testing across the sub-Saharan region.

Literature review

In the traditional African farming system, farmers were able to maintain stable (but low) levels of productivity and avoid serious erosion. However, population and urbanization pressures have forced farmers away from traditional shifting cultivation with 6 to 15 fallow years to systems where the cropping cycles become more frequent. With this intensified cropping, fertility (especially organic matter and N levels) declines and erosion problems become more severe. These trends can be halted or reversed by the proper use of appropriate fertilizers [36,40]. With proper fertilization and weeding, for example, it was possible to maintain maize yields at 6,000 kg grain/ha for 5 years while yields in plots not receiving fertilizer ultimately declined to 450 kg/ha [33].

The transformations that fertilizer N may undergo upon application to the soil are presented in Figure 2. Upon entering the soil, fertilizer N mixes with the pool of mineral N in the native soil, which interacts with the clayfixed N pool, the soil biomass, and the standing crop root system. Losses of fertilizer N and competition with the plant and biomass may subtract from the mineral N pool, whereas mineralization of soil organic matter adds to the mineral pool.

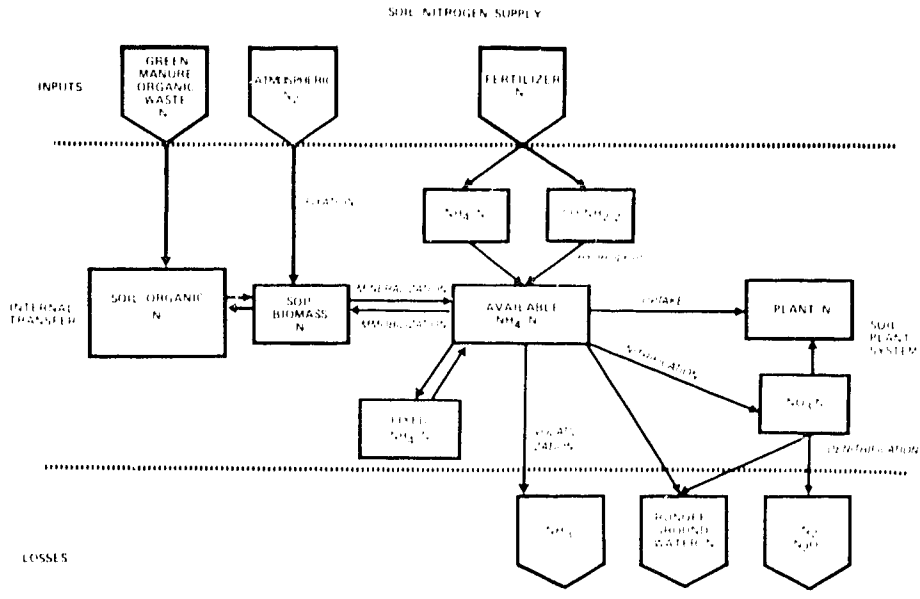


Figure 2. Nitrogen inputs, losses, and internal transfers in the soil system.

The amounts of fertilizer required to maintain high crop yields depend a great deal on the crop species and variety as well as the location at which the crop will be grown. In many places in sub-Saharan Africa, a good response to N fertilizer will only occur if sufficient P is applied as well [42]. In addition, in central Africa N responses are only pronounced in the presence of adequate sulfur [10].

In testing three rates of N applied as CAN to maize in Samaru, Nigeria, Jones [29] found that responses of maize were generally large and significant to rates of 56 kg and 112 kg N/ha; on the average, these rates increased yields 2,000 and a further 1,000 kg, respectively. Higher application rates at 224 kg N/ha resulted in further increases of only 600 kg grain/ha. Summarizing 50 trials conducted using maize as the test crop throughout northern Nigeria between 1957 and 1964, Goldsworthy [23] found optimum N and P rates to be 65 kg N/ha and 38 kg P_2O_5/ha, respectively. A similar program involving 154 sorghum trials in the same region provided an optimum N rate of 25 kg N/ha if combined with 16-19 kg P_2O_5/ha [22]. Responses to N were limited in the absence of added P. When the recommended rates were used, yields increased an average of between 45% and 65%, the higher response being found in the central areas of the country. A nitrogen x density maize trial conducted at Ibadan, Nigeria, showed that the optimum N rate at all except very high densities was between 50 and 100 kg N/ha although the mean yield increase between those two rates was only 15% [1].

Comparable trends have been found at other sites in Nigeria for maize and sorghum although responses by sorghum were much lower and likely to be only marginally profitable [26]. On the basis of a large number of trials conducted between 1968 and 1979 in central and northern Nigeria, FAO has recommended fertilizer rates of 80 kg N/ha and 32-80 kg P_2O_5/ha for maximum sorghum yields in the varying provinces. Slightly higher rates were suggested to optimize maize production [14]. The 'best' fertilizer rate for millet in FAO demonstration trials was much lower, varying from 30-30-0 in Kano province to 18-13-0 in Sokoto province. Trials conducted in Burkina Faso using millet as the test crop also showed good responses to low rates of N where 40 kg N/ha increased the millet yield from 498 to 930 kg grain/ha [15]. A similar program conducted in Mali showed good response of maize and sorghum to N rates of 80 to 120 kg N/ha. Although a linear response was found for millet, the absolute amounts of millet grain produced were very low making N fertilization unprofitable [42]. Response of millet to N was much stronger in Senegal where a positive response was found at N rates up to 120 kg N/ha, which produced a yield of 3.0 t grain/ha [16].

Most fertilizer trials were conducted with only a single source, most commonly urea or CAN, or as in older trials, ammonium sulfate (AS). Ammonium sulfate has fallen into disfavor because of its strong tendency to acidify the soil after prolonged use [5,39]. Although it was found that ammonium sulfate, ammonium phosphate, and urea showed equal efficiency in Mali, Traore [42] recommended use of urea because its high N analysis made transportation costs much lower. In a comparison of AS, CAN, nitrate of soda, gypsum ammonium nitrate, and urea, Brown [6] found only slight differences among sources in terms of maize yield in Malawi. Over the nine experiments conducted at four sites, urea was 92% as effective as AS and 94% as effective as CAN per unit N added. Studies conducted at Samaru and Mokwa, Nigeria, showed that although urea and CAN produced less acidity than AS, the acidity produced by these two fertilizers still was significant [32]. The rate of acidification increased as the N rate increased, an effect that was more pronounced with AS.

Fayemi [12] found that splitting the fertilizer and applying it as two doses improved maize yields in the humid regions of Nigeria. In the subhumid and semiarid regions of northern Nigeria, the recommended practice was to apply 40% at 2 weeks after planting (WAP) and the rest at 6-8 WAP [21]. However, in studying the effect of a single large application of CAN at planting, 3½ WAP, or 7 WAP versus a series of split application combinations in subhumid Nigeria, Jones [29] found that all N application combinations performed equally well except the single application at 7 WAP. This treatment was slightly poorer at high N rates (112 and 224 kg N/ha) than the others. There was a slight tendency toward a higher response with the splits, but this

was not significant in terms of yield. It was concluded that the best application method would be as a single dose at 3 WAP because that would save labor costs to the farmer. Brown [6] had earlier arrived at similar conclusions after conducting fertilizer timing trials in Malawi.

Leaching in the subhumid areas of Nigeria is believed to be limited [45], and NO_3^- movement is of the order of 0.38 to 0.66 cm/cm rainfall [31]. This could explain the lack of advantage of a split N application. In cases where N is applied as a large single dose early in the season, it generally does not penetrate below the 75 cm depth in the profile. Thus all the N is available to the plant. Splits may become advantageous in humid sites where leaching is more severe and N is being removed from the profile before it is available to the plant. Arora and Juo [4] found that leaching losses in the humid zone were reduced from 58% to 28% of the applied N when the fertilizer was applied in three splits instead of as a single dose. This translated into increased yield of maize and increased N uptake.

Maize is often not grown as a sole crop but instead is intercropped with the legume cowpeas. Even though cowpeas generally do not respond to N, their cultivation can result in a net exportation of N from the soil. Because only approximately 6% of the plant's N is found in the roots, 94% of the N in the plant is exported as fodder for animals or grain for human consumption [11]. Studies comparing maize following cowpeas with maize following groundnuts showed that cowpeas provided little N for the following crops while cereal yields were significantly higher following groundnuts [30]. Cowpeas can provide advantages only when no additional N sources are available but can depress millet yield when intercropped with no additional N. At high N rates, the healthy maize shades the cowpeas thereby reducing cowpea yields [3,2].

For the peasant farmer the most important aspect of any fertilization program is the information that allows him to gain maximum output in terms of yield and profits with minimum inputs. In discussions concerning fertilizer use this is termed the agronomic efficiency (AE) of the product, i.e., the response in yield per unit of fertilizer input. However, AE is dependent upon the rate of application and follows the rule of diminishing returns. Thus, in order to accurately determine AE, fertility trials must be conducted using a number of N rates to give a good picture of the N response by the crop in question. At a given rate of application, AE is further determined by (1) the fertilizer recovery fraction and (2) the crop's efficiency in transforming N uptake into yield [24]. Both of these factors are influenced by a number of environmental conditions, as well as numerous crop, water, and fertilizer management practices, e.g., weeding, date of planting, planting density and geometry, timing and method of water and fertilizer application [44]. Fertilizer nitrogen applications are designed to complement the nitrogen available

from soil organic matter, including plant residues, manure additions, and biologically fixed nitrogen. The fertilizer recovery fractions are greatly affected by the size of this available N pool [25]. Additionally, losses of fertilizer N through leaching, denitrification, runoff, or NH_3 volatilization have a direct bearing on the recovery of N.

Traditionally, fertilizer recovery has been calculated as the difference in N uptake between the fertilized and nonfertilized crop per quantity of applied N (apparent recovery). However, in soils with a strong response to N, additional uptake of soil N may occur because of stimulated mineralization of soil N (priming effect) or simple mineralization-immobilization turnover [28], combined with the increased demand from the healthier plant and a better developed root system to scavenge the soil. The stable isotope ^{15}N has been widely used to gain additional insight into the utilization of fertilizer N by tracing the fertilizer N through the soil-plant system. In many cases, ^{15}N recovery over- or underestimates the true fertilizer effect [44]. While a farmer may be more concerned with the immediate fertilizer effect and thus with high nitrogen recovery, agronomists are equally concerned with soil fertility maintenance and thus with replenishment of the soil nitrogen exported by crops [38]. Studies with ^{15}N provide a means of evaluating the role of nitrogen applications in soil fertility maintenance.

Few reports of ^{15}N studies conducted in sub-Saharan Africa exist in the literature. Results of some studies with cereal crops are summarized in Table 1. The data presented in Table 1 suggest the following trends:

1. Apparent uptake of fertilizer N exceeds measured uptake using ^{15}N.
2. Uptake of ^{15}N-labeled fertilizer and apparent recovery of unlabeled fertilizer N decrease with increasing rates of application.
3. Loss of ^{15}N-labeled fertilizer to the atmosphere increases and recovery of N in the soil decreases with increasing rates of fertilizer application.
4. Estimated losses of N are high regardless of N source.

Studies have shown that the application of N fertilizers to African soils enhances mineralization of soil N and crop exploitation of native soil N [9,18,8]. At higher rates of fertilizer N application, the low fertilizer recovery seems to more than compensate for this effect [9]. Increased loss of fertilizer N and depressed exploitation of soil N at high N application rates may result in lower apparent recoveries of fertilizer N at high application rates.

Reports from trials in which ^{15}N fertilizers were used show high gaseous losses of fertilizer N regardless of N source. Since ammonium sulfate would not be expected to be a source of volatile ammonia in acid soil conditions, one could speculate that denitrification losses of N occurred in the trial conducted in Cameroon [19]. Denitrification and ammonia volatilization represent possible pathways of N loss from urea [18,8].

To date, little is known about where or how much fertilizer N is lost in

tropical Africa. With a total N consumption in 1981 of 480,000 tonnes in tropical Africa, a reduction of only 10% (48,000 tonnes) in loss would constitute savings of at least US $19 million annually. To gain insight into the extent of N loss, basic studies on the fate of fertilizer N are absolutely essential.

Reports of ^{15}N studies in legume and mixed cereal/legume crops present another perspective on the use of N fertilizers in sub-Saharan Africa. Applications of N fertilizers to legumes are apparently poorly utilized by the crop. Huxley [27] reported that only 2% of the 10 kg N/ha starter fertilizer applied to cowpeas was taken up by the plant and that amount had no effect on crop growth or yield. Increased rates of N application to legumes have adverse effects on nodule formation and N fixation. Thus, increasing rates of N application to legumes show increasing uptake of fertilizer N [11], a trend which is opposite that shown by cereal crops.

The cost of ^{15}N-enriched fertilizer sources is such that application to full

Table 1 Results of ^{15}N fertilizer studies conducted in sub-Saharan Africa

Location	Bambey, Senegal			Marola, Cameroon	Bouake, Ivory Coast		Bouake, Ivory Coast		Gagnoa, Ivory Coast	
N rate, kg N/ha	150	90	150	100	100	200	60	120	50	100
Plant recovery of ^{15}N-labeled fertilizer (%)	34	31	30	40-45	45	28	33	27	43	34
Apparent plant recovery of unlabeled N fertilizer (%)	39	ND[a]	ND	ND	65	33	67	67	60	37
Recovery of ^{15}N-labeled fertilizer in soil (%)	18	29	25	10-15	ND	ND	60	34	ND	ND
Losses of ^{15}N-labeled fertilizer to atmosphere (%)	47	31	36	40-50	ND	ND	5	35	ND	ND
Leaching losses of ^{15}N-labeled fertilizer (%)	1	9	9	0	ND	ND	1	4	ND	ND
Annual rainfall of site (mm)	450			800	1,100		1,100		1,450	
Soil clay (%)	4			12-25	25		25		10-35	
N source	urea			ammonium sulfate	urea		urea		urea	
Crop	millet			sorghum	maize		upland rice		maize	
Reference	[17]	[18]	[18]	[19]	[9]		[8]		[9]	

[a] ND = Not determined.

plot sizes is prohibitively expensive. Commonly used plot sizes for fertilizer evaluation experiments range from 8 to 50 m^2 for various cereal crops. The cost of applying ^{15}N at 5% excess to these plots is estimated at US \$8.62/m^2 for 10 kg N/ha. It is clear that such research would quickly lose its appeal if no effort was made to reduce the cost. The use of relatively cheap ^{15}N-depleted sources makes great demands on analytical capabilities. Therefore, scientists usually have resorted to isolating subplots within the plots (microplots) that receive the ^{15}N-labeled source. The remaining plot receives the same fertilizer without label.

The dimensions of the microplot are determined by a number of factors such as crop type, planting geometry, soil type, border depth, fertilizer management, and climatic conditions. The microplot size should be such that at the time of sampling a large enough area in the center of the microplot remains unaffected by isotopic dilution from the surrounding plot so that representative soil and plant samples can be taken for analysis. Relatively little information on optimum microplot size is available in the literature [37] and virtually none from the tropics. Because of the complexity of the factors affecting this border effect, IFDC has generally taken the approach of experimentally determining the minimum microplot dimensions by sampling transects through microplots and studying the excess ^{15}N levels in plant material.

The common practice is to install shallow borders around microplots in order to prevent cross-contamination due to runoff. In a series of experiments conducted in India, IFDC (Moraghan, Personal Communication) evaluated the possibility of reducing microplot size by using deep (120 cm) borders to prevent root development outside the microplot. The experimental plot was planted in sorghum and compared the ^{15}N balance of 1.5 x 2.5 m plots with deep (120 cm) and shallow (30 cm) borders. The ^{15}N balance data for the different microplots were in excellent agreement, with ^{15}N recoveries in the plant of 55.9% in the deep-bordered plots and 56.5% in the shallow-bordered plots. Therefore, for the soils (Alfisols) at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Center in India, the 30 cm deep borders were as effective as the 120 cm deep borders. There may be more lateral root development and movement of ^{15}N in the soils in West Africa, and here the installation of deep borders may help to decrease the minimum required size of microplots.

An accurate fertilizer N balance requires a proper estimate of fertilizer N in the soil. Soil sampling procedures for ^{15}N analysis have posed a serious problem in IFDC's collaborative experiments. Moraghan et al. [35] initiated ^{15}N fertilizer research at ICRISAT (India) on sorghum in 1980. In the first year, soil samples were taken by hand auger (core samples) in all ^{15}N-treated plots. Variability among replicates, particularly in the top 30 cm, was so high

that soil recoveries for this experiment were not reported. In the subsequent year, heterogeneity problems were overcome by sampling several 20 cm wide strips across various rows in two layers (0-15 and 15-30 cm deep). Thus, the estimate of the ^{15}N remaining in the soil, 60%-70% of which resided in the top 30 cm of soil, was greatly improved.

Sites and experimental procedures

The IFDC African research program may be divided into two parts, the field trials conducted in Africa itself and, equally important, the support studies and analyses conducted at IFDC Headquarters.

At Headquarters, the ^{15}N fertilizers were prepared and samples from the fields trials were analyzed. Also, several short-term trials were conducted under controlled conditions in order to help explain results obtained in the field. This supplementary work will be discussed following discussion of the main body of the field research conducted in Africa.

The focus of the field program can be divided into two broad categories reflecting the stated objectives of the nitrogen program. The trials involving unlabeled fertilizer materials were conducted in order to evaluate the performance in terms of yield of two very common fertilizers in Africa (urea and CAN) as well as management factors such as method and timing of fertilizer addition. A practice of deep-point placement of an experimental urea product – the urea supergranule (USG) – was also evaluated using the major food crops of each urea.

Concomitantly, ^{15}N-enriched isotope balance trials were conducted in order to obtain data about the fate and efficiency of the fertilizer materials and management practices tested in the unlabeled trials.

Nitrogen response studies

Various combinations of nitrogen fertilizer treatments were tested in different locations in order to screen different fertilizer sources and management practices. These sites were chosen to reflect a variety of climates, soils, and crops within the mandate zone in order to better assess the climatic and geographic factors influencing fertilizer use efficiency.

A. Experimental sites

The locations of the experimental sites are indicated on Figure 1. Some geographic and climatic information for these locations is summarized in Table 2. The annual rainfall ranges from about 250 to 1,800 mm, thus representing the majority of the climatic zones of Africa in which food crops are produced. The sites were characterized as humid, subhumid, and semiarid on the basis of total rainfall and prevailing cropping practices. Bimodal rainfall patterns, allowing two successive crops, were characterized as humid, while monomodal patterns with single, mixed, or relay cropping systems were considered subhumid if based on maize or semiarid if only millet-based cropping was possible. The humid zone is characterized by high rainfall in excess of 1,300 mm of rain, whereas the subhumid zone receives approximately 700-1,300 mm of rain annually. The distinction between these two zones is not great, and both support a variety of crops though the principal one is maize. At the drier sites in the subhumid zone the principal crop tends to be sorghum. The semiarid zone is that area in which rainfall does not exceed 700 mm. Such low rainfall is generally sufficient to produce only millet.

All sites except Kenya were located at low altitudes (< 200 m). The Kenya site was at 1,941 m and consequently experienced cooler temperatures (lowest mean monthly temperature of 12.6°C in January). Crops at all sites were grown under rainfed conditions. However, in some locations (e.g., Kabete) supplemental irrigation was practiced to prevent crop failure during drought. Drought conditions were experienced at various sites, particularly in 1984.

The range in soil types of tropical Africa is relatively narrow and is dominated by the light-textured Alfisols and Ultisols. These soils are of great importance in the subhumid and semiarid African regions, covering over 40% of tropical Africa [40]. The soils are generally very sandy with low pH, organic matter content, and cation exchange capacity (CEC). Such soils are generally quite responsive to applied nitrogen.

B. Fertilizer treatments

Table 3 indicates the treatments that were included in the various experiments. The treatments were selected by mutual agreement between IFDC and collaborating scientists of the host countries. The treatments reflected (1) the objectives of the project and of the national programs, (2) manageability of the experiment, and (3) availability of resources (land, labor, etc.). Whenever possible, common treatments were incorporated at all sites in order to allow comparisons among sites. Application rates ranged from 0 to 160 kg N/ha for the humid and subhumid tropics, and from 0 to 60 kg N/ha for the

Table 2 Soil and climatic data for test sites

Ecological zone	Site	Classification of soil (USDA)[a]	Organic matter (%)	Total N (%)	Soil pH	Cation exchange capacity (meq/100 g)	Sand (%)	Clay (%)
Humid	Ikenne, Nigeria	Paleustalf	1.7	0.11	5.9	4.1	72	20
	Owerri, Nigeria	Ultisol	2.2	0.13	4.3	2.4	88	7
	Njala, Sierra Leone	Oxidic plintic paleudult	5.2	0.30	4.0	NA[b]	57	19
	Kabete, Kenya	Oxic paleustalf	NA	NA	5.9	24.0	NA	79
Subhumid	Mokwa, Nigeria	Typic paleustalf	0.4	0.06	5.8	1.9	77	13
	Zaria, Nigeria	Alfisol	1.0	0.08	5.8	4.3	70	17
	Sefa, Senegal	Alfisol	1.0	0.05	5.4	1	88	8
	Sarakawa, Togo	Plinthustult	0.5	0.03	6.6	3.5	85	7
	Glidji, Togo	Ultisol	0.4	0.03	5.4	3.5	87	10
	Farako-ba, Burkina Faso	Alfisol	NA	NA	5.4	NA	NA	NA
Semiarid	Sapu, Gambia	Eutrustox	0.9	0.04	5.3	4.7	68	7
	Saria, Burkina Faso	Alfisol	0.5	0.02	5.3	2.7	69	9
	Gobery, Niger	Alfisol	0.3	0.02	5.2	1	95	2
	Magaria, Niger	Alfisol	0.3	0.02	6.2	1.3	96	2
	Sadore, Niger	Torripsamment	0.3	0.02	4.7	1	94	1
	Serkin Yama, Niger	Alfisol	0.2	0.02	6.2	1.0	91	3
	Tounga, Niger	Alfisol	0.5	0.02	6.6	2.2	92	6

[a] USDA = United States Department of Agriculture.
[b] NA = not available.

semiarid tropics, with at least three nonzero rates in each experimental treatment. Phosphorus, potassium, sulfur, and micronutrients (if needed) were supplied at the rates recommended by national scientists (Table 3). Experiments were carried out in completely randomized blocks with 4-8 replications, depending on variability of the experimental site.

Planting densities were 1 x 1 m for millet and 0.75 x 0.25 m for maize in most cases. The cowpea or bean intercrop was planted between maize plants either in the row or between the rows. Fertilizers were applied by (1) broadcasting, (2) banding, or (3) point placement. Banded and point-placed (supergranules) fertilizers were incorporated into the soil at a distance of approximately 10 cm from the plant at a depth of 8 cm. Urea and CAN were in the prilled form for broadcast and band applications, whereas point placement of urea was facilitated through the use of urea supergranules (large granules weighing 0.55 to 1.65 g depending on the rate of N required). These supergranules allowed all the fertilizer to be placed below the soil surface near the plant as a single dose. This is the recommended practice in Niger (Goubé – Personal Communication), and it was found to be an effective method of N application in Malawi [6]. The practice of point placement is attractive to the average farmer because he can easily and quickly make a hole in the soil, drop in the fertilizer, and close the hole. The use of a supergranule allowed addition of the precise amounts of N required to run fertilizer trials. However, a farmer applying granulated urea in a hole using a calibrated spoon could achieve the same results. Fertilizer was applied either as a single dose at planting (basal dressing) or in two equal splits, one at planting and the second 2-6 weeks after planting, depending on the recommendations of the collaborators. In Sefa, Senegal, urea was split applied according to the local recommended practice, i.e., 15% at planting and 42.5% each at 18 and 27 days after planting.

Upon harvesting, dry weights were determined for grain and stover, and subsamples were taken for N analysis. This report will deal with grain production data only.

C. Statistical procedures

Statistical analyses were made for each experimental site within agroecological areas or climatic zones. Grain yields of maize, millet, cowpeas, and beans were the only dependent variable analyzed and were considered the main plant response factor affected by variations due to changes in rates, time, and mode of application of nitrogen sources and changes in weather and soil characteristics. Variations due to management practices were minimized by using the same crop practice within the agroecological areas selected.

Table 3 Experimental sites and conditions and selected cropping system and treatments

Climate	Site	P Rate (kg P_2O_5/ha)	K Rate (kg K_2O/ha)	Rainfall (mm)	Treatment[a]	Cropping system	Number of years
Humid	Ikenne, Nigeria	90	90	1,156	B,E,G,H,I	Maize/cowpeas	1982
	Ikenne, Nigeria	90	90	796	C,G,I	Maize/cowpeas	1983
	Ikenne, Nigeria	90	90	1,263	B,G,I	Maize/cowpeas	1984
	Owerry, Nigeria	90	90	1,800	C,G,I	Maize/cowpeas	1984
	Njala, Sierra Leone	100	30	1,623[b]	C,G,I	Maize/cowpeas	1983
	Njala, Sierra Leone	100	30	1,396[b]	C,G,I	Maize/cowpeas	1984
	Kabete, Kenya	100	80	1,051	C,G,I	Maize/bean	1983
	Kabete, Kenya	100	80	573	C,G,I	Maize/bean	1984
Subhumid	Mokwa, Nigeria	90	90	928	B,E,G,H,I	Maize/cowpeas	1982
	Mokwa, Nigeria	90	90	654	C,G,I	Maize/cowpeas	1983
	Mokwa, Nigeria	90	90	908	C,G,I	Maize/cowpeas	1984
	Sarakawa, Togo	60	60	1,298	C,G,I	Maize	1984
	Glidji, Togo	60	60	1,325	C,G,I	Maize/cowpeas	1984
	Sefa, Senegal	55	83	665	E,G	Maize	1983
	Sefa, Senegal	55	83	715	E,G,I	Maize	1984
	Zaria, Nigeria	90	90	882	C,G,I	Maize/cowpeas	1984
	Farako-ba, Burkina Faso	40	30	815	C,E,G,I	Maize	1984

Table 3 Continued

Climate	Site	P Rate (kg P_2O_5/ha)	K Rate (kg K_2O/ha)	Rainfall (mm)	Treatment[a]	Cropping system	Number of years
Semiarid	Sadore, Niger	30	30	370	A,D,E,G,H,I	Millet	1982
	Sadore, Niger	30	30	598	C,G,I	Millet	1983
	Sadore A, Niger	30	30	260	C,G,I	Millet	1984
	Sadore B, Niger	30	30	260	A,B,C,D,F,L	Millet	1984
	Magaria, Niger	40	30	345	C,E,G,I	Millet	1983
	Magaria, Niger	40	30	291	C,E,G,I	Millet	1984
	Serkin Yama, Niger	40	30	282	C,E,G,I	Millet	1984
	Gobery, Niger	30	30	326	G,I	Millet	1984
	Barkiawel, Niger	30	30	–	C,G	Millet	1984
	Tounga, Niger	40	30	350	C,E,G,I	Millet	1983
	Tounga, Niger	40	30	348	C,E,G,I	Millet	1984
	Sapu, Gambia	50	56	–	C,G,I,J,K	Maize	1984
	Saria, Burkina Faso	40	30	699	C,E,G,I	Sorghum	1984

[a] A = CAN, basal broadcast, incorporated
B = CAN, split, broadcast, incorporated
C = CAN, split, banded, incorporated
D = Urea, basal broadcast, incorporated
E = Urea, split broadcast, incorporated
F = Urea, basal, banded, incorporated
G = Urea, split, banded, incorporated
H = Urea supergranule, basal, point placed (USG), incorporated
I = Urea supergranule, split, point placed (USG), incorporated
J = 18:46:0, split banded, incorporated
K = 26:14:0, split banded, incorporated
L = CAN, basal, banded, incorporated

[b] Rainfall for growing season only

Basic analysis of variance to account for the effect of sources and rates was made according to the experimental design proposed:

$$Y_{ijk} = \mu + \iota_i + \beta_j + \lambda_k + (\iota\lambda)_{ik} + \varepsilon_{ijk} \quad (1)$$

where: ι_i represents the effect due to the ith source. β_j represents the effect due to the jth replicate. λ_k represents the effect due to the kth rate. $(\iota\lambda)_{ik}$ represents the differential response of the ith source with the kth rate. ε_{ijk} represents the experimental error.

Empirical response functions were assumed to represent yield response to increasing rates of nitrogen. Generalized least squares analysis was used to estimate the parameters from the following functions:

$$Y_{ij} = \beta_0 + \sum_{i=1}^{s} \beta_i X_i + \sum_{i=1}^{s} \beta_{ii} X_i^2 + \varepsilon_{ij} \quad (2)$$

$$\text{or } Y_{ij} = \beta_0 + \sum_{i=1}^{s} \beta_i \log_{10} X_i + \varepsilon_{ij} \quad (3)$$

where β_i represents the i sources at X rates for the j sites.

Orthogonal comparisons of the means for the nitrogen sources and the slopes of the response functions for each site were used to test the main differences between urea and CAN.

Since one of the objectives of the project was to draw a general conclusion on the performance of the sources across climatic environments, a combined analysis of variance which included the effect of site and seasonal variations was performed using the following model:

$$Y_{ijklm} = \mu + \iota_i + \beta_{jl} + \lambda_k + \alpha_m + (\iota\alpha)_{im} + (\lambda\alpha)_{km} + \varepsilon_{ijklm} \quad (4)$$

where α_m represents a seasonal variation and $(\iota\alpha)_{im} + (\lambda\alpha)_{km}$, the respective interactions between seasonal variations and the ith source and k^{th} rate. A statistical test of significance was made for comparing mean effects of time and mode of application of the nitrogen sources by using the interaction with seasonal effects as error term. This test was made by assuming that yield variations within each agroecological area were due mainly to the controlled factors of time and mode of application for each source in spite of the random variations of the sites and weather during the period of experimentation.

Before combining sites and seasonals periods, a test for homogeneity of variances for the sites within each agroecological aea was performed to account for the basic assumptions in the error term of model (4).

A response function to evaluate the effect of time and mode of application of the N sources for each agroecological area across the site and seasonal variation was developed and yielded the following model:

$$Y_{ij} = \beta_o + \sum_{i=1}^{S} \beta_i X_i + \sum_{i=1}^{S} \beta_{ii} X_i^2 + \alpha_1 Z_1 + \alpha_2 Z_2 + \varepsilon \quad (5)$$

$$Y_{ij} = \beta_o + \sum_{i=1}^{S} \beta_i \log_{10} X_i + \alpha_1 Z_1 + \alpha_2 Z_2 + \varepsilon \quad (6)$$

where β_i and β_{ii} represent the linear and quadratic terms of the function and α_1, and α_2 the dummy factor for estimating changes in weather and site factors during the 3 years of experimentation. Statistical tests of significance were made to compare the time and mode of application over the range of the N rates applied for the response functions in model (5) and (6). The test was made by using an F test on reduced models for the linear and quadratic effects of time and mode of application according to the general linear hypothesis:

H_o: $CB = 0$
H_1: $CB \neq 0$

where C represents the matrix of specific comparisons between time and mode of application and B represents the corresponding vector of estimates for the linear and quadratic estimates.

Nitrogen balance studies using ^{15}N

A. Sites

In 1982 the ^{15}N studies were conducted at Sadore in Niger and Mokwa and Ikenne in Nigeria, representing the three different ecological zones of West Africa. Two additional sites were added in 1983, one subhumid site at Sefa, in the Casamance region of Senegal and the other in the high-altitude humid region at Kabete, Kenya. In 1984 again two sites were added, both in the subhumid region of West Africa at Glidji, Togo, and Zaria, Nigeria. Site locations and their characteristics are shown on Figure 1 and in Table 4.

Table 4 Location and characteristics of ^{15}N field sites

Location	Year	Ecological zone	Soil					
			Classification	pH	CEC	Sand	Clay	N
			(USDA)[a]		(meq/100 g)	(%)		
Ikenne, Nigeria	1982, 1983	Humid	Alfisol	5.9	4	72	20	0.11
Kabete, Kenya	1983, 1984	Humid[b]	Ultisol	5.9	24		79	
Mokwa, Nigeria	1982, 1983, 1984	Subhumid	Alfisol	5.8	2	77	13	0.06
Zaria, Nigeria	1984	Subhumid	Alfisol	5.8	4.3	70	17	0.08
Sefa, Senegal	1983, 1984	Subhumid	Alfisol	5.4	1	88	8	0.05
Gliji, Togo	1984	Subhumid	Ultisol	5.4	3.5	87	10	0.03
Sadore, Niger	1982, 1983, 1984	Semiarid	Entisol	4.7	1	94	1	0.02

[a] USDA = United States Department of Agriculture.
[b] Altitude = 1,941 m.

Table 5 Details of ^{15}N experiments

Location	Year	Cropping system	Cereal crop planting distance		Legume crop planting distance		Fertilizer source management	Fertilizer rate	^{15}N Microplot dimensions
			Interrow	Intrarow	Interrow	Intrarow			
			(cm)					(kg N/ha)	(m)
Ikenne	1982	Maize/cowpea sequential	75	25	75	25	Urea/S Br	120	4.5 x 2.0
							Urea/S Br I[a]	80	4.5 x 2.0
							Urea/S Bd [a]	80	4.5 x 2.0
							USG/Ba[a]	80	4.5 x 2.0
							USG/S[a]	80	4.5 x 2.0
							CAN/S Br I[a]	80	4.5 x 2.0

Table 5 Details of ^{15}N experiments

Location	Year	Cropping system	Cereal crop planting distance		Legume crop planting distance		Fertilizer source management	Fertilizer rate	^{15}N Microplot dimensions
			Interrow	Intrarow	Interrow	Intrarow			
			(cm)					(kg N/ha)	(m)
Ikenne	1983	Maize/cowpea sequential	75	25	75	25	Urea/S Br	120	4.5 x 2.0
							Urea/S Bd	80	4.5 x 2.0
							USG/S	80	4.5 x 2.0
							CAN/S Bd	80	4.5 x 2.0
Kabete	1983	Maize/bean intercrop	75	30	25	15	Urea/S Bd	50	3.0 x 3.0
Kabete	1984	Maize/bean intercrop	75	30	25	15	Urea/S Bd	100	3.0 x 3.0
							USG/S	100	3.0 x 3.0
							CAN/S Bd	100	3.0 x 3.0
Mokwa	1982	Maize/cowpea relay	75	25	75	25	Urea/S Br	120	4.5 x 2.0
							Urea/S Br I[a]	80	4.5 x 2.0
							Urea/S[a]	80	4.5 x 2.0
							USG/Ba[a]	80	4.5 x 2.0
							USG/S[a]	80	4.5 x 2.0
							CAN/S Br I[a]	80	4.5 x 2.0
Mokwa	1983	Maize/cowpea relay	75	25	75	25	Urea/S Br	120	4.5 x 2.0
							Urea/S Bd	80	4.5 x 2.0
							USG/S	80	4.5 x 2.0
							CAN/S Bd	80	4.5 x 2.0

Table 5 Continued

Location	Year	Cropping system	Cereal crop planting distance		Legume crop planting distance		Fertilizer source management	Fertilizer rate	^{15}N Microplot dimensions
			Interrow	Intrarow	Interrow	Intrarow			
			(cm)					(kg N/ha)	(m)
Mokwa	1984	Maize/cowpea relay	75	25	75	25	Urea/S Bd	80	4.5 x 2.0
							USG/S	80	4.5 x 2.0
							CAN/S Bd	80	4.5 x 2.0
Zaria	1984	Maize/cowpea relay	75	25	75	25	Urea/S Bd	80	4.5 x 2.0
							USG/S Bd	80	4.5 x 2.0
							CAN/S Bd	80	4.5 x 2.0
Sefa	1983	Maize sole	90	25			Urea/S Br I	100	3.6 x 2.0
							Urea/S Bd	100	3.6 x 2.0
Sefa	1984	Maize sole	90	25			Urea/S Br I	100	3.6 x 2.0
							Urea/S Bd	100	3.6 x 2.0
							USG/S	100	3.6 x 2.0
Glidji	1984	Maize sole	75	25			Urea/S Bd	90	3.0 x 3.0
							USG/S	90	3.0 x 3.0
							CAN/S Bd	90	3.0 x 3.0

Table 5 Continued

Location	Year	Cropping system	Cereal crop planting distance		Legume crop planting distance		Fertilizer source management	Fertilizer rate	^{15}N Microplot dimensions
			Interrow	Intrarow	Interrow	Intrarow			
			(cm)					(kg N/ha)	(m)
Sadore	1982	Millet sole	125	125			Urea/Ba/Br/I	30	7.5 x 3.75
		Millet sole	100	100			Urea/Ba/Br/I[a]	30	5.0 x 5.0
							Urea/S/Br/I[a]	30	5.0 x 5.0
							Urea/S/Bd[a]	30	5.0 x 5.0
							USG/Ba[a]	30	5.0 x 5.0
							USG/S[a]	30	5.0 x 5.0
							CAN/Ba/Br/I[a]	30	5.0 x 5.0
Sadore	1983	Millet sole	100	100			Urea/S/Bd	30	4.0 x 4.0
							USG/S	30	4.0 x 4.0
							CAN/S/Bd	30	4.0 x 4.0
Sadore	1984	Millet sole	100	100			Urea/Ba/Br/I	30	6.0 x 3.0
		Millet sole	100	100			Urea/S/Bd	30	4.0 x 4.0
							USG/S	30	4.0 x 4.0
							CAN/S/Bd	30	4.0 x 4.0

[a] Some trials conducted in 1982 received ^{15}N fertilizers of low isotope enrichment and were intended only to measure uptake of fertilizer N.

Note:
S = split applied
Ba = basally applied

Br = broadcast
Bd = banded

I = incorporated

Detailed description of the experimental sites at Ikenne, Mokwa, and Sadore has been presented in Section III. Details of ^{15}N experiments are given in Table 5. The ^{15}N trials at Ikenne, Mokwa, and Sadore were conducted by IFDC staff members. Trials conducted at Kabete, Zaria, Sefa, and Glidji were conducted by scientists from national programs.

B. Fertilizers

The isotope-labeled fertilizer N sources that were tested included urea, USG, and CAN. All fertilizers were manufactured by the Fertilizer Technology Division of IFDC. Timing of N application was either basal, where all the fertilizer was applied as a single dose, or split. Fertilizers were surface broadcast, followed by incorporation, or banded. In the case of urea supergranules, banding implies the deep placement of one granule near each maize hill. Cropping systems and rates of application of ^{15}N fertilizers used reflected the recommendations of national scientists.

C. Plot layout

Studies using different ^{15}N source/management combinations were conducted in microplots placed within plots of the main N management trials. The microplots and main plots received the same fertilizer treatment with and without ^{15}N label, respectively. The area of the microplots was generally 9 m^2 for maize and 16 m^2 for millet, with the exact area and border dimensions determined by the spacing between the rows and between plants within the row. Orientation of plant rows within the microplot was such that a maximum number of rows fell inside the microplot. Microplots were enclosed by physical borders when the need was dictated by site slope or, in the case of the very sandy soils of Niger, by the need to limit wind erosion.

At maturity, the plants in the central portion of each microplot were sampled for analysis of ^{15}N uptake. The number of plants sampled ranged from 4 in the case of millet in Niger to 12 for maize in Togo. Cereal crops were separated into leaf, stem, cob, and grain samples and dried, weighed, and then ground for analysis. Legume crops were harvested as one sample at 50% blooming.

Transect sampling was carried out to determine the amount of ^{15}N dilution of the border rows within and outside the plot as well as the relative homogeneity of the ^{15}N contents of the samples in the middle of the plot. Such simple tests can provide valuable information concerning minimum plot sizes and also whether borders are needed on the ^{15}N plots.

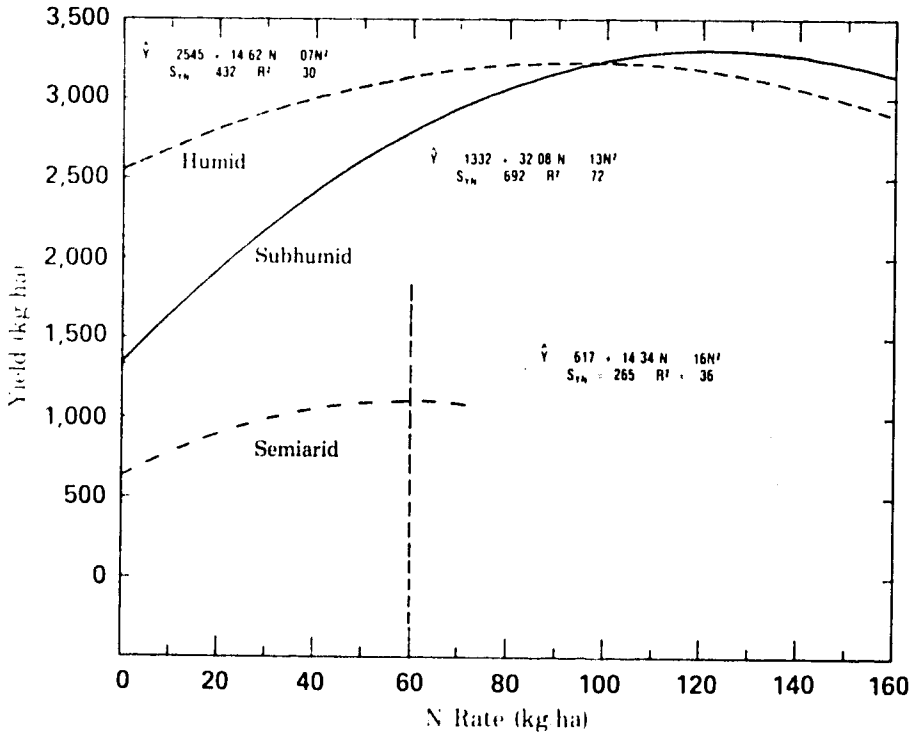


Figure 3. Average response functions for various climatic zones in tropical Africa.

The area of soil sampled for ^{15}N analysis was Ikenne 1.5 x 0.5 m, Kabete 1.5 x 0.6 m, Mokwa 1.5 x 0.5 m, Zaria 1.5 x 0.5 m, Sefa 1.8 x 0.5 m, Glidji 1.5 x 0.5 m, and Sadore 1.0 x 1.0 m. The area of soil to be sampled was isolated by a metal border, and roots were removed as a separate sample; then the topsoil layers were totally removed and subsampled. Subsoil layers were sampled by taking at least four soil cores from the same area.

Results and discussion

Nitrogen response and exports

Response curves for the three agroecological zones, averaged for CAN and urea for all sites within each zone, are represented in Figure 3. Comparison of yield levels between the humid and subhumid tropics, where maize was the dominant test crop, shows that the yield level at the zero N rate was higher in the humid tropics (2,550 vs 1,350 kg/ha). Application of 100 kg/ha of nitrogen compensated for this difference, giving nearly equivalent produc-

tion levels for maize. This indicates that soil nitrogen fertility is the major constraint in the subhumid tropics rather than rainfall. In fact, seasonal rainfall in the humid and subhumid tropics of Africa is not necessarily greatly different. Although overall yield levels for millet in the semiarid tropics are much lower than those for maize in the more humid zones, soil moisture is not the only limitation to crop production in this zone. Within the limits set by the climate, application of N can double the yield in this environment.

The R^2 values for the generalized response curves for the humid and semiarid tropics are substantially lower (0.3-0.4) than that for the subhumid zone (0.7). This reflects the greater variability in response among sites and from year to year in these zones. Site variability is more important in the humid tropics, whereas temporal variability dominates in the semiarid tropics. The sites in the semiarid zone are plagued not only by large year-to-year changes in total rainfall (598 mm in 1983, 260 mm in 1984 at Sadore, Niger) but also by very uneven distribution of the rainfall through the growning season.

In the range of application rates where fertilizer applications may be economical (linear response), a farmer could expect to gain around 15 kg of grain per kg of applied N in the semiarid and humid tropics, whereas returns per kg of N are twice as high in the subhumid zone. With domestic prices of 1 kg of maize or millet being roughly equivalent to the government-subsidized price of 1 kg of N in many tropical African countries, the application of N appears highly profitable in the subhumid and fairly profitable in the humid tropics and semiarid tropics. In the humid and semiarid tropics, the risk of N application without profitable returns is higher, as reflected by the low R^2 for the generalized response curves. However, it should be recognized that these returns on nitrogen application are realized only with the application of phosphorus and, in some cases, potassium and sulfur. Removal of fertilizer subsidy will drastically increase domestic fertilizer prices (four to fivefold), and this would render fertilization with N a questionable practice in these two zones.

In experiments at Ikenne (humid), Mokwa (subhumid), and Sadore (semiarid), typical grain N contents were 1.8%, 1.4%, and 2.3%, respectively. Assuming these values to be unaffected by N rate, unfertilized plots would export an average of 38 kg N/ha per season in the humid tropics, if farmers attain the yield level predicted by Figure 3 and if all the straw is returned to the field. The export level in the subhumid tropics would be 18 kg N/ha and in the semiarid region 12 kg N/ha. Fertilization at recommended levels (80 kg N for maize, 30 kg N for millet) results in net imports of 20-40 kg N/ha in the humid and subhumid zones, and 12 kg N/ha for the semiarid zone. These gains may be partly offset by losses of applied N. When straw is taken off the field as well, the nitrogen budget looks less favorable, particularly in

the humid zone (Table 6). Thus, unless the farming system ensures N inputs from biological nitrogen fixation or farmyard manure, the system without fertilization will rapidly exhaust the mineral nitrogen in the soil. Although, in absolute terms, the rate of depletion is highest in the humid zone, the lower levels of organic matter in the dryer zones (Table 2) provide less capacity to replenish the lost mineral N.

Nitrogen sources

Urea and CAN are among the most common fertilizers offered by fertilizer-exporting countries to African nations. Moreover, several countries across Africa may be faced with the decision of which fertilizer to produce. In order to help answer this question, urea and CAN were tested at nearly every site in this program, generally as a part of a more elaborate N-fertilizer testing experiment (Table 3). A simple orthogonal comparison of the means of the response curves revealed that there was no significant difference between the sources in the humid tropics and semiarid tropics. Urea performed better than CAN at only two of the nine locations in the subhumid tropics (northern Togo and Gambia). The results of the combined analysis of variance for testing sources, time, and mode of N application for each zone are included in Table 7.

A more detailed analysis of the response curves for CAN and urea in the three ecological zones is provided in Figure 4, where the relative yield increase (kg grain/kg N applied) is plotted against the N rate. The two sources (CAN and urea) behaved almost identically over the entire range of rates in the humid and subhumid tropics. In the semiarid tropics (SAT), the initial response to CAN tended to be better than to urea ($\alpha = 0.1$), while maximum yields were attained at 50 kg N/ha with CAN as opposed to 75 kg N/ha with urea ($\alpha = 0.05$]. However, the orthogonal comparison of the means showed

Table 6. Net nitrogen export (–) or input (+) in fertilized and nonfertilized fields in various parts of Africa

	No fertilizer		Fertilized[a]	
	Grain	Grain + Straw	Grain	Grain + Straw
Humid	38	60	+20	+15
Subhumid	18	27	+38	+17
Semiarid	14	27	+7	–7

[a] Fertilizer rates are 80 kg N/ha for humid and subhumid area (maize) and 30 kg N/ha for semiarid region (millet).

Table 7 Analysis of variance and mean square values of source of variation for maize and millet yield in three agroecological areas of Africa

Source of variation	Degrees of freedom			Agroecological area		
	Humid	Subhumid	Semiarid	Humid maize	Subhumid maize	Semiarid millet
Replicates (sites)	17	20	40	10,007,323.67[b]	2,388,615.45[b]	472,766.47[b]
Sources	6	6	10	780,688.14[b]	619,856.13[b]	1,597,225.20[b]
Timing	3	3	4	14,328,034.48[b]	30,274,877.76[b]	176,185.59[a]
Mode	1	1	1	357,847.28	2,018,452.28[a]	147,544.62[a]
Timing [a]mode	–	–	1	–	–	29,167.19
Rates	4	4	4	3,320,636.23[b]	6,544,979.24[b]	83,961.72
Timing [a]mode	–	–	7	–	–	54,094.52
Mode [a]rate	12	12	3	302,849.03	625,562.12	256,416.40[b]
Years	2	2	2	9,209,842.84[b]	70,272,546.45[b]	13,303,040.97[b]
Years [a]mode	6	6	6	2,370,778.20[b]	3,701,577.80[b]	690,016.52[b]
Years [a]rate	–	–	5	–		166,189.92[b]
Error	395	518	1,101	561,779.56	466,141.49	49,901.70
CV				32.46	40.40	30.74
X				2,308.84	1,689.70	726.57

[a] Significant at the 0.05 probability level.
[b] Significant at the 0.01 probability level.

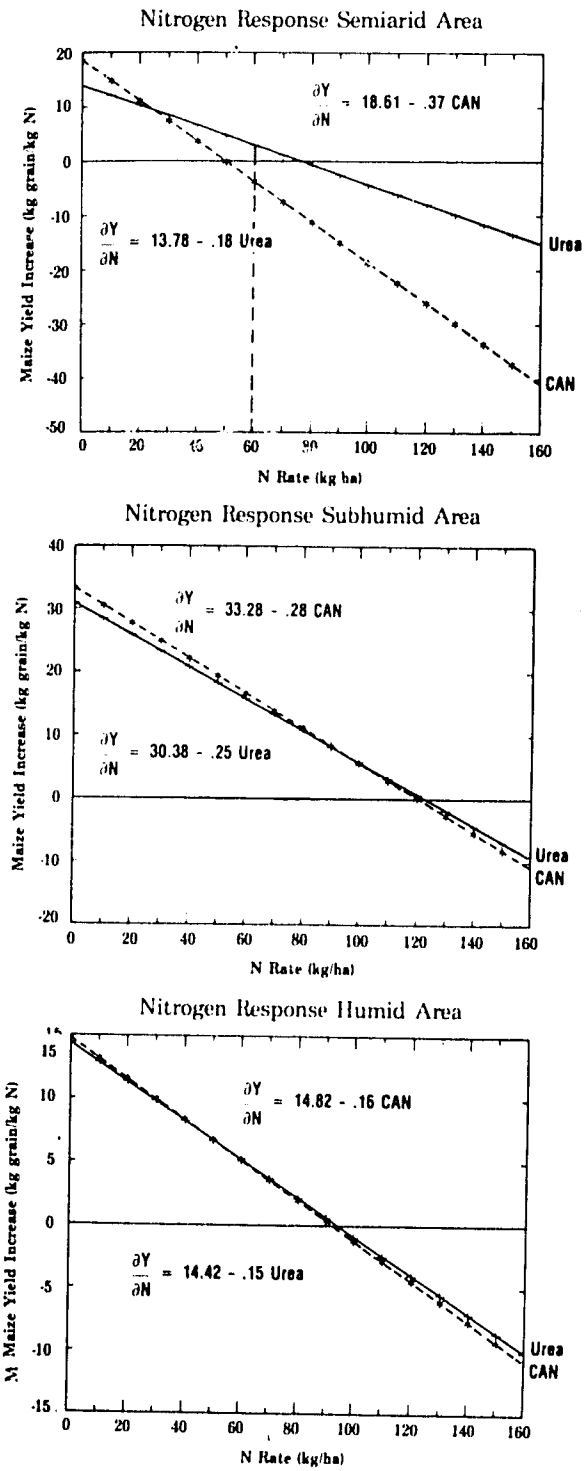


Figure 4. Average rate functions for CAN and urea in various climatic zones.

no significant difference between the two sources, probably because of the high variability observed in experimental fields in the SAT. The difference between the two sources in the SAT as shown in Figure 4 is large enough to warrant further study. Data from volatilization trials conducted at IFDC Headquarters in sandy soils suggest that the lower response to urea could possibly be explained by the fact that losses from urea in this zone tended to be higher than those from CAN. Such losses would require a compensatingly higher input of urea than CAN to obtain equivalent yields. The greater response to CAN may be due to a better calcium nutrition of the crop. However, since the plots received $CaSO_4$ from the single superphosphate basal treatment applied to all plots, this explanation is less likely.

Mode of application

Three different methods of urea application were evaluated for all climatic zones: (1) broadcasting, (2) banding, and (3) deep-point placement (urea supergranules). Figure 5 shows the response curves of maize and millet using these application techniques. Estimates for the response functions are presented in Table 8. Orthogonal comparison of the means of the response curves showed no difference among application methods for any zone. However, when comparing the entire response curve, broadcasting in the humid

Table 8. Regression coefficients for model comparisons of N mode of application for different agroecological zones

Variate	Equation $\hat{Y} = b_0 + \Sigma\, biXi$	Agroecological zone		
		Humid maize	Subhumid maize	Semiarid millet
Intercept	b_0	1,638.03	543.44	624.33
Urea broadcast	X_1	21.19[b]	36.70[b]	15.70[b]
Urea banded	X_2	12.07[b]	26.50[b]	14.03[b]
Point placed	X_3[a]	13.16[b]	25.17[b]	10.53[b]
	X_1[a]X_1	-.11[b]	-.17[b]	-.20[b]
	X_2[a]X_2	-.03	.11[b]	-.15[b]
	X_3[a]X_3	-.05	.11[b]	-.13[b]
R^2 (adjusted)		.28	.52	.36
S_{yx}		1,000.31	953.50	264.06
N		446	461	1,175

[a] Significant at the 0.05 level.
[b] Significant at the 0.01 level.
Hypothesis H_0: bi = 0.
H_1: bi ≠ 0.

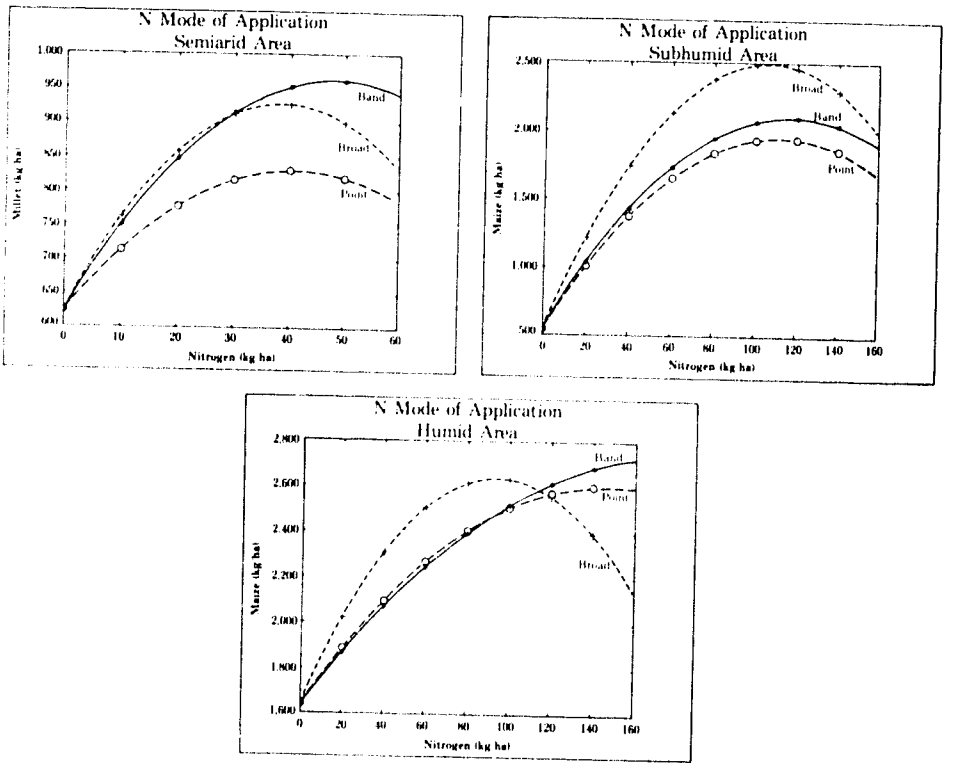


Figure 5. Effect of mode of N application on grain yield (Ikenne [Humid zone], Mokwa [Subhumid zone], and Sadore [Semiarid zone]).

and subhumid tropics performed significantly (α = .05) better than either band or point placement. The difference between band or point placement was insignificant in these climatic zones (α = .05). In the semiarid tropics, point placement significantly decreased the performance of urea, whereas broadcast and band applications behaved similarly, except at high application rates.

The observations appear to indicate a better availability of N in the more humid climates when urea is evenly distributed across the soil. Concentrated placement of urea in points or bands may lead to increased leaching of fertilizer N because of limited access to the sorption sites of the soil. The light texture of most of the soils studied here may have accentuated this problem. This phenomenon was also encountered in light-textured soils planted in rice [43,34]. On the sites with heavier textured soils (e.g., Kenya), point placement appears to have an advantage over banding, suggesting that leaching of applied N may be less of a problem on such soils. Generally, rainfall in the humid and subhumid environments appears to have been frequent enough to avoid extended exposure of urea on the soil surface with its concomitant loss of N through ammonia volatilization.

In the semiarid tropics, the poor performance of point-placed urea is presumed to be due to loss of applied N. Whether these losses are due to leaching or ammonia volatilization cannot be determined on the basis of yield data alone. Results from ^{15}N experiments conducted at Sadore (Niger) and rainfall data for this site suggest that ammonia volatilization was the major loss mechanism. This assumption is further reinforced by the data produced in Headquarters volatilization trials using urea supergranules in Niger soil. In those studies very large losses were observed via ammonia volatilization.

Because it was presumed that splitting of fertilizer N would both improve its agronomic efficiency and reduce risk for the farmer, most of the experiments summarized above involved split application. Only in 1982 were basal applications of point-placed urea included in the experiments at the key research sites of the various agroclimatic zones. The results summarized in Figure 6 confirm the advantage of split applications. In all zones, basally applied urea performed significantly more poorly than split applications, with an approximate relative yield reduction at the maximum yield level of 9%, 34%, and 15% for the humid, subhumid, and semiarid zones, respectively.

The experiments conducted with maize in the subhumid tropics of Nigeria were intercropped with cowpeas and those in Kenya with beans (Table 3). In general there was no response to N by the intercropped legume, even when the maize response indicated a low soil N status (Figure 7). In early experiments in Nigeria, shading from the fertilized maize reduced the relay-cropped cowpea yield. In subsequent years this problem was overcome by use of recently developed short-duration cowpea varieties released by the International Institute of Tropical Agriculture (IITA), to minimize the intercrop period.

The fate of applied N (^{15}N trials)

A. Plot design

The results of two transect studies are presented in Figure 8, representing different agroclimatic environments in West Africa – humid tropics (Ikenne) and subhumid tropics (Mokwa). The two sites, located in Nigeria, were planted with maize at a 75-cm spacing between the rows (interrow) and a 25-cm spacing between the plants within the row (intrarow). Microplot size was 4.5 m x 2 m in Ikenne and Mokwa. The data suggest that only the border row experienced isotopic dilution. Data on the excess ^{15}N within the row suggest that for maize the border effect was limited to the outer two plants under the

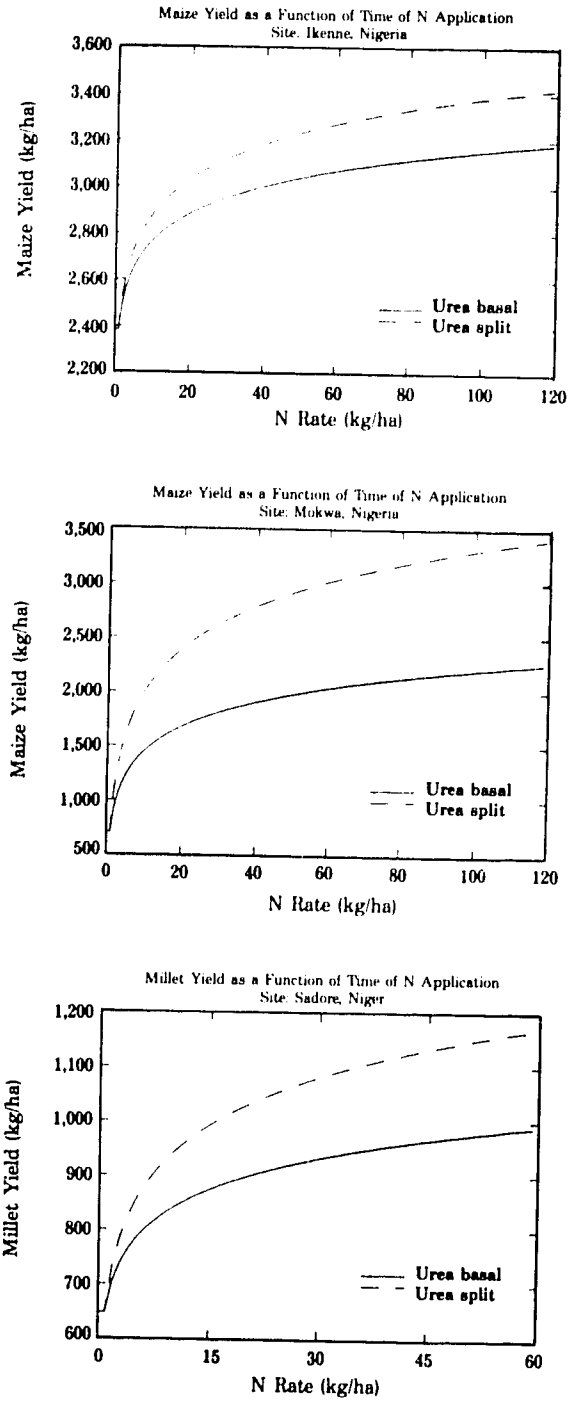


Figure 6. Effect of basal versus split appllication of N on grain yield (Ikenne [Humid zone], Mokwa [Subhumid zone], and Sadore [Semiarid zone], 1982).

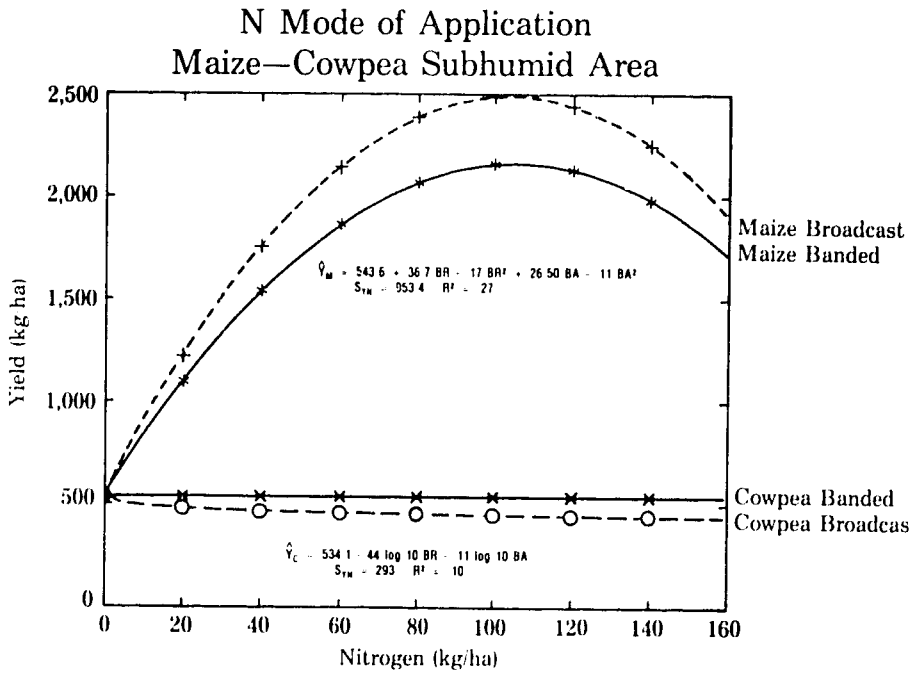


Figure 7. Effect of N mode of application on yield of maize and cowpea in the Subhumid zone.

conditions of the experiments. Once the area affected by the nonlabeled plot has been established, the minimum microplot size can be based on the minimum number of plants required to obtain a representative sample.

B. Humid zone

Trials were conducted in the humid zone of Nigeria at Ikenne in 1982 and 1983. Since only a low enrichment of ^{15}N was used at this site in most of the treatments in 1982, only plant uptake was determined. In 1983 fewer fertilizers were tested, but the ^{15}N content of those used was increased to 5% to allow soil analysis and permit a balance to be performed. A balance trial was also conducted at Kabete, Kenya.

The uptake trial in 1982 consisted of five treatments involving prilled urea and point-placed urea supergranules compared with CAN. Neither grain yield data nor plant ^{15}N uptake data showed a large difference among the various fertilizer treatments although plant N uptake from CAN tended to be higher than that of the other treatments (Figure 9). Total plant ^{15}N uptake was from 54% for CAN to 39% for the urea treatment while grain uptake ranged from 36% to 22%. The reason for the superior performance of CAN

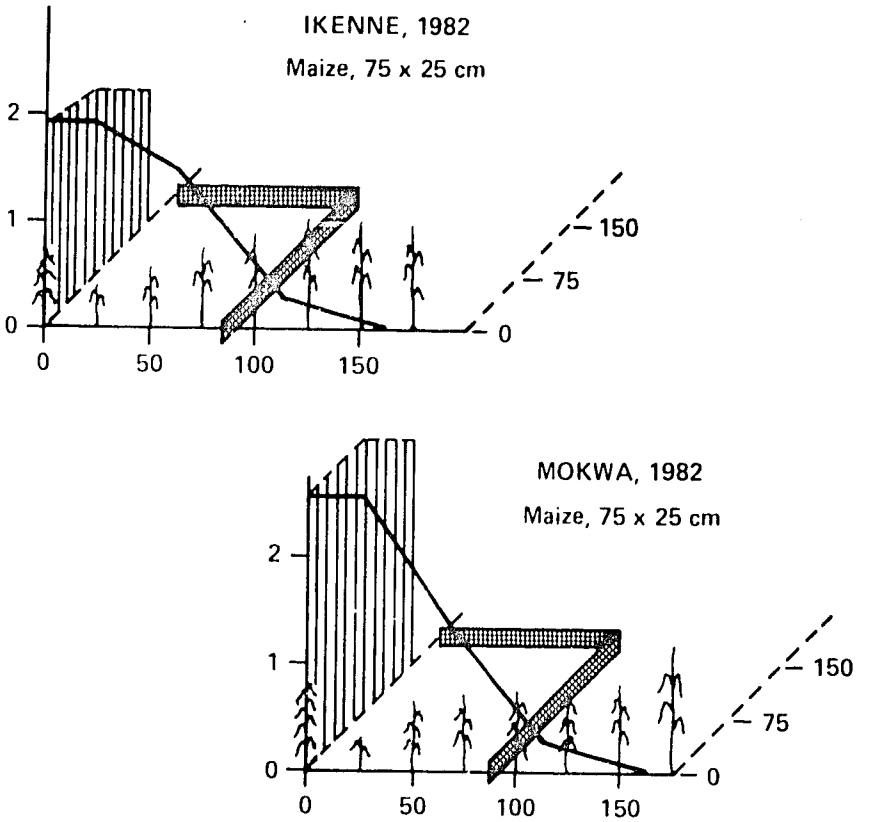


Figure 8. ^{15}N enrichment in maize plants across a microplot.

may be that one-half of the N applied was in the form of nitrate which is very mobile and could easily move to the maize root zone where rapid uptake was possible. No difference was found in either plant or grain ^{15}N uptake due to the method of urea application to maize. Although broadcast application of urea is generally not believed to be the optimum method of urea application, the broadcast and incorporated treatment performed as well as the point-placed and banded treatments in all respects. Grain N uptake was decreased slightly when the urea was applied as a single basal application as opposed to a split-application method.

A single ^{15}N balance was performed in 1982 at Ikenne, and three were performed at that site in 1983. Since the rates and mode of N application differed among these trials over these 2 years, the data are not directly comparable. In 1982, 64% of the added broadcast N was found in the maize crop and 2% in the cowpeas which followed (Figure 10). Only 26% of the nitrogen remained in the soil. Although most of the soil N derived from the fertilizer remained in the 0-15 cm layer, little nitrogen remained in the active root

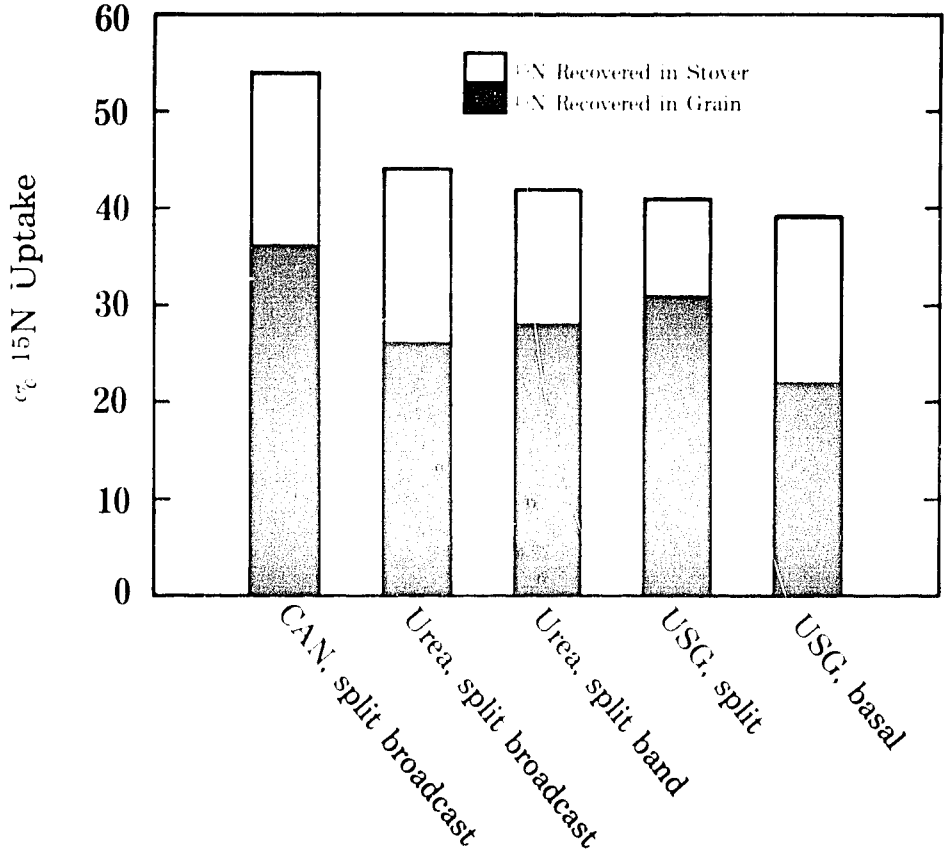


Figure 9. Plant ^{15}N uptake, Ikenne, 1982.

zone of 15-45 cm, most having been taken up by the plant (Figure 11). At the 45-75 cm depth 5.6% of the applieds ^{15}N was recovered. The presence of ^{15}N-N at this depth indicates that leaching may have been a mechanism of fertilizer loss in this zone.

In 1983 plant recoveries of urea were very similar to those found in 1982 (Figure 10). Calcium ammonium nitrate appeared to do somewhat more poorly in 1983 than in 1982. In 1983 the differences between CAN and urea were not significant. No significant grain yield differences were found between sources. Similar amounts of fertilizer N were found in the soil under all three treatments (Figure 11). As in 1982, large amounts of nitrogen were found in the deeper soil layers, a tendency which was especially strong with the CAN treatment. This reinforces the conclusion drawn from the 1982 data that leaching may be a loss mechanism of nitrogen in humid zones. Rapid leaching of fertilizer N out of the most active areas of the root zone could have been one cause for the relatively low grain and plant uptake of CAN by

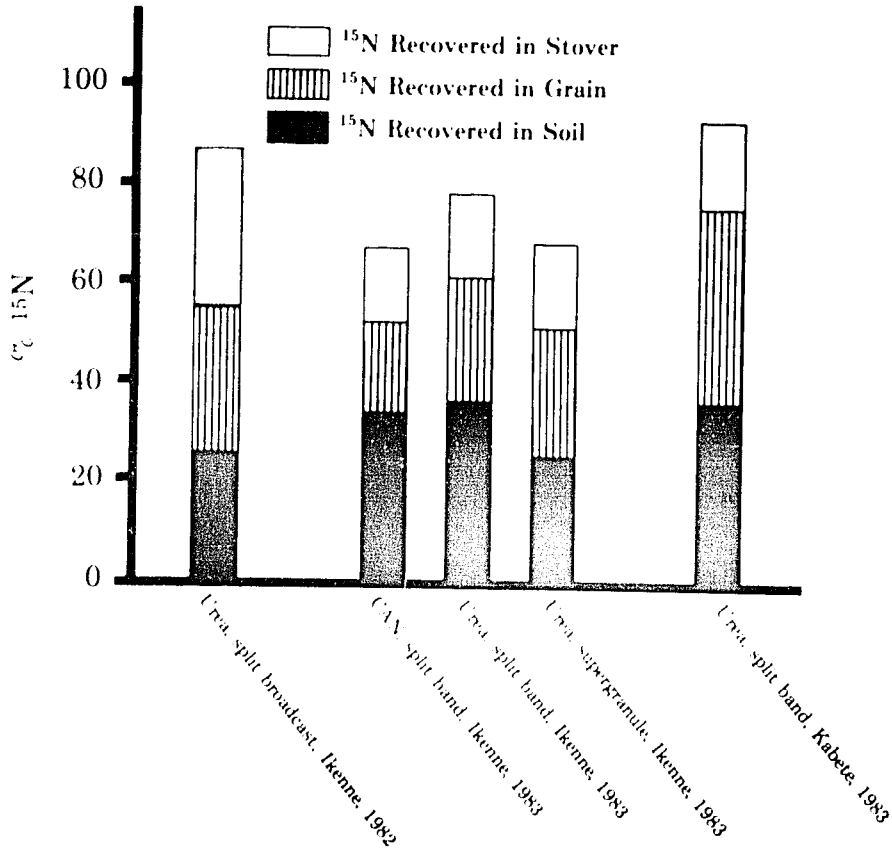
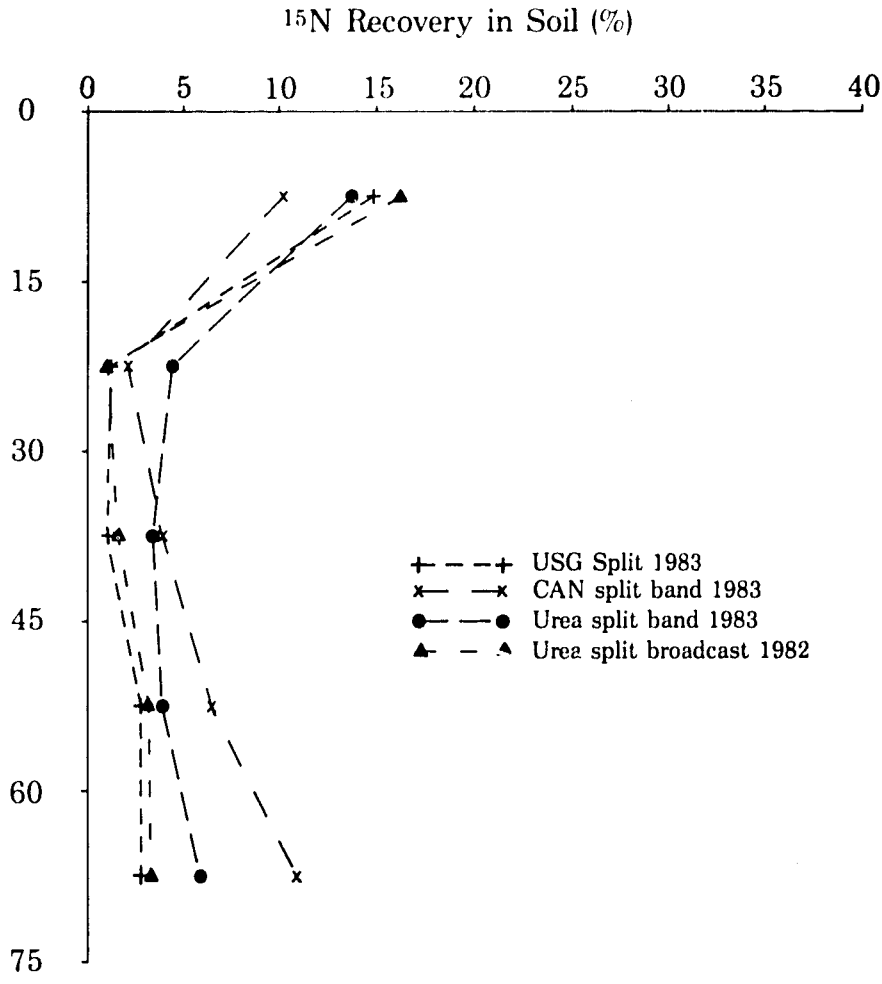


Figure 10. ^{15}N balances at Ikenne 1982, 1983 and Kabete 1983.

maize. Conversely, in the case of the urea point-placement treatment, a large percentage of the soil N remained in the 0-15 cm layer where it could have been more susceptible to N loss via volatilization.

A single ^{15}N balance was conducted at Kabete, Kenya, in 1983 using split-banded urea. As in Ikenne, plant uptake was high (59%) and losses were slight (5%) (Figure 10). Because of the high clay content of the soil, little leaching occurred and most (36%) of the nitrogen remaining was found in the surface 30cm.

Summarizing the humid zone data over 2 years, no significant differences were found among different products or management factors in term of N loss, uptake by the grain, or amounts of N remaining in the soil. Broadcasting fertilizer tended to increase total plant uptake but had no effect on grain N content. Crop uptake was usually high, and losses ranged from 5% to 33%. Uptake by cowpeas never amounted to more than 3.5% of the applied N. Leaching appears to have been one mechanism of N loss, especially for CAN.



Note: Datum points represent the percentage of applied N recovered in each respective layer.

Figure 11. Soil ^{15}N distribution, Ikenne, 1982/83.

C. Subhumid areas

Trials were conducted at five sites within the subhumid zone between 1982 and 1984. Data will be presented from trials at Mokwa and Zaria in Nigeria, Sefa in Senegal, and Glidji in Togo.

In 1982 Mokwa was the site of a plant ^{15}N uptake trial involving urea and CAN under differing management practices and a single balance study using split broadcast urea. Yields in the trial were unaffected by nitrogen source or

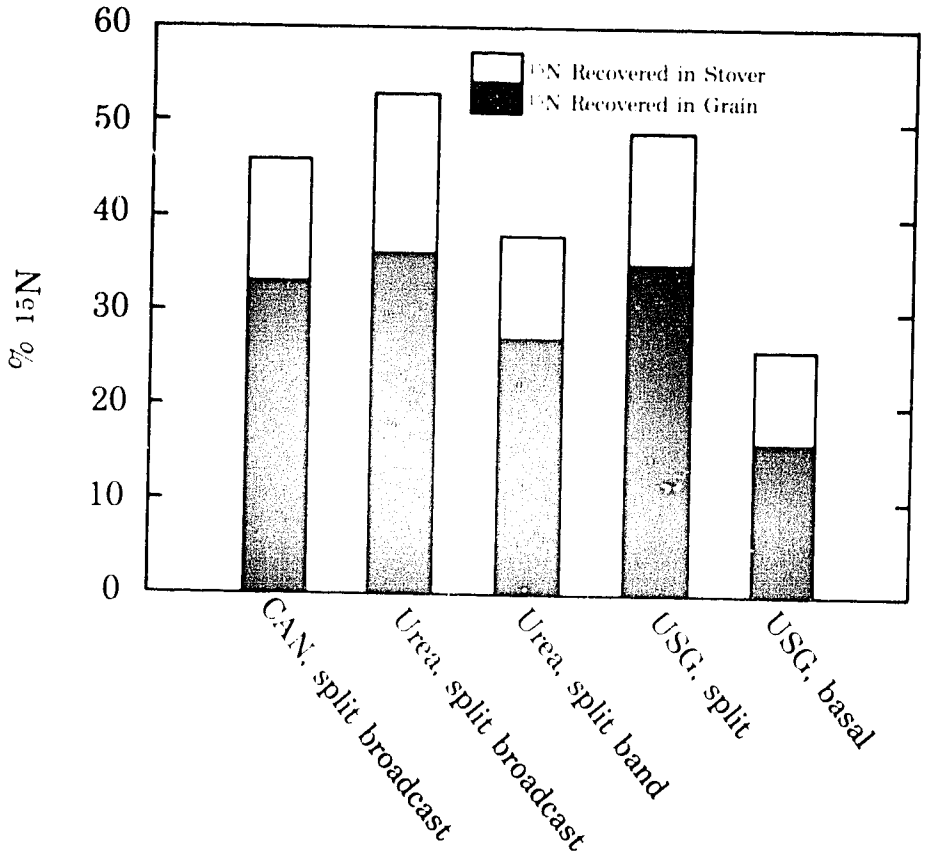


Figure 12. Plant ^{15}N uptake, Mokwa, 1982.

by method or time of application except in the case of the basally applied point-placed urea supergranules which gave poor yields. Plant uptake of ^{15}N corresponded well with plant yield as ^{15}N uptake of basally applied supergranules was much lower than that of any of the other treatments (Figure 12). Total plant recoveries ranged from 56% in the case of split broadcast urea and splitbanded USG to 27% for basally applied point-placed supergranules.

The balance trial showed complete recovery of ^{15}N-N in the plant and soil, and no losses were recorded (Figure 13). The amount of N in the plant tissue during the balance trial was the same as that in the case of the N uptake trial. Most of the soil nitrogen was found in the top 30 cm, and little had penetrated to depth although some enrichment was found at depths of 1 m.

In 1983 the nitrogen trial was decimated by *Striga* and very little yield was obtained. Plant uptake in all three treatments was not significantly different and ranged from 13% to 16% of the N applied. The amounts remaining in the soil ranged from 49% to 35%, the most being found in the CAN treatment

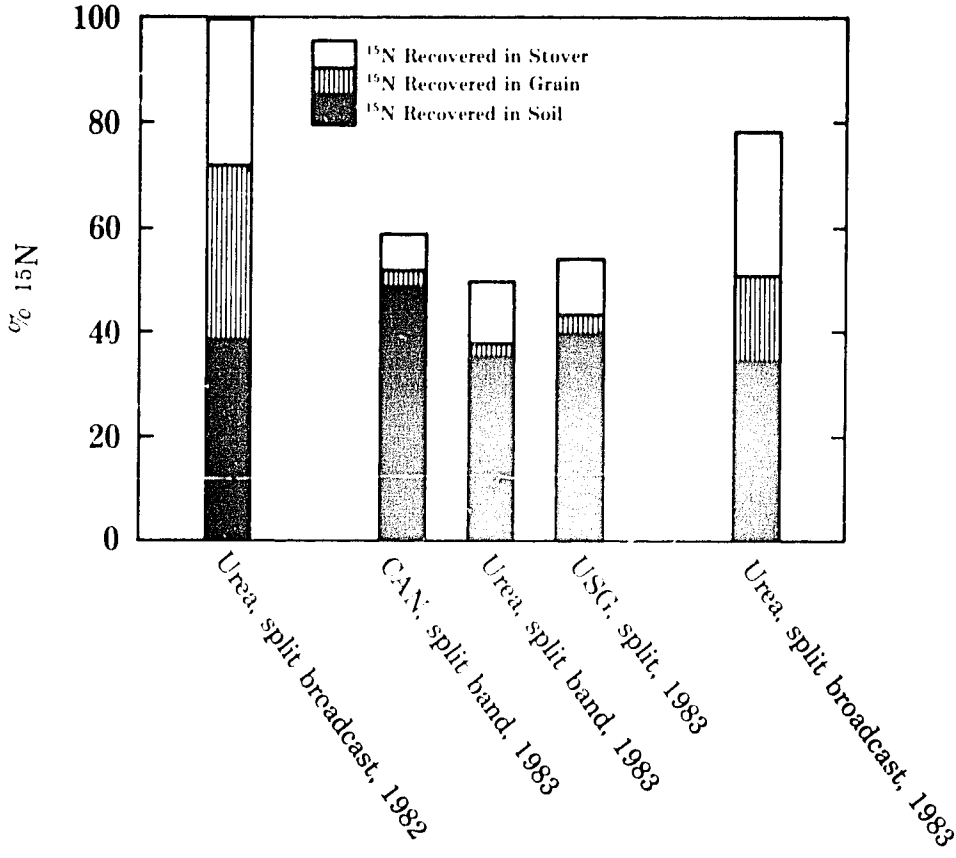
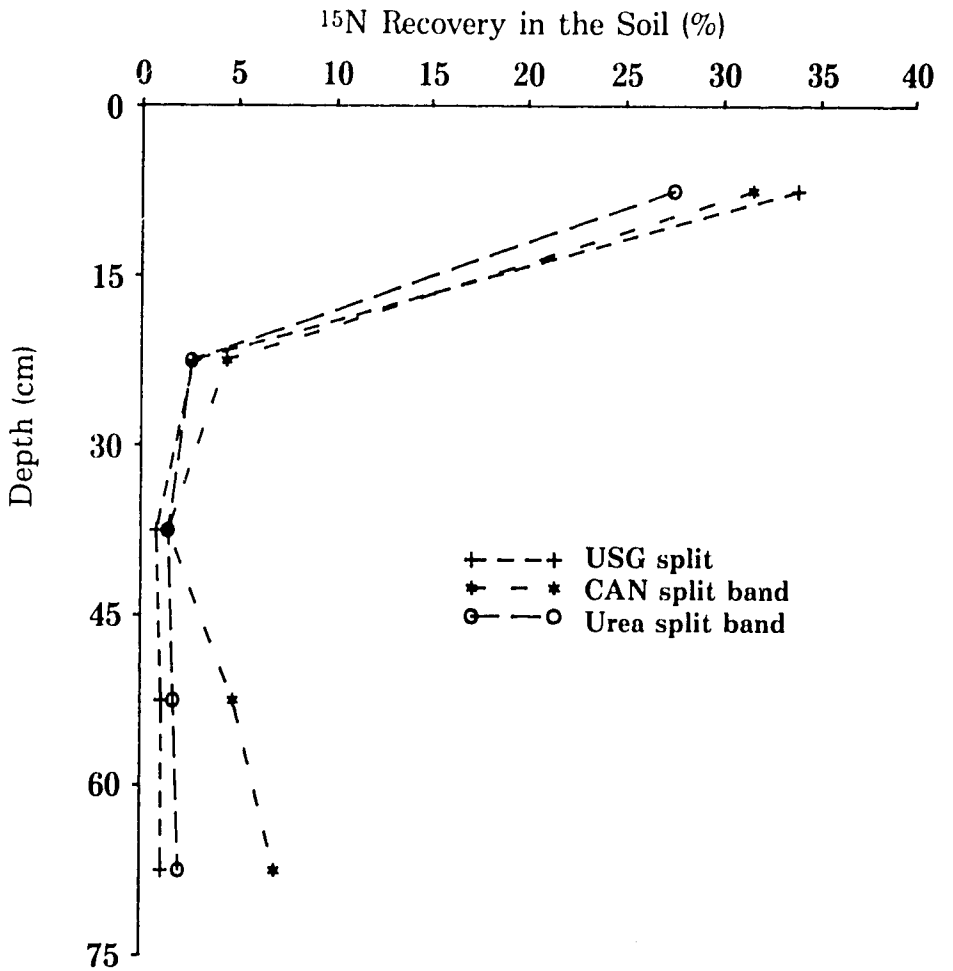


Figure 13. ^{15}N balances, Mokwa, 1982, 1983.

(Figure 13). In both urea treatments most of the nitrogen remained in the surface layers, whereas CAN penetrated to greater depths because of the high mobility of its nitrate component (Figure 14). Losses were most likely due to volatilization in the case of urea and possibly leaching in the case of CAN. Losses ranged from 36% to 52% with CAN being significantly more stable than the urea banded treatment. Another balance trial which was not affected by *Striga* was conducted at the same station in 1983. In this trial, plant uptake, because of the presence of a healthy crop, was much higher and equaled 44% of the N applied. Losses were reduced to only 22% instead of the higher values found in the *Striga*-afflicted plots (Figure 13). Thus, in the presence of an actively growing crop one could speculate that the high losses reported for the *Striga* plots would have been reduced greatly.

Similar trials were conducted at Zaria in 1984, and the uptake trends were the same as those found in the Mokwa studies. CAN tended to be taken up more readily by the plant than urea banded or point-placed (supergranules),



Note: Datum points represent the percent applied N recovered in each respective layer.

Figure 14. Soil ^{15}N distribution, Mokwa, 1983.

although the differences were not significant. Similar trends were found in grain yields, where CAN treatments outyielded point-placed urea. Plant uptake ranged from 63% to 49%, and amounts remaining in the soil were 32% to 33% with most of the N being in the surface 15 cm. Losses tended to be low and reached a maximum of only 18% in the case of the point-placed supergranule treatment (Figure 15).

High recoveries and low losses were also found at Sefa, Senegal (Figure 15). However, recovery of N in the plant and grain at Glidji, Togo, was quite low in comparison to that found at the other sites. The recovery of fertilizer N in the soil with the CAN treatment at Glidji was very high (56%); most of the

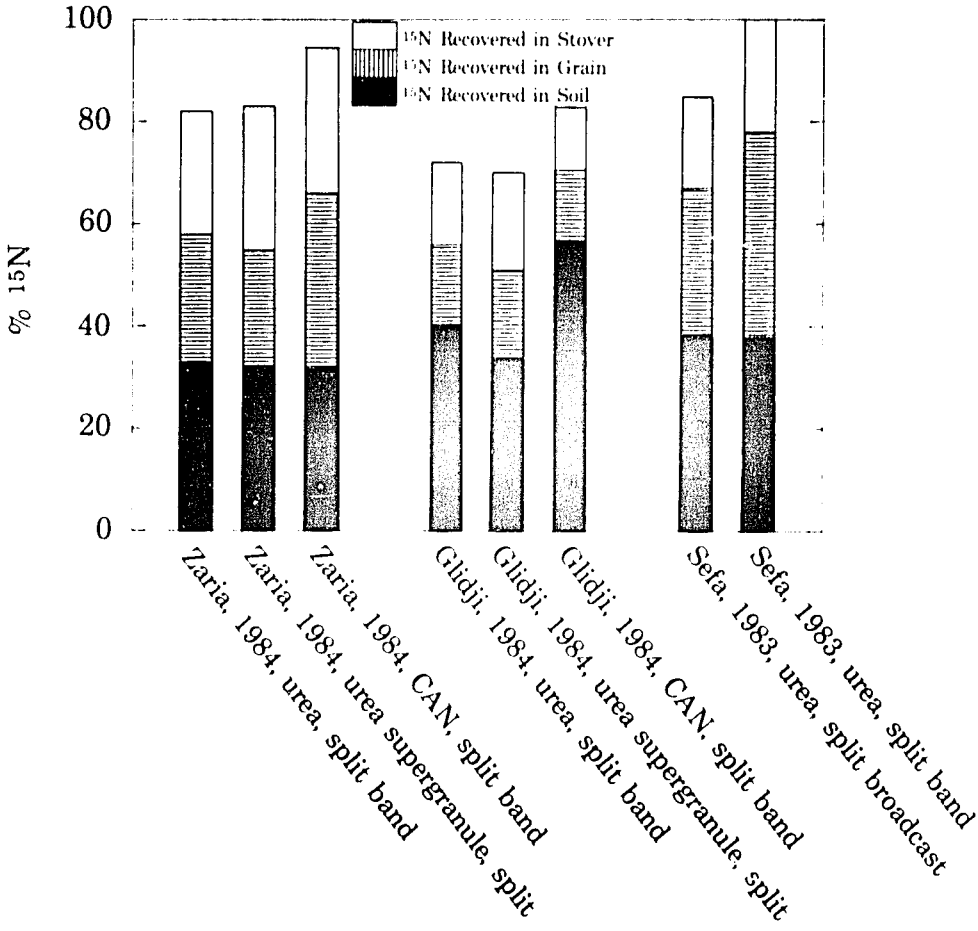


Figure 15. ^{15}N balances in Zaria, Glidji, and Sefa.

nitrogen was found in the 30-60 cm (11%) and 60-90 cm (16%) layers. This indicates that leaching of nitrogen into the profile had occurred and thereby guarded the fertilizer N from N loss mechanisms such as volatilization. In contrast, a major portion of the urea N remained in the topsoil. Since losses from urea did occur, it is probable that the mechanism involved was ammonia volatilization. Although N losses were negligible with CAN, the high amounts of fertilizer N in the soil were not easily available to the plant. Grain yield and plant N uptake were unaffected by source of N. This trial crop suffered severe grain loss from bird damage which may help account for some of the low N recoveries.

It is interesting to note that Sefa, Senegal (1984) was the only site at which urea supergranules outperformed broadcast urea (Figure 16). Higher uptake in both the plant and in the grain itself translated into significantly higher

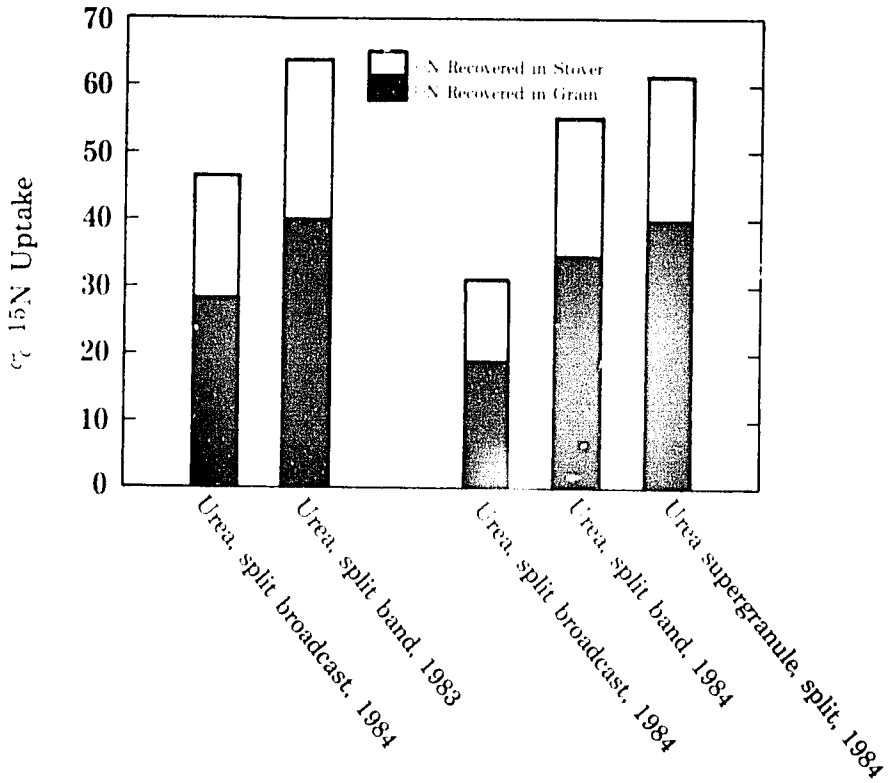


Figure 16. Plant ^{15}N recovery at Sefa, Senegal, 1983/84.

grain yields at this site. It thus appears that point placement could still hold potential in some situations, and this possibility highlights the need for continued experimentation with the supergranule concept. The deeply placed nitrogen, either banded or point placed, was apparently less succeptible to volatilization than the broadcast treatment. The balance trial in 1983 (Figure 15) indicates a lower loss of N at Sefa if banded at depth than if broadcast on the surface.

Summarizing the subhumid zone trials, it may be concluded that, in the presence of an actively growing, healthy crop, losses of fertilizer N, be it in the form of urea or CAN, can be expected to be low. Management practices had no significant effect on fertilizer efficiency as measured by plant uptake, except for basally applied point-placed supergranules which resulted in significantly lower N uptake and yields. This was reflected in significantly higher yields for CAN and urea banded or broadcast than for point-placed supergranules. In all the trials at all sites except Sefa (1984), broadcasting fertilizer improved grain uptake of N over point placement but was comparable to band placement. Generally, fertilizer nitrogen tended to stay in the

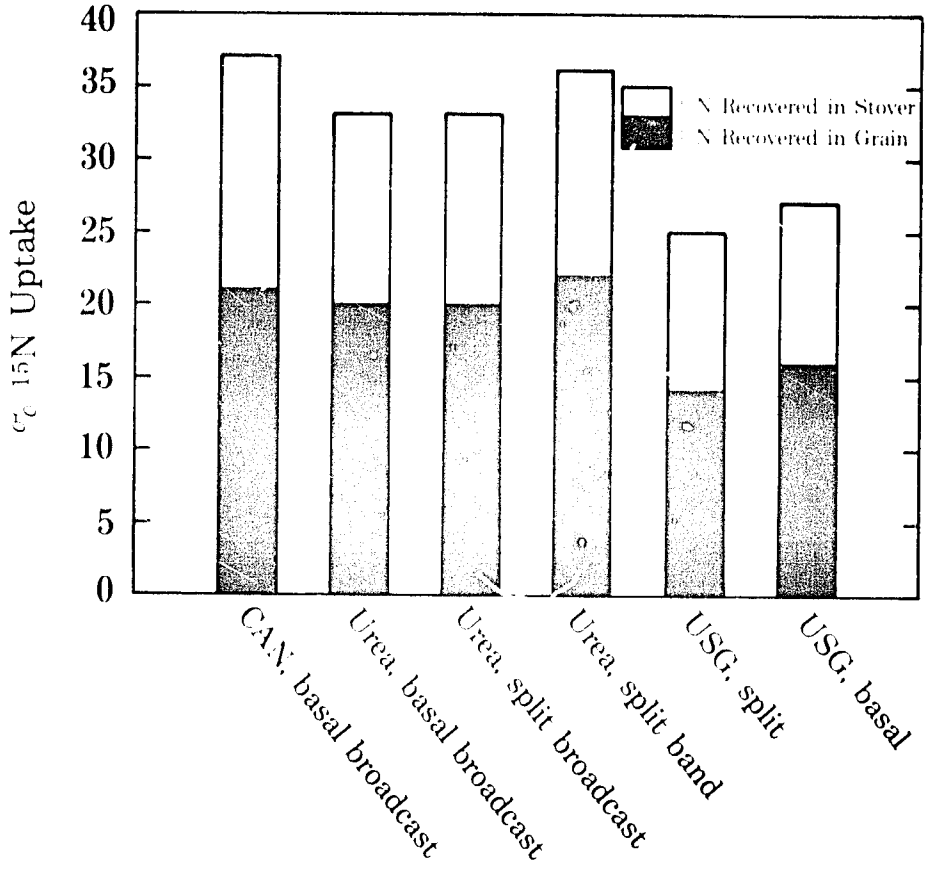


Figure 17. Plant ^{15}N uptake, Niger, 1982.

surface layers, although some leaching of N was found in the CAN treatment. The amounts of CAN remaining in the soil were significantly higher than total soil recovery of urea under any management practice.

D. Semiarid trials

The trials conducted in Niger differed from those conducted in the humid and subhumid regions in several respects. Although the crop in the other sites was maize intercropped or followed by cowpeas at a plant density in excess of 40,000-50,000 plants/ha, the Niger trials were sparsely cropped to millet at a density of 10,000 plants/ha (i.e., 1 m x 1 m spacing). The soils in Niger were extremely light, being 94% sand and therefore having a very low CEC. The other sites, though also sandy, contained more silt and clay (Table 2). Finally, the climate in Niger was much drier than that in any other ^{15}N trial

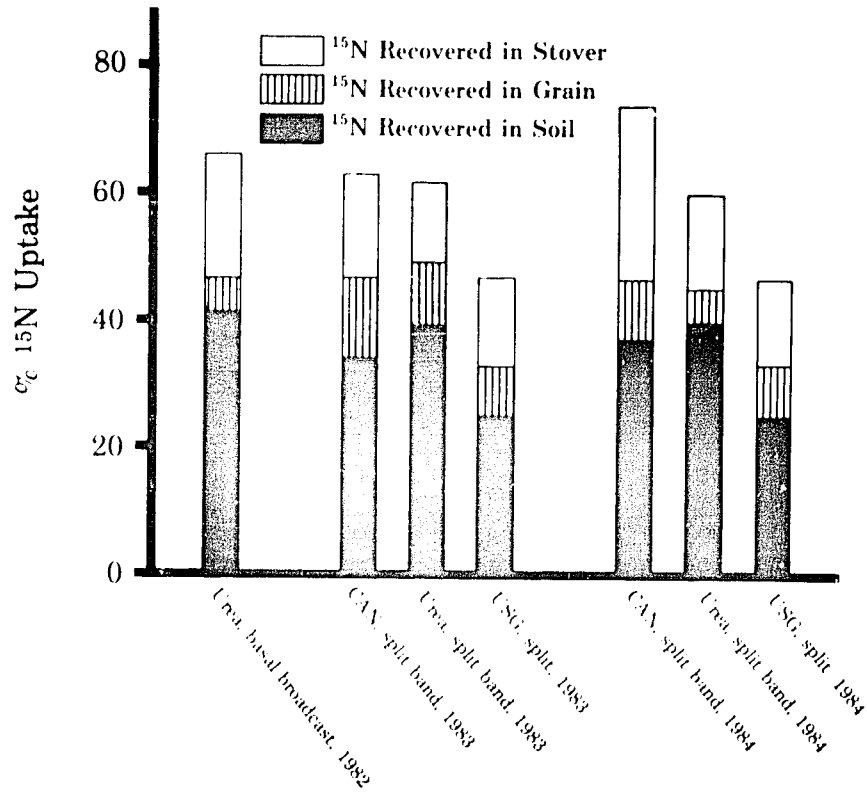


Figure 18. ^{15}N balances in Niger, 1982, 1983, and 1984.

location in Africa. These factors combined to cause different patterns of both plant uptake of fertilizer N and N loss.

In a plant uptake trial conducted in Niger in 1982 little significant difference was found among the treatments, although CAN and urea tended to outperform the supergranule treatments. Fertilizer N uptake by the plant ranged from 37% to 26% and was lower than in the more humid areas. The grain uptake ranged from 21% to 14%, again lower than in the more humid sites. No differences were found between basal and split broadcasting although split banding tended to increase yield and plant N uptake (Figure 17). A balance study using basally broadcast urea showed uptake patterns similar to those found with the other sources (Figure 18). Forty percent of the applied fertilizer remained in the soil, most of it in the surface (15 cm), although movement to depth was noted. It is evident that large losses occurred; 34% of the N applied could not be accounted for in the soil at depths of up to 2 m or in the various plant parts.

Balance trials conducted in 1983 with banded CAN, urea, and point-placed urea supergranules showed the same trends found in 1982. Uptake in

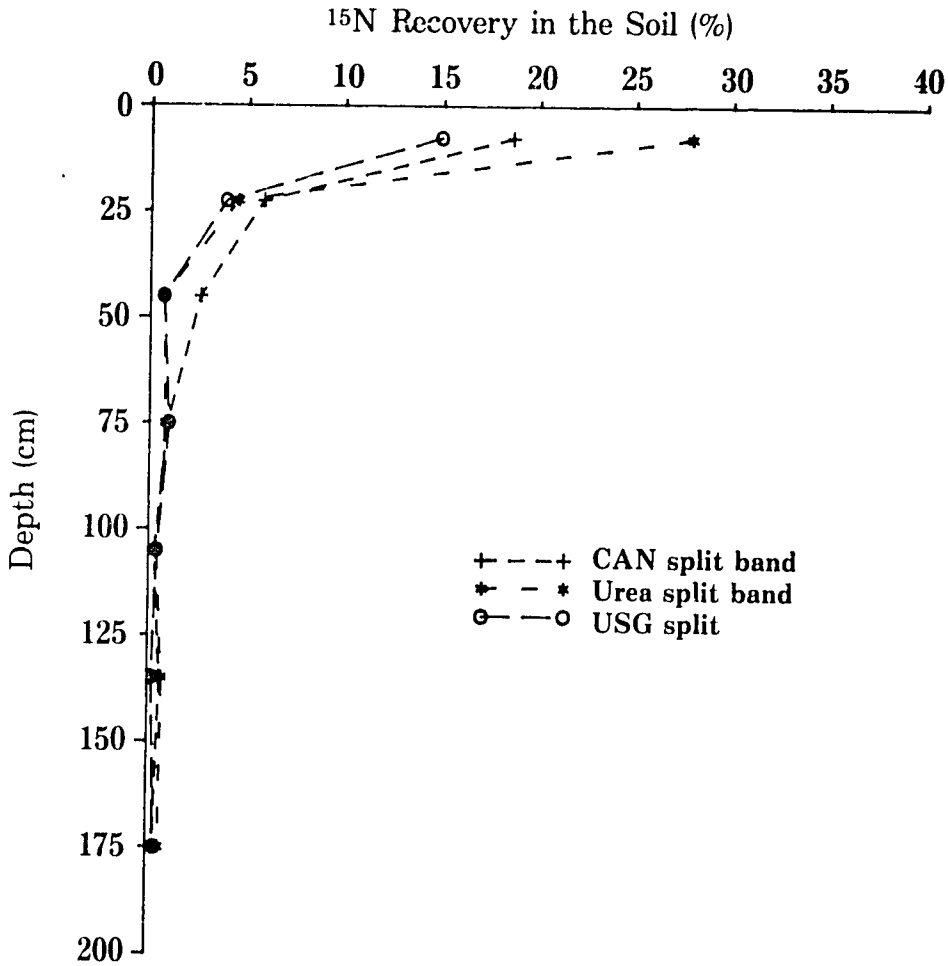
the grain was significantly lower in the point-placed treatment, although overall plant uptakes did not vary significantly (Figure 18). Grain ^{15}N uptake data correspond well with yield trends where lower yields were found with the point-placed treatment. Significantly less fertilizer N remained in the soil under the point-placed treatment than with the banded urea or CAN treatments. When plant data are combined with soil data it is evident that losses from the point-placed treatment were more severe than those of the CAN or urea banded treatment. With the banded treatments, more ^{15}N remained in the surface 0-15 cm layer with urea than with the more mobile CAN although similar amounts were found when summing up the data in the 0-60 cm deep layers (Figure 19). As in 1982, losses, even in the best treatment, were high and ran from 37% for CAN to 53% for the point-placed urea supergranule.

In 1984 the trials at Sadore suffered a severe drought and as a result, although overall plant uptake was not diminished, little ^{15}N-N was found in the grain (Figure 18). In terms of plants uptake, CAN was significantly better than banded and point-placed urea treatments. In terms of grain N uptake, however, CAN was significantly better than the banded urea treatment. The amounts of N remaining in the soil were similar in the urea banded and CAN banded treatments but significantly lower in the point-placed supergranule plots (Figure 18). CAN had penetrated to a greather depth than the urea treatments and, because of this, was less susceptible to volatilization losses (Figure 20). In addition, since the lack of rain was so severe, the surface layers remained dry for long periods of time making the N in those layers unavailable to the crop. The CAN, which had penetrated to greater depths because of the mobility of the NO_3 ion, remained available to the plants, whereas the surface-applied urea was isolated in the dry surface soils. A fourth urea trial, which used basally broadcast urea and for which plant analysis has not been completed, showed a distribution of N and total soil recovery similar to that found for the urea banded treatment.

Summarizing the ^{15}N data for the semiarid area, CAN significantly outperformed urea in terms of plant nitrogen uptake, and this was translated into significantly higher yields of millet. Losses from all sources were high and were significantly worse in the case of point-placed urea supergranules. Nitrogen that remained in the soil tended to stay near the surface for all urea treatments, whereas under the CAN treatments it moved into the soil to deeper layers where it was easily taken up by the plant.

Headquarters research

Several experiments pertaining directly to the African field program were conducted at IFDC Headquarters in Muscle Shoals, Alabama.



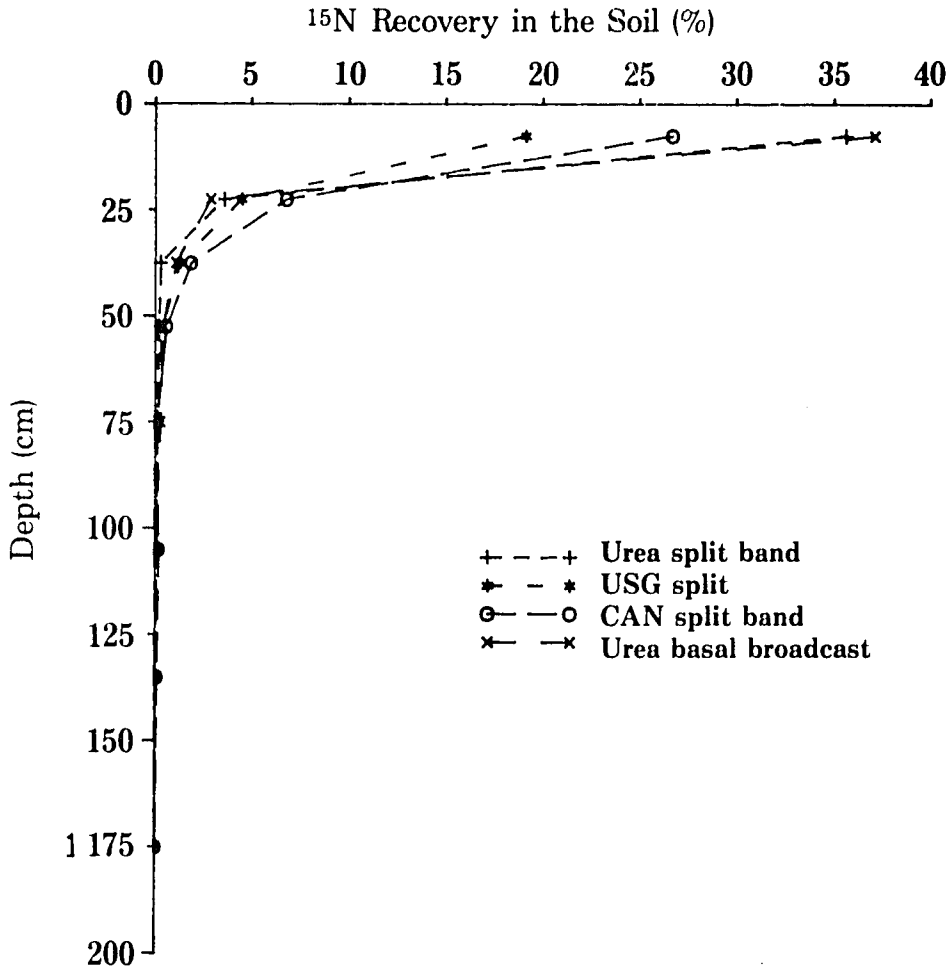
Note: Datum points represent the percent of the applied N recovered in each respective soil layer.

Figure 19. Soil ^{15}N distribution, Niger, 1983.

Volatilization studies

A. Methods

An incubation trial was conducted at IFDC in order to deduce why the deep placement of urea supergranules in the fields resulted in lower N responses than had been found with broadcast or banded urea or with CAN. The characteristics of the four tropical African soils used in this trial are listed in



Note: Datum points represent the percent of the applied N recovered in each respective layer.

Figure 20. Soil ^{15}N distribution, Niger, 1984.

Table 9. Although all of the soils had a high sand content, the pH, organic matter, percentage clay, and cation exchange capacities differed greatly. The potted soils were placed in individual volatilization systems which could trap all the ammonia gas evolving from the soil surface [41]. Urea supergranules labeled with the stable isotope ^{15}N were placed in the various soils at a depth of 4 cm and covered completely with soil. Ammonia in the traps was analyzed at the end of 1, 2, 3, and 5 weeks. The samples were incubated a further 3 weeks and then analyzed to determine the amounts of ^{15}N remaining in the soil.

Because the Niger soil had shown severe volatilization losses in the preliminary supergranule trial, the same soil was used in a complementary volatili-

Table 9 Soil properties and losses of point-placed urea applied to some African soils

Soil	Origin	Organic matter	pH	CEC	Sand	Clay	^{15}N Loss from soil as ammonia		^{15}N recovery in soil week 8	Total ^{15}N accounted for
							Week 1	Total at 5 weeks		
		(%)		(meg/100 g soil)			(%)			
Sadore	Niger	0.3	4.7	1	94	1	40.8	63.5	31.5	95.0
Egbeda	Nigeria	2.4	6.7	14	71	18	2.0	22.6	69.0	91.6
Maiduguri	Nigeria	0.7	6.9	5	77	3	49.4	61.2	30.9	92.1
Onne	Nigeria	1.3	4.4	11	65	24	0.4	4.3	96.8	101.1

Table 10 Influence of nitrogen source on volatilization losses as ammonia

Fertilizer source	^{15}N Loss from soil as ammonia					^{15}N recovery in soil (Week 4)	Total ^{15}N accounted for
	Week 1	Week 2	Week 3	Week 4	Total		
				(%)			
Urea pellets (broadcast)	10.3	3.7	2.6	1.8	18.4	78.1	96.5
Urea supergranule, 4 cm deep (buried)	47.7	16.6	3.5	1.8	69.7	31.7	101.4
Urea + PPD pellets (broadcast)	0.3	0.3	0.5	0.8	1.9	96.9	98.8
CAN pellets (broadcast)	3.1	2.3	1.0	0.8	7.1	92.5	99.6

zation trial designed to test alternative N sources for volatilization losses. One such product was urea + 2% phenylphosphorodiamidate (PPD), a urease inhibitor known to reduce the rate of urea hydrolysis in soils [7]. Surface-broadcast urea-PPD was compared with broadcast treatments of urea and of CAN and with a supergranule of urea placed in the soil as in the first experiment.

B. Results

Although losses via ammonia volatilization were negligible with the heaviest textured Onne soil, almost 70% of the applied N was lost in the case of the supergranules applied to the sandy Sadore and Maiduguri soils (Table 9). The high losses were probably due to the low buffering capacity of the light soils, which permitted the pH to rise during urea hydrolysis and thereby promote volatilization losses [13].

The results of the second trial show that the high volatilization losses over 4 weeks found with the point-placed supergranule (69.7%) could be reduced to a negligible level by the use of CAN or urea-PPD (Table 10). Losses from broadcast urea were much lower than those from point-placed supergranules, showing that fertilizer management is very important in minimizing N losses. The more than 96% N accounted for with the four nitrogen sources in the Niger soil indicates that nitrogen losses by processes other than ammonia volatilization were negligible.

These trials have identified ammonia volatilization as a major mechanism for loss of fertilizer nitrogen. They further show that replacement of urea with CAN or urea sources amended with urease inhibitors could increase N efficiency in the ligh-textured soils of Africa.

Leaching studies

A. Methods

This trial was conducted in order to determine the effects of continued heavy applications of fertilizers upon the pH of two Nigerian soils from the humid region. The two products used, urea and CAN, are very commonly used in the humid zones of Nigeria and are replacing ammonium sulfate as principal N fertilizer sources. Calcium ammonium nitrate is 23% calcium carbonate by weight, the carbonate having been added in order to neutralize the acidity created during ammonium nitrification to nitrate. Theoretically, sufficient

$CaCO_3$ is present to neutralize approximately 58% of the acid that will be produced.

Fertilizer was placed atop columns (60 cm long) packed with Nigerian soil. Regularl . small amounts of water were slowly added to the columns, and the leachate was collected at the bottom. After several months, water addition was stopped, and the columns were allowed to dry to simulate the dry season. There are two such dry seasons yearly in the region of Nigeria from which the soil was collected. After four such cycles, several columns were removed from the experiment and sectioned into layers, and the pH of the various layers was determined. Leaching continued in other columns for a further six cycles before they too were sectioned and analyzed.

B. Results

It is evident that serious acidification had occurred in the soils (Table 11). This was especially severe in the surface horizons of the Egbeda soil where the pH dropped 2.6 units for urea and 2.2 units with CAN over 10 wet/dry cycles. Onset of acidification was rapid with a decrease in pH of 1.5 units after only four cycles. Onne soil, initially quite acid, was not further acidified by the addition of high rates of urea or CAN. Generally, CAN was not strikingly better than urea in terms of reducing soil acidity.

Table 11 Acidification of two west African soils following 0, 4, and 10 applications of N at 300 kg N/ha

Soil Layer	Egbeda soil (Ibadan, Nigeria), Alfisol					Onne soil (Onne, Nigeria), Ultisol				
	N applications					N applications				
	0	4		10		0	4		10	
		Urea	CAN	Urea	CAN		Urea	CAN	Urea	CAN
	(pH)									
0-5 cm	6.8	5.3	5.2	4.2	4.6	4.9	4.6	4.9	4.2	4.6
5-20 cm	6.8	5.8	6.1	4.5	4.4	4.9	4.7	5.0	4.1	4.1
20-60 cm	6.7	6.0	6.2	5.4	5.8	4.3	4.8	4.8	4.0	4.0

Uptake efficiency of alternative fertilizers

A. Methods

Previous volatilization trials showed that CAN was much less susceptible to volatilization losses than was urea. This trial with three soils (Vernon – calcareous clay, pH 7.9; Savannah – acidic sand, pH 5.3; and Hartsells – acidic loam, pH 5.6) was designed to compare the plant uptake efficiency of maize for urea, CAN, and four other N sources (urea phosphate, diammonium phosphate (DAP), ammonium nitrate, and sodium nitrate). All fertilizers were labeled using ^{15}N. The plants in this greenhouse trial were harvested after 8 weeks, dried, ground, and analyzed for ^{15}N uptake.

B. Results

Uptake efficiency as measured by ^{15}N uptake varied greatly with soil type (Table 12). Generally, the uptake efficiency of sources containing the nitrate ion was higher than the uptake from urea or DAP. Utilization of N supplied by the NP source urea phosphate was not significantly greater than that of urea alone, and the other NP source tried (DAP) was the least efficient in all cases. Uptake of fertilizer N was generally four times as high for the Savannah soil as for the Hartsells soil even though they both had similar pH values. These results illustrate the need to test fertilizers in the soils in which they will be used. It would not be easy to extrapolate results obtained with the Hartsells soil to the Savannah soil or vice versa. These results also show that all fertilizer sources are not the same, even if applied under the same temper-

Table 12 Maize recovery of ^{15}N-nitrogen from six fertilizer sources

Source	Soil		
	Vernon	Savannah	Hartsells
		(% recovery in plant)	
Urea	38.6^{CD}	59.0^{AB}	13.6^{A}
Calcium ammonium nitrate	49.5^{B}	65.8^{A}	14.8^{A}
Urea phosphate	38.2^{CD}	66.1^{A}	19.2^{A}
Ammonium nitrate	50.4^{B}	65.2^{A}	15.2^{A}
Sodium nitrate	64.1^{A}	58.4^{AB}	14.5^{A}
Diammonium phosphate	32.7^{DE}	42.0^{C}	13.6^{A}

Note: Means followed by the same letter are not significantly different.

ature and soil conditions to the same crop. Comparison tests of the various N products available must be made before any recommendations can be made to the farmer.

Summary

Experimentation on the management of nitrogenous fertilizers in tropical Africa was conducted for 3 years in a collaborative effort between international and national agricultural research organizations. The experiments covered a number of agroecological zones, cropping systems, and sources/management techniques for applied N. The data obtained from the different experimental sites were composited and analyzed statistically.

Nitrogen response was most dramatic in the subhumid zone, which indicates that N is a major limitation to crop production in that zone. In the semiarid tropics, water deficits or other limitations appear to limit the response to N. In the humid tropics, lower response may be due to higher levels of native soil N.

There appeared to be no difference in response to CAN and urea in the humid and subhumid zones. In the semiarid tropics, the response to CAN was slightly better than to urea. Irrespective of N source, broadcast applications seemed to outperform band or point placement in the humid tropics. With few exceptions, point placement of urea is an inferior application method in all climatic zones. However, if point placement is practiced, split application is better than basal application in all zones, possibly indicating an improved spatial availability of the second application.

The ^{15}N data tended to be quite site specific, and it is difficult to draw firm conclusions across agroecological zones other than to note general trends. Nitrogen-15 data tended to differ little between the humid and subhumid sites, but both were quite different from the semiarid location. Losses tended to be quite low in the humid and subhumid areas; they averaged 20% and 24%, respectively, and were significantly less than the average loss of 40% found over all treatments and sources in Niger at the semiarid site. These low losses may, in part, be attributed to high crop densities which can be supported in the more moist zones and which result in a high uptake of applied N by the plant. Plant uptake accounted for 45% of fertilizer N in the humid and subhumid zones compared with only 28% in the semiarid zone. The living plant material acts as a sink for fertilizer N, trapping it and reducing its loss via volatilization or leaching. In the absence of an active dense crop, such as was the case in the *Striga*-afflicted trials in Mokwa in 1983, losses can be severe and equal those found in the semiarid sites (Figure 21). Only 2%-3% of the ^{15}N applied was taken up by the cowpea crop that had been intercropped with the maize.

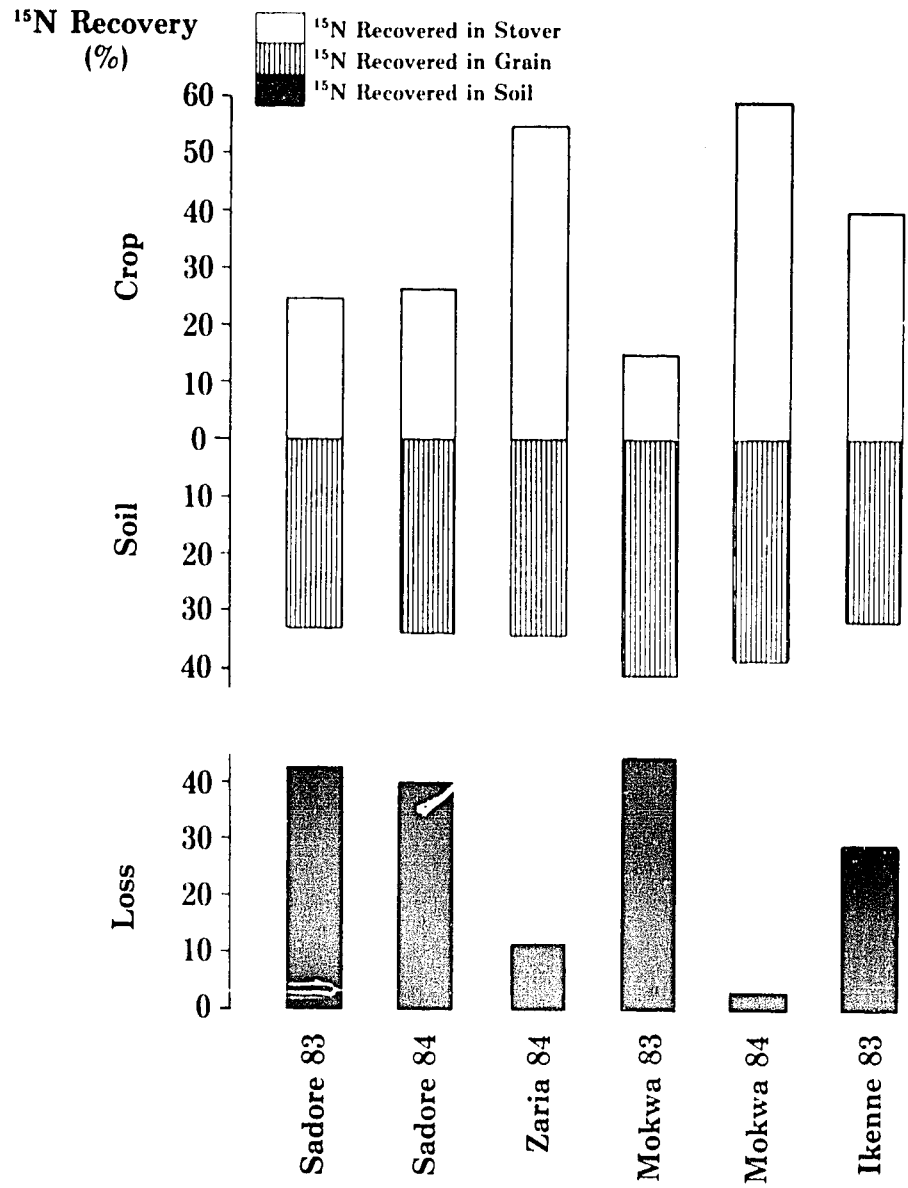


Figure 21. ^{15}N recoveries in the crop and soil, averaged over three nitrogen treatments, for six trials in West Africa (loss of fertilizer nitrogen is estimated from the difference between the amounts of ^{15}N applied and recovered).

The relation between the ^{15}N recovery fraction in the grain and grain yield of maize (Nigeria) and millet (Niger) is further illustrated in Figure 22. If all applied nitrogen (NF; kg N/ha) is completely mixed with the soil mineral nitrogen pool (NS; kg N/ha), and there are no losses of fertilizer nitrogen and

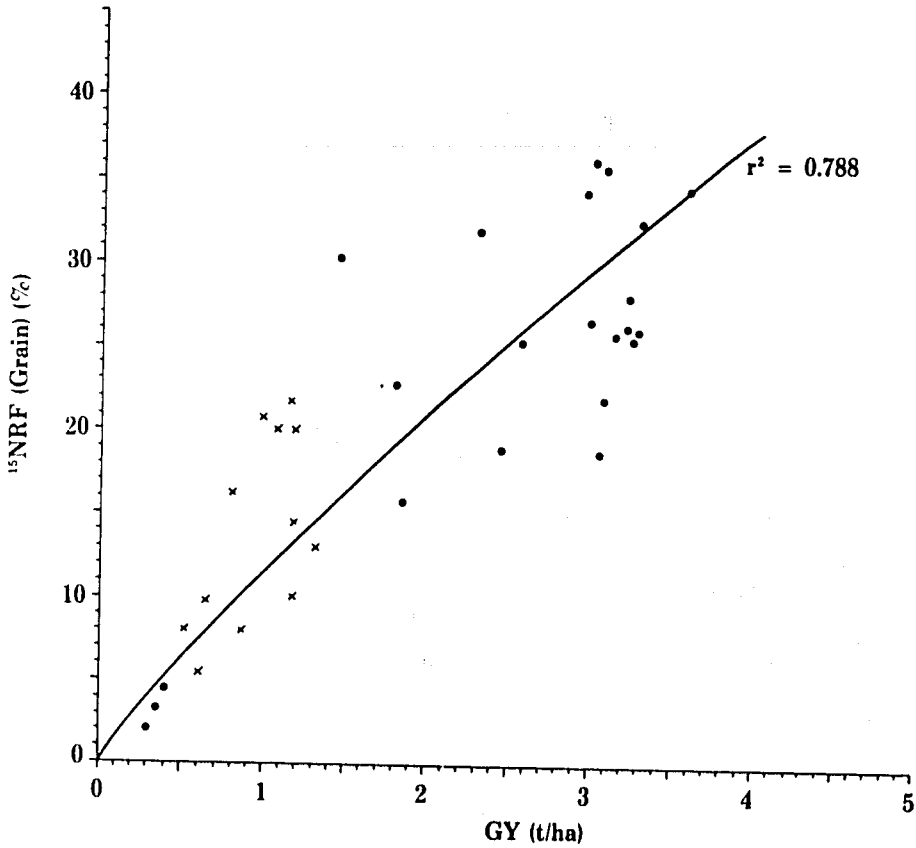


Figure 22. The ^{15}N recovery fractions in the grain (^{15}NRF) of maize (dots) and millet (crosses) as a function of the grain yield (GY).

no immobilization of ^{15}N, then the ^{15}N recovery fraction (^{15}NRF) in the grain is given by:

$$^{15}\text{NRF (grain)} = \text{GY} * \frac{\text{GN}}{\text{NF} + \text{NS}}$$

where GY is the grain yield (kg grain/ha) and GN is the nitrogen content (% w/w) of the grain. It can be seen that ^{15}NRF (grain) tends to increase with GY and GN. Grain nitrogen contents are generally in the range of 2.0%-2.6% for millet and 1.2%-1.8% for maize and tend to increase slightly with increasing rate of fertilizer application. In nitrogen-deficient soils, GY increases with the available-nitrogen: NF + NS. However, when NF + NS approaches the potential nitrogen requirement of the crop, nitrogen uptake decreases and ^{15}NRF (grain) decreases with increasing NF + NS. Hence, if NS is large,

^{15}NRF will be low because of the dilution of ^{15}N in the available-N pool [25].

In terms of soil recoveries of ^{15}N-nitrogen by zone, no difference was found between the arid and subhumid zones (although plant recoveries were higher in the subhumid zone): recoveries in both zones were significantly higher than at the humid zone sites. Thus, one reason for high N losses in Niger may have been the thin plant stand that can be supported by the soils and climate.

It would be expected and is recommended by national scientists of Niger that point placement near the plant would be a good strategy to follow to increase N uptake in the semiarid zone. However, over all zones, the point-placed supergranule tended to do poorly and performed significantly worse than other sources in Niger. The best combination of N source and management over all sites was the urea split broadcast treatment which gave both the highest N uptake in the grain and the lowest losses. Split broadcast CAN also resulted in high grain N contents, and broadcasting was the best method of application to ensure good N uptake in the grain.

From the ^{15}N data it appears that research strategies aimed at decreasing N losses through the development of new sources would not bring about large increases in yield in the humid and subhumid areas. If the nitrogen is split-applied to an otherwise healthy crop, losses will be low and uptake high. More frequent, smaller splits may improve fertilizer efficiency in the humid areas by reducing leaching. In the semiarid regions this is not the case. Uptake is low and losses high, even for CAN which is not well known as a source that suffers volatilization losses. Further work needs to be done on the loss mechanisms in Niger, and sources need to be found that are easily solubilized and thus able to move deeper into soil layers where they are available during the frequent dry periods found during the semiarid zone's growing season.

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Phosphate deposits of tropical sub-Saharan Africa

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Introduction

Africa is the second largest of the world's continents; it has an area of about 30 million km², approximately three times the size of Europe, and a population approaching 500 million. From north to south in a straight line, the maximum distance is about 8,000 km, and from east to west it is about 7,200 km. Although the equator cuts almost exactly midway across the continent, with about two-thirds of the total area lying between the Tropics of Cancer and Capricorn, more than half of the continent lies in the northern hemisphere because of the extensive 'bulge' occupied by North and West Africa and the Sahara Desert. Virtually the entire area of the sub-Saharan region considered in the present report lies within intertropical Africa (Figure 1). As such, it embraces some 30 independent states with the notable exception of South-West Africa (Namibia). A significant number of the countries referred to are also landlocked; striking examples are Burkina Faso, Mali, Chad, Niger, and, in southern Africa, Burundi, Uganda, Malawi, Rwanda, Zambia, and Zimbabwe. There is a remarkably smooth coastline, with an almost uniformly narrow continental shelf, a feature that reduces the chances of discovering major oil fields; on a smaller scale, there is also a marked absence of natural harbors.

Africa comprises a single tectonic plate, though some authorities would differentiate the area east of the Rift Valley system. Almost the entire continent is a geologically stable landmass of Precambrian 'basement' metamorphic rocks (mainly schists and gneisses) overlain in part by a sedimentary cover. Apart from the Cape Ranges of Hercynian age in the extreme southwest corner of the continent and the Atlas Mountains of the Alpine (Tertiary) orogeny in the northwest, the stability of the African plate is broken only by the great Rift Valley system. Although the African continent has remained a relatively rigid and stable plate since Precambrian times and has

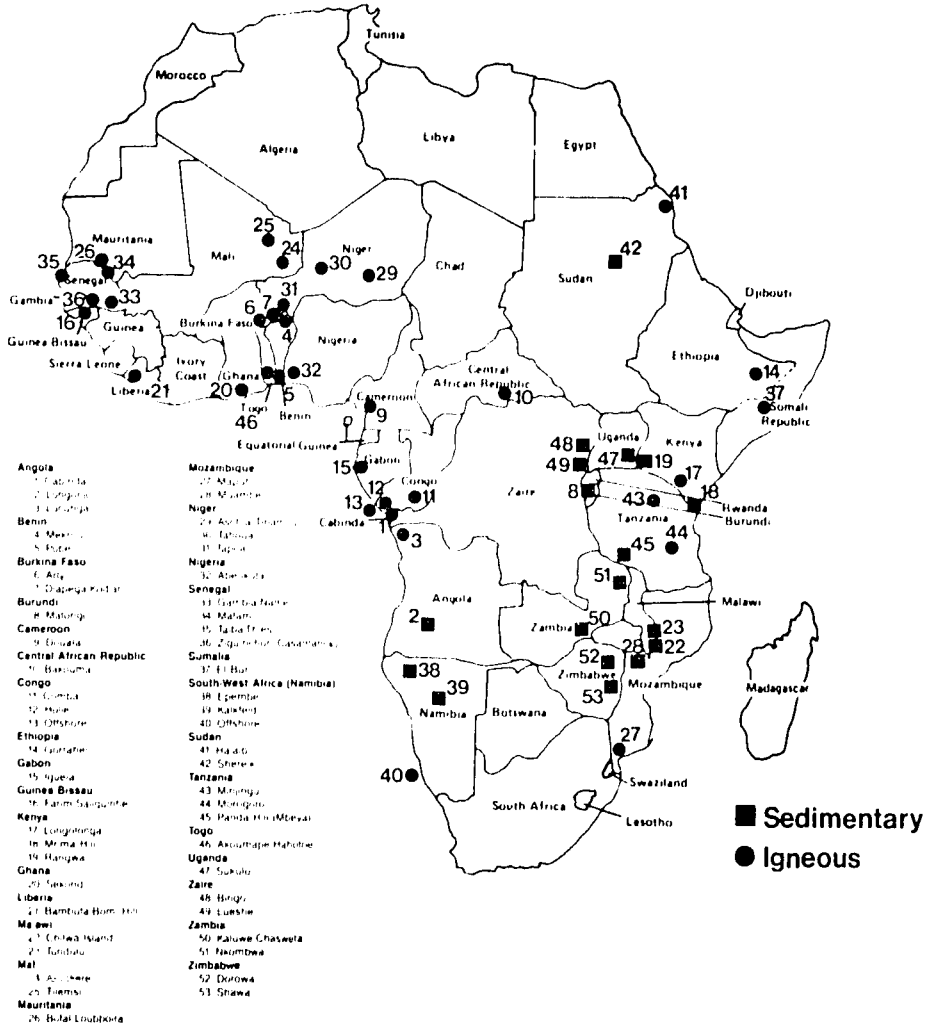

Figure 1. Phosphate occurrences of sub-Saharan Africa.

consequently remained a landmass through most of this period, occasional marine incusions took place across the narrow coastal plains and the present Sahara during Jurassic, Cretaceous, and Tertiary times. The predominantly vertical (epeirogenic) movements, which produced broad warping and block faulting, have combined to give Africa a structural pattern characterized by broad basins separated by areas of uplift similar in many respects to the 'basin and range' province of the western United States. The larger basins, such as the Karroo and Congo, have been important receptacles of continental clastic sediments represented by the Karroo system (Upper Carboniferous-Triassic) of southern Africa and the Nubia Sandstone (Creta-

ceous) of northeastern Africa, the 'Continental Intercalaire' (Cretaceous) which is of sporadic occurrence, and the widespread 'Continental Terminal' (Tertiary).

In eastern Africa the structural swells rise into a coalescing series of plateaus traversed by the spectacular Rift Valley system. This feature extends from the Zambesi River northward to as far as Syria in southwest Asia, a total distance of nearly 5,000 km. In their present form the rift valleys are mainly of late Pliocene to mid-Pleistocene age, but they are imposed on earlier structures. A characteristic feature of the Rift Valley system is the frequent occurrence of alkaline intrusive igneous complexes, often with carbonatite, which tend to be aligned in zones parallel to the main structural trend.

Distribution of resources

Phosphate rock occurs in the sub-Saharan region in two different geological environments, namely, sedimentary and igneous. By far the most geographically extensive are deposits of sedimentary origin occurring in strata predominantly of Lower Eocene age. In northern Africa (outside the sub-Sahara) they form one of the most important commercial phosphate provinces in the world, the Tethyan Phosphogenic Province, which extends from Morocco eastward into Egypt and also into the Middle East as far as southern Turkey. The phosphate resources and potential of this province are considerable.

In contrast, however, phosphate resources in the sub-Saharan region are limited (Table 1), although geographically of wide distributions (Figure 1) [62]. Total resources amount to over 4,000 million tonnes, reserves of mineable rock residing mainly in the marine sediments of Senegal and Togo. The potential development of a number of occurrences in the sub-Saharan region has been reviewed [40,47]. It is the main purpose of this paper to summarize the distribution within the region of known resources of phosphate rock, both sedimentary and igneous, taking into account that insufficient data are often offered with regard to the technical and economic feasibility of producing marketable grades of phosphate rock by use of modern mining and beneficiation techniques.

At least 26 sub-Saharan African countries have some phosphate resources or reserves (Table 1). Eight countries have deposits that are producing or recently have produced marketable or usable phosphate rock. Seven other countries have resources with fair to good prospects, at least for domestic use (Figure 1).

An additional 18 countries have identified or inferred deposits that, on the basis of available information, can be classified only as promising for such

reasons as inadequate descriptions, small size or poor quality, inaccessibility, or lack of local demand (Figure 1). In this connection it should be noted that the information available may not always be accurate or up to date. In some cases exploration is known to be in progress, but recent results have not been reported.

Although phosphate deposits in West Africa are chiefly of Eocene age [79], Upper Cretaceous occurrences are found also in the Atlantic coastal basins as far south as Angola, the continuity of the phosphate-bearing sediments being interrupted by Precambrian rocks extending to the coast. Tertiary and/or Upper Cretaceous sediments also occur extensively in the plains of middle Niger and Dallol Bosso in central West Africa. Geographically there are two

Table 1 Estimated resources of phosphate rock in sub-Saharan tropical Africa[a]

Country	10^6 Tons of rock	P_2O_5	Type of rock	10^3 Tons[b] 1982 production
		(%)		
Angola	28	25	Sedimentary	18
Burkina Faso	300	26-32	Sedimentary	6
Burundi	25	11	Igneous (residual)	–
Guinea Bissau	112	30	Sedimentary	–
Malawi	2	5 (Min)	Igneous	–
Mali	20-25	15-32	Igneous	–
Mauritania	94	19-20	Sedimentary	–
Niger	100	18-35	Sedimentary	6
Senegal[b]	40[c]	29	Sedimentary	-
	100[d]	37.5	Sedimentary	975
	90[e]	28	Sedimentary	–
Tanzania	10	20	Sedimentary	100
	125[f]	6 (Max)	Igneous	–
Togo	100	28-32	Sedimentary	2,128
Uganda	230	11-13	Igneous	–
Zaire	30[g]	4-10	Igneous (residual)	–
Zambia	500[h]	8	Igneous	–
	200[i]	1-4	Igneous	–
Zimbabwe	37	8	Igneous	120

[a] Lucunga Valley. Total resources may exceed 200 mt.
[b] Total resources may exceed 700 mt.
[c] Matam.
[d] Reserves at Taiba, quoted in terms of marketable product (82% BPL).
[e] Thies (aluminum phosphate).
[f] Panda Hill (Mbeya).
[g] Lueshe.
[h] Nkombwa.
[i] Kaluwe.

regions: (1) the Saharan, covered by a shallow Upper Cretaceous-Eocene sea which advanced from the North African coastal area where phosphate was being deposited, and (2) the Nigerian, invaded also by a gulf of the sea and extending up the present Benue, Gongda, and middle Niger valleys to the foothills of Air and Adrar des Iforas. The southern sea probably joined the Saharan sea by a narrow strait between the Tibesti and the Ahaggar massifs, while to the northwest it joined the northern sea between Araouane, Adrar des Iforas, and the western Ahaggar. Other Cretaceous-Eocene gulfs occupied Senegal, The Gambia, Ivory Coast, Togo, Benin, and Nigeria, as well as other coastal areas, particularly of Cameroon, Gabon, Zaire, and Angola.

Phosphate deposits have been found in most of these coastal basins, and the geological indications are that further discoveries might be made as systematic exploration proceeds. For example, the comparatively recent discovery of phosphate rock of Precambrian age astride the Burkina Faso-Niger-Benin border region suggests that considerable effort should be made to determine the location of similar sedimentary basins in Precambrian areas in order to determine their phosphate potential. Sedimentary phosphate rock has been found also in coastal sediments in eastern Africa, in Mozambique and Malagasy, generally as thin, nodular beds apparently of limited extent. The indications are not promising, but in the absence of systematic exploration, the presence of more extensive beds of phosphate rock in these areas cannot be ruled out entirely. Similarly, the large sedimentary basins of southern Africa, such as those of the Karroo and Congo, are filled mainly with continental sediments that reflect environments unfavorable to phosphate deposition. However, some of the Cretaceous and Tertiary sequences are of shallow-water, marine origin and may contain phosphate.

In contrast to the northern and western parts of the sub-Saharan region, phosphate deposits in the southern part of the region are associated mainly with alkaline/carbonatite igneous complexes, including their weathering derivatives [24]. The complexes occur singly, as at Mrima Hill in Kenya, but more often in groups, of which probably the best known are contained in the Chilwa-Zambesi province of Upper Jurassic to Lower Cretaceous age to the south of Lake Nyasa. They are invariably closely associated with the impressive Rift Valley system. Other igneous provinces that have been recognized include the Lower Cretaceous province in Angola and the Tertiary western Kenya-eastern Uganda province. Alkaline complexes, some with carbonatites, have been found in Ethiopia and Somalia, but their phosphate potential has not been investigated, as far as is known.

Angola

Phosphate rock occurs in parts of northern Angola and in the enclave of Cabinda, in a sequence of marine Upper Cretaceous to Lower Eocene rocks deposited in the coastal Congo Basin or as reworked material in sediments of more recent age. Both regions were originally prospected for phosphate by the Servicos de Geologia e Minas de Angola.

Lucunga [19,2]
– Phosphate was first discovered in 1951 in northern Angola near the port of Ambrizete, and subsequent exploration led to the discovery of deposits in the Lucunga River [62], east of Quinzau. The deposits consist of phosphatic nodules (described as coprolites) and phosphatic limestone. They are believed to be of a Lower Eocene age, but most of the occurrences are residual and alluvial concentrations in sediments of Middle to Upper Eocene age, such as those found in the Coluge and Lendiacolo Rivers, or of Pleistocene age in the Quindonacaxa area. Total phosphate rock reserves in the Lucunga Valley average 25% P_2O_5 and 0.6 m in thickness and are estimated at 28 million tonnes, with an average thickness of overburden of nearly 2 m. Phosphate samples show a considerable variation in P_2O_5 content, with a maximum of about 33% and generally more than 15% SiO_2.

The commercial feasibility of working the deposits by opencast methods at the rate of about 500,000 tpy has been studied, and a 15,000-tpy experimental mine was reported to have begun operating toward the end of 1981 in the Quindonacaxa area about 16 km southeast of Quinzau under a joint project with Bulgaria. Phosphate resources in the area are placed at 200 million tonnes. Immediately to the north, phosphatic nodules occur in argillaceous sandstone about 4.5 m thick. Samples from this area contain from 18% to 27% P_2O_5. Samples from the Coluge and Lendiacolo Valleys, lying respectively about 78 km northeast and 14 km east of Quinzau, are of similar chemical composition, and in the Coluge area outcrops of calcareous phosphorite show P_2O_5 contents ranging from 26% to 32%.

The most southerly known phosphate occurrence in Angola is at Subida, about 10 km south of Mocamedes, where phosphatic limestone 4 m thick and with 5% P_2O_5 outcrops along the margins of the Koroka River.

Cabinda [17,29,15]
– Phosphate nodules and phosphatic limestones of variable thickness have been recorded at many localities within a coastal zone for a distance of over 80 km between Massabe and the port of Cabinda. At least five groups of deposits – Cacata, Chibuete, Chivovo, Mongo n'Tando, and Cambota – have been located within two adjacent asymmetrical folds, the Inhibo anticline

and the Chivovo syncline, and are estimated to contain some 16 million tonnes, of which 3.3 million tonnes are proved. Much of the phosphatic material is extremely siliceous; the P_2O_5 content generally ranges from 12% to 34%.

Benin

Sedimentary phosphate deposits of Lower and Middle Eocene age are found at several localities in southern Benin [80,78], but unlike those situated in the adjacent area of southern Togo, with which they can be correlated, none of the known occurrences in Benin are of economic importance at present.

Although the existence of phosphate in southern Benin has been known since 1906, it was not until 1952 that preliminary surveys were made by the former Comptoir des Phosphates de l'Afrique du Nord. Subsequently, more detailed investigations were made by the Syndicat de Recherches de Phosphate du Dahomey. The results indicated that there was little likelihood of finding commercial quantities of phosphate rock in southern Benin, and the investigations ceased in 1958. The phosphate beds form part of a sedimentary sequence, the Serie de la Lama, composed of clays, marls, and thin limestones dipping gently to the south or southeast. Typically they are interstratified with finely laminated attapulgite-bearing clays and are themselves frequently glauconitic. They are exposed along the northern edge of a series of low-lying plateaus between the sea and the Lama Depression. The principal phosphate bed of Ypresian age occurs about 5 km north of Pobe and is about 0.7 m thick with green phosphatic nodules set in a greenish clay matrix. Chemical analyses of the nodules frequently show between 27% and 30% P_2O_5, but the entire bed is variable in composition. The overlying, relatively homogeneous chalk is usually less than 2 m thick; two samples from the Kpome area, 36 km north-northeast of Allada, analyzed 9.3% and 2.5% P_2O_5, respectively. Farther to the southwest at Toffo, about 22 km north-northwest of Allada, there are several very thin phosphate beds containing 23% P_2O_5. At Lokossa, 6 km northeast of Athieme, three phosphate beds have been identified in the upper part of the Lutetian sequence, the top and bottom beds being separated by about 30 m of marls and clays. The topmost bed is stratigraphically equivalent to that being worked in Togo, but it is only 12 cm thick and has a lower phosphate content.

Mekrou [86]

– Potentially the most important deposits in Benin, however, were located by the Service des Mines during the late 1970s in the Mekrou area in the extreme northern part of the country. The deposits occur in the Middle

Voltaian Mekrou Formation, which is of Late Precambrian age, representing an extension of the deposits of the same general age found in the neighboring parts of Burkina Faso and Niger. The phosphate-bearing zone is up to 550 m thick and comprises two phosphatic sequences separated by grey and green shales, a phosphatic sandstone in the lower phosphatic sequence exceeding 10 m in thickness. Typically, the phosphatic sandstones are hard, massive rocks, medium to dark grey, and containing between 20% and 26% P_2O_5. Phosphate mineralization extends over approximately 200 km^2, but the area is structurally and stratigraphically complex. Geologists from the United Nations Development Programme (UNDP) have indicated that, in the most promising Perimetre Sud Marikire, proved reserves to a depth of 30 m amount to about 3.3 million tonnes, averaging 25.1% P_2O_5 and underlying an area of 0.225 km^2.

Burkina Faso (formerly Upper Volta)

Sedimentary phosphate rock of Late Precambrian age was discovered during the late 1960s in the Pares Nationaux du 'W' area astride the Burkina Faso-Niger-Benin borders approximately 135 km south-southeast of Niamey. The main occurrences at Diapaga (224 million tonnes), Kodjari (80 million tonnes), and Arly (up to 4 million tonnes) are located in the northern part of the Volta basin in the Pendjari Group [86,56]. This group consists of a lower Kodjari Formation, which has a thickness of about 50 m and comprises, in turn, tillite, dolomitic limestone, and bedded chert capped by phosphate-bearing argillaceous siltstones. Individual beds or lenses of phosphorite range from 1 to 15 m in thickness and contain 15%-32% P_2O_5.

The well-bedded Kodjari deposits, which average 27.5% P_2O_5 and are interpreted as being of primary origin, have been worked with the assistance of the Federal German Agency for Technical Cooperation (GTZ) at the rate of 1,000 tpd for direct application to the soil. They are characterized by their fine-grain size and good sorting, being composed essentially of structureless grains of cryptocrystalline, brown and isotropic apatite, and minor amounts of angular silt-sized quartz, in a cement in which quartz and microcrystalline and colorless apatite predominate. At Arly, the phosphorite bed reaches a maximum thickness of 1.5 m. Its chemical analysis shows 26%-32% P_2O_5, 39%-44% CaO, and 29%-34% SiO_2, with minor amounts of Al_2O_3, Fe_2O_3, and MgO. Locally, the phosphorites contain up to 0.03% uranium. Compared with Kodjari rock, Arly phosphorite is coarser grained and contains composite grains of nearly pure and cryptocrystalline apatite, as well as more abundant detrital material. It is interpreted as a reworked deposit.

Cameroon

Siliceous, phosphatic nodules occur in the coastal area of northwestern Cameroon [88] in Lower Eocene marls, clays, and grits (Serie de Bongue), which are exposed in the Bongue River Valley near Kompina, a railway station about 50 km north-northwest of Douala. Information is not available on the extent of the occurrences, which all lie within the Douala sedimentary basin, but so far they have not proved of economic interest. In the lower part of the Serie de Bongue phosphatic nodules containing 15%-18% P_2O_5 occur in black sandy clays up to 2 m thick; at the top of the series, nodules associated with thin limestones have shown analyses between 12% and 18% P_2O_5.

Central African Republic

Mapping by the Commissariat a l'Energie Atomique during the 1960s revealed the presence of sedimentary phosphate rock near Bakouma [6], about 480 km northeast of Bangui and approximately 1,500 km inland from the Cameroon port of Douala. There, small phosphatic lenses are interstratified with silts and sandstones of the M'Patou Formation, which is of Eocene age. The lenses are reported to be intensely weathered to depths of 5 m or more, giving rise to secondary aluminum phosphate mineralization. The phosphate rock contains an average of 0.25% U_3O_8, and the feasibility of working the Bakouma deposits as a source of uranium has been investigated.

Congo

Phosphate rock occurs in Maastrichtian (Upper Cretaceous) to Ypresian (Lower Eocene) strata in the coastal area of the Congo [34]. The most important deposits are situated south of Holle on the Congo-Ocean railway about 50 km northeast of Pointe-Noire and in the Sintou-Kola area north of Pointe-Noire and approximately 40 km from the coast, where the deposits were discovered during oil exploration in 1934. Although not of economic importance at present, these and other phosphate occurrences in the coastal strip between Mayoumba (in Gabon) and the Angolan enclave of Cabinda were investigated between 1955 and 1957 by the Syndicat de Recherches de Phosphate au Moyen-Congo, when the feasibility of exploiting some of the deposits for use in a proposed electrometallurgical plant at Pointe-Noire was under consideration. They were again investigated during the late 1960s under Soviet and Bulgarian technical assistance programs. Two phosphatic facies are recognized – a very coarse, conglomeratic 'coprolitic-quartzose' facies and a

finer grained detrital 'phosphato-siliceous' facies with a phosphatic or quartzose cement, the former being probably of deltaic origin.

The deposits discovered in 1945 occur in the Seviede-Holle [54], which is of variable thickness but does not exceed 10 m. Individual phosphatic lenses are generally from 2 to 8 m thick and contain 16%-25% P_2O_5, with resources estimated at 15 million tonnes containing 21%-25% P_2O_5. The low grade and siliceous nature of the phosphate rock are considered to render beneficiation impractical on a commercial scale, although laboratory tests have shown that heavy-media separation and flotation yield a product containing 35% P_2O_5 (75% BPL). A concentrate with 30% P_2O_5 (65% BPL) could be obtained by mechanical separation alone, but the recovery is only 40%-50%.

The Sintou-Kola [69] deposits, which were first prospected by the Service des Mines de Brazzaville between 1936 and 1938, outcrop in the Celo, Tchissa, M'Bandza, and Missiessi Valleys over a distance of 10 km and represent an extension of the phosphate series south of Holle. They lie within a sedimentary sequence about 24 m thick composed chiefly of fossiliferous marly sandstones, individual beds of soft, phosphatic sandstones and marls having an average thickness of 2 m. The principal outcrop contains approximately 300,000 tonnes with a grade of 21% P_2O_5. Phosphatic nodules containing 28%-35% P_2O_5 occur in the middle Niari Valley near Comba, 110 km west of Brazzaville. The occurrences are associated with late Precambrian strata (Serie Schisto-Calcaire). Although known since the beginning of the century, their potential does not seem to have been investigated.

Offshore Congo-Gabon [18,35]

Phosphorite deposits considered to have been reworked into sediments of Miocene-Quaternary age occur on the seafloor of Pointe Noire at a depth of about 40 m. The potential resources have not been evaluated as far as is known.

Ethiopia

There is limited reliable information on the reported occurrences of phosphate rock in Ethiopia. Two beds of phosphatic rock were reported by Sinclair Oil in one of its wells drilled in 1956 near Gorrahei in the southeastern Ogaden Desert in the 793-830 m and 866-884 m core intervals, respectively. The beds are believed to be of Eocene age and thus part of the Upper Palaeocene-Lower Eocene Auradu Series which consists predominantly of massive limestone with chert concretions and thinly bedded, chalky or

gypsiferous limestone. Apatite occurs also in the central parts of Ethiopia in various igneous and metamorphic rocks, the phosphate potential of which has still to be fully assessed.

Gabon

Nodular phosphate beds of Upper Cretaceous (Santonian to Maastrichtian) age occur in the coastal region of southern Gabon [32] in the Serie de Komandji, a sequence of generally bituminous limestones and sandstones more than 600 m thick outcropping between the Fernan Vaz and Iguela lagoons south-southeast of Port Gentil. The beds have been extensively silicified and are not of economic interest at present, although a reinvestigation of some of the occurrences found north of Iguela lagoon was carried out by the French Bureau de Recherches Geologiques et Minieres (BRGM) in 1965. Near Pombou, grades of up to 32% P_2O_5 have been reported; a sample of phosphatic sandstone from the coastal area between Pointe Sainte Catherine and Pointe Iguegue analyzed by the Service des Mines de Brazzaville gave 8% P_2O_5.

The Gambia

Upper Cretaceous and Eocene sedimentary formatons that are known to contain phosphate deposits in the adjoining areas of Senegal may be traced into The Gambia, suggesting that phosphate deposits may be found there also. In view of the irregular distribution and lenticular character of the predominantly arenaceous beds outcropping in the country, however, it is unlikely that deposits of commercial value are present. In 1961 the BP-BRP Exploration Company (Gambia) Limited reported that phosphatic nodules associated with sandstones and grits of Upper Cretaceous (Maastrichtian) age occur between depths of 432 m and 526 m in their Sara Kunda No. 1 oil exploration well near Banjul.

Ghana

Phosphatic nodules containing 14.75% P_2O_5 have been found in shales in a coastal cliff section beside Fort Orange at Sekondi, about 180 km southwest of Accra. The occurrence appears to be of very limited extent and is unlikely to be of any economic value as a source of phosphate. The shales belong to the Sekondi Series [3], for which an Upper Devonian to Lower Cretaceous

age has been suggested, and possibly form part of the uppermost formation of the series known as the Sekondi Sandstone.

The Precambrian formations known to be phosphate bearing in Burkina Faso, Benin, and Niger are also widespread in northern Ghana. However, the phosphate potential of such rocks in Ghana has not been evaluated.

Guinea Bissau

A recent discovery of a phosphate deposit in Guinea Bissau has been made by the BRGM. The deposit is reported to occur in the Upper Cretaceous and Eocene formations that are known to be phosphatic in Senegal. Preliminary data indicate that the deposit is lenticular in shape and contains up to 20 million tonnes of resources. Although the ore body is soft and friable like that in Taiba, the overburden is reported to be an even thicker series of sands that may increase the cost and complicate the mining of the deposit.

Liberia

Secondary phosphate deposits occur in western Liberia [4,83,71] north of the port of Monrovia at Bomi Hill and near Bambuta, in association with magnetite-hematite ores of Precambrian age worked by the Liberia Mining Company Limited. Investigations carried out jointly by the Geological Survey of Liberia and the United States Geological Survey indicate that at least 1 million tonnes of phosphate rock containing 32% P_2O_5 is present in the Bambuta area. However, both the Bomi Hill and Bambuta deposits have a complex mineralogy and are unlikely to prove amenable to mining on a large scale as a source of phosphate.

On Bomi Hill about 65 km north of Monrovia, scree deposits are composed of blocks and fragments of massive magnetite-hematite in a light-colored matrix of iron phosphate. The latter includes the minerals identified as strengite and leucophosphite which are present also as fissure infillings in the iron-ore bedrock and as replacement minerals in massive iron ore on the floors of caves developed in the cliffs. The scree material on Bomi Hill was found to be phosphatic in 1949, and similar deposits were subsequently discovered some 40 km east of Bomi Hill about 2 km southwest of Bambuta. Here the aluminum phosphate minerals variscite and augelite have been found in the upper zones of the deposits, with strengite and barrandite occurring at depth.

Mali

Stratigraphical and paleontological investigations carried out on Cretaceous and Tertiary strata in eastern Mali by French geologists since 1920 have led to many discoveries of phosphatic bone beds and phosphate rock in sediments of Middle Eocene age [50,44,67]. The Eocene rocks have a semicircular outcrop around the southern part of the Precambrian massif of Adrar des Iforas and continue eastward along the northern edge of a large tract of younger sediments known as the Iullemmeden Basin. The phosphate deposits generally contain between 23% and 32% P_2O_5, and resources of between 20 and 25 million tonnes have been estimated to be present in the Tilemsi Valley near In Tassit, about 150 km north of Gao, where phosphate rock was discovered in 1935 during investigations by the Office du Niger. Further exploratory work has been carried out by the BRGM, and a research program was begun by the International Fertilizer Development Center (IFDC) in 1981. The Tilemsi deposits have been worked at the rate of about 2,000 tpy since 1976, and a mill capable of processing up to 30,000 tpy has been constructed under the auspices of GTZ.

Nearly 20 km northeast of In Tassit (17°26'N, 0°08'E), a lenticular bed of phosphate 2-2.5 m in thickness underlies part of Tamaguilelt, an isolated plateau rising above the Tilemsi Valley. Southeast of Tamaguilelt, the phosphate series is extremely variable in thickness. In Chanamaguel, for example, it is only about 0.5 m thick, while at Andarakoyen, about 10 km northeast of Samit, it attains a thickness of 1.6 m. Partial analysis of samples collected in 1951 from Tamaguilelt, Chanamaguel, and Andarakoyen showed between 23% and 36% P_2O_5. Southeast of Tamaguilelt, the deposit in Wadi Ganchiran lies about 20 km from its convergence with the Tilemsi Valley. The phosphate bed is approximately 2.5 m thick and is composed almost entirely of coprolitic material, while in the escarpment of Tim Edam, about 18 km north-northeast of Samit, the phosphate beds attain a thickness of 4 m. Partial chemical analysis of samples of phosphate and coprolitic nodules from the two localities showed a range of 23%-36% P_2O_5. In the Assakarei Valley, situated on the western edge of the Iullemmeden Basin about 290 km east of Gao, Middle Eocene shales contain a phosphatic bed up to 1 m thick. The shales are known to continue through the Niger Republic, where nodular phosphatic beds have been reported, and into Sokoto Province, western Nigeria; they are probably the stratigraphical equivalents of phosphate-bearing shales at Oshosun in Abeokuta Province.

Mauritania

The presence of phosphate rock in the Lower Eocene strata of the Middle Senegal River has been known since 1910, and investigations carried out between 1936 and 1938 by the Service des Mines et de la Geologie [41,66] resulted in the discovery of about 1 million tonnes containing between 23% and 30% P_2O_5 (50% and 65% BPL) near Matam, some 320 km east of the port of St. Louis in western Senegal. A small quantity was worked for use in agricultural trials, but the deposits did not otherwise prove to be of commercial interest. In 1966, it was reported that resources totaled 4 million tonnes, but this is probably a conservative estimate because phosphate beds occur also near Ornolde, some 32 km southeast of Cive. At Cive, there are usually three, or sometimes four, lenticular beds composed of hard, chalky, phosphatic nodules set in a clay matrix. They have a maximum aggregate thickness of nearly 2 m, generally containing between 25% and 30% P_2O_5.

Potentially the most important phosphate deposits in Mauritania are those near Bofal and Loubboira [11], situated to the west and east, respectively, of Wadi Guellouar, between Kaedi and Bogue. There, a phosphatic sequence 12 m thick contains a highly siliceous phosphate member; it consists of a phospharenorudite with bone fragments, coprolites, and fish teeth, and with clayey, quartzitic exogangue. At Bofal, the phosphate bed is 1.7 m thick averaging 20% P_2O_5; at Loubboira, it averages 2 m thick with 19% P_2O_5. Probable resources available to open pit mining are placed at some 94 million tonnes. Structurally, the area investigated is relatively undisturbed, the strata dipping imperceptibly to the south.

In northern Mauritania [82], phosphate rock occurs in Palaeozoic sediments in the Zemmour el Akhdhar area near Bir Maghreinm located at 25°10'N, 11°35'W on the Route de Mauritanie. Traces of phosphate have been found throughout the entire Ourmat ek Ham Series of Lower to Middle Cambrian age, the greatest concentration occurring as nodules of phosphatic sandstone. The nodules contain up to 31.7% P_2O_5. Phosphatic nodules occur also in Lower and Middle Devonian sediments, containing up to 22.8% P_2O_5. The area is remote, and none of the occurrences found to date are sufficiently thick or extensive to be of commercial interest.

Mozambique

Sedimentary phosphate and phosphatic bat guano have been recorded at various localities in Mozambique [23], but only deposits of the latter, occurring in Tertiary limestone caves in the coastal area about 100 km northwest of Vilanculos, have been found to be workable in the past.

Slightly phosphatic, calcareous sandstones of Upper Cretaceous age were found in 1924 northeast of Sabie, about 75 km west-northwest of Maputo (Lourenco Marques) on the left bank of the River Inkomati. The sandstones also contain glauconite, and the possibility of utilizing the rock as a fertilizer was investigated in 1954 by the Servicos de Agricultura. However, no mining appears to have been carried out.

Niger

Phosphorites of Upper Cretaceous age were first recorded in Niger from boreholes drilled by the Service de l'Hydraulique between 1954 and 1955 at Aschia Tinamou, in eastern Niger northeast of Zinder and about 45 km west-southwest of the Massif de Termet [37]. The almost horizontal strata are not known to outcrop, and the occurrences are not of economic interest, although their association with attapulgite-clays suggests a depositional environment similar to that favorable to the development of the phosphate series in Benin and Togo. At Aschia Tinamou, the sedimentary rocks found in the borehole sequence are interbedded with thin beds of conglomeratic phosphorite, often associated with fossiliferous, lenticular limestones.

Phosphatic nodules and pellets showing between 30% and 33% P_2O_5 occur in western Niger in clays of Paleocene-Ypresian age, notably near In Akkar approximately 63 km north-northwest of Tahoua, where a deposit has been worked at a rate of some 1,000 tpy for direct application to the soil. These resources have not been quantified, and production has stopped.

The stratigraphical equivalents of the Late Precambrian Kodjari and Pendjari Groups in Burkina Faso and Benin also extend into the extreme souht-western part of Niger [86]; resources in the Tapoa area along the Niger River are estimated at 1,250 million tonnes with 200 million tonnes of reserves averaging 23% P_2O_5.

Nigeria

Lower Eocene sedimentary phosphate deposits containing between 22% and 32% P_2O_5, but frequently with high percentages of aluminum phosphate, were discovered in 1921 by W. Russ of the Geological Survey of Nigeria, near Ifo Junction and Oshosun, between 43 and 48 km north of Lagos [73]. They are not of economic importance, however, as investigations conducted by the Geological Survey since the Second World War [43] have shown. In the Oshosun area only about 30,000 tonnes of phosphate rock and intercalcated shale, together averaging 1.5 m thickness, with an overburden

of less than 3 m, could be worked economically by open pit methods. Of this total, only 20,000 tonnes of phosphate rock would be available, and the average aggregate thickness of the phosphate section would be about 1 m. Field surveys and a drilling program carried out in 1958 to locate further deposits of phosphate west of the Oshosun-Ifo Junction area have indicated that there are no occurrences of economic value between this area and the Benin border. Total resources exceed a little over 1 million tonnes.

The principal phosphate occurrences are equivalent in age to the important deposits worked in Senegal and Togo, although they are now extensively altered by weathering. In the Oshosun-Ifo Junction area, lenticular phosphate beds assigned to the Ilaro Formation form part of a more extensive succession of almost horizontal Tertiary rocks up to 100 m in thickness. Pittings have shown that their thickness is extremely variable, ranging from only a few centimeters to about 1 m, while the overburden in places may be as much as 15 m. Three (locally four) separate phosphate beds are recognized, of which the uppermost phosphate is the most important and comprises granular and nodular types best developed near Oshosun and Balogun, where it reaches a thickness of nearly 1.3 m.

Laboratory tests carried out by the Anglo American Corporation of South Africa Limited on samples of granular phosphate rock from Ifo Junction have shown that significant increases in grade can be achieved by gravity separation methods.

Senegal

Senegal is a major producer of phosphate rock, currently ranking seventh among world suppliers, and is one of the few sources of high-grade concentrate. Its output in 1983 amounted to 1.3 million tonnes averaging 82% BPL (nearly 38% P_2O_5); most of this was exported to the United Kingdom, India, Greece, and France. Senegal, together with Togo, is the only major producer of phosphate rock in the sub-Saharan region.

Sedimentary phosphate rock occurs at a number of localities in Senegal [85,63]. By far the most extensive deposits are those of the Lutetian (Middle Eocene) age which have been worked since 1960 on Thies Plateau in western Senegal, near Taiba, and to a lesser extent at Tam Tam. Residual aluminum phosphate deposits are also worked at Pallo, near Thies, but at the rate of less than 300,000 tpy. In northeastern Senegal, the Matam (Ouali-Douala) deposits on the left bank of the Senegal River have recently been explored, as have relatively new discoveries of Precambrian and Cambrian age in the southeastern part of the country, notably near Namel south of the Gambia River.

Taiba [25,81,55]

– Phosphate beds were found in 1948 near Taiba about 20 km north-northwest of Tivaouane on the Dakar to St. Louis railway, by the Bureau Minier, shortly after the discovery of deposits farther to the southeast at Pire Goureye. The beds, which lie at the southwestern margin of a phosphate-bearing area of at least 146 km^2, generally contain between 18% and 39% P_2O_5, and prospecting has shown that they fall into three zones. Phosphate mining is confined to the Keur Mor Falls, an area of about 1,000 ha near the location of proven reserves (up to 82% BPL concentrate) of 100 million tonnes which occur to depths of nearly 30 m. In this zone, the phosphate rock contains thin intercalcations of clay and sand as well as lenticles and nodules of flint. It averages 7 m in thickness; an overburden 25 m thick consists mainly of aeolian sands but includes an indurated, porous zone of aluminum phosphate that is sometimes 3 to 4 m thick. Elsewhere the Taiba deposits have a somewhat lower grade and thicker overburden.

Pallo [14,48,31]

– Aluminum-calcium phosphate deposits of secondary origin are worked near the village of Pallo, about 15 km north of Thies. The deposits are known to occur over more than 500 km^2 of the plateau, locally under thick laterite, but only the area north of Thies, including Pallo, Lam Lam, and Tivaouane, has been explored in detail. Deposits of aluminum phosphate in the area average 5 m in thickness and contain at least 28.5% P_2O_5; the reserves are estimated at 90 million tonnes. Reserves of lower grade material are appreciably greater. The aluminum phosphate zone is of variable chemical composition and has a thickness ranging from nearly 3 m in the central part of the plateau near Thies, to 5-70 m in the Pallo area, to a maximum of 30 m north of the Pallo district.

Lam Lam [89]

– In 1945 the Pechiney Company discovered irregular beds of phosphate rock near the village of Lam Lam, about 16 km northeast of Thies and less than 3 km from the St. Louis to Dakar railway. Prospecting by this company in collaboration with the Service Geologique proved reserves of about 4 million tonnes of marketable product averaging 33% P_2O_5 (77% BPL), of which 1.5 million tonnes has an overburden not exceeding 24 m. The principal phosphate bed, selected samples of which contain up to 39% P_2O_5 (85% BPL) and 3.5% SiO_2, ranges from 5 to 8 m in thickness and averages about 7 m.

Matam

– Phosphate occurrences on both banks of the Senegal River have been known for some years. The most important occurrences in Senegal are the

Ouali-Douala (Matam) deposits, which are estimated to contain more than 40 million tonnes averaging 28.7% P_2O_5. Three main sedimentary facies have been established; the argiliaceous phosphatic-dolomitic limestone assemblage contains lenses of phosphate rock that may reach 3 m in thickness. The lenses contain abundant bone fragments, fish teeth, and coprolites.

Other occurrences

- Phosphate has been recorded at many other localities in western and southern Senegal, but only a few of the deposits are of potential economic interest. Beds of Upper Lutetian age interstratified with marls and limestones occur in the Pire Goureye, Gueoul, Mekhe, and Kebemer areas near the St. Louis to Dakar railway between Loaga and Tivaouane. The deposits, which are said to be similar to those at Lam Lam, are relatively uniform in composition with 15%-38% P_2O_5 overlain by sand and sandstones ranging from 3 to 35 m in thickness. At Pire Goureye, some 25 million tonnes of 75% marketable product is estimated to be available, the phosphate bed exceeding 6 m in thickness with 25 m of overburden.

A phosphatic series of Lower Eocene age occurs sporadically in southern Senegal, particularly near Thies, Sebikotane, and Pantior, as well as near Pointe Sarene and southeast of M'Bour. The series contains an upper layer of siliceous phosphatic limestone 0.7-1.5 m thick, averaging 9% P_2O_5. Some of the samples contain more than 32% P_2O_5.

Lutetian phosphatic marls were intersected between depth of 220 and 230 m in an oil exploration well sunk in 1953 by the Societe Francaise des Petroles near Ziguinchor on the Casamance River [36]. Samples analyzed by the Service de Geologie et de Prospection Miniere show up to 10.2% P_2O_5. However, recent studies by the BRGM have revealed the presence of 10 m phosphatic marls averaging 15.7% P_2O_5.

Phosphate rock of Infracambrian age was discovered in southeastern Senegal during a scintillometer survey in the mid-1970s. Subsequent field studies revealed a sequence near Namel which is 3-12 m thick and is exposed over a distance of about 1 km. The phosphates are highly siliceous, and chemical analyses show up to 32% P_2O_5 and from 12% to nearly 45% SiO_2.

Somalia

Sedimentary phosphate rock of Precambrian age is reported to occur in the Bur area of southern Somalia and has been investigated as part of a UNDP project. Carbonatites have been described from various localities, but significant concentrations of apatite have not been recorded. Deposits of phosphatic bird guano on Mait Island, situated about 60 km northeast of the coastal

port of Heis and some 40 km from the mainland near Cape Humbeis, have been worked on a very small and intermittent scale for many years [27]. All of the output has been exported, chiefly to the Saudi Arabian port of Mukalla for use as a fertilizer on the tobacco crops of the Hadhramaut Province. Reserves are negligible, but the supply of guano is being constantly renewed by the numerous colonies of sea birds that nest on the island. Partial chemical analyses by the Mineral Resources Division, London, in 1934 and 1951 on material collected from different parts of the island, gave a range of 10%-28% P_2O_5.

South-West Africa

Phosphatic guano has been produced for many years from the so-called Northern Group of Government Guano Islands situated between Cape Cross and the Orange River and administered as part of South Africa. They annually provide a significant tonnage of guano for sale to Cape Province farmers as fertilizer. Apatitic carbonatites occur northeast of Cape Cross [87,8], and apatite occurs also in carbonatite near Swartbooisdrif on the Cunene River. The carbonatite occurrences appear to have some potential as a source of phosphate in the light of current mining and benefication technology.

South-West African continental shelf [9]

Phosphatic sediments have been found on the continental shelf off South-West Africa, but these are unlikely to be of economic importance in the foreseeable future. Investigations carried out on samples collected off the coast of South-West Africa in 1963/64 have shown that glauconitic sands contain a maximum of 4.1% P_2O_5. In this area glauconitic sediments lie at depths of about 230-300 m, generally in narrow bands in a zone transitional between the shelf and the continental slope, particularly between Luderitz and Walvis Bay and also near Cunene River in the extreme northwestern part of South-West Africa. The sediments generally contain more than 10% glauconite, and locally they may contain 40%.

Sudan

Phosphate rock is said to occur in the Halaib district on the Red Sea coast approximately 300 km north-northwest of Port Sudan [90]. It is probable that the bed lies within the sediments of Late Cretaceous (or Paleocene) to

Recent age that extend along the Red Sea coast of Sudan. The predominantly clastic nature of these sediments and the presence of thick evaporite beds suggest that the phosphate rock is unlikely to be sufficiently well developed to be of commercial interest. However, no systematic evaluation has been carried out.

Apatite occurs in small quantities near Shereik close to the River Nile in the Northern Province of Sudan, about 150 km north-northwest of Atbara in pegmatites that cut schists and slates of basement complex (Archaean age). The pegmatites consist chiefly of quartz and microcline feldspar and contain, in addition to apatite, small amounts of tourmaline, garnet, and beryl.

Tanzania

Significant resources of sedimentary phosphate rock of Recent age occur near Lake Manyara, Mbulu District, and ores averaging 24.6% P_2O_5 have been exploited on a commercial scale since the end of 1982 [84]. Tanzania's State Mining Corporation (Stamineo) is currently mining this ore at the rate of around 165,000 tpy of product averaging about 30% P_2O_5.

Minjingu [84,26]

– Sedimentary deposits situated about 110 km southwest of the railway terminal of Arusha were discovered in July 1956 when an aerial geophysical survey revealed a radioactive anomaly over Minjingu Kopje, a small hill to the east of Lake Manyara. Specimens submitted to the Geological Survey Department were found to be phosphatic, and the occurrence was investigated between 1957 and 1960 by New Consolidated Gold Fields Limited, a wholly owned subsidiary of Consolodated Gold Field Limited. Pitting and drilling completed in 1959 indicated that proved and provable reserves of phosphate rock to a depth of 60 m amounted to 10 million tonnes averaging 20% P_2O_5. Individual phosphate beds range from about 1.3 to 3 m in thickness and become progressively thinner with increasing distance from the hill until they virtually disappear at a maximum distance of 240 m.

Slightly radioactive phosphate deposits have been found also in the area known as 'The Pyramids', low hills situated about 10 km south of Minjingu Kopje. Pitting by New Consolidated Gold Fields Limited during 1959 and 1960 revealed at least two phosphatic beds underlain by soil or silt ranging from 5 to 6 m in thickness. Insufficient work was done, however, to establish the resources present. Around the northern half of Mwembe Hill, compact, soft phosphatic sands are interbedded with varying amounts of silt. The phosphate usually averages 20% P_2O_5.

Chali Hills

– Phosphate deposits similar to those at Minjingu are found in the Chali Hills west of Dodoma, where they form a thin veneer and fill joints in quartzite outcropping on two narrow ridges, that rise above the surrounding lake sediments. Some of the phosphatic material contains 20% P_2O_5, while that found as a thin, discontinuous apron around the lake sediments revealed one layer about a meter thick with less than 5% P_2O_5.

Togo

Togo is one of the smallest and most densely populated countries in Africa. As in the case of Senegal, Togo is a major world producer of high-grade phosphate rock: the output in 1983, for example, amounted to 2.1 million tonnes of concentrate averaging 79% BPL (36% P_2O_5). Nearly all of this was exported, primarily to markets in Western and Eastern Europe. Unlike Senegal, and several other African producers, Togo has not yet embarked on the construction of phosphoric acid/fertilizer facilities as a means of enhancing the value of its natural phosphate resources.

Occurrences of low-grade phosphate rock were discovered in 1952 by the geologist, L.D. Visse, between Akoumape and Animabio; subsequently, a phosphate-bearing zone was proved by the former Societe Miniere du Benin to be over 2 km wide and to extend from northwest of Lake Togo, across the Haho River, and then northeastward to the Benin border, a total distance of over 35 km.

Mining began in the late 1960s; at present two ore bodies, Hahotoe (the 'northern site') and Kpogame, are worked, although the intention is eventually to develop the Dagbati deposit farther to the northeast at the eastern end of the main phosphate-bearing zone. The three ore bodies together are estimated to contain proved reserves of 130 million tonnes of marketable phosphate rock averaging about 79% BPL (about 36% P_2O_5) on a dry basis. Mining is by opencast methods, with giant bucketwheel excavators being used to remove both the clay and sand overburden, which ranges from 7 to 30 m in thickness, and the main phosphate bed.

All of the phosphate occurrences in Togo are of Lower Eocene (Ypresian to Lutetian) age and occur within strata of the Série de la Lama, a series of clays and shales with minor sandstone and limestone beds, dipping imperceptibly toward the southeast [77,45], all forming part of the coastal sedimentary of southern Togo. In the area currently exploited [16,70], there are essentially two phosphate beds separated by phosphatic marls, but only the uppermost bed (Bed 1), which is of Ypresian age, is of suitable thickness and grade to be of commercial importance. The main bed contains abundant fish

remains and is a fine-grained argillaceous phosphorite 2-6 m thick.

Bed 1 is underlain by phosphatic marls, clays, gravels, limestones, and ver thin beds of phosphate rock (Bed 2), in turn underlain by a discontinuou and variable bed of higher grade phosphate rock (Bed 3). These two uni comprise Bed 2/3 which, taken on its own, is too erratic and too thin to b worked at present, although current benefication technology suggests that th bed could eventually be mined and processed.

Igneous phosphate resources

More than 100 carbonatite deposits have been identified in sub-Saharan A rican countries south of the equator and as far north as Kenya in eastern an central Africa. Carbonatites are igneous plugs or intrusions which are gene ally circular in shape. Many of them contain apatite; in Brazil such deposit are a main source of phosphate raw materials. Most of the Africa carbonatites in tropical areas are extensively weathered to a clay-like consis tency. Weathering frees the apatite crystals from the rock and facilitates re covery of high-grade apatite (up to 42% P_2O_5) by beneficiation yielding high quality concentrate. The deposits sometimes contain other valuable mineral such as niobium. Not all carbonatites contain useful percentages of phos phate, and some have not been investigated.

Angola

Age determinations and paleogeographic constructions show that the alkalin igneous complexes of Brazil and Angola may be tectonically related [57]. A least four of the Cretaceous Brazilian occurrences are known to contain phos phates and are under development or actual exploitation. Thus, it may b possible that Angolan intrusives that occur along the same lineament als contain phosphates. Preliminary reports support this conclusion althougl detailed data are not available. In central Angola, apatite is reported to b abundant in parts of the carbonatite centered about 3 miles southwest o Longonjo, but the economic potential of the occurrence has not been evaluat ed.

Burundi

In 1982 the British Sulphur Corporation reported on development work or phosphates associated with carbonatite at Matongo-Bandaga about 40 km north of the capital, Bujumbura. So far, 1,200 m of drilling has established

in excess of 5 million tonnes of phosphate ore. Petrographic and mineralogical studies have identified apatite plus some rare earth mineralization. The associated carbonatite may be used in cement production.

Kenya

Concentrations of phosphate minerals have been found in parts of southern Kenya igneous alkaline ring complexes and their weathering products and, to a minor extent, with basement system (Precambrian) rocks which occupy large areas of the Rift Valley.

Mrima Hill [7]
– The largest phosphate occurrence in Kenya occurs as pyrochlore-containing ferruginous soils covering the Mrima Hill carbonatite about 65 km southwest of Mombasa. Most of the phosphate is accounted for by the presence of the barium aluminum phosphate mineral, gorceixite; chemical analysis of the soil shows an average of 3%-4% and a maximum of 23% P_2O_5. At Mrima Hill the gorceixite is intimately associated with goethite or hematite; apatite is sometimes intergrown with gorceixite.

Subordinate amounts of apatite occur in kyanite-graphite schists (basement system) near Longalonga, about 50 km northeast of Taveta. Larger deposits might be found in the neighboring Longalonga Hill where these schists are better exposed.

Rangwa
– During the 1950s, small accumulations of apatite were discovered by the Geological Survey of Kenya in alkaline ring complexes which are probably of Miocene age. These accumulations form the conical hills of Rangwa near Lake Victoria about 30 km west of Homa; those of Sokolo Point, Tuige, North Ruri, and South Ruri, all lie less than 12 km from Homa. Chemical analyses by the former East African Industrial Research Board of samples of carbonatite from Sokolo Point show a range of 0.46%-5.81% P_2O_5.

Mount Elgon
– Precambrian limestones near Kitale and calcareous tuffs on the southeastern flanks of the Mt. Elgon volcano, northwest of Kitale, have been found to be phosphatic; however, although relatively widespread, the occurrences apparently have not been fully evaluated. The Department of Agriculture surveyed the limestone resources of the area in 1932; the samples collected showed only 1%-4% P_2O_5.

Malawi

Apatite mineralization has been recorded at several localities in southern Malawi, and deposits of potential economic importance are associated with the Tundulu carbonatite complex about 3 km southeast of Lake Chilwa. The remoteness of the deposits and lack of local demand for phosphatic fertilizer have so far limited their exploitation.

Tundulu [33]
– Deposits of apatite on Nathace Hill, in the western part of the Tundulu carbonatite complex, were discovered in 1954 by the Geological Survey Department of Nyasaland. This complex, which is up to 2.5 km in diameter, forms part of the Chilwa Alkaline Province (Upper Jurassic to Lower Cretaceous age) consisting essentially of three separate ring structures. The main deposits occur as lenticular, steeply inclined ring dikes of apatite-rock, apatite-sovite, and apatite-rich bastnaesite-carbonatite of the second ring structure emplaced in feldspathic breccia and agglomerate. The ring dikes have a true thickness ranging from 6 to 60 m, and chip and grab samples of the apatite-bearing rocks showed between 8% and 39% P_2O_5. In deeply weathered zones some of the apatite is partly recrystallized as white fibrous or feathery crystals of francolite similar to that found in weathered apatite-sovite in Uganda.

The Nathace Hill deposits were examined in 1956 by the Anglo American Rhodesian Mineral Exploration Limited as a possible source of phosphate for a fertilizer factory near Harare (Salisbury) in Zimbabwe. The results of pitting by the Geological Survey Department indicated that reserves to a depth of 30 m exceed 800,000 tonnes of apatite-rock containing over 20% P_2O_5, with a further 1 million tonnes of apatite-sovite and apatite-rich bastnaesite-carbonatite with more than 10% P_2O_5. Nearly 500,000 tonnes of feldspathic apatite-sovite with an average P_2O_5 content of about 5% is also available.

Chilwa Island
– The largest of the carbonatite and breccia ring complexes in Malawi contains limited areas on the inner slopes of the Northern Spur and on the Central Cone, which consist of ring dikes of apatite-sovite, with a maximum of 50% apatite, and of veinlets of massive apatite up to a few centimeters thick.

Mlindi [10]
– Apatite occurs in biotite-pyroxenite of the basement complex in the center of the Mlindi ring structure, about 10 km south of Neno, where some speci-

mens contain as much as 30% apatite (about 14% P_2O_5) although the average grade is probably much lower. Samples of alluvial soil overlying pyroxenite near Ligowe showed a maximum content of 2.8% P_2O_5, equivalent to 15.7% apatite, with an average corresponding to nearly 8% apatite. Slightly weathered biotite-pyroxenite near Butao (nearly 2 km south of Ligowe) contains about 12% apatite. Fertilizer was made which consisted of 40% finely ground biotite-apatite rock and weathered material from the pyroxenite, 20% finely ground, hand-picked apatite, and 40% ground dolomitic marble, also obtained nearby. The fertilizer was distributed to various Government experimental stations and to private coffee and tobacco estates for testing.

Mozambique

Apatite occurs in the Muambe complex, in the Tete region of western Mozambique, in carbonatite and feldspathic agglomerates and breccias. The complex has attracted interest as a potential source of pyrochlore.

South-West Africa

Phosphatic guano has been produced for many years from the so-called Northern Group of Government Guano Islands situated between Cape Cross and the Orange River and administered as part of South Africa. These islands annually provide a significant tonnage of guano for sale to Cape Province farmers as fertilizer. Apatitic carbonatites occur northeast of Cape Cross [87,8], and apatite occurs in a carbonatite near Swartbooisdrif on the Cunene River. These occurrences may have some potential as a source of phosphate through use of modern mining and beneficiation technology.

Kalkfeld

– The Kalkfeld, Osongombo, and Ondurakorume (Kameelberg) carbonatite complexes are three of a belt of igneous ring complexes which extend from Cape Cross northeastward for a distance of about 370 km. The trend is roughly parallel to that of the carbonatite complexes in Angola (see previous section). The complexes, which are assumed to be of Late Karroo, probably Jurassic age, lie near the railway station of Kalkfeld, southwest of Otjiwarongo and about 200 km northwest of Windhoek. Chemical analyses show about 6.5% P_2O_5. In addition to apatite, pyrochlore has been found in all three carbonatites, particularly at Ondurakorume, while rare-earth minerals occur at both Ondurakorume and Kalkfeld. Strontianite is a common constituent of the Ondurakorume carbonatite. Iron ore has been mined there,

and the complex is also a potential source of thorium, containing about 0.5% ThO_2.

The Ondurakorume carbonatite situated about 13 km northeast of Kalkfeld, is a small, poorly exposed plug which includes beforsite ring dykes attaining widths of up to 32 m. These often contain abundant segregations and networks of white crystalline streaks of apatite; a fairly representative sample shows an analysis of 10.1% P_2O_5. Sampling carried out by African Metals Corporation Limited in 1964 showed up to 17.3%, with an average of about 7% P_2O_5.

The Osongombo diatreme, about 12 km southwest of Kalkfeld, consists mainly of volcanic breccia but includes a centrally situated weathered carbonatite (beforsite), with microcrystalline aggregates of apatite forming an irregular network of white veinlets locally swelling into apatite-rich bodies about 0.3 m or more in cross section. Quartz is associated with apatite; pyrochlore is a fairly abundant accessory mineral.

At Epembe, southwest of Swartbooisdrif on the Cunene River and approximately 32 km northwest of Chopoho, carbonatite forms a ridge-like body approximately 6 km long and over 400 m wide. Investigations carried out by the Geological Survey of South Africa in 1965 have shown that samples of this deposit contain between 1.79% and 9.21% P_2O_5 and average about 3.5% P_2O_5.

Tanzania

Concentrations of apatite have been reported from Precambrian rocks, and the mineral is an important accessory constituent of carbonatites associated with the Rift System, particularly the Panda Hill carbonatite near Mbeya, where apatite could be recovered as a byproduct of pyrochlore extraction.

Panda Hill [28]

– Apatite and magnetite are common accessory minerals in the pyrochlore-bearing Panda Hill (Mbeya) carbonatite about 20 km west-southwest of Mbeya. The carbonatite is composed mainly of apatite-sovite and prior to 1960 was investigated as a possible source of pyrochlore by Mbeya Exploration Company Limited. Chemical analyses of apatite-sovite showed 5.5% P_2O_5. Resources amount to some 125 million tonnes with 0.3% Nb_2O_5. Phosphate mineralization has also been found in tuffs and pyroclastic rocks of the Rungwe volcanics at the foot of Chamoto Hill, about 50 km east-northeast of Mbeya. The hill is surrounded by lake sediments, including clays, suggesting a mode of occurrence similar to that at Minjingu; however, pitting by the Geological Survey Department failed to find further traces of phosphate.

Morogoro

– An occurrence of weathered apatite-marble was discovered in 1931 by the Geological Survey Department near the Great Ruaha River about 50 km south-southwest of Kisaki, some 110 km south of Morogoro, in basement complex biotite- and hornblende-gneisses [38]. Whether the occurrence is carbonatitic does not seem to have been established, but the marble occurs as a steeply dipping to vertical lens averaging 33 m, but probably ranging up to 41 m, in thickness, with an outcrop length of 1,200 m along the strike. Resources have been estimated at 2 million tonnes per 30 m of depth. Chemical analyses of seven samples show from 3.15% to 10.57% P_2O_5. Beneficiation tests have shown that a concentrate of 25% P_2O_5 can be obtained either by gravity separation or by calcining, slaking, sieving, and washing.

Uganda

Apatite deposits associated with carbonatite complexes probably of Cretaceous age occur in parts of southeastern Uganda, the most important being the residual deposits developed around the Sukulu and Bukusu complexes near Tororo [20,21]. The Sukulu deposits, among the most outstanding examples of their kind, were worked on a commercial scale from 1962 until 1979 for use in the manufacture of single superphosphate. The possibility of rehabilitating the phosphate industry at Sukulu has recently been investigated by a team led by Bearden-Potter Corporation, under World Bank auspices, apparently with encouraging results. The deposits at Bukusu were also worked from 1944 until March 1964; they provided a total of about 58,000 tonnes of low-grade phosphate rock, nearly all of which was transported to Kenya for use in the manufacture of a fused phosphatic fertilizer known as 'sodaphosphate'.

Sukulu

– The economic potential of the apatite in the thick unconsolidated soils, which marginally cover and have been derived from the Sukulu carbonatite complex by intense weathering, was not fully appreciated until 1949/50 when C.E.F. Williams of the Geological Survey of Uganda conducted a search for workable limestone deposits. The complex, which lies about 6 km southwest of Tororo, is some 4 km in diameter and is composed almost entirely of carbonatite (sovite) represented topographically by a circular group of hills. Apatite-rich soils fill three dry re-entrant valleys, designated North Valley, West Valley, and South Valley; the deposits range from 15 m to a maximum of 67 m in thickness. Magnetite and pyrochlore also occur and have been

considered as possible byproducts. The recent studies by Bearden-Potter have indicated resources of 230 million tonnes, comparable to the earlier estimates made in the 1950s by Mackay & Schnellman of 202 million tonnes averaging 11%-13% P_2O_5 and up to 0.36% Nb_2O_5 [65]. Additional resources lie outside the perimeter of the hills investigated.

The Sukulu soil is relatively uniform in composition, containing about 31% apatite, 28% magnetite, 29% hematite, hydrated iron oxides and ferruginous clays, 7% quartz, and minor amounts of ilmenite, zircon, mica, pyrochlore, and baddeleyite. Its extremely fine size and the closely similar physical properties of many of the mineral constituents have presented considerable beneficiation problems. Apatite is contained mainly in the middle size range (minus 52- plus 300-mesh), magnetite in the coarser fractions (plus 100-mesh), and pyrochlore in the very fine subsieve sizes. The beneficiation process previously adopted at Sukulu [30] involved magnetic separation, desliming, and flotation; this yielded a concentrate usually containing more than 40% P_2O_5 (87% BPL) and less than 1% combined Al_2O_3 and Fe_2O_3.

Zaire

Apatite occurs in minor amounts in an alkaline igneous complex in the Lueshe Valley south-southwest of Lake Edward at approximately 1°0'S and 29°8'E. The Lueshe complex [22], which was discovered in 1938, consists chiefly of a plug of pyrochlore-aegirine-sovite (carbonatite) about 1.5 km in diameter surrounded by a ring of cancrinite-syenite. Extensive pitting and trenching operations carried out during the late 1950s by the Societe Miniere de Nyambuku revealed about 30 million tonnes of pyrochlore ore with 1.34% Nb_2O_5, particularly in the thick mantle of ferruginous rock produced by weathering, but plans to produce niobium concentrates have not been implemented. The ferruginous material generally contains between 10% and 25% apatite (4.2%-10.0% P_2O_5), which could conceivably have been removed as a byproduct. Near the summit of Busoro Hill, one of the four hills comprising the Lueshe carbonatite, a considerable thickness of apatite rock occurs between the sovite and an outlier of metamorphosed sediments. Two samples of carbonatite analyzed by the Service Geologique du Congo Belge et du Ruanda-Urundi showed 3.65% and 4.67% P_2O_5, equivalent to about 8.8% and 11.2% apatite, respectively.

Apatite is reported to occur in significant amounts in the Bingo carbonatite complex, situated approximately 110 miles to the north of the Luesche intrusion, and the mineral is present also in Precambrian pegmatites associated with granites that intrude metamorphosed sediments of the Kabara-Urundi and Ruzizi Groups. Many attain considerable size and are worked for

cassiterite, tantalite, and columbite; the most important is the pegmatite worked chiefly for cassiterite at Manono. At present, the apatite content does not seem to be sufficiently high to justify recovery.

Zambia

Apatite and monazite occur as minor constituents in the carbonatite complexes forming Nkombwa Hill, near Isoka in northeastern Zambia, and the Chasweta, Mwambuto, Nachomba, and Kalue Hills in the lower valley of the Rufunsa River near the Mozambique border [5]. At these localities, pyrochlore has been the principal mineral of economic interest. Investigations by the Geological Survey Department of Northern Rhodesia, as well as sampling and drilling between 1955 and 1958 by Chartered Exploration Limited, indicated that significant tonnages of pyrochlore and apatite are probably present at Nkombwa and Kaluwe, but subsequently little interest has been shown chiefly because of the technical difficulties encountered in concentrating and treating pyrochlore. The phosphate potential of some of the complexes is again being investigated by Mineral Exploration Department (Minex) of Zimco, Ltd.

Nkombwa

– Apatite is relatively widespread at Nkombwa Hill, almost 25 km east of Isoka. The deposit was identified as a carbonatite in 1952 by the Geological Survey Department of Northern Rhodesia. The complex, which is part of the late Proterozoic North Nyasa alkaline province, intrudes basement complex granite-gneisses, schists, and quartzites. Two samples of transported soil from the northeast corner of the hill were analyzed by the Mineral Resources Division, London, and found to contain 3.25% and 7.98% P_2O_5, corresponding to about 8% and 19% apatite, respectively. Some of the residual soils on Nkombwa Hill appear to contain higher percentages of apatite.

Resources have been estimated at 500 million tonnes averaging 7.7% P_2O_5, but since much of the phosphate present at Nkombwa is in the form of isokite [68], a white or pinkish spherulitic fluorophosphate of calcium and magnesium, beneficiation would be a serious problem. A peculiar green cryptocrystalline variety of monazite also occurs.

Kaluwe

– Apatite is present in each of the four carbonatite structures (Kaluwe, Nachomba, Mwambuto, and Chasweta) discovered since 1956 in the Rufunsa Valley approximately 190 km east of Lusaka. Kaluwe, the largest and most accessible of the intrusions, is a sheet-like body or sill with a sur-

face area of 12.5 km^2 and nearly 250 m thick in the center. Resources are estimated at 200 million tonnes of low-grade ore; samples show a range of 2.8%-11.0% apatite (1%-4% P_2O_5). In a middle zone up to 10% apatite is present, and narrow bands may sometimes contain as much as 50% of the mineral. Bulk samples of the overlying residual soil have shown from 1.6% to 16.5% P_2O_5, with an average of 9.8% P_2O_5; the finer soil fractions (passing 20-mesh) contained between 3.8% and 17.0% P_2O_5, with an average of 9.5%. Significant tonnages are believed to be present.

Details about the mode of occurrences in Chasweta are lacking, but apatite-rich bands occur at Nachomba and Mwambuto and are up to 0.6 m thick at Mwambuto.

Chilembwe and Mumbwa North

– Concentrations of apatite have been found recently within syenite intrusions near the village of Chilembwe in Eastern Province (about 450 km east of Lusaka) and also near Mumbwa, situated 150 km east of the capital. Near Chilembwe [64], several lenticular bodies all trending north-northwest south-southeast have been delineated by pitting and trenching; preliminary estimates indicate the presence of between 1 million and 2 million tonnes containing 10%-15% P_2O_5. Similar bodies have been located at the Mumbwa North prospect, but it is not yet known whether apatite occurs there in potentially economic quantities.

Zimbabwe

Apatite deposits in the Dorowa carbonatite complex have been worked since 1965 to supply the fertilizer factory at Rodia, near Harare. Apatite associated with magnetite, vermiculite, and mica also occurs in the carbonatite complexes of Shawa, 16 km south-southwest of Dorowa, and Chishanya, some 80 km to the southeast. The three complexes lie in the upper Sabi Valley to the south-southeast of Harare, where they intrude granite-gneisses of Precambrian (basement complex) age [61,42].

Dorowa

– The Dorowa igneous complex is about 3 km long from north to south and about 1.5 km wide and comprises an outer zone of syenitic fenite surrounding central areas of ijolite. All the rocks are cut by small masses of carbonatite and by dikes and veins containing apatite, magnetite, serpentine, and vermiculite. Weathering and decalcification extend to depths of 60-120 m. The ore is thus a weathered product and consists of a reddish-brown soil or clay matrix mixed with fragments of igneous rock, containing up to 20% apatite.

Two ore bodies corresponding to areas of biotite-apatite mineralization have been delineated. Drilling and pitting carried out between 1952 and 1956 by the Anglo American Corporation of South Africa Limited to a depth of 122 m indicated that total reserves were about 37 million tonnes containing an average of nearly 8% P_2O_5. The southern ore body, which constitutes the main reserve, is associated with veins and disseminations of biotite-apatite rock that cut and replace fenite and ijolite with a tabular mass of magnetite-apatite rock 61 m long, 20 m wide, and about 1.2 m thick in the northeastern part of the mineralized zone.

Shawa

– The Shawa igneous complex lies about 16 km south-southwest of Dorowa, between the Mworshare and Mrove Rivers. It has a diameter of nearly 6 km and consists largely of a plug of serpentinized dunite enclosed by arcuate bodies of ijolite and an outer zone of fenite. Pale green apatite is a common accessory mineral of the ijolites, occurring as crystals or as fine-grained granular masses; in places there are concentrations composed of irregular pods of apatite-rich ijolite. Preliminary exploratory work has indicated that possible reserves amount to 12 million tonnes of weathered rock and soil in the ijolite zone to a depth of 2 m containing an average of 2.6% P_2O_5, with a further 6 million tonnes of soil overlying dunite to a depth of 4 m with 4.9% P_2O_5.

Chishanya

– Apatite occurs as knots, dissemitions, and veinlike bodies in carbonatite of the Chishanya alkaline igneous complex, situated about 80 km southeast of Dorowa. The complex comprises three carbonatite plugs. A specimen of carbonatite from the most northerly plug forming Bepe Hill contained about 7.5% P_2O_5 as fine-grained apatite. Reserves of carbonatite are said to be considerable.

Uses of phosphate resources

IFDC has expertise in using poblem ores even when the deposits or demand is too small for a large conventional plant; some way often can be found to adapt indigenous ores to local needs. Each phosphate deposit tends to present different problems so it may be difficult to devise general methods that will benefit many countries. Direct application of ground phosphate rock may be particularly useful for some countries and is a good alternative for ores that are unsuitable for chemical processing.

IFDC assists countries in the evaluation and use of their indigenous deposits of phosphate rock. Phosphate resoures are widespread in Africa and repre-

sent a primary nutrient resource that can often be used with little processing. Surveys have shown that Africa has large areas covered by infertile Oxisols and Ultisols. Phosphate is considered the most limiting nutrient on many of these soils. IFDC has been working and continues to work with various international and national groups in evaluating indigenous phosphate ores and products made from them in increasing the fertility of such soils. Results from technical, agronomic, and economic studies have identified methods of using these local resources as phosphate sources on some of these infertile acid soils.

The evaluations usually begin with a detailed mineralogical, petrographic, and chemical study of a representative sample of each ore type occurring in a given deposit. The chemical and mineralogical studies indicate the principal constituents in the ore and their mode of occurrence. These data establish the phosphate grade of the ore and its chemical quality based on the nonphosphatic constituents present. These factors suggest alternative uses such as:

(1) direct application; (2) acidulation to produce phosphoric acid of finished products, including partially acidulated phosphate rock (PAPR); and (3) the production of thermally altered phosphates, including fused magnesium phosphate, Rhenania phosphate, and defluorinated phosphate.

In many cases the run-of-mine (ROM) ore is considered for use in production of fertilizer intermediates and products. If, however, this is not possible, the mineralogical data are combined with rock texture studies to determine the type and degree of beneficiation that is needed to provide an acceptable phosphate concentrate. These studies determine the kind and amount of grinding needed to liberate the phosphate from the impurities prior to application of beneficiation processing. Phosphate value can often be recovered from most of the difficult ore types (calcareous and dolomitic ores, siliceous ores, and high iron-aluminum ores).

The goal of these activities is to produce concentrates that are acceptable in grade and quality with the highest recovery possible using the simplest applicable technology. Variations in rock characteristics often require the development of a specific process flowsheet for each ore. Local conditions, such as water resources and fuel availability, are also considered when developing a beneficiation flowsheet.

After an acceptable concentrate is prepared, process performance data are needed to design plants for its use or to predict its performance in existing production units. Actual rock test performance data for the preparation of mineral concentrates, phosphoric acid, and fertilizer products should be collected in suitable laboratory or pilot-scale units as part of an organized development program.

Problem identification

The identification of phosphate as the major nutrient deficiency in large areas and its availability in numerous local geologic occurrences have resulted in an initial emphasis on raw materials studies that use these indigenous phosphate resources. There has been increasing interest in processing these phosphate raw materials that may contain higher than usual levels of impurities because of their ready availability and normally lower cost. Such studies were largely academic before 1973 because the international market had an adequate supply of high-quality, rather inexpensive ore. When substantial price increases occurred, many countries began exploration and development programs to discover new occurrences and expand the technical capability to beneficiate and process ores with lower grades and quality. Several of these programs were successful, and a number of developing countries located new resources or expanded the knowledge of previously known, but unexploited, deposits.

The combination of the new discoveries and the expansion of mine output from existing deposits has created the oversupply of phosphate raw materials in the international market. Nevertheless, developing countries continue to place a high priority on developing their indigenous resources, particularly those countries with a substantial domestic requirement or regional market potential.

Developing countries have several reasons for opening new deposits even when there is a surplus supply on the world market. There is a natural nationalistic desire to be independent of foreign sources; these countries have not forgotten the lessons learned during the shortages of 1973/74 when they were at the mercy of major international suppliers. Domestic production can also provide savings in high-value foreign exchange and increase local employment. Although world market prices have declined, they still remain higher than the pre-1973 levels, and international loans still have high interest rates that add to the costs. Transportation costs is a major factor affecting phosphate raw material costs. Transportation costs for indigenous ores may be lower than for imported rock and are not subject to variations in fuel costs and international freight rates. Collectively these factors are used to justify the economics and desirability of developing an indigenous deposit.

Exploitation of these new deposits and new ore types may present some problems in mining, beneficiation, and conventional processing. IFDC's experience with phosphate ores from developing countries has identified a few general characteristics that distinguish them from the ores most marketed in international trade. In Africa, most of the smaller ore deposits occur in rather old geologic terrains that often are far from the coasts. This limits their potential for development for export and dictates a local or regional use. Often

the economic portions of the deposits are restricted to the weathered zones of ore that occur where meteoric water has altered the deposit to leave a residual, enriched ore. This natural beneficiation process can produce ore that can be used 'as is', and thus it has a significant impact on the economic development of certain deposits. The apatite minerals in these ores have a narrow range of composition and often have low agronomic and chemical processing reactivities. Also, these ores and their overburdens may be hard and massive and require hard-rock mining techniques (such as blasting) that contrast with the methods often used by large international producers. The ores produced may be well-indurated rocks that require high grinding costs (15-20 kWh/tonne compared with about 10-12 kWh/tonne for most rocks) and high enrichment ratios in order to produce acceptable concentrates. However, concentrates and some unbeneficiated ores have good processing characteristics because of their low organic carbon and carbon dioxide content, low acid consumptions, and low corrosion potentials.

Characterization of ores

Carbonate fluorapatites are the most important source of phosphate in commercial ores; therefore, the characterization methods described will concentrate on this ore type. It is likely that a similar detailed study of the other classes of phosphate minerals would reveal systematic relationships in their compositions and properties.

This presentation summarizes the methods developed and used to examine apatite-containing ores from a large number of phosphate deposits in sub-Saharan Africa. The examinations were made by chemical analysis, x-ray powder diffraction, and polarized light microscopy. A rapid, preliminary characterization suitable for broad classification of samples can be made by using these techniques [59].

Of the more than 25 elements that have been reported to occur in fluorapatites (Table 2), most are present in minor to trace amounts; the apatites containing them are usually from igneous or metamorphic sources. As shown previously [53,58], however, the compositions of carbonate fluorapatites in sedimentary phosphate rocks can be closely approximated by their contents of CaO, Na_2O, MgO, P_2O_5, and CO_2. Extensive reports of analytical data collected on the apatites in phosphate rocks have been included in earlier related publications.

This evaluation scheme has been applied to a series of phosphate rock samples to demonstrate how their physical and chemical quality factors can be rapidly estimated. The samples were selected to represent both well-known sources and some more recently developed deposits from this region.

All are authentic concentrates or ores but are not necessarily representative of current production.

The compositions of these phosphate rocks are compared in Table 3. For simplicity, only the main constituents are included here. These analyses immediately reveal the chemical quality of individual raw materials with respect to P_2O_5 content and their contents of undesired chemical impurities. However, such comparisons based on chemical composition give no direct indication of their potential for further upgrading to improve their chemical quality and acidulation performance.

Sedimentary apatites have been shown [53,58] to have compositions that can be represented quite adequately by the series with the following end-member empirical formulas:

$$\underset{\text{(fluorapatite)}}{Ca_{10}(PO_4)_6F_2} \rightarrow \underset{\text{(francolite types)}}{Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_{0.4x}F_2}$$

These correspond to the chemical composition shown in Table 4.

After the composition of the apatite is established, these data can be combined with the chemical analysis of the rock to evaluate the significance of constituents other than P_2O_5. The primary objective here is to determine how certain key impurities are distributed between the apatite and gangue-mineral fractions. From this, one can determine the potential benefits of further upgrading by physical methods to improve the chemical quality of the phosphate raw material.

This approximation is illustrated using as an example the Mekrou, Benin,

Table 2 Substitutions in the apatite structure

Fluorapatite $Ca_{10}(PO_4)_6F_2$	
Constituent ion	Substituting ion
Ca^{+2}	Na^{+1}, Sr^{+2}, Mn^{+2}, K^{+1}, U^{+4} Mg^{+2}, $RE^{+2,+3}$ (lanthanons and yttrium)
P^{+5}	C^{+4}, S^{+6}, Sr^{+4}, As^{+5}, V^{+5} Cr^{+6}, Al^{+3}
F^{-1}	CH^{-1}, Cl^{-1}
O^{-2}	F^{-1}, OH^{-1}
Francolite $Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_{0.4x}(F,OH)_2$	

Table 3 Chemical analyses of sub-Saharan phosphates[a]

Location	P_2O_5	C.S. P_2O_5[b]	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	Cl	F
	(wt %)									
Igneous Deposits										
Sukulu, Uganda[c]	37.9	1.2	49.5	0.80	0.80	0.04	0.39	0.21	0.006	1.9
Chilembwe, Zambia	17.1	1.4	30.5	1.0	5.0	8.3	–	0.11	0.44	0.9
Dorowa, Zimbabwe[c]	33.1	0.7	50.2	0.58	2.6	1.0	0.76	0.08	0.007	1.6
Sedimentary deposits										
Cabinda, Angola	37.0	4.5	51.0	2.0	0.4	0.11	0.82	0.04	0.006	4.0
Mekrou, Benin	29.3	1.9	41.5	0.8	1.0	0.01	0.09	0.03	0.005	2.8
Kodjari, Burkina Faso[c]	25.4	2.3	34.5	3.1	3.4	0.27	0.11	0.23	NA	2.5
River Delta Congo	32.9	7.0	52.6	0.1	0.7	0.43	1.2	0.02	NA	3.8
Tilemsi, Mali[c]	28.6	4.2	41.4	2.1	6.1	0.52	0.37	0.10	0.007	3.1
Unknown, Mozambique	30.3	NA	45.0	0.3	0.4	0.45	0.78	0.03	0.018	0.6
Parc W, Niger[c]	28.5	2.6	39.9	1.0	1.9	0.03	0.13	0.04	0.004	1.5
Tahoua, Niger	28.0	1.5	43.9	2.1	13.0	0.20	NA	NA	NA	3.8
Matam, Senegal[c]	28.7	4.5	44.4	1.8	2.0	1.60	0.36	0.09	0.005	3.3
Taiba, Senegal	37.4	3.1	51.2	1.0	1.0	0.06	0.20	0.06	NA	4.0
Thies, Senegal[d]	32.0	12.0	9.3	30.9	12.4	0.04	1.9	0.04	0.005	0.7
Minjingu, Tanzania	29.0	5.6	41.7	1.2	0.9	3.20	1.3	0.78	NA	3.1
Hahotoe, Togo[c]	35.7	3.1	52.6	0.8	1.3	0.10	0.20	0.04	0.03	3.9

Table 3 Continued

Location	S	CO_2	SiO_2	$(Fe_2O_3+Al_2O_3)$ P_2O_5	$(Fe_2O_3+Al_2O_3+MgO)$ P_2O_5	CaO/P_2O_5
	(wt %)					
Igneous deposits						
Sukulu, Uganda[c]	0.02	0.30	6.0	0.04	0.04	1.31
Chilembwe, Zambia	–	0.8	30.2	0.35	0.83	1.78
Dorowa, Zimbabwe[c]	0.05	5.4	5.4	0.10	0.13	1.52
Sedimentary deposits						
Cabinda, Angola	0.46	2.2	1.1	0.06	0.07	1.38
Mekrou, Benin	< 0.1	1.3	22.6	0.06	0.06	1.42
Kodjari, Burkina Faso[c]	0.04	1.0	26.2	0.26	0.27	1.36
River Delta Congo	0.92	5.3	0.4	0.02	0.05	1.60
Tilemsi, Mali[c]	0.33	2.4	9.4	0.29	0.30	1.45
Unknown, Mozambique	0.22	5.0	0.1	0.02	0.04	1.48
Parc W, Niger[c]	0.04	1.2	25.2	0.10	0.10	1.40
Tahoua, Niger	0.20	1.1	7.9	0.54	0.55	1.57
Matam, Senegal[c]	0.22	2.9	12.9	0.13	0.19	1.55
Taiba, Senegal	0.10	1.7	2.9	0.05	0.06	1.37
Thies, Senegal[d]	0.05	0.4	2.3	1.26	1.26	0.33
Minjingu, Tanzania	< 0.1	3.1	9.4	0.07	0.18	1.44
Hahotoe, Togo[c]	0.18	2.1	3.7	0.06	0.06	1.47

[a] Analyzed by IFDC.
[b] Citrate solubility measured in neutral ammonium citrate solution.
[c] Used to prepare IFAD experimental materials.
[d] Iron-aluminum phosphates.

rock sample (Table 5). The analysis demonstrates the potential advantages of further beneficiation. The removal of the silica would produce a high-grade concentrate, but the costs of this benefit must be considered carefully. Phosphate losses that occur during ore preparation and beneficiation must be added to the beneficiation processing costs.

Once established, francolite and apatite compositions provide an opportunity to test the quality of the phosphate concentrates. This is illustrated (Table 6) where the theoretical P_2O_5 of the apatites is used to determine the ratio of phosphate to gangue in the samples. This comparison immediately reveals differing degrees of beneficiation with respect to the mineral impuri-

Table 4 Comparison of fluorapatite and francolite compositions

Constituent	Fluorapatite	Francolites
(%)	(x = 0)	(x/6 = 0.30[a])
CaO	55.6	55.1
P_2O_5	42.2	34.0
CO_2	0	6.3
F	3.77	5.04
Na_2O	0	1.4
MgO	0	0.7

[a] Maximum degree of substitution found and predicted for francolite-type apatites.

Table 5 Modal analysis of chemical constituents in sample of Mekrou, Benin

Constituent	Francolite (Theoretical)	Phosphate rock	Apatite[a] fraction (78%)	Gangue[b] fraction (22%)
		(wt %)		
CaO	55.5	41.5	39.2	2.25
P_2O_5	39.5	29.3	28.3	1.0
CO_2	2.0	1.3	1.1	0.2
F	4.1	2.8	2.8	–
Na_2O	0.35	0.09	0.09	–
K_2O	–	0.03	–	0.03
MgO	0.17	0.01	0.01	0.01
Al_2O_3		0.81		0.81
Fe_2O_3		1.0		1.0
SiO_2		22.6		22.6

[a] Estimated amounts; derived from the P_2O_5 of the francolite.

[b] Includes all nonphosphate diluents such as quartz (22.6%), goethite (1%), variscite (1.2%), and crandallite group (0.86%).

ties and its implications regarding the chemical quality of concentrates. Note that the gangue-mineral fraction ranges from 4% to 59%, indicating that their respective potentials for further physical upgrading range from small to large.

Mining factors

In determining the mineability of a low-value mineral such as phosphate rock, it is necessary to consider a number of technical and economic factors simultaneously. The difficulty in making a practical assessment of minability is that no one factor is absolute. For each deposit there exists a unique combination of factors that determines whether mining is both technically and economically feasible. Phosphate deposits differ so much in their geological settings and ore characteristics that nearly identical conditions rarely, if ever, exist.

From the case histories of successful mine operations, however, it is possible to establish some limits on the flexibility of factors that permit economic mining under current conditions. At present, this usually requires high-volume removal of waste overburden plus ore, large annual tonnage output,

Table 6 Mineralogical composition of some sub-Saharan phosphate rocks

Source	Apatite[a]	Gangue
	(wt %)	
	Igneous rocks	
Sukulu, Uganda	90	10
Chilembwe, Zambia	41	59
Dorowa, Zimbabwe	78	22
	Sedimentary rocks	
Cabinda, Angola	96	4
Mekrou, Benin	74	26
Kodjari, Burkina Faso	65	35
River Delta, Congo	93	7
Tilemsi, Mali	74	26
Unknown, Mozambique	72	28
Parc W, Niger	73	27
Tahoua, Niger	72	21
Matam, Senegal	79	4
Taiba, Senegal	96	25
Minjingu, Tanzania	75	8
Hahotoe, Togo	92	

[a] Weight % apatite = actual P_2O_5 (theoretical P_2O_5 100% apatite).

high recovery efficiency, and upgrading to prevailing market-grade specifications. Some deposits require little or no overburden removal or beneficiation. Such favorable conditions can make small tonnage output profitable, especially when inexpensive local labor is available.

The basis for assessing the mineability can change rapidly with time. In recent years, for example, minimim ore-grade limits have decreased from about 18% to less than 10% P_2O_5; processing plants accept a wider range of concentrate grades, and market values of products have advanced. No permanent significance can be assigned to the limits of variability in the factors that define mineability under present conditions.

Some of the major factors that affect mineability are the geological character of the deposit, ore-to-waste ratio, mining methods applicable, ore quality and grade, concentration ratio, recovery efficiency, and mine-to-mill transportation. Any of these factors can change a phosphate deposit from economic reserve to noneconomic resource as well as substantially influence the "average mining cost" of a deposit. For a more complete discussion of these factors, see Lehr and McClellan [52].

In the extensive literature on phosphate mining, little has been published on direct mining cost for current extraction methods. One does find occasional reference to cost data, but it is usually an estimate based on fragmentary data or an average over broad cost ranges. Neither basis has much practical value as an economic guideline.

In a U.S. Bureau of Mines (USBOM) survey, Service and Peterson [75] concluded that no direct mining costs are available although inferences can be drawn by evaluating various phases of the total operation. No real significance can be attachted to such "average mining costs" because of the wide variation in direct costs from mine to mine.

Some comparative mining costs, which are now out of date, were reported by Ruhlman [72] and provide one of the few examples of published cost figures. In 1967 the USBOM estimated an average cost of $1.39/tonne of surface-mined rock delivered to the mill [75]. Everhart's 1971 estimate of direct mining costs of $1-$2/tonne of ore recovered included this earlier figure. The low costs are still applicable to some mining operations. In 1979 Sheldrick and Stier [76] estimated the cost for producing phosphate rock under various conditions (Table 7). These figures were comparable to the $12.95/tonne of concentrate calculated by Russell [74] for phosphate rock. About one-fourth to one-sixth of these estimates was direct mining cost; the remainder applied to transportation, milling, beneficiation, and fixed overheads. Underground mining costs were stated to be in the range of $4-$5/tonne in 1958 and have probably increased fivefold in the past 25 years. In 1973, Allsman and Yopes [1] stated that the average cost per cubic meter of nonmetal materials mined was $5.18. If an average concentration ratio of 3:1

is assumed, the figure of $15-$20/tonne seems to fit the mining industry average. A 1983 study in West Africa established a mining cost of $2.60/tonne of an ore with a total cost of production of $31/tonne of concentrate (IFDC unpublished data).

Beneficiation factors

Various technical methods are used to upgrade phosphate ores to acceptable concentrates. The beneficiation requirements for any given mill operation are largely determined by ore characteristics and specifications of the concentrates. The limits of commercial beneficiation are usually restricted by economics rather than technical capability. Satisfactory upgrading methods exist for virtually every known ore type, but for some the costs may be too prohibitive, the process too complicated, or the recovery too low to be of any practical significance.

Since no standard scheme of beneficiation applies to all phosphate ores, no universal average cost can be calculated. Beneficiation processes often are developed to process the ore at a given cost per unit of product and are not optimized. Beneficiation costs vary with the combination of factors that affect the processing of the ore (hardness, texture, mineral composition), the required enrichment ratio, and overall recovery ratio.

Numerous beneficiation techniques that are used in commercial processes have been described in the literature [72,12] and are briefly summarized here. Physical beneficiation, including grinding, wet- of dry-sizing, desliming, washing, and air classification, is the simplest and most widely used technology. More sophisticated and expensive technologies involving flotation may be required by ores needing high concentration ratios. Expensive thermal treatment may be required to alter the physical or chemical properties of some ores.

Beneficiation technology is used to separate the phosphate from undesirable accessory minerals that dilute the ore. The major ore types that require beneficiation are those with high contents of silica, carbonates, and clays. Because of the variable properties of phosphate ores, combinations of beneficiation steps may be required to produce acceptable concentrates of the quality and grade desired with acceptable recovery rates of phosphate from the process. These variable combinations of beneficiation processes make a general evaluation of costs difficult. An acceptable cost for beneficiation will often equal the cost of mining the ore (Table 7). At the West African site mentioned in the previous section, beneficiation costs were nearly 10 times the mining costs. If calcination is required, another $3-$4/tonne or more in costs will be added to the beneficiation process.

In summary, benenficiation costs are essentially process specific and are difficult to evaluate as industry averages because of the variable nature of the ores treated. There is a general need for such data, but there are inherent risks in using the data too strictly.

Types of ores

Phosphate ores usually are considered difficult to process if they present problems in the production of wet-process phosphoric acid. The general term applied to such materials is 'low-grade' phosphate, although many of the processing problems encountered are not directly related to the phosphate content of the rock itself. During the 1970s, workers in the fertilizer field began to recognize that a number of physical and chemical factors other than phosphate grade could be related to problems encountered in processing ores [44,60] (Table 8). These factors are largely the result of the diversity of geological settings in which phosphate ores are found. Igneous rocks provide about 15% of the world's phosphate production as apatites; most of the remainder comes from sedimentary sources, although metasediments can be important locally. In all rock types the sources of chemical impurities are isomorphous substitutions in the apatite structure (primarily divalent cations, carbon dioxide, and minor amounts of oxy-metal anions) and impurities derived from accessory minerals remaining in the ore. Although the list of

Table 7 Estimated investment and production costs for phosphate rock[a,b] (1984 U.S. dollars/annual tonne)

	Developed site	Undeveloped site
Plant investment	64.4	244.1
Working capital	4.4	6.4
Investment	68.8	250.5
Mining	7.2	7.2
Beneficiation	9.3	9.3
Other (storage, laboratory, administration, etc.)	3.6	3.6
Operating costs	20.1	20.1
Depreciation	3.3	12.1
Transportation and loading	3.6	8.6
10% Capital charge	6.9	25.0
Production cost	33.9	65.8

[a] Three million tonnes per year of product using a low-grade ore with low recovery and high processing requirements.

[b] After reference [12], Table 6-6.

reported contaminants is long. iron, aluminum, and magnesium are the most important in ores that are chemically processed. The iron and aluminum are usually derived from the weathered oxides, hydroxides, or clay minerals; the magnesium occurs in the apatite as well as associated clay minerals and carbonates.

Thus, Kouloheris [46] was able to make a definite distinction between low-grade and low-quality phosphate rock. Low-grade rock (27.5%-28.9% phosphate or 60-63 BPL) is diluted with inert material such as quartz sand, but chemical impurities such as iron, aluminum, and magnesium are within acceptable processing limits. Low-quality rock also may be low in phosphate grade, but the impurity levels of iron, aluminum, and magnesium are great enough to adversely affect the processing chemistry and product quality. Because most chemical impurities are derived from the accessory minerals, concentrates and ores with lower phosphate grades aremore sensitive to impurity problems. Lehr [51] has shown that the tolerance levels for the major chemical impurities mentioned above decrease linearly with declining grade. Thus, beneficiation requirements on the iron, aluminum, and magnesium contents of concentrates become stricter as the quality and the grade of the feed ore decline (Table 3).

The common problem ores are siliceous, high in carbonate, or high in iron and aluminum. However, many problem ores contain combinations of impurities that cause them to be included in more than one category. Siliceous ores may be difficult or expensive to beneficiate. The silica is usually present in an unreactive form (quartz in most cases) which causes no special problems in plants designed to handle such ores. Usually the costs of using unbeneficiated ore, partially beneficiated ore, or fully beneficiated ore (minus the losses of phosphate incurred during beneficiation) are compared with the additional handling and equipment costs. Often the final economic decision depends on the cost of transporting the low-grade ore in comparison with the cost of extensive beneficiation.

Table 3. Chemical quality of phosphate rocks

1.	P_2O_5 grade (28%-42%)
2.	$CaO:P_2O_5$ ratio (1.32-1.61 in apatites)
3.	$(Fe_2O_3 + Al_2O_3):P_2O_5$ ratio < 0.10
4.	$MgO:P_2O_5$ ratio < 0.022
5.	$(Fe_2O_3 + Al_2O_3 + MgO):P_2O_5$ ratio < 0.12
6.	$F:P_2O_5$ ratio < 1.05
	Chlorine content (< 300 ppm)
8.	Uranium (average about 100 ppm)
9.	Toxic elements (Cd, As, Fe, Pb, Cr, Hg ≥ 10 ppm)
10.	Micronutrients (Cu, Zn, Mn variable ppm levels)

Ores high in calcite and/or dolomite are estimated to make up about 75% of all sedimentary phosphates. These ores consume acid and cause undesirable foaming during acidulation. Magnesium derived from dolomitic ores is particularly troublesome in the production of phosphoric acid and related products. Processing economics often depends upon the cost of the extra acid consumed compared with the cost of beneficiation. For many years calcination followed by slaking to remove the oxides was the only practical treatment to enrich these ores. Calcining requires substantial fuel, and this is a serious drawback in most countries. Over the past 10-15 years, a variety of flotation processes have been developed, and a few are used in commercial plants [39,49].

Ores with high contents of iron and aluminum may contain the impurities as phosphates or nonphosphates (such as silicates, oxides, hydroxides, or sulfides). The ores that contain aluminum phosphates can be converted into effective agronomic phosphate sources by calcination and grinding (for example, Phospal in Senegal), but they are difficult to process chemically. The most successful chemical treatments are solubilization with nitric acid and removal of the soluble iron and aluminum by ion exchange. The iron and aluminum present as accessory oxides, hydroxides, and silicates in concentrates can cause poor physical properties and undesirable precipitates in acidulated products.

Other impurities, such as chlorides, organic matter, and heavy metals, can also cause problems in processing ores. In some cases the problem constituent offers an advantage — for example, the fuel value of associated organic matter that is burned during calcination of a phosphate. Chloride problems often are minimized by a simple countercurrent washing process or by leaching in piles.

Transportation factors

Transportation factors that contribute to higher selling costs of mine concentrate include: (1) movement of the extracted ore from mine to concentration plant, (2) transport of concentrate products to conversion plants or transportation terminals, (3) transport of intermediate products to markets or final product conversion sites, and (4) transport of inflowing supplies, plant equipment, fuel, chemicals, and related material needs to the various plant sites. Transportation costs can impose such rigid limitations on economic evaluations that most authorities consider transportation problems as a critical step in the evaluation of phosphate resources, and it may be the single overriding factor despite other favorable aspects of the deposit.

Freight becomes a major cost factor because of the low unit value of the

phate, \$0.05-\$0.15/kg of P_2O_5. The fact that virtually all commercial deposits competing in international trade are located within 100 km of deepwater seaports points to the importance of location and transportation. High-grade ores that are cheaply mined and require little or no beneficiation can partially compensate for an otherwise unfavorable location. The recent shutdown of a production unit in Queensland, Australia, represents an example of the changing infuence of transportation on the economic viability of a large deposit.

Another possible solution to transportation problems is to ship value-added products or intermediates manufactured at or near the deposit. This onsite production may use unbeneficiated or partially beneficiated rock to produce a more concentrated product resulting in additional cost saving. The unique combination of transportation factors that exist for each deposit will dictate which scenario has the greatest economic potential.

The profitability of a phosphate deposit is determined largely by its location with respect to domestic or international production facilities and markets and by the distance and modes of transportation available. Transportation costs per kilometer can vary from a low of \$0.0015/tonne for backhaul ocean shipping to \$0.16/tonne by truck or rail in developing countries. Changing energy costs and inflation can substantially alter these prices. Transportation factors often favor deposits located near the coasts with available export markets while restricting their domestic market to areas immediately adjacent to the production site. Similarly, these factors can also restrict the export markets for interior deposits and confine their production to local or regional markets. The solution of transportation problems has been and will continue to be crucial to the exploitation of major deposits in Africa, South America, Mexico, and Australia.

The investment cost estimates for phosphate mines (Table 7) show that in the two case studies transportation can account for 22% of the rock production cost at an undeveloped site; at a developed site, transportation may be about 13% of the production costs. In an actual analysis of two rock production sites in West Africa, the differences are even greater. An analysis of the rock costs showed that the mining costs at the two sites are the same (about \$10/tonne), but the transportation costs from site A are three and one-half times greater than from site B; the transportation from site A is 85% of the production cost versus 60% of the production cost at site B. Distance and road conditions can limit the usable truck size, and this affects the delivered costs per tonne. The importance of transportation in the economics of processing indigenous phosphate ores cannot be overemphasized. In this example, two ores that are rather similar can thus be separated into acceptable and unacceptable types on the basis of their relative transportation costs.

Conclusions

Sub-Saharan Africa has a large number of known phosphate occurrences as indicated in the preceding text. However, both the quality and the quantity of information describing these occurrences are highly variable. In a few cases the information describing the geology, mineralogy, petrography, chemistry, resources and reserves, and mineral processing is complete. In the remainder, the descriptions are often fragmentary and concentrate on single features that provide little information on the economic geology (composition and size of the deposits, for example) that is so important in the deposit's exploitation. The lack of professional and financial resources has often prevented many of these countries from inventorying important mineral deposits that could be used to meet the food requirements of a growing population.

There is also a significant potential to discover new phosphate occurrences in this vast area. Only a few of the many sedimentary basins have been investigated. These would include a number of Precambrian and Infracambrian basins as well as more than 20 identified Phanerozoic basins [13]. Additional resources should also be found in the offshore deposits (similar to the Congo river delta and Walvis Bay deposits) and previously under- or uninvestigated igneous occurrences.

Ore production from some of these deposits may be difficult because of mining problems (overburden thickness, indurated rocks, low ore recovery). Rates of production may also be small resulting in high unit costs. In some cases, an unfavorable geographic location may result in high transportation costs. Exploitation at remote locations often becomes expensive when there is an absence of infrastructure (transportation, housing, utilities) to support the project. An economic assessment of some deposits may show that the resources are adequate for local exploitation but do not justify major capital investment. This decision may cause the government to lose interest in the project.

Some of these ore types may present unique processing problems to the metallurgical and chemical engineers because the ROM ore and concentrates produced may contain higher than normal levels of some impurities. This may require some process modifications to accept these new ores and the development of processes that are tolerant to these impurities. Finally, any processing has to result in a product that is acceptable in quality, price, and performance to the farmer who must use it.

Clearly there is a large challenge ahead in utilizing sub-Saharan Africa phosphate deposits. These deposits include some high-quality, high-grade ores that are easily processed, but they also include most of the problem ore types that occur. Becauseeach ore has its own characteristics, technology may

have to be adapted to accept a specific ore of interest. A significant effort will be required to document the known occurrences in sub-Saharan Africa as well as stimulate the search for and development of new deposits. The necessity to relieve the food deficit over a large area of this region should provide the stimulus for this much-needed work.

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Processing phosphate ores into fertilizers

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Introduction

The International Fertilizer Development Center (IFDC) phosphate program has placed substantial emphasis on assisting developing countries in the evaluation and development of their indigenous deposits of phosphate rock, particularly those located in landlocked countries or more remote areas where transportation costs have made imported phosphates extremely expensive. Furthermore, emphasis is also directed toward those deposits that are marginal in quality and not amenable for production of phosphate fertilizers by conventional processes. The combined goal is to develop products that primarily improve the raw material and product use efficiency, particularly for the tropics and subtropics.

There has always been an interest in processing indigenous ores that may contain higher than usual levels of impurities because of their availability and potentially lower cost. Such studies were largely academic before 1973 because the international market had an adequate supply of high-quality, rather inexpensive ore. When substantial price increases occurred, many countries began exploration and development programs to discover new occurrences and expand the technical capability to beneficiate and process ores with lower grades and quality. Several of these programs were successful, and a number of developing countries located new indigenous deposits or expanded the knowledge of previously known, but unexploited, deposits.

The combination of the new discoveries and the expansion of mine output from existing deposits has created the oversupply of phosphate raw materials in the international market. Nevertheless, developing countries continue to place a high priority on developing their indigenous resources, particularly those countries with a substantial domestic requirement or regional market potential.

Developing countries have several reasons for opening new deposits even

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when there is a surplus supply on the world market. There is a natural desire to be independent of foreign sources; these countries have not forgotten the lessons learned during the shortages of 1973/74 when they were at the mercy of international suppliers. Domestic production also can provide savings in high-value foreign exchange and increase local employment. Although world market prices have declined, they still remain higher than the pre-1973 levels, and international currency loans have inflated interest rates that add to the costs. Transportation is a major factor affecting phosphate raw material costs. Transportation costs for indigenous ores may be lower than for imported rock and are not subject to variations in international freight rates. The combined effect of these factors usually justifies the economics and desirability of utilizing indigenous deposits. Many of these considerations are not limited to developing countries, although the developing countries are IFDC's main concern.

This paper examines the possible process routes and their preliminary production economics. It includes those that are being evaluated under the programs of the International Fund for Agricultural Development (IFAD).

Phosphate product alternative for sub-Saharan Africa

Phosphate rock has many uses and about 85% of the total production is for fertilizer manufacture, including direct application to the soil [10]. As a fertilizer, the use of phosphate rock has progressed from bone meal to finely ground rock, to acidulated rock products, to various thermal phosphates, and finally to modern high-analysis, water-soluble products. Each progression, however, has been characterized by the complexity of process and less tolerance to the impurity contents of the rock. Since the early 1930s, advances in mining and beneficiation technology have provided industry with raw materials of low-impurity content on which the present generation water-soluble phosphate compounds are based. Such high-analysis fertilizers enjoy advantages in transportation and distribution costs over the lower grade, less-soluble products; consequently, the bulk of today's worldwide phosphate fertilizer is supplied by the high-analysis fertilizers. Chemical and thermal fertilizers, in a solid form, are produced by various treatments, and although many products are made, most of the fertilizer phosphate is consumed as a few products (Table 1).

In most sub-Saharan African countries, single superphosphate (SSP) has been the traditional phosphatic fertilizer. However, in recent years the availability of triple superphosphate (TSP), diammonium phosphate (DAP), and other compound (NP or NPK) fertilizers has diminished SSP's importance. Nevertheless, SSP continues to be used along with other specialty fertilizers

that are tailored to requirements of specific crop types. In the following paragraphs, the possible product alternatives are discussed in light of the chemical analyses of selected sub-Saharan phosphates (Table 2).

Sub-Saharan Africa has enough identified phosphate resources (Figure 1) to be self-sufficient in the production of fertilizers [21]. However, only the large, easily accessible deposits are being exploited, mainly for the export market. Smaller resources of fertilizer raw materials in isolated areas or landlocked countries are in various stages of study, development, and exploitation. Often these deposits have significant economic disadvantages, including high transportation costs, which limit the use of the ore and its products to domestic or regional markets. Expanded food production in sub-Saharan Africa will require the establishment of fertilizer industries that can assure a sustained and uninterruptible supply. The optimum use of the most appropriate fertilizer is one of the cheapest and most effective ways to increase food production.

Direct application

Direct application of finely ground phosphate rock may be one of the cheapest ways to supply phosphorus to crops grown in the tropics and subtropics. In some cases finely ground rock is as effective as the more expensive soluble phosphate fertilizers, whereas in others the full potential of the rock is not realized within a given time unless some soluble phosphate is added, either mixed with the rock or derived from the rock by partial acidulation.

Because of its unpredictable value to agriculture, the use of phosphate rock for direct application has been a subject of much controversy. Many factors contribute to this unpredictability, and some of the important ones are mentioned here. Phosphate rocks vary widely in their reactivity and subsequent agronomic value [17]. Agronomic response to phosphate rock depends

Table 1 Examples of popular phosphate fertilizers in use

Material	P_2O_5 content
	(%)
Diammonium phosphate	46-48
Monoammonium phosphate	50-55
Triple superphosphate	46-48
Single superphosphate	16-22
Nitrophosphate	15-30
Phosphate rock	26-33

Table 2 Chemical analyses of selected sub-Sahara phosphates[a]

Location, country	Chemical analyses													Weight ratio		
	P_2O_5	C.S. P_2O[b]	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	Cl	F	S	CO_2	SiO_2	$(Fe_2O_3 + Al_2O_3)$ / P_2O_5	$(Fe_2O_3 + Al_2O_3 + MgO)$ / P_2O_5	Cao / P_2O_5
	(wt %)															
Cabinda, Angola	37.0	4.5	51.0	2.0	0.40	0.11	0.82	0.04	0.006	4.0	0.46	2.2	1.1	0.06	0.07	1.38
Mekrou, Benin	29.3	1.9	41.5	0.80	1.0	0.01	0.09	0.03	0.005	2.8	< 0.1	1.3	22.6	0.06	0.06	1.42
Kodjari, Burkina Faso[c]	25.4	2.3	34.5	3.1	3.4	0.27	0.11	0.23	NA[d]	2.5	0.04	1.0	26.2	0.26	0.27	1.36
River Delta, Congo	32.9	7.0	52.6	0.10	0.70	0.43	1.2	0.02	NA	3.8	0.92	5.3	0.40	0.02	0.04	1.60
Tilemsi Valley, Mali[c]	28.6	4.2	41.4	2.1	6.1	0.52	0.37	0.10	0.007	3.1	0.33	2.4	9.4	0.29	0.30	1.45
Unknown, Mozambique	30.3	NA	45.0	0.30	0.40	0.45	0.78	0.03	0.018	0.6	0.22	5.0	0.1	0.02	0.04	1.48
Parc W, Niger[c]	28.5	2.6	39.9	1.0	1.9	0.03	0.13	0.04	0.004	1.5	0.04	1.2	25.2	0.10	0.10	1.40
Tahoua, Niger	28.0	1.5	43.9	2.1	13.0	0.20	NA	NA	NA	3.8	0.20	1.1	7.9	0.54	0.55	1.57
Matam, Senegal[c]	28.7	4.5	44.4	1.8	2.0	1.60	0.36	0.03	0.005	3.3	0.22	2.9	12.9	0.13	0.19	1.55
Taiba, Senegal	37.4	3.1	51.2	1.0	1.0	0.06	0.20	0.06	NA	4.0	0.10	1.7	2.9	0.05	0.06	1.37
Thies, Senegal[e]	32.0	12.0	9.3	30.9	12.4	0.04	1.9	0.04	0.005	0.72	0.05	0.8	2.8	1.26	1.26	0.33
Minjingu, Tanzania	29.0	5.6	41.7	1.2	0.9	3.20	1.30	0.78	NA	3.1	< 0.1	3.1	9.4	0.07	0.18	1.44
Hahotoe, Togo[c]	35.7	3.1	52.6	0.8	1.3	0.10	0.20	0.04	0.03	3.9	0.18	2.1	3.7	0.06	0.06	1.47
Sukulu Hills, Uganda[c]	37.9	1.2	49.5	0.80	0.80	0.04	0.39	0.21	0.006	1.9	0.02	0.30	6.0	0.04	0.04	1.31
Chilembwe, Zambia	17.1	1.4	30.5	1.0	5.0	8.3	NA	0.11	0.440	0.9	NA	0.80	30.2	0.35	0.83	1.78
Dorowa, Zimbabwe[c]	33.1	0.7	50.2	0.58	2.6	1.0	0.76	0.08	0.007	1.6	0.05	5.4	5.4	0.10	0.13	1.52

[a] Analyzed by IFDC.
[b] Citrate soluble P_2O_5 measured in neutral ammonium citrate solution.
[c] Used to prepare IFAD experimental materials.
[d] NA = not available.
[e] Iron-aluminum phosphates.

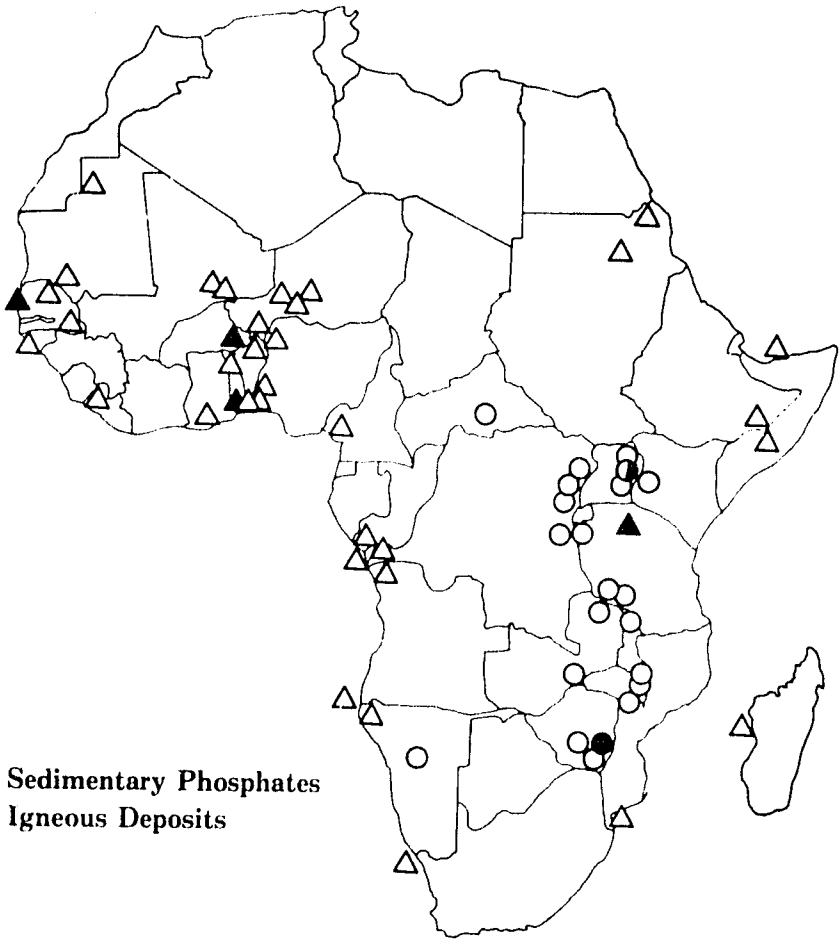

Figure 1. Phosphate occurrences of sub-Saharan Africa.

strongly on soil type and to some extent on crop and climate. Factors such as time, method of application, and particle size can also affect response. Phosphate rock often has a more favorable long-term rather than short-term response, making economic and agronomic evaluation rather difficult.

There are certain advantages of ground rock for direct application, particularly for the development of highly reactive rock deposits in landlocked regions and/or in proximity to important agricultural areas of appropriate crop varieties and soil type (acid soil). Under such circumstances, this approach may offer an attractive alternative to conventional phosphates because of these factors:

1. Relatively low cost. For example, in 1979 the delivered costs to the farmer of bagged, ground Kodjari rock (Burkina Faso) and bagged, granular, imported TSP averaged around \$400/tonne P_2O_5 and \$1,000/tonne P_2O_5, respectively [25].

2. Relatively simple technology and use of local expertise for operation.
3. Low capital costs [25].
4. Low energy requirement – about one-third that of TSP [4].
5. Use of rocks unsuitable for other types of processing.
6. Production costs that are not too sensitive to the economy of scale.
7. The possibility of a quick, and perhaps the cheapest, way to start building a basic phosphate industry in a developing country, particularly where a local phosphate deposit exists.

The main disadvantages of directly applied rock are these: the lack of predictability of agronomic value; limitation to acid soils, except for aluminum phosphates [10]; a relatively low P_2O_5 content compared with TSP or ammonium phosphates; and difficulties in handling, shipping, and application due to dustiness. The problems due to dustiness can be alleviated by granulation. The available data indicate that granular products are less effective than finely ground rock during the first year of application. Granules made with soluble salt binders disaggregate and disperse in the soils and approach the effectiveness of finely ground rock. However, some water-soluble binders may lead to irreversible agglomeration. Further, granulation increases the cost of products by about \$10-\$20/tonne depending on the binder and local conditions [9].

In spite of the potential advantages of directly applied rock and efforts by IFDC and others to promote its use, it accounted for a relatively small fraction of the total P_2O_5 consumed in sub-Saharan Africa. The rocks that are reported to be in use as a direct application source include Cabinda, Angola; Kodjari, Burkina Faso; Tilemsi Valley, Mali; and Tahoua, Niger.

Despite this relatively small share of the total market, it is believed that the directly applied phosphate rock will become an important fertilizer material in sub-Saharan Africa as the fundamental factors affecting their agronomic efficiencies become better defined.

Thermally altered phosphates

Thermally altered phosphates are materials that can be prepared from a variety of raw materials to meet the phosphate needs of developing countries; they represent a level of technology that partially fills the gap between direct application of phosphate rock and conventional chemical fertilizer technology. Some factors that may encourage the use of these types of materials are undesirable properties of the indigenous phosphates (low reactivity, low grade, composition, etc.), the specific agronomic conditions (soil, climate, crop), and poor transportation facilities.

Hydrated iron and aluminum phosphates (crandallite, wavellite, millisite),

when calcined at about 550°C, constitute a class of thermal phosphate for direct application. Calcination removes the water of hydration and destroys the crystallinity of the phosphate minerals; thus, it makes them available to plants. This process has been used to treat ores near Thies, Senegal. The 'as-mined' ore contains about 29% P_2O_5 on a dry basis; after calcination it contains around 32% P_2O_5 (Table 2). The calcined product is ground to 95% smaller than 0.15 mm and marketed under the trade name 'Phospal'. Solubility and field test data show that this product has good availability on acid, neutral, and alkaline soils [1].

Another class of phosphatic fertilizers can be prepared from premium- and nonpremium-grade rocks by thermally promoted reactions in the range of 1000–1450°C that destroy apatite structures and allow the recombination of $(PO_4)^{3-}$ into more reactive compounds. Various inorganic reagents (Table 3) may be used to promote the decomposition of the rock and to evolve fluorine; the resulting products contain water-insoluble but citrate-soluble phosphates. Despite the wide choice of reactants, products can be conveniently grouped on the basis of structural form and composition, as illustrated in Table 4.

Most of these fertilizer substances have a long history of testing and use in agriculture, but their energy-intensive processing and inferior product quality in comparison with chemical fertilizers have restricted their importance to a relatively minor fraction of total phosphate production. However, this cost factor is somewhat offset by the advantages of using unbeneficiated low-quality phosphate rocks and cheaper reagents than are required in wet chemical processes. Also, their slow-release characteristics and retained contents of secondary and micronutrients may enhance their usefulness in some agricultural practices.

Table 3 Reagents for thermal phosphates

Silica minerals	*Phosphates*
Quartz, opal, chert	H_3PO_4
Feldspar (Na, K, Al silicate)	Alkali phosphates
Olivine, serpentine (Mg silicate)	$AlPO_4 \cdot nH_2O$
Alkali metals	*Alkaline earths*
Carbonates (Na, K)	$CaCO_3$, $CaMg(CO_3)_2$
Sulfates (Na, K, NH_4)	$CaSO_4 \cdot 2H_2O$ (gypsum)
Silicates (Na, K type)	$Mg(Na,K)_2(SO_4)_2 \cdot 4H_2O$
Hydroxides (Na, K)	$CaCl_2 \cdot 6H_2O$
	$MgCl_2 \cdot 6H_2O$

Phosphoric acid

The manufacture of high-analysis fertilizers now consumes about 90% of the phosphate rock raw material, with phosphoric acids probably being the most important intermediates [20]. Extensive descriptions of phosphoric acid production processes are well documented [28,2], and no attempt will be made to elaborate on them. Instead, effects of some chemical quality factors of phosphate rock for wet-process phosphoric acid (WPA) production will be discussed, taking into consideration the chemical composition of the sub-Saharan phosphates (Table 2).

In the production of WPA, the $CaO:P_2O_5$ weight ratio ranks above all others in importance because of its major effect on process economics (Table 5). When the $CaO:P_2O_5$ weight ratio is significantly greater than 1.6, the sulfuric acid requirement may become uneconomical. The $CaO:P_2O_5$ weight ratio of the apatite mineral ranges from 1.31 up to 1.61 so that nearly total removal of all other calcium-bearing minerals by beneficiation may appear to be required, but this may not be technically or economically feasible, particularly with carbonate-type ores. For captive use, the additional costs for H_2SO_4 reagents must be weighed against added beneficiation costs to find the most economical process. These beneficiation costs may be unavoidable if the concentrate is to compete in open markets.

The iron and aluminum ($Fe_2O_3 + Al_2O_3$) impurities are particularly troublesome in WPA and its ammoniation products. They are mainly responsible

Table 4 Some types of thermal phosphate products

Theoretical composition	Types of materials	Reagents[a]
$(Ca,Mg)_3(PO_4)_2$	Tricalcium phosphates	(None)
$Ca_2O(PO_4)_2$	whitlockite; glasses; hilgenstockite basic slags	Alkaline earths
$CaNaPO_4$	Rhenania compounds	Alkalies
$CaKPO_4$		
$Ca_2P_2Si_2O_{16}$		
$(Ca,Mg)_2P_2Si_2O_{16}$	Nagelschmidtite	Silica
$Ca_2Na_2(P,Si)_4O_{16}$		Mg silicates
$Ca_3P_2SiO_{12}$	Silicocarnotite	Silica
		Silicates
$Ca_{(n+1)}(P_mO_{(3m+1)})_{(n+2)}$	Poly- and meta-phosphates	Phosphates
$Ca_5(Cl)PO_4$	Chlorospodiosite	
$Mg_5(F)PO_4$	Wagerite	Halides

[a] Accessory mineral components in phosphate rock may supply part or all of the necessary reactants.

for postprecipitated sludges in phosphoric acid, scale formation in acid concentration equipment, and insoluble compounds in ammonium phosphate products, etc. [16]. Phosphate concentrates with iron and aluminum contents above 2%-3% are unattractive for phosphoric acid production since they decrease the plant capacity and often decrease the P_2O_5 recovery. An accepted $(Fe_2O_3 + Al_2O_3):P_2O_5$ ratio, by industry standard, is about 0.05 or less [14].

In the reactor stage of the phosphoric acid production, an increase in magnesium content of the rock causes it to precipitate with aluminum and iron and blind the filter cloth. Magnesium also increases the viscosity of concentrated acid and increases the scale formation in the concentration equipment. Magnesium occurs in rocks mainly through accessory carbonates (Mg-calcite and dolomite) or as a constituent of the apatite itself [18]. Usually rocks containing magnesium-bearing carbonates are beneficiated to reduce the detrimental effect of magnesium and also decrease sulfuric acid consumption. The amount of MgO in the sub-Saharan apatites varies widely and ranges between 0.01% (Mekrou, Benin) and 8.3% (Chilembwe, Zambia). The desired $(Fe_2O_3 + Al_2O_3 + MgO):P_2O_5$ ratio in the rock for WPA production is 0.1 or less [15].

In WPA production, filtration problems may arise from the presence of finely divided quartz or silica gel as well as from a deficiency of silica. When silica is present in amounts sufficient to complex the fluoride released during acidulation of the apatite (at least a 4:1 mole ratio), more filterable alkali fluorosilicates are usually precipitated. However, in the absence of sufficient silica, complex fluorides and alumino-fluorides may be formed. These are usually fine grained and have a detrimental effect on the filtration rates. Silica in the form of coarse, angular quartz grains acts as an abrasive that may erode plant equipment.

Soluble chloride is undesirable in phosphoric acid technology because of its corrosive action on plant equipment and undesirable fume problems rath-

Table 5 Effect of $CaO:P_2O_5$ weight ratio in phosphate rock on sulfuric acid consumption for WPA production

Rock source[a]	Weight ratio $CaO:P_2O_5$	Sulfuric acid consumption tonnes H_2SO_4/tonne P_2O_5[b]
Sukulu Hills, Uganda	1.31	2.427
Taiba, Senegal	1.37	2.534
Hahotoe, Togo	1.47	2.714
Dorowa, Zimbabwe	1.52	2.803
River delta, Congo	1.60	2.866

[a] Refer to Table 2 for complete chemical analyses.
[b] Theoretical calculations based on the chemical analyses of the rock.

er than chemical interference with the manufacturing process. The usual sources of chloride in sedimentary rocks are the evaporite salts or residues from seawater that may be used in beneficiation steps. Both of these sources can be minimized by washing the ore with fresh water. In igneous rocks, the cloride is usually present in the apatite as a substitution for fluoride and may require thermal treatment to reduce its concentration [7]. In general, chloride contents higher than 500 ppm cannot be tolerated because corrosion rates become excessive for common stainless steel.

The presence of organic carbon in phosphate rock causes problems due to foaming in WPA production and effectively reduces reactor volume and increases reagent control costs. Organic carbon contributes to the discoloration of WPA and thus makes the product cosmetically less desirable to the consumers. Organic carbon also may aggravate chloride corrosion by creating a reducing environment during acidulation [26]. Thermal treatment at 400°-500°C should remove the organic carbon. Organic carbon levels below about 1% usually are considered acceptable.

The above discussions suggest that, aside from the P_2O_5 content of the rock, other chemical factors play an important role in its evaluation for phosphoric acid productions. The detrimental effects of certain chemical constituents in phosphoric acid processes affect the relative market values of phosphate rocks that otherwise would appear competitive on the basis of only their P_2O_5 grade. There are no industry-wide standards on the chemical factors because they are process and end-product specific. Nevertheless, the phosphate industry is striving to produce phosphate concentrate with as low an impurity content as possible. This is resulting in a lower P_2O_5 recovery in the beneficiation step and higher cost.

In new or unconventional technology, the use of unbeneficiated or minimally beneficiated rock in the WPA production is being evaluated by IFDC and others. Such a plant might be designed for processing local ores that may not meet conventional chemical grade or quality specifications. The economic decision favoring such a plant is based on the advantages and disadvantages of handling more raw material if the grade is low, increased acid consumption if the calcium oxide/phosphate ratio is high, higher grinding costs if the ore is hard, and lower plant efficiency if processing is affected by clays and/or organic matter. The relative merit of a particular ore can be determined by comparing various processing parameters with a selected standard [29]. This approach allows selection of ores with the best value and the merit, if any, of incurring additional costs to improve them as compared with the cost of processing the unbeneficiated ore.

In the case of siliceous ores, the use of low-grade rock adds to the amount of inert material carried through the system. This can increase the requirements for rock grinding, filter capacity, and solids disposal. Silica also can

increase erosion problems with agitators and pumps. Decreased beneficiation capital and operating costs and a significant reduction in phosphate losses during beneficiation are major benefits to processing unbeneficiated siliceous ores. Also, these ores usually will contribute only a small amount of metal impurities during acidulation. Some examples of sub-Saharan phosphates that may be candidates for acidulation in an unbeneficiated form are Parc W, Niger, and Mekrou, Benin.

Single superphosphate

Because SSP processes have a fairly wide tolerance for rock compositions, these processes may be the only practical use for some indigenous sub-Saharan rocks for local or regional markets where grade specifications are less important than cost and availability. SSP has an impressive list of advantages. For example, it involves a simple process that requires little technical skill and small capital investment, and it has excellent fertilizer characteristics that have been a standard for many years. (This product also supplies secondary calcium and sulfur as well as phosphate). The main disadvantage is the low grade (16%-22% P_2O_5), which results in a higher unit delivery cost when compared with more concentrated fertilizers.

SSP plants can be justified in locations where (1) both sulfur and phosphate are deficient, (2) imports are scarce and expensive, (3) byproduct sulfuric acid is available, and (4) phosphate deposits or markets are small. These conditions seem to occur often in various developing countries that need to exploit their indigenous rock resources.

Because the phosphate content of SSP varies with the grade of the rocks, factors that decrease grade, such as silica content and calcium-to-phosphate ratio, diminish the nutrient content of the product. Iron and aluminum contents can only be tolerated within certain limits. A study of the effects of various factors on the production of SSP from 15 rock sources showed that decreases in water-soluble phosphate and increases in citrate-soluble phosphate were directly related to the iron and aluminum contents of the ores studied. These data also showed that SSP made from igneous rock sources containing relatively high amounts of iron and aluminum showed less than 70% conversion to water-soluble phosphate after 4 weeks of storage, that made from sedimentary ores of low reactivity averaged about 75%-80% conversion, and that made from reactive sources averaged about 90% conversion.

In some apatite concentrates from igneous rock, iron has a very significant deleterious effect in superphosphate processing. For example, in laboratory tests with a sub-Saharan igneous concentrate, an increase in iron content

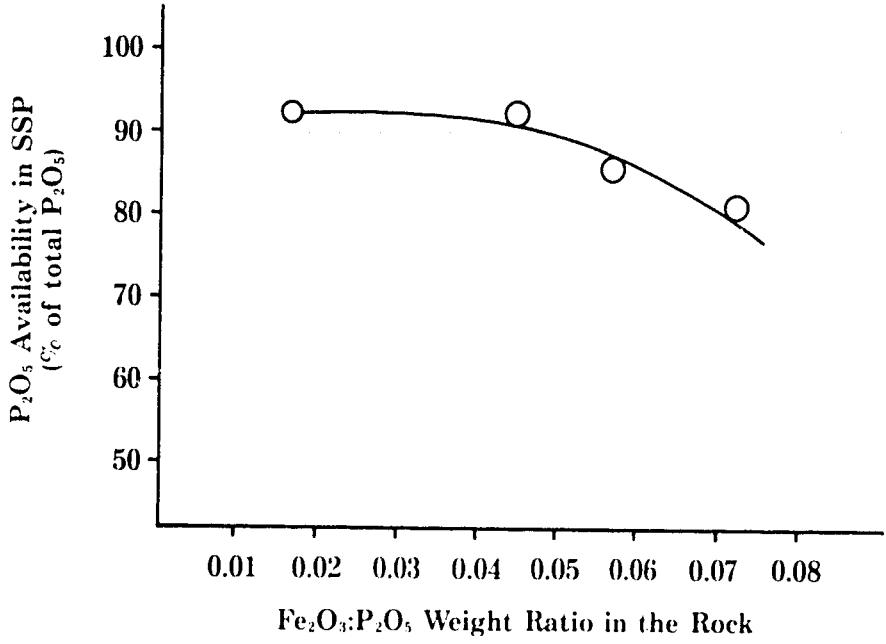

Figure 2. Effect of Fe_2O_3:P_2O_5 weight ratio on P_2O_5 availability of 4-week cured SSP produced from African concentrate.

caused a systematic decrease in available phosphate (Figure 2). The decrease in availability resulted from a reversion of available phosphate to an unavailable form during curing. Fine grinding of the apatite concentrate apparently reduced reversion reactions (Figure 3). IFDC has identified an additive that will reduce reversion in some ores. Igneous concentrates seem to be more sensitive to reversion reactions than sedimentary ores containing the same level of impurities. SSP made from a Florida concentrate (sedimentary) containing about 2% iron shows about 92% conversion to available phosphate after 4 weeks of curing, whereas the product made from two igneous concentrates processed at the same time shows only 82% conversion.

The granulation of SSP often depends on local preference. In many cases nongranular SSP is acceptable. Various minerals or chemical compounds can be added to supply secondary or micronutrient elements in either form. Granulation can be accomplished after denning, or after curing – the most popular practice in most commercial plants. In some cases, SSP is used to produce granular compound fertilizers or bulk blends. Economics often limits SSP production to plants that serve local markets where suitable raw materials are available and importation of more concentrated or alternative materials is more expensive. Special agronomic circumstances requiring sulfur as a nutrient can make SSP more valuable than non-sulfur-containing alternatives.

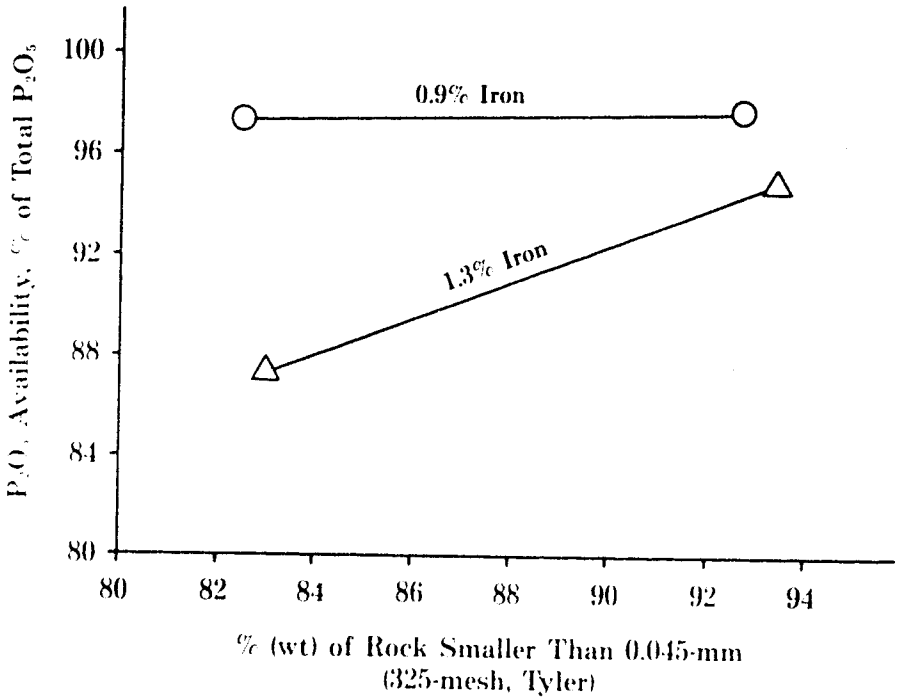

Figure 3. Effect of rock grind on the availability of 2-week cured products prepared from low- and medium-iron African concentrates.

Double superphosphate

'Enriched' or double superphosphate can be made by acidulation of phosphate rock with a mixture of sulfuric and phosphoric acids. Processes and equipment are similar to those used with SSP, but grades are higher and range from 25% to 35% P_2O_5. Some advantages of double superphosphate over TSP are the inclusion of sulfate as a nutrient and the use of dilute phosphoric acid (30% P_2O_5) in the mixture. The latter is possible because the proper concentration results when the dilute phosphoric acid is mixed with 93%-98% sulfuric acid. The heat of dilution is sufficient to avoid concentrating the dilute phosphoric acid in a separate step.

Enriched superphosphate can be important in the use of indigenous resources because its higher grade helps decrease transportation costs. The use of mixed acids allows some flexibility in product grade, preserves a portion of the agronomically valuable sulfate content, and reduces the requirement for phosphoric acid. A product with essentially the same properties can be made by mixing SSP and TSP in varying proportions.

Triple superphosphate

TSP is the highest grade of straight fertilizer that can be derived directly from relatively low-cost phosphate rock. The percentage of phosphate in the product derived from the ground rock portion of the mixture varies from 25% to 40% depending on the rock grade, the calcium oxide: phosphate ratio, and the impurity content of the acid and rock. In general, TSP produced from low-grade rock derives a smaller proportion of its phosphate from the rock fraction of the mixture. TSP will contain chemical impurities (including metal oxides) that are derived from the phosphate rock as well as those that occur in the phosphoric acid. In many phosphoric acid plants, the 'sludge acid' derived from clarification steps of processing has become a major component in some TSP products, and indeed metal phosphates have even replaced monocalcium phosphate as the main component in some products [6]. Thus, low-quality phosphate rock or low-quality phosphoric acid, or both, can be the source of the same impurities and yield similar end products. The amount of impurities that can be tolerated depends on the criteria used to establish the commercial value of the products. Where a high level of water solubility is the criterion, both rock and acid should have low iron and aluminum contents. If citrate solubility or available phosphate is the main criterion, then higher impurity levels may be acceptable.

In superphosphate processes, the physical properties of the reaction mixture (fluid, plastic, and solid stages) are important in handling the material during processing. Thus, rock reactivity is a significant factor affecting the processing of some ores. Unreactive rocks may require fine grinding and/or long process retention times to achieve suitable final products. Some igneous apatites with low surface areas may require extra processing steps which still may not yield high conversion of the phosphate to water- or citrate-soluble forms.

In a TSP test comparing an igneous apatite and a sedimentary phosphate concentrate in which about 85% of the particles were smaller than 0.075 mm, the percentage of reaction occurring in the den was only 44% for the igneous apatite compared with 99% for the sedimentary ore. When the particle size of the igneous apatite was reduced to 95% passing 325-mesh (0.045 mm), its reactivity was still only 60% of that of the sedimentary ore. After 4 weeks of curing, the TSP made from the igneous apatite showed less conversion to available forms than did the sedimentary ore (the difference of about 90% versus 96%). Increasing the acidulation temperature can increase conversion and decrease the moisture in the final run-of-pile product. This can be accomplished by adding small amounts of concentrated sulfuric acid to the phosphoric acid to achieve the desired temperature. In general, IFDC's experience has shown that TSP made from igneous apatites requires two to four

times as much denning time as that derived from sedimentary ores of comparable grade and particle size. (Similar retention time increases also may be necessary in the reactor of direct-slurry processes that produce TSP.)

The effects of iron and aluminum on the production of TSP are shown by the following examples. An igneous rock from Asia with a rather high impurity content (36.4% P_2O_5, 48.3% CaO, 4.6% Fe_2O_3, and 1.9% Al_2O_3) was processed into a TSP product that contained 49.1% P_2O_5 – 73.1% of which was water-soluble and 87.0% available. And 58.4% of the rock's P_2O_5 was converted into the available form. It will be noted that this test was successful even though the ratio of (Fe_2O_3 + Al_2O_3):P_2O_5 was relatively high (0.17). A similar test using the unreactive Kodjari rock (Burkina Faso) (24.0% P_2O_5, 32.2% CaO, 4.1% Fe_2O_3, 5.7% Al_2O_3, and 27.7% SiO_2) resulted in a technical failure that produced a sticky, uncuttable product after it was denned. The unreactive nature of this rock caused unusually long fluid and set times and resulted in products with low phosphate availabilities. The high iron and aluminum contents of this rock resulted in a low, constant level for water-soluble phosphate during curing while the citrate-soluble phosphate increased. The iron and aluminum contents of these two samples seem to follow the criterion of Dee, Nunn, and Sharples [5] that combined iron and aluminum oxides should not exceed 5.0% for good water solubility and 7.5% for good availability (water- plus citrate-soluble phosphate). As indicated above, the ratio of impurities to P_2O_5 may be a more meaningful criterion than the absolute values. Acceptable weight percentages of impurities thus decrease linearly with the grade of rock.

The level of water-insoluble iron and aluminum phosphate reaction products in TSP that is acceptable with respect to agronomic performance has not been established. In areas with very high rainfall, these water-insoluble phosphates may be advantageous, but this remains to be demonstrated. Perhaps more work is needed to define the proportions of water- and criteria-soluble phosphate that are acceptable under various agronomic conditions. Such findings could be important in assessing the effectiveness of a number of fertilizer materials.

Partially acidulated phosphate rock

The superphosphate industry was born when the technology for acidulating bones was developed in the early 1800s. Over the next 100 years the technology was improved and production expanded [12]. As experience was gained, larger commercial quantities of the product were manufactured, and the sources of phosphate raw materials were expanded to include a variety of rocks from various geographic locations. The experience gained from this

expanded raw materials base established that there was a considerable variation in the acid requirements for acidulating rocks from different sources. An excess or deficit of acid in the reaction mixture was based on the economic consideration of the operator and the desired physical properties of the product. Marshall and Hill [19] point out that reducing the degree of acidulation to produce dicalcium phosphate in the product may be desirable where high water solubility is not required. Products containing dicalcium phosphate are good for direct application and blending. Conversely, overacidulation may be used to get faster conversion and better ammonia-holding capacity in the product.

Underacidulated products have been made in several countries and have produced good results on acidic soils. A well-known product of this type produced in Finland is the so-called Kotka phosphate [27]. This product contains about half the sulfuric acid usually mixed with phosphate rock in the same equipment. The economics of the process shows that one unit of total phosphate can be produced at much less cost than can one unit of water-soluble phosphate; thus, Kotka-type underacidulated products should compete favorably with superphosphates, even where the agronomic effectiveness is lower.

Nordengren [24] reported that Kotka phosphate gave results as good as those with superphosphate on mineral soil and was 80%-89% as effective as superphosphate on peat soils having a pH below 5.2. He also suggested that underacidulated products be based on phosphoric acid and reported that Kotka phosphate would be compatible with ordinary raw materials to make NPK mixtures.

The terminology normally used to describe underacidulated products is not very precise. Therefore, for this discussion we propose to use the following definitions. A fully acidulated rock product describes a phosphate rock that has been treated with a sufficient (stoichiometric) quantity of acid to convert the phosphate to a water-soluble form (monocalcium phosphate monohydrate). The precise quantity of acid required to fully acidulate a phosphate rock is difficult to predict (calculate) because of the effects of acid-consuming and acid-producing constituents in the rock. Reasonable estimates of the stoichiometric requirements can be made on the basis of certain assumptions and experiences derived from acidulating a number of phosphate ores. In most cases these data agree with commercial experience with the same ore.

Partially acidulated phosphate rock (PAPR) refers to an underacidulated product that has been treated with only a portion of the acid (usually sulfuric or phosphoric) required to convert the calcium phosphate in the rock to monocalcium phosphate monohydrate, a water-soluble salt. The proportion of acid(s) is expressed as percentage of the stoichiometric quantity of

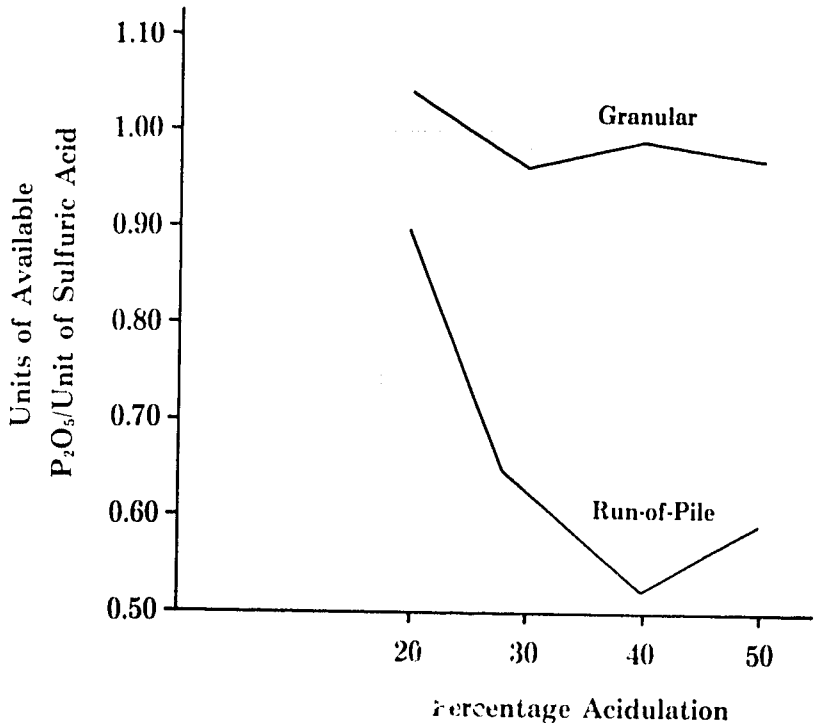

Figure 4. Units of available phosphates at various acidulation levels.

acid required to fully acidulate that particular phosphate rock. Thus, if a particular fully acidulated rock requires 604 kg of 100% sulfuric acid per tonne of rock, a 50% acidulated product would use 302 kg of 100% sulfuric acid per tonne of rock. Because PAPR products contain a mixture of monocalcium phosphate monohydrate and dicalcium phosphate, the amount of available P_2O_5 (water- plus citrate-soluble P_2O_5) produced per unit of sulfuric acid may be higher than in fully acidulated products. A plot of the available P_2O_5 produced per unit of sulfuric acid (Figure 4) for Kodjari rock shows that the process is both efficient in its use of acid and tolerant of high levels of impurities under proper conditions. Available phosphate may be more appropriate than total P_2O_5 in describing the agronomic usefulness of such products. Significant sulfur savings can result from PAPR. For example, a 50% PAPR product that is 80% as effective agronomically as SSP represents a saving of 40% in sulfuric acid consumption per unit of product.

Another advantage of PAPR is process tolerance for low-quality unreactive ores. A specific example is the Kodjari rock described above that is high in iron and aluminum and could not be made into a satisfactory TSP product. Several partially acidulated nongranular and granular products were made from this ore by using varying levels of acidulation (20%-50% acidulated with

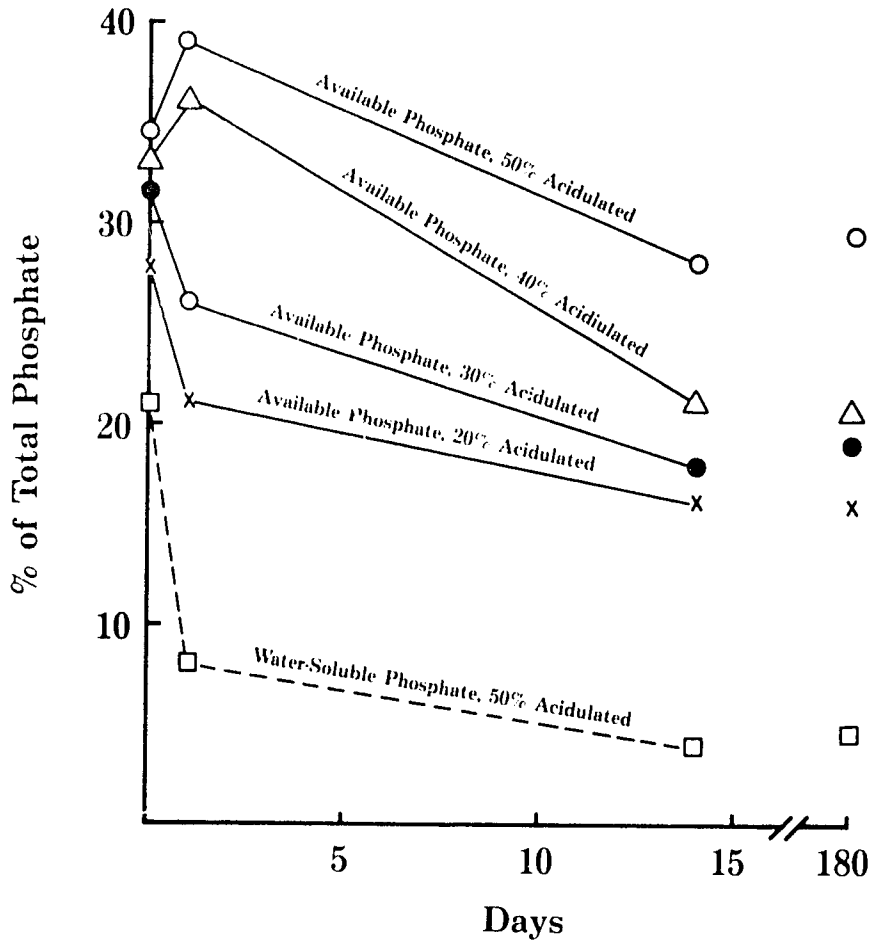

Figure 5. Variation in extractable phosphate with time.

sulfuric acid). Some results from the nongranular studies (Figure 5) show a general increase in available P_2O_5 with increasing levels of acidulation. A comparison of the water-soluble and available P_2O_5 data in the figure shows that the citrate-soluble P_2O_5 is an important component in samples stored longer than 1 day. This is expected from underacidulated products that contain dicalcium phosphate. The decrease in available phosphate is thought to result from reactions with the iron and aluminum oxides and hydroxides that occur in the ore.

The iron and aluminum reaction products may be partially or totally citrate insoluble and thereby cause a decline in availability. These undesirable reactions seem to be complete after about 2 weeks of storage, and availability remains constant or improves slightly during the 6-month storage period (Figure 5). Tests confirmed that acidulation levels greater than 50% of this rock resulted in wet, sticky products.

Granular PAPR products (1-3 mm) made from this ore were significantly better than the nongranular products (Figure 4). Water-soluble and available P_2O_5 were significantly improved in all products. This may have been due to better mixing of the acid and rock prior to granulation and to the minimal reaction of iron and aluminum to form citrate-insoluble compounds. Drying the product immediately after the acidulation-granulation step decreased the volume of the reactive liquid phase present in the granules and decreased the potential for the iron and aluminum phases to react. Several sub-Saharan phosphates were used to produce granular PAPR by a process developed by IFDC (Table 6). This process allows simultaneous acidulation and granulation of phosphate rock using typical commercial granulation configuration and equipment.

PAPR products should be less expensive to produce than are fully acidulated superphosphates because less acid is required. For example, about 1.7 tonnes of sulfuric acid is required to produce 1 tonne of phosphate in SSP. This quantity of acid often represents 15%-30% of the total cost of SSP production. Therefore, attention should be given to the production of agronomically acceptable products that can be made at significant savings in the consumption of acid.

The idea of underacidulated products seems to be becoming more attractive. At present there are several European producers, and there has been a dramatic increase in producers and tonnages in developing countries in the Middle East and Latin America. The latter producers use processes that have been specifically developed to match operating conditions to the unique characteristics of the indigenous ores being treated.

Compound fertilizers

This term is used to describe all fertilizes that contain more than one of the three primary nutrients (N, P, K). Varied grades are formulated to supply different proportions of the nutrients as required by various crops and soils. Compound fertilizers may also contain one or more secondary and/or micronutrient elements when an agronomic need has been established.

Most of the existing production facilities in sub-Saharan Africa produce only single-nutrient materials, such as SSP, TSP, or monoammonium phosphate, or double-nutrient materials like DAP. Although very useful, the 'straight' materials usually do not supply all the necessary nutrients for achieving maximum yield.

Compound fertilizers can be prepared by simply mixing (bulk blending) dry materials or by more complex 'wet' or 'chemical' granulation methods [22]. In either case to ensure good storage, handling, and application proper-

Table 6 Partially acidulated phosphate rock products prepared for agronomic evaluation under IFDC-IFAD project[a]

Rock source	Intended acidulations[b] (%)	Chemical analyses				Raw Materials Consumptions	
		Total P_2O_5	Water-Soluble P_2O_5	Available P_2O_5[c]	S	Rock	Acid[d]
		(wt %)				(tonne/tonne product)	
Kodjari, Burkina Faso	20	21.2	2.4	5.8	2.1	0.852	0.076
Kodjari, Burkina Faso	30	20.5	3.5	6.4	3.3	0.824	0.101
Kodjari, Burkina Faso	40	19.2	5.3	8.2	4.7	0.771	0.137
Kodjari, Burkina Faso	50	18.0	6.5	9.5	5.6	0.723	0.161
Tilemsi Valley, Mali	15	25.2	2.5	7.5	2.9	0.910	0.080
Tilemsi Valley, Mali	30	22.7	6.0	11.0	5.5	0.810	0.136
Parc W, Niger	25	23.8	5.4	8.2	4.1	0.818	0.096
Parc W, Niger	40	21.6	9.3	11.4	6.8	0.758	0.142
Parc W, Niger	50	20.2	9.9	11.8	7.8	0.723	0.169
Matam, Senegal	25	22.3	4.7	7.9	4.4	0.801	0.130
Matam, Senegal	50	19.8	8.0	10.8	5.2	0.711	0.227
Hahotoe, Togo	25	28.6	7.2	10.6	4.8	0.785	0.112
Hahotoe, Togo	50	25.0	11.7	13.9	7.1	0.714	0.204
Sukulu Hills, Uganda	25	30.3	6.1	7.1	3.5	0.820	0.122
Sukulu Hills, Uganda	50	25.3	14.0	14.6	7.8	0.681	0.198
Dorowa, Zimbabwe	25	24.8	6.3	7.5	6.4	0.785	0.210
Dorowa, Zimbabwe	50	23.0	8.8	10.0	7.9	0.725	0.239

[a] Products in granular form, 1-3 mm.
[b] Percentage of sulfuric acid required to produce SSP.
[c] Summation of water- and citrate-soluble P_2O_5. Citrate-soluble P_2O_5 measured in neutral ammonium citrate solution.
[d] Based on 100% H_2SO_4.

ties, it is essential that the finished products (compounds or straights) be in the form of strong, free-flowing granules.

Some products made from indigenous resources that might be used in compound fertilizers are ammoniated superphosphates, nitrophosphates, and NPK fertilizers based on phosphate rock.

Ammoniated superphosphate

– Nongranular superphosphate can be ammoniated by using various nitrogen solutions (ammonia, ammonium nitrate, and urea). Ammoniation of superphosphate decreases its water solubility, but this may not be important if the available P_2O_5 is used as the criterion for marketing the product in local or regional areas. Ammoniated TSP may have only 50% of its available P_2O_5 in the water-soluble form, and only 20% of the P_2O_5 in ammoniated SSP may be water soluble. Overacidulation of products may be used to achieve faster conversion and better ammoniation capacity. Ammoniated superphosphate contains two primary nutrients, and it also has good physical properties and improved compatibility in mixtures with other fertilizer materials, particularly urea.

Partially acidulated products that contain dicalcium phosphate or other citrate-soluble phases also are good for blending. However, these salts usually contain fewer acidic hydrogen ions in their formulas and thus have lower ammoniation capacities. The quantities and types of impurities that often occur in indigenous phosphate ores indicate that partially acidulated products are a good technical and economic choice. Ammoniation of the largely citrate-soluble products is not warranted for the reasons stated above.

Nitrophosphates

– Nitrophosphate processes using the indigenous ores of developing countries have been somewhat limited although plants are established in several countries – Turkey, Pakistan, China, India, and Colombia, to name a few. The historical trend has been an increase in nitric acid acidulation processes when the price of sulfur rises above a certain level. The principal advantage of nitrophosphate processes is the dual purpose served by the nitric acid – solubilizing the phosphate rock and providing fertilizer nitrogen in the product. Further, some of the nitrophosphate processes can tolerate a relatively high level of iron and aluminum in the rock.

The simplest process is analogous to SSP production in which phosphate rock and nitric acid are converted to monocalcium phosphate monohydrate and calcium nitrate. A typical product might contain 8% nitrogen and 16% phosphate. The low analysis and the hygroscopic character are serious disadvantages for these products.

Most nitrophosphate processes involve dissolution of the apatite in the rock to form phosphoric acid and calcium nitrate. Calcium usually is removed by precipitation or ion exchange from the reaction mixture prior to ammoniation. The degree of calcium removal determines the grade of the product and, to an extemt, its solubilities (water- and citrate-soluble P_2O_5). Nitrophosphate processes have been used to process indigenous ores in developing countries in Asia and Latin America.

Phosphate rock-based nitrogen-phosphorus-potassium (NPK) fertilizers – The feasibility of using indigenous phosphate resources, regardless of quality, can often be enhanced if the phosphate is incorporated into the overall fertilizer supply strategy for a particular crop or region. Such a strategy usually involves the use of the three primary nutrients – nitrogen, phosphorus, and potassium – as well as a number of secondary and micronutrients.

The mixing or compounding of phosphate (ground rock, acidulated rock, or phosphoric acid) with other nutrient sources, such as urea, ammonium sulfate, potash, and kieserite, is not always feasible. In some cases, chemical reactions between the ingredients call for certain precautions with respect to mixing, processing, and storing the product.

Urea is expected to remain the most available source of nitrogen in the developing world. Theefore, there is a continuing need to identify phosphate materials that are compatible with urea and other ingredients in the compounds. This need is further amplified by the expansion of the agriculture sector in the developing world, an often shrinking rural labor force, high energy costs, and inadequate transportation facilities and infrastructure.

A cogranulated product containing P_2O_5 from phosphate rock and nitrogen from urea is a potentially economical NP fertilizer for sub-Saharan African countries. The $N:P_2O_5$ ratios in the product can be varied depending on the agronomic needs, rock reactivity, and soil characteristics [3]. IFDC has demonstrated production of such products using three rock sources varying in reactivity, with no apparent difference in product quality and processing conditions [11].

The use of superphosphate-type materials with urea has been suggested as a possible alternative. However, such a mixture tends to react to form an adduct. This reaction is accompanied by the release of water, which is very troublesome because the rate of release is quite unpredictable. In some cases, depending upon the characteristics of the superphosphate, it occurs rapidly – during the granulation process, for example – and leads to overgranulation, sticking, plugging, and the general upsetting of the process. In other cases it may occur slowly and manifest itself weeks or months later in the form of deteriorated and caked products. Several techniques to avoid this have been proposed, including drying or ammoniation of the superphosphate; the

added cost and lack of reliability of these techniques are cited as the major reasons for their limited adoption. Ingredients other than superphosphate (potassium chloride and some magnesium salts, for example) in some urea-containing compound fertilizers may also adversely affect the processing and storage characteristics of the products, although the reasons for this phenomenon are not always clearly understood. Mixtures of urea and superphosphate are usually avoided, especially if long-term storage is anticipated. Superphosphate has been largely replaced with ammonium phosphates, particularly DAP because it is the most compatible source of phosphate for mixing with urea. As with superphosphate, the characteristics of the phosphate rock used to produce the phosphoric acid and the ammonium phosphate may still influence the feasibility of mixing the ammonium phosphates with urea.

The agronomic potential of some sub-Saharan soils is limited by deficiencies in both sulfur and phosphate [13]. The water-soluble P_2O_5 sources such as SSP and PAPR have been found to be effective in these soils [23]. However, the production of these fertilizers requires the use of sulfuric acid, which may not always be available. One product with good potential is a mixture of phosphate rock and element sulfur. Traditionally, such a product has been difficult to produce because of explosion and fire hazards [8], but current IFDC research is attempting to alleviate these problems through raw materials and process modification.

Economic potential

The economic potential of an indigenous deposit depends on many factors [20] including (1) market price, (2) quality and grade of the deposit, (3) location of the deposit relative to the processing plant and consuming area, (4) cost of mining and beneficiation (if required), (5) quality and grade of the beneficiated product, and (6) environmental factors. In recent years increasing importance has been given to environmental problems, especially as they relate to the destruction and/or alteration of wildlife habitats and pollution of natural water supplies.

The potential economics of mining a deposit for domestic use is related to the alternatives of using imported ore or imported fertilizer based on the projected demand for phosphatic fertilizers. A complete study evaluating these alternatives is a prerequisite to opening of a mine. Such a study should determine whether phosphate fertilizer can be manufactured from domestic ore and delivered to domestic farmers at a lower cost than would be required with imported ore, taking into account the value of foreign exchange needs. The stability of price and supply of imported rock and also the secondary

benefits to the national economy of mining a deposit should be assessed in formulating the final recommendations.

For the purpose of this paper, two case studies have been selected to illustrate the positive and negative impacts of using indigenous rocks that may be low in cost but that also represent significant problems.

Direct application in Mali

In a cooperative project, the Government of Mali and IFDC have been testing phosphate rock for direct application from the indigenous deposit at Tilemsi Valley. The rock and some derived products (15% and 30% PAPR) were compared with imported TSP on corn, rice, millet, cotton, sorghum, and peanuts at various application rates at 10 locations in several agrolimatic regions in Mali. An economic analysis was made on the crop data collected during 1982, the first-year trials of a 3-year project.

This analysis showed that all of the phosphate materials tested increased crop yields and the farmer's net return. Assuming that TSP costs 50% more per kilogram of P_2O_5 and PAPR costs 62%-94% more than finely ground phosphate rock per kilogram of P_2O_5, the economic analysis showed that finely ground rock and PAPRs produced net returns that were comparable to those from the imported TSP regardless of the method of application. For some crops farmers can maximize net returns by using a basal application of ground phosphate rock followed by small annual applications of water-soluble fertilizers (TSP).

Data from the 1983 growing season have confirmed the good agronomic response obtained with Tilemsi Valley ground rock, although some effects of drought have been observed. Also, a new grinding facility has been effective in reducing the mean particle size of the finely ground rock from about 0.160 mm to about 0.076 mm. The result has been improved agronomic response and more choice in the time of application. The economic analysis of the 1983 data has not been completed, although preliminary yield data show a very positive response to the direct application of finely ground rock. Changes in international currency exchange rates during 1983/84 are also positive factors favoring use of the indigenous rock because all imports (superphosphate and sulfur) have become more expensive.

In future work in Mali more attention will be given to the evaluation of ground Tilemse Valley rock and its economic performance. This may be an important decision considering the fact that an indigenous supply of effective phosphates, the limited opportunities for gaining foreign exchange, and the small (about 10,000 tonnes/annum) phosphate market seem to make it impractical to develop a more complex fertilizer plant for producing superphosphate or PAPR.

Partially acidulated phosphate rock

Surveys have shown that sub-Saharan Africa has large areas covered by infertile Oxisols and Ultisols. Phosphate is considered the most limiting plant nutrient on these soils. IFDC has been working with various national and international groups in evaluating the role of indigenous phosphate ores and modified products made from these ores in increasing the fertility of such soils in the tropics and subtropics. Results from technical, agronomic, and economic studies have identified methods of utilizing local materials as potential phosphate sources on some infertile acid soils.

Finely ground phosphate rock can be used as a fertilizer in certain agronomic situations or on acid soils where it is a source of both phosphate and lime. However, the impact of direct-application rock on crop production may be rather low if the rock has a low reactivity (citrate-soluble P_2O_5). Partial acidulation of the rock can substantially increase its water- and citrate-soluble P_2O_5 contents and thus have a greater immediate impact on crop production.

In two cases presented for comparison, two unreactive sedimentary rocks of different grades from sub-Saharan Africa were acidulated with sulfuric acid to about 50% of the theoretical requirement for producing SSP. This acidulation level was chosen because it is the maximum at which a satisfactory product can be produced when only one of the rocks is used. Either imported sulfuric acid or sulfuric acid locally manufactured from imported sulfur could be used. A preliminary analysis indicates that it might be more economical to manufacture the acid locally. Importing bulk sulfur rather than sulfuric acid has advantages in supply, transportation, and handling.

The two products from ores of different grades have about the same total P_2O_5 content because of variations in the acid: rock ratio. The comparative production economics (Table 7) shows that a 50% partially acidulated product made from rock A costs about 30% more than the product made from rock B, although the cost contribution from acid consumption for rock B is 30% more than that for rock A. The major difference occurs in the cost of rock from these two sources. An analysis of the rock costs shows that the mining cost is the same (about $10/tonne), but the transportation cost for rock A is more than three and a half times the cost of transportation for rock B. The differences occur because of the distances between the point of production and the agricultural (market) area. Rock A receives a favorable freight rate (about $0.96/tonne/km) because backhaul cargoes are available, but the distance is much farther than for rock B. Road conditions can also limit the usable truck size, and this affects the delivered costs per tonne. The importance of transportation for the economics of processing indigenous phosphate ores in a given situation cannot be overemphasized in developing countries because of its impact on the feasibility of the project.

Table 7 Comparative manufacturing costs for production of PAPR using two sub-Saharan phosphate rocks[a,b]

	Rock A		Rock B	
	Basis	$/tonne	Basis	$/tonne
Raw materials cost				
Rock	0.85 tonne @ $65/tonne	55.30	0.75 tonne @ $25/tonne	18.80
Sulfur	0.062 tonne @ $260/tonne	16.10	0.068 tonne @ $310/tonne	21.10
Subtotal		71.40		39.90
Conversion costs[c]		65.40		65.40
Total cost		136.80		105.30

[a] Product analyses (wt %):

	Rock A	Rock B
P_2O_5	20.0	20.0
Water-soluble P_2O_5	7.7	10.0
Available P_2O_5	10.9	11.9
Free water	2.0	2.0

[b] 60,000 tonnes per annum; sulfuric acid produced from imported sulfur; 1984 U.S. dollars.

[c] Fixed plus variable costs.

Conclusions

Production of phosphate fertilizers in sub-Saharan African countries, as a group, has lagged behind its use. As a result, these countries are importers of phosphatic fertilizers. This situation, combined with rapidly increasing needs and the presence of most of the required raw materials, provides an opportunity for sub-Saharan African countries to establish phosphate fertilizer manufacturing industries and thereby help improve their economies.

Phosphate rocks of sub-Saharan Africa vary in P_2O_5 content, reactivity, and quality and require different processing techniques. Each technique, however, has certain advantages and disadvantages with respect to agronomic requirements and process economics. During the past 10 years, IFDC has attained considerable expertise in developing procedures needed for making such decisions on a number of phosphate ores from sub-Saharan Africa. In some cases processes are modified to accommodate the peculiarities of a specific ore. At other times product specifications are adjusted to allow for the use of local resources. In all cases, however, the ultimate objective is to provide lower cost fertilizer to the farmers.

In this paper examples of alternative processing techniques for sub-Saharan properties have been discussed along with some of the advantages and disadvantages of each process. Also discussed are some non-process-related factors that must be considered in the overall evaluation of the economic potential of a deposit. In particular, transportation has been cited as a specific problem that is evident in landlocked countries or large countries where facilities are limited.

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Phosphate reactions with tropical African soils

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E. Rhodes

Introduction

Phosphorus deficiency in tropical African soils is a major factor that reduces food prouction in the region. In some soils of the savanna zone of western Africa, the deficiency is so acute that plant growth ceases as soon as the phosphorus stored in the seed is exhausted.

Relative to work on other nutrients, much more effort has been expended by research workers in tropical Africa primarily to define the areas where phosphorus deficiency is most acute and to overcome the short-term effects of this limitation through application of manures and fertilizers. For example, as early as 1937, Hartley attributed the excellent crop response obtained with small dressings of farmyard manure in northern Nigeria to the phosphorus contained in the manure [29]. After more than 50 years of research, we are still trying to determine the right type of phosphorus fertilizer to apply and the best way to manage it. The problem is compounded by the fact that its solution involves knowledge and application of both physical and chemical principles.

Granular fertilizers are most commonly used by tropical African farmers. The agronomic effectiveness of water-soluble granular phosphate fertilizers is dependent on the chemistry of fertilizer-soil interactions. Because of the characteristics of the colloidal systems in tropical African soils, phosphorus is not only a nutrient but also a soil amendment.

In this review, we examine the characteristics of colloidal systems of tropical African soils and how these affect the behavior of different phosphorus fertilizers. We also discuss how a knowledge of fertilizer-soil reaction can be utilized to estimate the phosphorus needs of tropical African soils and crops.

Characteristics of tropical African soils

Soil mineralogy

Among the soil properties that have been found to correlate with phosphorus behavior in acid and neutral soils in tropical African regions, the chemical and mineralogical composition of the clay fraction is probably the most common. The soils of tropical Africa fall into three groups on the basis of their mineralogy:

1. Fine-textured, oxidic, base-rich Alfisols, Oxisols, and Inceptisols typical of the East African highlands.
2. Coarse-textured, kaolinitic (often with plinthite) highly compacted Alfisols and Ultisols typical of the savanna and savanna/forest transition regions of West Africa.
3. Strongly acidic and highly leached, weatherable mineral-poor Oxisols and Ultisols characteristic of the low-attitude tropics.

In a study of eight representative soil profiles from southern Nigeria, Gallez et al. [25] found that kaolinite is the predominant clay mineral for all the soils studied. Halloysite occurs in freshly weathered materials, and smectite is present in poorly drained, lower members of the toposequence. Gibbsite occurs in soils derived from cretaceous arenaceous rocks in the high-rainfall areas. In soils derived from basalts, both aluminum silicates and aluminum oxides are present in amorphous forms, while iron oxides are predominantly in the crystalline forms of goethite and hematite. Some aluminum for iron substitution was present in goethite in the clay fraction of some Nigerian soils (37). Although the amounts of aluminum and iron sesquioxides may comprise only a small percentage of the clay fraction in tropical soils, which usually are dominated by 1:1 layer silicates, these oxides and hydroxides of aluminum and iron are often very important to phosphorus sorption and release. This is especially true in the fine-textured oxidic Alfisols, Oxisols, and Inceptisols where immobilization of large amounts of added soluble phosphorus (fixation) is possible.

Surface charges of soil minerals

On the basis of the electrochemical behavior, soils may be conveniently classified in accordance with two well-known types of colloids: (1) those with constant surface charge and (2) those with variable surface charge or constant surface potential. A mixed model of soil minerals containing variable charges with small amounts of constant charge has been recently developed and tested [74,26].

In general, agricultural soils of the temperate regions are characterized by surfaces bearing a constant surface charge, whereas soils of the humid tropics are characterized by surfaces having a variable surface charge which is determined by the potential-determining ions H^+ and OH^-. Examples of pH-dependent charge minerals are the oxides and hydrous oxides of Fe (hematite, goethite, lepidocrocite) and Al (gibbsite, boehmite). Among the phyllosilicates, kaolinite, halloysite, and Al-interlayed chlorites are the most common.

The surface charge of minerals with constant surface charge and constant surface potential is related to surface potential through the expression:

$$\sigma_0 = \left(\frac{2n\varepsilon kT}{\Pi}\right)^{1/2} \sinh\left(\frac{ze}{2kT}\Phi_0\right) \qquad (1)$$

where: σ_0 = net surface charge density
n = electrolyte concentration
ε = dielectric constant of the medium
k = Boltzman constant
T = absolute temperature
z = counter ion valence
e = electron charge
Φ_0 = surface potential

For constant surface charge minerals, surface charge arises from ion substitution in the interior of the crystal lattice so that the charge is constant and permanent. For minerals with constant surface potential and a pH-dependent charge, the surface potential is related to H^+ concentration through the expression:

$$\Phi_0 = (RT/F) \ln (H^+/H_0^+) \qquad (2)$$

where: R = gas constant
F = Faraday constant
H^+ = hydrogen ion activity
H_0^+ = hydrogen ion activity at the zero point of charge (ZPC)

Equation (2) can be simplified to:

$$\Phi_0 = 59\ (pH_0 - pH)\ \text{mv at } 25°C \qquad (3)$$

Thus, equation (1) can now be expressed as a function of pH:

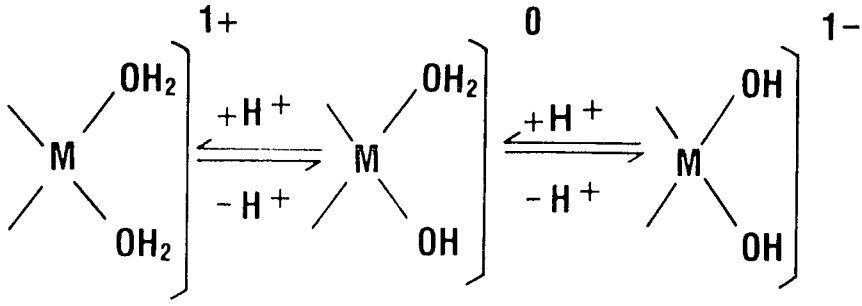


Figure 1. A simple model of variable surface charge mineral (M = Al or Fe) (adapted from Rajan et al. [63]).

$$\sigma_0 = \left(\frac{2n\varepsilon kT}{\Pi}\right)^{1/2} \sinh (1.15)z\,(pH_0 - pH) \qquad (4)$$

For the minerals of oxides of Fe and Al, surface charge arises not from replacements within the clay lattice but from reactions on the surface and the edges of clay crystals. At these sites there are surface hydroxyl or water molecules that can gain or lose H^+, depending on the pH, and hence vary the surface charge. A simple model can be depicted as shown in Figure 1.

Phosphate sorption by variable surface charge minerals

Juo and Fox [40] attempted to classify some western African soils from Nigeria, Togo, and Liberia according to their P-sorption capacity as related to soil mineralogy (Table 1). Desilicated amorphous material sorbs the highest amount of P whereas quartz sorbs the least.

Since it is generally accepted that amorphous oxides and hydroxides of Al and Fe in tropical soils are mainly responsible for P sorption and since these minerals are classified as variable surface charge minerals, the following dis-

Table 1 Classification of soil P-sorption capacity as influenced by soil minerals

Standard P requirement	Scale	Usual mineralogy encountered
(μg P/g soil)		
< 10	Very low	Quartz, organic materials
10-100	Low	2:1 clays, quartz, and 1:1 clays
100-500	Medium	1:1 clays with oxides
500-1,000	High	Oxides, moderately weathered ash
> 1,000	Very high	Desilicated amorphous material

Source: Juo and Fox [40].

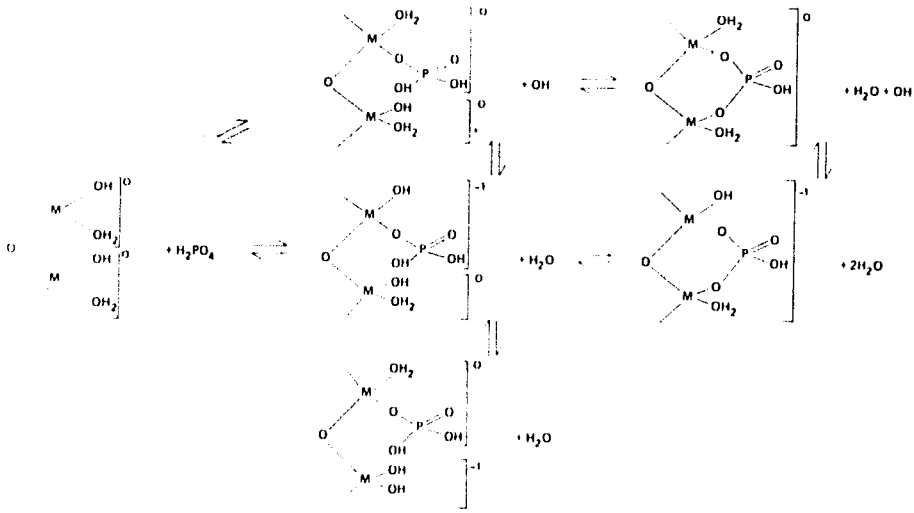


Figure 2. Changes in charge and possible changes in configuration following adsorption of phosphate on the surface of a metal oxide.

cussion will be limited to only the P sorption by variable surface charge minerals.

A simple model for changes in surface charge and possible changes in configuration following sorption of phosphate ion on the surface of Fe or Al oxides is shown in Figure 2. It can be seen that phosphate is closely and chemically bonded to the surface of Fe and Al oxides by specific bonds. The reaction may be regarded as partly a displacement of water molecules and partly a displacement of hydroxyls. An important feature as shown in Figure 2 is the transformation of the phosphate ion from that sorbed in the monodentate ligands form to that in the bidentate ligands (or ring structure) form. Hingston et al. [30] suggested that the phosphate sorption in the former form is reversible, whereas the latter form favors irreversibility. In other words, the phosphate ion in the latter form would be less likely to be desorbed and hence available to plant. Another important characteristic of phosphate sorption is that sorption increases the negative charge on the surface of Fe and Al oxides. This means that it becomes increasingly difficult for each additional increment of phosphate to be sorbed [6]. This may explain the effect of previous phosphate applications on decreasing the slope of phosphate sorption isotherm as shown by Fox and Searle [23].

Rajen et al. [63] proposed a model to determine which groups were reactive when phosphate was adsorbed at different concentrations on a hydrous Al oxide surface. At low concentrations phosphate mainly replaced water groups, but as adsorption increased and phosphate concentration increased, more hydroxyl groups were involved. At the adsorption maximum, phos-

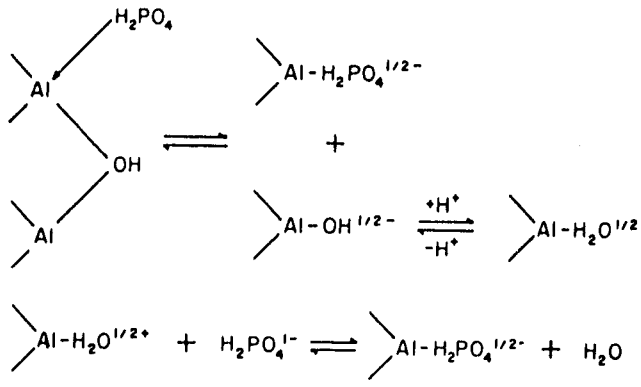


Figure 3. Surface reaction of phosphate ion with a hydrous Al oxide (after Rajan et al. [63]).

phate was mainly replacing hydroxyl groups. A breaking of a hydroxyl bonded to two Al^{+3} ions occurred when phosphate adsorption exceeded the adsorption maximum (Figure 3).

Phosphate ions can be adsorbed by Al and Fe oxides when the oxide surface exhibits net negative, net positive, or net zero charge. An example of phosphate adsorption by Fe oxide surface with three different charges is shown in Figure 4. For more detailed information on the mechanisms of surface reactions of phosphate with Al and Fe oxides and hydroxides, see a recent review article by Parfitt [61].

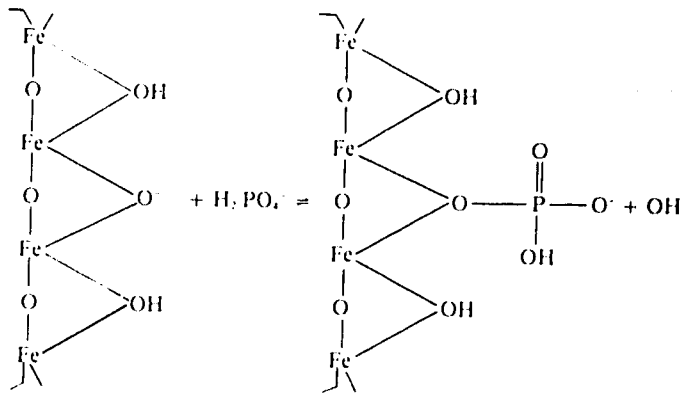
Phosphate sorption characteristics for some West African soils

Use of P-sorption isotherms for determination of P fertilizer requirements and for establishment of P fertilization practices has been advocated for West African soils [53,40,4]. Very limited current information exists on sorption characteristics of soils in the Guinea and Sahel zones of West Africa. We, therefore, conducted a study on the P-sorption characteristics of some major agricultural soils collected from different agroecological zones ranging from the perhumid to the Sahel in three West African countries (Nigeria, Mali, and Niger) (Figure 5). Some of the soil properties are shown in Table 2.

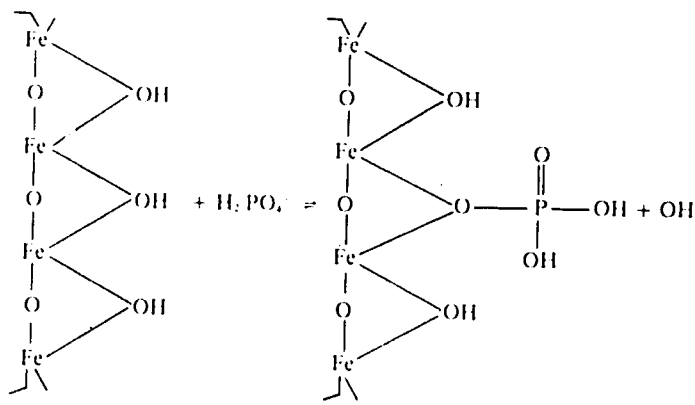
Experimental

Measurements of P sorption were conducted by equilibrating soil samples in 0.01 *M* $CaCl_2$ solutions containing P concentrations ranging from 0 to 25 μg P/ml for 6 days at 25°C. The amounts of P sorbed were calculated by difference. The P-sorption data were then fitted into the following three sorption equations:

a. Above the ZPC-oxide Surface Negatively Charged:



b. At the ZPC-oxide Surface with Net Zero Charge:



c. Below the ZPC-oxide Surface with Net Positive Charge:

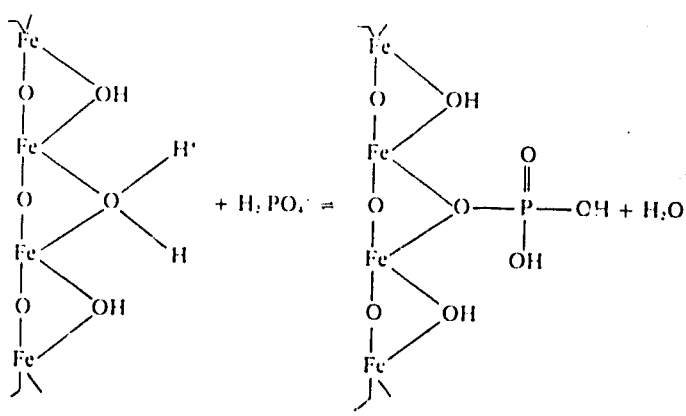


Figure 4. Phosphate sorption by Fe oxide at three different surface charges (after Sanchez and Uehara [69]).

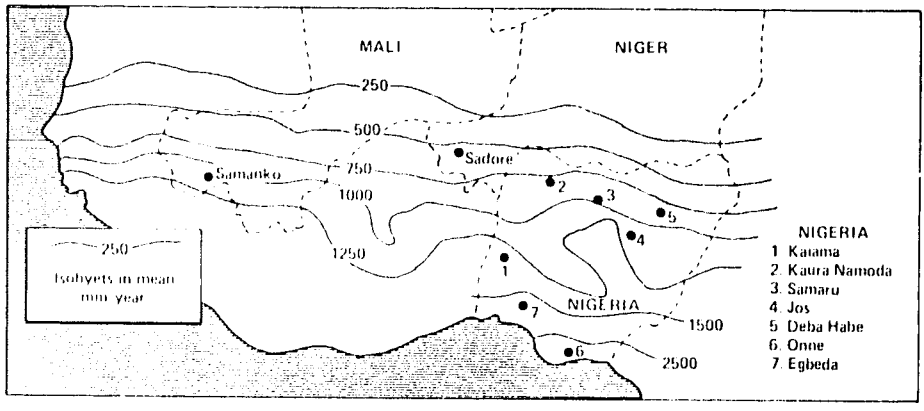


Figure 5. Location of soil samples collected in West Africa.

Langmuir equation:

$$C/X = 1/kX_m + C/X_m$$

where C = P concentration in solution, X = amount of P sorbed, X_m = P sorption maximum, and k = a constant related to the bonding energy.

Freundlich equation:

$$\log X = a + b \log C$$

where a and b are constants.

Temkin equation:

$$X = a' + b' \log C$$

where a' and b' are constants.

Observations

The amounts of P sorbed by the soils varied widely (Figure 6). At the P rates used, sorption did not seem to reach a maximum even at the highest rate of P addition (250 µg/g soil) for any of the soils except the Sadore (Niger) soil whose P-sorption capacity was already saturated at the P rate of 100 µg/g soil. Differences in P-sorption capacity among the soils also widened as the rate of P addition increased. At the lowest rate (50 µg P/g soil), all the soils except the Sadore soil appeared to have about the same magnitude in P-sorption capacity, whereas a distinct order of differences was observed at the highest rate of P addition.

The P-sorption data of all the soils, except Sadore, were fitted to the three equations by regression analysis. The Sadore soil was not included because it had only two data points for fitting to the equations. The results (Table 3) show that the three equations are all able to describe the sorption data ade-

Table 2 Some physical and chemical properties of the soils in tropical West Africa

Country	Location	Soil order	Clay	pH[a]	Organic C	Cation exchange capacity	Oxalate-extractable		
							Fe	Al	Mn
			(%)		(%)	(meq/100 g)	(μg/g soil)		
Nigeria	Kaura Namoda	Entisol	10	6.20	0.13	3.71	1.656	161	45
	Deba Habe	Alfisol	14	6.54	0.88	10.23	1.072	307	253
	Jos	Alfisol	22	5.33	1.53	3.79	1.716	720	110
	Samaru	Alfisol	9	5.85	1.08	4.15	1.913	240	82
	Egbeda	Alfisol	20	6.00	1.04	8.73	1.745	640	872
	Onne	Ultisol	18	4.30	0.64	2.86	2.277	1.345	76
	Kaiama	Alfisol	7	5.93	1.14	5.65	1.744	586	253
Mali	Samanko	Alfisol	8	5.75	0.43	2.75	1.499	350	265
Niger	Sadore	Entisol	4	5.53	0.17	1.00	259	68	22

[a] Soil: water (1:1).

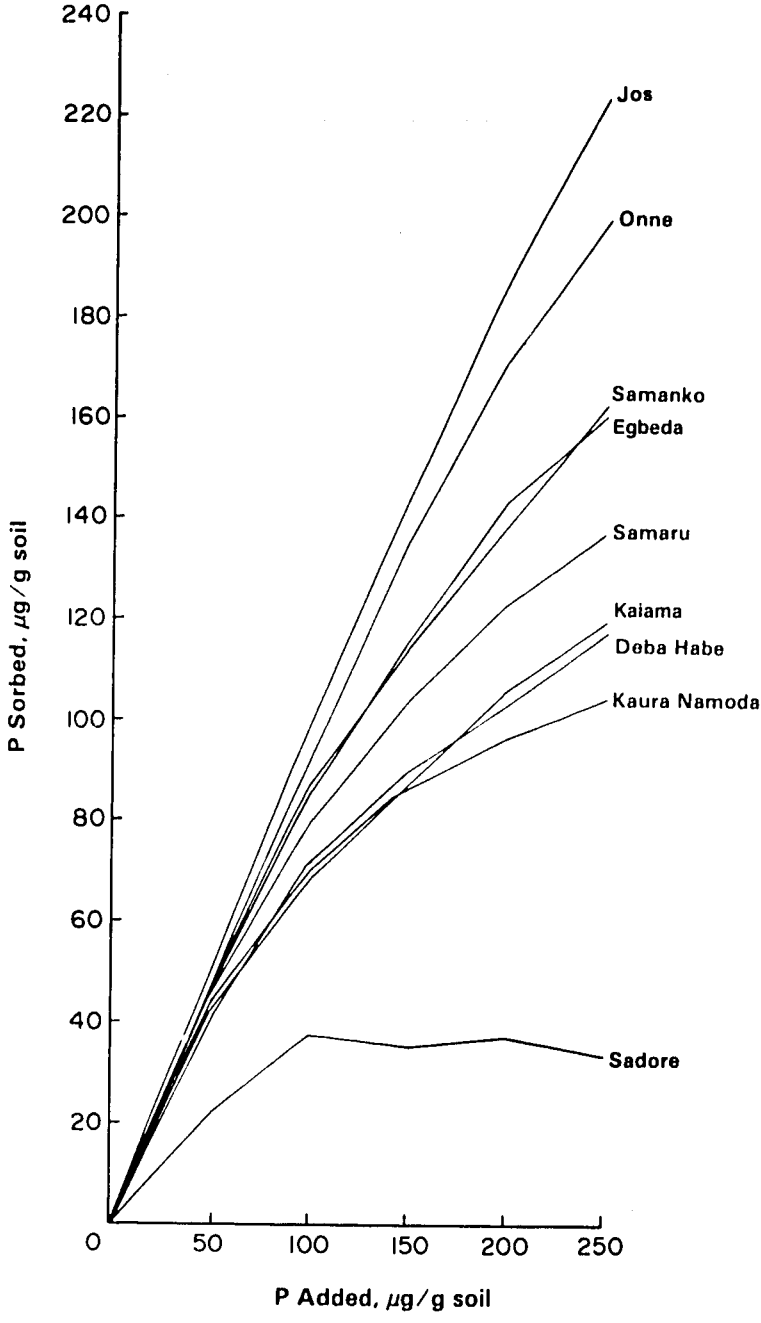


Figure 6. Phosphorus sorption by the soils.

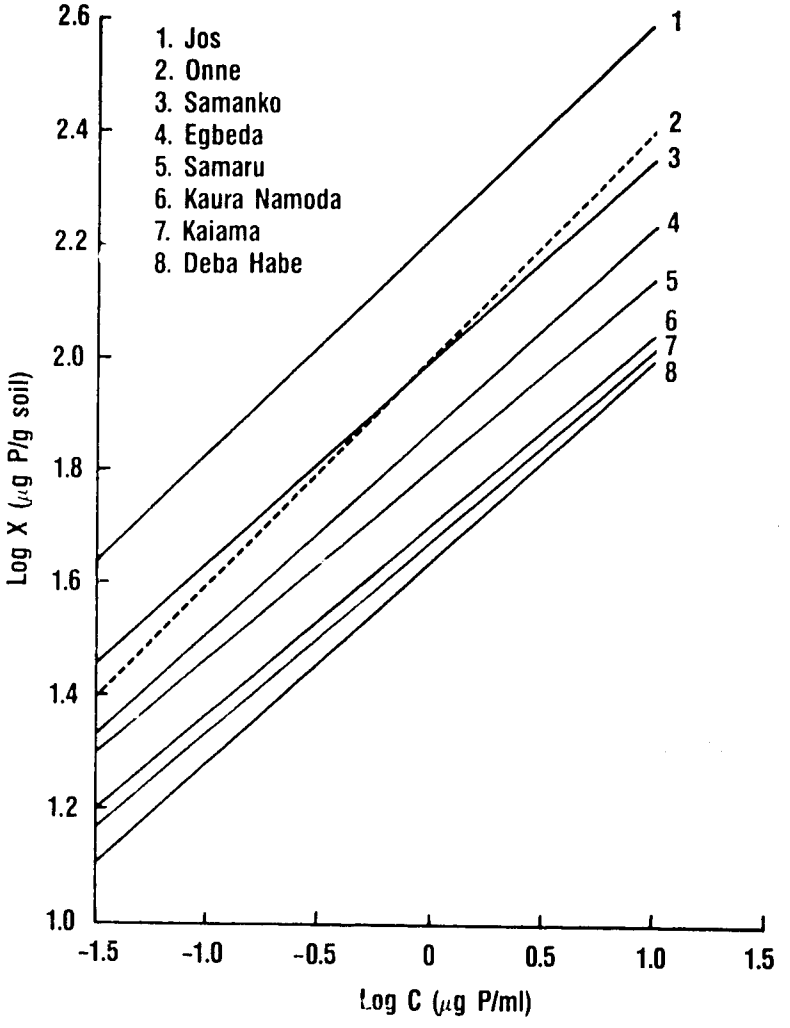


Figure 7. Freundlich plot for P sorption by the soils.

quately as judged by their highly significant correlation coefficients ($P < 0.01$). The Freundlich equation appears to perform slightly better than the Langmuir and Temkin equations for two soils (Kaiama and Samanko).

It is interesting to note that the Freundlich plots for all the soils, except Onne, are parallel, possessing a relatively constant value (0.35) of slope as shown in Figure 7. A regression of the intercept (a) of the Freundlich equation versus soil pH for all the soils resulted in the following relationship:

$$a = 4.49 - 0.45\ pH, \qquad r = 0.87^{**}$$

Thus, a unified Freundlich equation for all the soils, except Onne, may be expressed as:

$$\log X = 4.49 - 0.45\ pH + 0.35 \log C$$

This equation implies that the Freundlich sorption isotherm of P for many Alfisols and Entisols in West Africa, for the purpose of comparing their P-sorption capacity, may be constructed by simply measuring soil pH alone. More soil samples are needed to test further whether this relationship holds.

The P-sorption maxima, as estimated by the Langmuir equation for the soils used in this study, ranged from 36 to 244 μg P/g soil (Table 3). With the exception of the soils from Jos and Onne, all the soils can be considered as having a relatively low P-sorption capacity, particularly if compared with many soils from tropical Latin America [15]. The values, however, are in agreement with those obtained by Enwezor and Moore [20] and Ayodele et al. [4] for Nigerian soils but are much lower than the values obtained by Rhodes [64] for Sierra Leone soils.

Relationships between soil properties with P-sorption maxima as estimated by the Langmuir equation (Table 3) were examined by linear regression analysis. Positive significant correlations were found with clay content and oxalate-extractable Fe and Al (Table 4). Other soil properties such as soil pH, organic C, cation exchange capacity (CEC), and oxalate-extractable Mn were found not significantly correlated with P sorption.

Although the relationships between P sorption and soil properties for the

Table 3 Phosphorus sorption data of the soils as fitted into three sorption equations

Soil	P sorption maximum[a] (μg P/g soil)	Correlation coefficient, r[b]		
		Langmuir	Freundlich	Temkin
Jos	244	0.994	0.996	0.992
Onne	233	0.996	0.995	0.995
Egbeda	178	0.993	0.999	0.988
Samanko	172	0.986	0.998	0.975
Samaru	152	0.994	0.998	0.991
Kaiama	135	0.985	0.996	0.974
Deba Habe	133	0.995	0.995	0.997
Kaura Namoda	112	0.998	0.999	0.999
Sadore	36	–	–	–

[a] Based on the Langmuir equation except the Sadore soil in which the P-sorption maximum was actually measured (Figure 6).

[b] r = 0.959 (n = 5) at P = 0.01

West African soils appear to vary from soil to soil, it is a general observation that amorphous Fe and Al as extracted either by oxalate or dithionite seem to be the major components responsible for P sorption. In this study, the correlation between oxalate-extractable Fe and Al was not very high ($r = 0.677$), although it was statistically significant ($P < 0.05$). When the P-sorption maxima were correlated with the sum of oxalate-extractable Fe or Al, the correlation was significantly improved over that with oxalate-extractable Fe or Al alone (Table 4). This suggests that using the sum of oxalate-extractable Fe and Al instead of oxalate-extractable Fe or Al alone may be a better way to estimate the P-sorption capacity for the soils in tropical West Africa. The prediction might be improved even further if the organic matter-complexed Fe and Al are also included, in that Le Mare [43] found that P sorbed in the nonexchangeable form was highly correlated with organic matter-complexed Fe and Al. This parameter, however, was not measured in this study.

The relatively low P-sorption maxima imply that the so-called fixation of applied P in any substantial quantities is unlikely in these soils. Indeed, the International Fertilizer Development Center (IFDC) field trials in Sadore, Niger, showed that millet grain yields increased significantly from 300 kg/ha to 700 kg/ha with the first increment of only 6.5 kg P/ha and reached the maximum yield of 1,200 kg/ha at a rate of 13 kg P/ha (unpublished data). In Samaru, in the Northern Guinea savanna of Nigeria, Mokwunye [53] observed that approximately 65 kg P/ha was required to obtain maximum maize yield. The higher P requirement for maximum crop yield on the Samaru soil as compared with the Sadore soil can be explained by the higher P-sorption capacity of the Samaru soil (Figure 6). On the other hand, P application rate as high as 600 kg P/ha was required to obtain maximum maize yield in the Cerrado region of Brazil [27].

Table 4 Simple correlation coefficients for P-sorption maxima and soil properties

Soil property	Coefficient, r
Clay content	0.809[a]
pH	0.496[ns]
Organic C	0.415[ns]
CEC	0.483[ns]
Oxalate-Fe	0.789[a]
Oxalate-Al	0.791[a]
Oxalate-Mn	0.188[ns]
Oxalate-(Fe + Al)	0.876[b]

[a] Significant at 0.05 level.
[b] Significant at 0.01 level.
ns = Not significant.

Chemical reactions of phosphate fertilizers with soils

In order to understand the usefulness of phosphate fertilizers in promoting plant growth both in the short run and the long run, it is important to understand the nature of the solution formed when P fertilizers are added to the soil, the interactions between the phosphate solution and soil constituents, and the ability of the products of these interactions to release phosphorus into the soil solution for uptake by plants.

Reactions at the fertilizer granule site

The primary constituent of commercial phosphate fertilizers is monocalcium phosphate monohydrate (MCP) – $Ca(H_2PO_4)_2 \cdot H_2O$. The physicochemical processes that are initiated when a granule of phosphate fertilizer containing MCP is placed in the soil have been the subject of intensive investigation. Many of the early investigations were done by scientists at the National Fertilizer Development Center, Tennessee Valley Authority. These have been summarized by Huffman and Taylor [36] and Huffman [35]. Upon contact with the soil, MCP dissolves readily, its rate being affected by the rate of movement of moisture from the surrounding soil. As the granule dissolves, movement of moisture is in response to moisture gradients that are reflected in part by differences in vapor pressure between the granule site and surrounding soil (Figure 8). Lindsay and Stephenson [46] observed that moisture movement into the granule occurs as both liquid water and water vapor. Dissolution of MCP is accompanied by partial hydrolysis. The solution that is formed is saturated with respect to dicalcium phosphate dihydrate (DCPD) – $CaHPO_4 \cdot 2H_2O$ and undissolved MCP. This solution, known as the metastable triple point solution (MTPS), is highly enriched with phosphate (Table 5). Lindsay and Stephenson [46] estimated that approximately 21% of the original P in the MCP remains at the granule site as newly precipitated DCPD. The dissolution of MCP is dependent on the soil insofar as this medium is the source of moisture. However, the formation and composition of MTPS are independent of the soil.

Reactions in soil surrounding fertilizer granules

Because of the high concentration of P in MTPS, a gradient is created between the granule site and the surrounding soil. MTPS moves out as a liquid into the surrounding soil in response to this gradient. The contact of MTPS with surrounding soil initiates a series of chemical reactions. As a result of

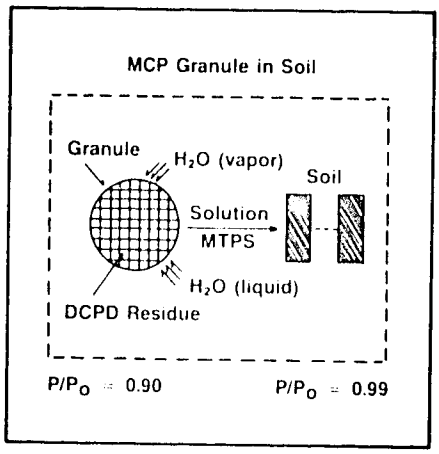


Figure 8. Dissolution of a granule of MCP in soils with the formation of MTPS and a residue of DCPD (Lindsay [44]).

the high acidity of MTPS (Table 5), large quantities of Al, Fe, Ca, silica, and other soil constituents are brought into solution. In acid soils the quantities of Fe and Al dissolved are substantial. The soil immediately surrounding the granule becomes partially depleted of its readily available components as MTPS continues to sweep through it. Farther out from the granule site, the pH of the advancing solution increases as more cations are dissolved. This increase in pH promotes the precipitation of products of the reaction of phosphorus and soil constituents.

Dicalcium phosphate dihydrate is one of the most important initial precipitation products of MCP not only at the granule site but also throughout the surrounding soil. The amount of DCPD formed at the initial reaction zone depends on the calcium content of the soil.

The formation of MTPS ceases when all the MCP is dissolved. Because the water vapor pressure of MTPS is approximately 90% that of pure water at 25°C, water vapor continues to move into the solution long after MCP has dissolved. The condensation of the water vapor into the concentrated fertilizer solution retained by the soil capillaries results in its dilution and causes a further expansion of the reaction zone. As the fertilizer solution comes in contact with fresh soil, additional constituents are dissolved, accompanied simultaneously by precipitation of Ca, Fe, and Al phosphates. Lindsay and Stephenson [47] observed that precipitation of the phosphate compounds accelerated as the pH rose above 2.3. As the pH rises, the environment of the reaction zone is controlled by the initial reaction products. In time, these initial reaction products dissolve at the expense of more stable phosphate compounds. The amount of phosphorus in solution for plant uptake is gov-

erned ultimately by the solubility of these reaction products. This subject will be discussed more fully later. It has been observed [46] that Fe and Al which are solubilized by the acid solution are generally carried in solution away from the fertilizer granule site. Closer to the fertilizer site the concentration of Fe tends to be higher than the Al concentration, which indicates that any Fe-phosphate association would occur closer to the fertilizer granule site than would Al-phosphate association. This observation has implications for crop nutrition. It suggests that Al-phosphate reaction products may be relatively more important for the supply of P to the crop than Fe-phosphate reaction products not only because Al products are less stable [39] but also because they would occur throughout a larger volume of soil.

Calcium phosphate fertilizer versus ammonium phosphate fertilizers

Most commercial phosphate fertilizers in use in tropical Africa are calcium phosphate (e.g., single superphosphate and triple superphosphate), ammonium phosphates (e.g., monoammonium phosphate and diammonium phosphate), or compound granular fertilizers containing potassium salts. We have thus far reviewed the dissolution of MCP in calcium phosphates. The dissolution of ammonium phosphates has been interpreted in terms of the three-component system, NH_3-P_2O_5-H_2O. In this system no hydrolysis or precipitation occurs [36]. The mechanism is that of a single congruent dissolution of the ammonium phosphate salt. No residues are left at the fertilizer site. Several processes may occur simultaneously:

1. Diffusion of the dissolved fertilizer in soil water away from the application site.

Table 5 Saturated solutions of phosphate salts at 25°C

Salt	Saturated solution			
	pH	Composition M		
		Ca	NH_4	P
$Ca(H_2PO_4)_2 \cdot H_2O + CaHPO_4$ (stable triple point, TPS)	1.01	1.34		4.50
$Ca(H_2PO_4)_2 \cdot H_2O + CaHPO_4 \cdot 2H_2O$ (metastable triple point, MTPS)	1.48	1.44		3.98
$NH_4H_2PO_4$	4.00		2.90	2.90
$(NH_4)_2HPO_4$	8.08		7.62	3.86

Source: Huffman and Taylor [36].

2. Movement of soil water from surrounding soil toward the application site.
3. Reactions between the fertilizer solution and soil constituents.

The composition of the saturated solution is shown in Table 5. From an agronomic standpoint, Terman [72] observed that in P-deficient soils early growth response was recorded and, occasionally, higher crop yields resulted from application of ammonium phosphates than from calcium phosphates of equivalent P content. Engelstad and Terman [18] attributed this phenomenon to the fact that the residue of dicalcium phosphate, which constitutes 20% or more of applied P and which remains from superphosphate granules, reduces immediate P availability.

Compound Granular Fertilizers

The behavior of compound granular fertilizers when added to the soil has been summarized by Huffman and Taylor [36]. Studies involving mixtures of MCP and KCl show that, in the presence of water and depending on the initial composition, the salts $Ca(H_2PO_4)_2 \cdot H_2O$, $CaHPO_4$, $CaHPO_4 \cdot 2H_2O$, $Ca_4KH(PO_4)_4 \cdot 2H_2O$, KH_2PO_4, and KCl may be present. Of particular interest is the presence of the calcium potassium phosphate. The formation of this salt depresses solution pH to as low as 0.5. In such an acid medium, the dissolution of cations and other soil constituents is intensified.

Water-Insoluble P Fertilizers

Phosphate Rock (PR)

– Several countries in tropical Africa have deposits of PR. Direct application of finely ground PRs from local deposits seems to be an economic means for P fertilization [73,54,41]. Apatite is the principal mineral in PR, but the apatite in each PR should be regarded as a distinct mineral species [10]. The solubility of apatite in soils is governed by its chemical and mineralogical properties and by the properties of the soil.

The dissolution of a carbonate apatite may be represented by the following equilibrium reaction [10]:

$$Ca_{10-0.42x}Na_{0.3x}Mg_{0.12x}(PO_4)_{6-x}(CO_3)_xF_{2+0.4x} \rightleftharpoons$$

$$(10-0.42x)Ca^{2+} + 0.3xNa^{+} + 0.12xMg^{2+} + (6-x)PO_4^{3-} + xCO_3^{2-} + (2+0.4x)F^{-} \quad (5)$$

In acid soils the PO_4^{3-} ions and other anions react with H^+ as follows:

$$PO_4^{3-} + 2H^+ \rightleftharpoons H_2PO_4^- \quad (6)$$

$$CO_3^{2-} + 2H^+ \rightleftharpoons H_2O + CO_2 \quad (7)$$

$$F^- + H^+ \rightleftharpoons HF \quad (8)$$

These neutralization reactions of phosphate and other anions in acid soils have been shown by Chien [10] to provide the driving force for the dissolution of carbonate apatite. Thermodynamic calculations suggest that these reactions are spontaneous.

Another important apatite mineral in PR is hydroxyfluorapatite, and its dissolution can be represented by the following equilibrium reaction:

$$Ca_{10}(PO_4)_6(OH)_xF_{2-x} \rightleftharpoons 10Ca^{2+} + 6PO_4^{3-} + xOH^- + (2-x)F^- \quad (9)$$

In acid soils, the neutralization of the anions with H^+ ions is the same as that of carbonate apatite with the modification that hydroxyl ions replace carbonate ions in the following reaction:

$$OH^- + H^+ \rightleftharpoons H_2O \quad (10)$$

The neutralization reaction provides the free energy for dissolution of apatite in acid soils.

Unlike water-soluble phosphate fertilizers, the phosphate concentration of solutions generated when PR reacts with soils is relatively very dilute [68]. Such dilute solutions are not expected to participate in precipitation reactions as was the case with MCP. However, release of phosphate from PR into the soil solution is usually followed by reactions of the P with the soil. Adsorption-type reactions have been identified [15]. In a study undertaken to characterize the nature of reaction products 5 years after PR was applied to a Colombian Oxisol, Chien [13] found that 2.5% of the reactive Sechura PR and 20.9% of the unreactive Pesca PR remained unreacted. However, the rate of PR decomposition in this Oxisol was apparently faster than is usually the case in temperature soils. It was concluded that since only a small fraction of the original apatite was unreacted, the reaction products were largely responsible for the residual P available to the crops. The exact nature of these reaction products is yet to be characterized.

Fused Phosphates

– Fused phosphates such as Rhenania phosphate are made by heating PR

with additives such as alkali carbonates and silica at temperatures in the range of 1200°-1400°C. The product of fusion is insoluble in water but soluble in ammonium citrate. The following equation illustrates the chemical process involved in the production of Rhenania phosphate:

$$Ca_{10}(PO_4)_6F_2 + 4NA_2CO_3 + SiO_2 \xrightarrow{\Delta} 6CaNaPO_4 + 2Ca_2NaPO_4 + 2Ca_2SiO_4 + 2NaF \quad (11)$$

The reaction of Rhenania phosphate in soil is similar to the reaction of PR. Increased soil acidity increases the dissolution of fused phosphates. Engelstad et al. [17] demonstrated that in acid soils Rhenania phosphate was as good as TSP. In laboratory studies, Chien [12] observed that more water-extractable P was maintained in an acid soil treated with Rhenania phosphate than in the same soil treated with TSP. Silicate in Rhenania phosphate decreased sorption capacity of the acid soil enabling more of the dissolved P to remain as water-soluble P.

Partially acidulated phosphate rock (PAPR)

As previously noted, the agronomic effectiveness of PR is determined by the properties of the soil and the chemical and mineralogical properties of the PR. Unreactive PRs dissolve so slowly in the soil that the amount of P released is insufficient to support the growth of fast-growing short-season crops. It is possible to improve the effectiveness of unreactive PRs by reacting them with portions of the sulfuric acid or phosphoric acid that would have been required to produce superphosphates. The products obtained in this manner are called PAPR. Depending on an acidulation efficiency of 100% and the acid used, the material manufactured during PAPR production consists mainly of the unreacted PR and a water-soluble phosphate compound. Most often, however, the material produced consists of the unreacted rock, a water-soluble product, and a number of other products, some of which are soluble in ammonium citrate and some of which are not. The water-soluble component is usually monocalcium phosphate monohydrate, and the reactions of this compound with soils have been reviewed.

Where PAPR has proved as effective as the superphosphate for crop production, there has been no agreement on the roles played by the water-soluble and unreacted rock components of PAPR. Although this controversy is far from being resolved, Mokwunye and Chien [56] provided data to support the findings of McLean and his colleagues [52,48] that there is an interaction between the water-soluble P and the unreacted PR in PAPR when added to

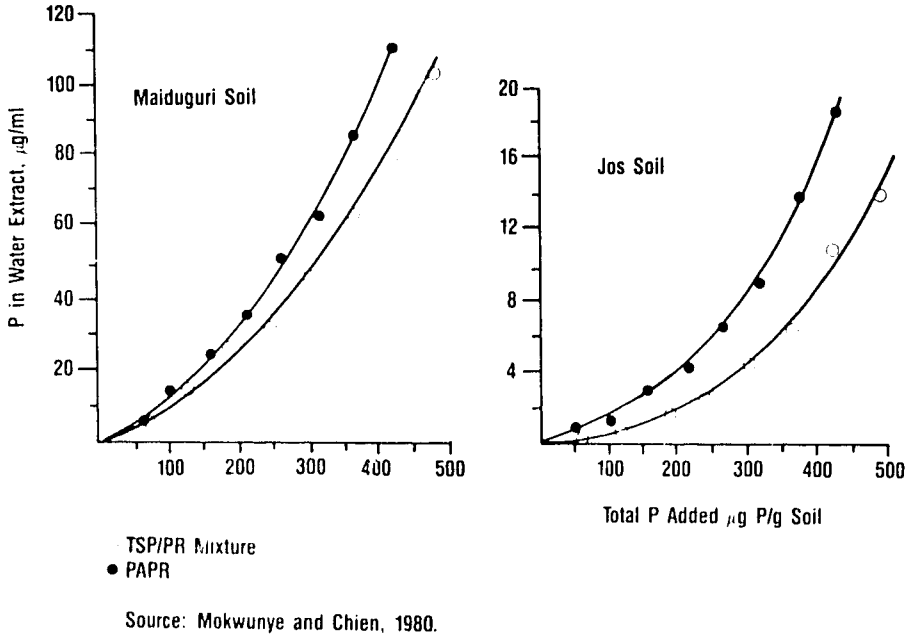


Figure 9. Water-extractable P in two Nigerian soils after 1 week's shaking at 20°C with nearly equal amounts of total P as the mixture of TSP and phosphate rock or as partially acidulated phosphate rock.

the soil. In laboratory studies, it was found that when water-soluble P was added in equal amounts to different soils and the soils were incubated for varying periods, the amount of water-extractable P was higher in PAPR-treated soils than in soils treated with TSP (Figure 9). The addition of PR to TSP resulted in an increase in water-extractable P. The results suggest that the presence of PR in PAPR and in the TSP/PR mixture slowed down the immobilization of water-soluble P by dissipating some of the acidity produced during MCP hydrolysis. The presence of PR served as a source of base for the highly acidic MTPS and thereby reduced the quantities of Al, Fe, and Mn solubilized.

Changes in reaction products with time

It was pointed out earlier in this review that the initial precipitation products, of which DCPD is a major component, are metastable. In time, these products change into P compounds that are more stable and less soluble. In calcareous soils, insoluble calcium compounds such as octacalcium phosphate (OCP) and tricalcium phosphate are presumed to be

formed from the breakdown of DCPD [51,59,21]. In acid soils one could say with certainty that OCP does not form because during the breakdown of calcium phosphates such as DCPD (a possible product at the granule site), the phosphate is removed from solution by soil constituents such as Fe and Al faster than OCP can be formed [51]. The rest of the picture is fuzzy. There is evidence to suggest that the abundance of Fe and Al in solution in acid soils results in the formation of amorphous Al-Fe compounds [16,70]. These compounds have been presumed to be converted to variscite or strengite upon aging [34,45]. However, in a series of experiments, Hsu [32,33] concluded that conditions for the formation of variscite do not exist in the soil under normal conditions. To date, no crystalline Al-P and Fe-P reaction products in P-fertillized soils have been isolated and identified.

On the basis of solubility principles, one would assume that the presence of high amounts of Al and Fe in many acid soils would encourage the formation of Al-P and Fe-P reaction products. It is probable that these are not discrete Al or Fe phosphate compounds but conglomerates of amorphous Al+Fe-P. Furthermore, the environment in which an acid soil occurs would determine the dominant reaction product. Some acid soils have relatively low Fe and Al contents (Table 2). The erosion of DCPD may be slowed down under these conditions, making DCPD an important contributor to the long-term P nutrition of crops. There is obviously a need to identify the reaction products of P fertilizers and tropical African soils; this knowledge is necessary in choosing the phosphate fertilizer and management practice most suitable for each environment.

Phosphorus needs of tropical African soils

Evaluation of native soil phosphorus

Three factors govern the ability of soils to supply phosphorus to crops: (1) the concentration of phosphorus in soil solution (intensity factor), (2) the amount of phosphorus present in the solid phase in equilibrium with phosphorus in soil solution (capacity factor), and (3) the rate of renewal once the concentration of phosphorus in soil solution is depleted, e.g., as a result of plant uptake (rate factor).

Various chemical extractants have been used to estimate 'available' phosphorus. Oteng and Acquaye [60] extracted 48 different soils from different ecological zones in Ghana with ten different extractants. The mean value was as low as 0.09 mg P/kg soil (using Morgan reagent) to as high as 8.77 mg P/kg soil (using 1% citric acid). Rhodes [65] found that the mean value extracted

by Bray 1 extractant in higly weathered Sierra Leone soils was 10.58 mg P/kg soil. Although chemical extraction methods have the attraction of involving fairly simple laboratory procedures, they require extensive correlation and calibration with crop response in the field. In general, satisfactory correlations have been found with most extractants from time to time in tropical Africa and none has been found to be always suitable in all areas [28].

The chemical potential of monocalcium phosphate to estimate the phosphorus status of soils, as suggested by Schofield [71], has been successfully used [42] to provide a reliable index of available phosphorus for cotton in Uganda.

More recently, phosphorus sorption techniques, which take into consideration the intensity/capacity relations, have been utilized to predict the phosphorus needs of soils and to estimate the external phosphorus requirements of crops [22]. Using the intensity/capacity relations, Mokwunye [55] reported that relatively low levels of phosphorus (50 kg P/ha and 25 kg P/ha for an Alfisol and an Ustipsamment, respectively) were required to maintain an equilibrium phosphorus concentration of 0.2 kg/ml. Proportionately higher rates of 35 kg P/ha were required to attain an equilibrium phosphorus concentration of 0.012 μg/ml in a Typic Umbriothox in Sierra Leone [66]. Appreciable variations exist in the amount of phosphorus sorbed at an equilibrium solution concentration of 0.2 μg/ml. From a study of soil profiles from Nigeria, Togo, and Liberia, Juo and Fox [40] showed that Alfisols and Ultisols derived from basalt have the highest phosphorus requirement compared with Alfisols, Ultisols, and hydromorphic soils derived from acidic, coarse-textured parent materials.

Extraction of phosphorus with anion resin has been used in several locations in tropical Africa (e.g., Maida [49]). Resin-extractable phosphorus, which reflects the intensity, capacity, and rate factors, gave the best correlation with crop phosphorus uptake for savanna soils of Nigeria [5] and for a wide range of tropical African soils [67].

The critical thresholds of phosphorus deficiency for six tropical African soils as determined by both chemical extractants and anion resin are presented in Table 6.

Evaluation of soil phosphorus after addition of various sources of phosphorus fertilizers

Phosphorus uptake by crops is principally a function of the amount of phosphorus in soil solution. The usefulness of a phosphorus fertilizer is therefore measured in terms of its ability to maintain a high enough concentration of phosphorus in soil solution to sustain crop growth. It is also critical to moni-

tor the ability of the reaction products, formed when the fertilizer reacted with soil constituents, to continue to replenish soil solution phosphorus over the long run.

Mackenzie [50] added monocalcium phosphate ($Ca(H_2PO_4)_2$) to some Ultisols from Sierra Leone and incubated them at room temperature for 0, 5, or 12 weeks. During the incubation period, the samples were subjected to wetting and drying cycles. At the end of each incubation period, phosphorus recovered by the Bray 1 extractant was measured. The results are summarized in Table 7. Phosphorus extracted declined with time. However, in all cases, the addition of 50 mg P/g of soil was sufficient to change the soil tests to levels at which no response to phosphorus fertilizers would be expected.

There is strong evidence, especially in West Africa, that phosphorus fertilizers have a strong residual effect [75]. Mokwunye [53] found that the buffer

Table 6 Assessment of critical thresholds of phosphorus deficiency

Extraction procedure	Oxisol	Ultisol	Vertisol	Entisol	Inceptisol	Alfisol
	(ppm)					
Truog P		15			8	15
Olsen Dabin P		30-40	30-40	20		25
Saunder P				60-95		85
Bray P2	10	15-20	10	10-15		15
Dalal P				60		50
Water-extractable P		0.50	0.25	0.20		
48-hour resin-desorbed P	10-15	10	17	10	10-17	10

Source Adapted from Roche et al. [67].

Table 7 Effect of time on phosphorus extractable by bray P1

Soil series	pH	P applied	Incubation period		
			0	5	12
		(ppm)	(weeks)		
Mokonde	4.6	0	7	8	8
		50	47	36	30
Pelewahun	4.5	0	21	21	22
		50	60	53	41
Bonjema	4.1	0	7	6	6
		50	48	44	40
Njala	4.0	0	8	9	9
		50	48	40	37

Source Mackenzie [50].

capacity of an Alfisol at Samaru dropped, 1 year after application of 150 kg P_2O_5/ha, from 13.44 kg P/ha per 0.1 μg/ml to 5 kg P/ha per 0.1 μg/ml. Consequently, the amount of phosphate fertilizer required to raise the equilibrium phosphorus concentration to 0.2 μg/ml changed from 50 kg P/ha to 29 kg P/ha.

Results from use of chemical extractants such as Bray 1 extractant on soils that have been fertilized with water-insoluble phosphate fertilizers have not lent themselves to uniform interpretation. For example, tests conducted in Kansas as reported by Chien [11] showed that Bray 1 solution was very useful in measuring the release of phosphorus from a Florida rock to forms that could be regarded as available for plant utilization. However, Peaslee et al. [62] found that the correlation between the plant-availability coefficient ratios and Bray 1 extractability coefficient ratios for Iowa soils to which a Florida rock had been applied was very poor. As suggested by Chien [11] phosphorus extracted from soils treated with phosphate rock is partly from the reaction products and partly from the unreacted apatite. In a field trial conducted in Sierra Leone (E.R. Rhodes, unpublished), soil tests made 12 months after application of 200 kg P/ha in various forms to pigeon pea showed that Bray P2 extracted more phosphorus than did Bray P1 from soils treated with phosphate rock (Table 8). Partial fractionation using the Chang and Jackson [8] procedure showed that Fe-P reaction products were in the greatest abundance. This would tend to suggest that the use of Olsen's P test (0.5 *M* $NaHCO_3$) could be a better choice in these soils [7].

Role of organic phosphorus in soil testing

Although mineralization of humus is thought of primarily in terms of the

Table 8 Bray P and partial fractionation of phosphorus (Chang and Jackson [8]) in a njala plinthic paleudult treated with phosphate fertilizers

Field plot treatment	Bray P1	Bray P2	Fe-P	Al-P	Ca-P
		(ppm)			
Basic slag	10.2	17.9	91.3	65.6	17.0
Single superphosphate	14.3	23.4	105.0	84.4	14.0
North Carolina rock phosphate	8.0	19.0	76.3	62.5	46.3
Senegal rock phosphate (Taiba)	4.0	12.5	59.4	46.9	66.5
Phosphal[a]	11.1	19.0	126.9	68.8	17.2
Untreated	5.0	6.8	55.0	46.9	7.4

[a] Phosphal is calcined aluminum phosphate from Thies in Senegal.
Source: Rhodes (unpublished).

amount of nitrogen released, in fact, a complete range of nutrients, both macro and micro, is released. Appreciable amounts of organic phosphorus have been reported in soils of West Africa. Acquaye [1] found that 46%-70% of the total phosphorus in different soils in Ghana was in organic form, and Enwezor and Moore [19] reported a range of 17%-72% for soils throughout Nigeria. Although savanna soils contain less organic matter than do forest soils, the organic phosphorus released during humus mineralization in the Sahel may be particularly important to crop production and may account for soil productivity increases after organic matter levels have been raised during fallow. In general, however, savanna soils contain less organic phosphorus than do soils from the forest zone [2,57].

Since phosphorus is usually taken up as the orthophosphate ion, the rate of mineralization of organic phosphorus is a crucial factor in determining the contribution of organic phosphorus to plant nutrition. Measuring the rate of mineralization of organic phosphorus is one phase of research that has not received adequate attention. In the savanna and Sahel zones of West Africa, the rate of humus mineralization during the cropping period is estimated to be between 4% and 5% [58,38,9]. Most chemical extraction procedures are concerned with the extraction of inorganic forms of phosphorus, and there are instances where crops have failed to respond to phosphate fertilizers although soil test data suggest that phosphorus should be limiting in such soils (IFDC: Fertilizer Research Program in Africa, Progress Report, 1984).

Where research has been done, mineralization of organic phosphorus has been used as an index of phosphorus availability. For example, Adepetu and Corey [3] reported that phosphorus mineralized during cropping with maize in a greenhouse correlated significantly ($r = 0.90$) with phosphate uptake by maize for soils from the Nigerian savanna region. In Kenya, Friend and Birch [24] reported significant correlation between organic phosphorus and phosphorus uptake by crops. There are instances, however, where poor correlations have been obtained [57,31,5]. Obviously, there is need for further studies to assess the significance of organic phosphorus in determining the phosphorus needs of tropical African soils and crops.

Summary

Phosphorus deficiency in soils of tropical Africa severely limits crop production. The agronomic effectiveness of phosphate fertilizers is a function of the chemical reactions between the fertilizer components and soil constituents. The nature of the colloidal systems in tropical African soils controls the behavior of phosphate fertilizers in these soils. Thus immobilization or fixation of phosphorus is encouraged in the fine-textured, oxidic, base-rich

Alfisols, Oxisols, and Inceptisols, whereas the low surface charge densities of the coarse-textured, kaolinitic, strongly acidic and often highly weathered Ultisols and Oxisols enhance crop response to even small doses of phosphorus fertilizers.

The amount of phosphorus in soil solution controls the uptake of phosphorus by crops. The agronomic value of a phosphate fertilizer is therefore dependent on its ability to maintain a sufficient quantity of phosphorus in soil solution for uptake by the crop. Several techniques have been developed to test the native phosphorus level in the soil and to determine the quantity of fertilizer needed to enhance crop growth. Although more time consuming, the techniques that take into consideration the relationships between the amount of phosphorus in soil solution, the phosphorus in the solid phase at equilibrium with that in solution, and the rate of replenishment of the soil solution phosphorus seem to hold much promise for assessing the phosphorus requirements of tropical African soils and crops.

Finally, the role of organic phosphorus as a primary source of inorganic phosphorus for crops must be considered. The need for additional research on this and other crucial aspects of the chemistry of phosphorus in tropical African soils cannot be overemphasized.

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Agronomic evaluation of phosphate fertilizers in tropical Africa

A. Bationo, S.K. Mughogho, and U. Mokwunye

Introduction

For over 50 years scientists have acknowledged the harmful effects on crop production of deficiencies of phosphorus in tropical African soils, and efforts have been made to (1) assess the extent of phosphorus deficiency in the soils [13,27,36,35,14,17], (2) estimate the phosphorus requirements of major food crops [10,11,19,28,22,31], and (3) evaluate the agronomic potential of various phosphate fertilizers including phosphate rock from local deposits [2,15,16,30,32,33,20,41,29,40]. In spite of these efforts, little information exists on the role of fertilizers in sustaining productivity of tropical African soils. There are three major reasons for this paucity of information: (1) the experiments were carried out with low management inputs including use of low-yielding local crop varieties with poor response to fertilizer; (2) the experiments were primarily annual trials; and (3) the experiments were carried out with little attempt to relate results to specific soil or ecological conditions [23].

Field studies were undertaken by the International Fertilizer Development Center (IFDC), and a major goal was to investigate means of improving fertilizer use and fertilizer efficiency in order to increase crop production in tropical Africa. More specifically the objectives of the phosphorus research program were as follows:

1. To assess the extent of phosphorus deficiency in tropical African soils by evaluating the response of cereals to phosphorus fertilizers.
2. To evaluate the potential of indigenous phosphate rocks for direct application or production of phosphate fertilizers at minimal cost.
3. To develop management practices for a more efficient utilization of phosphorus fertilizers.

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Methodology

Benchmark experiments

The experiments that were set up in 1982 by IFDC in collaboration with the International Institute of Tropical Agricultre (IITA) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) were designed to eliminate the three constraints listed earlier. They were set up in Ikenne (Nigeria), Mokwa (Nigeria), and Sadore (Niger) in the humid, subhumid, and semiarid agroecological zones, respectively, to study, among other things, the general response of the primary cereal crops (maize and millet) to phosphorus fertilizers. Since the rainfall pattern is bimodal at Ikenne, maize was grown during the first season and cowpea was grown during the second (shorter) season. At Mokwa, where the rainfall pattern is unimodal, a maize/cowpea intercrop system was adopted. Sole crop millet was grown at Sadore in Niger. At both Ikenne and Mokwa, phosphorus was applied at the rates of 0, 30, 60, and 90 kg P_2O_5/ha in the form of single superphosphate (SSP) in each of 2 years (1982 and 1983). At Sadore P was applied annually (1982, 1983, and 1984) at the rates of 0, 10, 20, 30, and 40 kg P_2O_5/ha in the form of SSP. At the two sites in Nigeria, nitrogen was applied at the rate of 120 kg N/ha in the form of urea and in two splits, one-third at time of planting and two-thirds 4 weeks after planting. Potassium (90 kg K_2O/ha), magnesium (10 kg Mg/ha), and zinc (2 kg Zn/ha) were applied uniformly to all plots. At Sadore the N rate was 30 kg/ha as urea, and K was applied at 30 kg K_2O/ha to all plots.

Phosphate fertilizer source evaluation

A second objective of the benchmark experiments was to evaluate the agronomic potential of different phosphate fertilizer sources, including phosphate rock (PR) and partially acidulated phosphate rock (PAPR), in the three agroclimatic zones. At both Ikenne and Mokwa the agronomic potentials of Togo phosphate rock (PR) and partially acidulated forms of Togo PR (PAPR) were compared with the performance of two standard commercial phosphate fertilizers, SSP and triple superphosphate (TSP). All P fertilizers were applied at the rates of 0, 30, 60, and 90 kg P_2O_5/ha. An additional treatment involving PR at three times the annual application rates (0, 90, 180, and 270 kg P_2O_5/ha) was included to study the influence of a relatively large dressing of PR on building up and sustaining the P fertility status of the soils as well as on the subsequent crop yield. At Sadore, Parc W phosphate

rock and its partially acidulated forms were compared with TSP and SSP at the rates of 0, 10, 20, 30, and 40 kg P_2O_5/ha. A triannual treatment of the PR was applied at rates of 0, 30, 60, 90 and 120 kg P_2O_5/ha. Nitrogen, potassium, and zinc (where required) were applied to all treatments as previously described. Each PR was acidulated at two levels, 25% and 50%. A streak-resistant maize variety TZSR was the test crop in the Nigerian sites; in Niger, CIVT millet variety was the test crop.

In 1983, the evaluation of Togo PR and PAPR was expanded to a second site in Mokwa as well as to Sarakawa, Togo. Evaluation of Parc W PR and PAPR was also expanded to Gobery and Mai-Gamji in Niger. Evaluation of a third phosphate rock was PAPR (Kodjari) was initiated at Saria in Burkina Faso using sorghum and millet. The P rates were 0, 30, 60, and 90 kg P_2O_5/ha at Mokwa; 0, 20, 40, and 80 kg P_2O_5/ha at Sarakawa; 0, 15, 20, and 40 kg P_2O_5/ha at Gobery; 0, 30, 60, and 90 kg P_2O_5/ha at Mai-Gamji; and 0, 15, 30, 45, and 60 kg P_2O_5/ha at Saria. Nitrogen was applied as urea at 120 kg N/ha at Mokwa and Sarakawa and at 30 kg N/ha at Gobery and Mai-Gamji. The treatments at Saria received N at 60 kg N/ha (as urea) and K at 44 kg K_2O/ha (as K_2SO_4).

Through a collaborative arrangement with the University of Nairobi, tests were begun in 1983 at the high altitude of Kabete, Kenya (1,941 m) on the use of Togo PR and PAPR for hybrid maize production. Beans (*Phaseolus* spp) were intercropped with the maize. The P rates were 0, 90, 180, and 360 kg P_2O_5/ha. Nitrogen as urea was applied to all plots at 50 kg N/ha, and sufficient K_2SO_4 was applied to supply 30 kg S/ha.

As the network grew, experiments were set up in 1984 with the aid of scientists from national research institutes at Nteje, Owerri, and Zaria in Nigeria; Njala in Sierra Leone; Davie in Togo; Tounga and Magaria in Niger; and Yundum (Sapu) in Gambia. Togo PR and PAPR were evaluated at all the sites in Nigeria, Sierra Leone, and Togo. The P rates at Njala and Sapu were 0, 25, 50, 100, and 200 kg P_2O_5/ha and 0, 15, 30, 45, and 60 kg P_2O_5/ha, respectively. The rates in Nigeria and Niger were as previously described. Maize was grown at Nteje, Owerri, Zaria, Njala, Davie, and Sapu. Millet was grown in Tounga and Magaria. In addition, groundnuts were grown at Sapu. Tilemsi PR and PAPR acidulated at 15% and 30% were used at Sapu. All treatments received adequate support nutrition.

A randomized complete block design was used for all experiments.

Farm-level evaluation of P fertilizers – Nigeria

In 1983 diammonium phosphate (DAP) was introduced into Nigeria. In response to the wishes of many consumers, particularly the World Bank-

assisted Agricultural Development Projects (ADPs), simple experiments were designed to evaluate the performances of DAP, SSP, 15-15-15, and Togo PAPR at 50% acidulation (PA50). The trials were set up at Ikole, Ikare, and Ado in the Ekiti-Akoko ADP in Ondo State of southwestern Nigeria. Phosphorus rates were 0, 30, and 60 kg P_2O_5/ha. All treatments received potassium as KCl at the rate of 60 kg K_2O/ha. Nitrogen as urea was applied to DAP, SSP, and PA50 treatments in amounts to equalize the N contained in all materials including 15-15-15 at each rate of P application. Maize (variety TZSR) was the test crop. After these experiments were set up, their management was handed over to staff of the Ekiti-Akoko ADP.

In 1984 the number of sites was increased to include Ilorin in the Ilorin ADP and Bida Junction in the Bida ADP.

A randomized complete block design was used for all experiments.

Farm-level evaluation of P fertilizers – Niger[1]

Tests conducted in previous years (see ICRISAT Annual Reports 1982, pp. 367-368 and 1983, p. 315), had shown that (1) while presently extended improved millet cultivars had very little or no advantage over local varieties, fertilizer increased yields of both local and improved cultivars significantly and (2) it was profitable to apply fertilizers. In order to better understand fertilizer response under farm conditions, tests were set up to concentrate mainly on phosphate fertilizer response.

A randomized split-plot design was used to test fertilizer response in trials jointly managed by researchers and farmers. Plot sizes were 250 m^2. Two sources of phosphorus, SSP and partially acidulated (50%) Niger Parc W phosphate rock, were compared at four levels of P_2O_5 (0, 12, 24, and 36 kg/ha) using farmers' traditional varieties. Thirty kilograms of nitrogen was applied as calcium ammonium nitrate on all treatments. The nitrogen was applied in two split doses, approximately 15 days after seedling emergence and approximately 30 days later. The phosphorus was broadcast but not incorporated at the time of plot layout, 2-4 weeks before planting. The tests were conducted in the fields of about 30 farmers in each of four villages where baseline studies are being conducted. Fertilizer application was done by research technicians, while farmers planted the plots and carried out all the cultural practices in their traditional way.

Statistical analysis

Statistical analyses were done in accordance with the objectives of the pro-

ject, for each of the individual sites and on an aggregated basis to enable the researchers to draw general conclusions for major agroecological zones, for major soil variations, and for specific experimental sites.

Data from each site were analyzed according to the experimental design used for the trial. The treatment design was aimed at obtaining a response function of yield to increasing rates of P_2O_5 for different phosphorus sources. At all locations, the experimental design used was a completely randomized block design with different number of replicates as dictated by the site variation. The basic model for this design is:

$$Y_{ij} = \mu + \quad_i + \beta_j + \varepsilon_{ij} \qquad (1)$$

where: Y_{ij} represents the yield from the ith treatment and j^{th} replicate.
$\quad_i$ represents the effect on the general mean of the ith phosphorus source.
β_j represents the effect of the jth replicate.
ε_{ij} represents the experimental variation associated with each site.

From the results of the analysis of variance for each site, multiple comparisons were made between treatments by using the Waller-Duncan t-test.

The response function for each phosphorus source and cropping system was calculated by using regression equations estimated by general linear models. The models have the form:

$$Y_{ik} = \beta_{0k} + \beta_k X_{ik} + \gamma_k X_{ik} + \varepsilon_i \qquad (2)$$
$$Y_{ik} = \beta_{0k} + \alpha_k \ln X_{ik} + \varepsilon_i \qquad (3)$$

where: Y_{ik} represents the yield of the ith observations for the kth phosphorus source.
β_k, γ_k, and α_k represent the parameters to be estimated in order to evaluate the effect of the sources over the range of the rates used.
β_{0k} represents the general means for the experimental sites.

The analysis for agroecological zones was done by combining the specific site data representative of the zones during the years of experimentation. Care was taken to evaluate those sites with the same sources and rates and thus avoid confounded effects and biased estimates.

The statistical model used to give general conclusions for the agroecological areas has the following form:

$$Y_{ijk} = \mu + \quad_i + \beta_j + (\quad\beta)_{ij} + \alpha_k + (\alpha\quad)_{ik} + \gamma_l + (\gamma\quad)_{il} + \varepsilon_{ijkl} \qquad (4)$$

where: $_{i}$ represents the effect of rates and sources of phosphorus.
β_{j} represents the effect of the jth replicates.
$(\ \beta)_{ij}$ represents an error term to test the phosphorus sources.
α_{k} represents the effect of the kth experimental site.
$(\alpha\ \ )_{ik}$ represents the interaction of site * P sources.
γ_{l} represents the effect of the lth year.
$(\gamma\ \ )_{il}$ represents the interaction year * P sources.
ε_{ijkl} represents the combined error term.

To combine sites and year, it was considered important to evaluate the variances on each site and year to be consistent with the basic assumptions of the general linear models with respect to the parameter estimates and error term.

Since the yield response to phosphorus sources is related to the amount of phosphorus already present in the soil, a linear model was developed which related the percentage of crop yield to soil P as measured by Bray extraction procedure. The percent yield is defined as:

$$Z = \%\ \text{yield} = \frac{\text{Yield without applied P}}{\text{Yield with applied P}} \times 100.$$

This index represents the crop response to supplemental P derived from the P sources. The model relating this index with the soil P has the form:

$$Z_{ik} = \alpha_{o} + \alpha_{k} \mathrm{Ln} P_{ik} + \varepsilon_{i} \qquad (5)$$

where P_{i} represents the soil P test and α_{k} the change in Z_{i} where there is a change in soil P for the different P sources or agroecological areas considered.
Basically:

$$\frac{\delta Z_{ik}}{\delta P_{i}} = \frac{\alpha_{k}}{Pi}. \qquad (6)$$

The analysis to evaluate yield response to P sources in sites belonging to the same soil orders (*Soil Taxonomy*) was done by combining the sites and years within a defined soil order.

A combined analysis of variance was made using model (4) for each major unit in soil classification. A general response function was developed for each P source within each soil order. The response functions have the following form:

$$Y_{ik} = \beta_{o}\ \gamma_{k} \ln X_{ik} + \alpha_{j} D_{ij} + \varepsilon_{ik} \qquad (7)$$

where γ_k represents the effect of the kth source and α_j represents the effect of the jth site and year. Statistical tests of significance were made on the estimates to evaluate hypothesis on each of the P sources.

From the response function (7), an agronomic index of efficiency was obtained. The agronomic index has the following form:

$$AEI = \frac{\hat{\gamma}_k \ln X_k}{\hat{\gamma}_k^1 \ln X_k^1} = \frac{\hat{\gamma}_k}{\hat{\gamma}_k^1} \tag{8}$$

where in most of the cases $\hat{\gamma}_k^1$ referred to the estimate obtained for the SPP P source, and $\hat{\gamma}_k$ is the estimate for any other P sources. A statistical test of significance was made on the agronomic index. The statistical test used was a t-test, based on the general hypothesis:

$$\begin{aligned} H_0&: \hat{\gamma}_k - \hat{\gamma}_k^1 = 0 \\ H_1&: \hat{\gamma}_k - \hat{\gamma}_k^1 \neq 0 \end{aligned} \tag{9}$$

A basic analysis on residual P effect was made by using the model shown in equation (7) and the agronomic index in model (5). A more detailed work in statistical modeling is being developed to evaluate P residual effects.

Results and discussions

Characterization of benchmark sites

As previously stated, the benchmark experiments were located at Ikenne in the humid forest region of Nigeria, Mokwa in the subhumid southern Guinea savanna region of Nigeria, and Sadore in the semiarid Sahel region of Niger.

The Ikenne experiment was located at the research station of the Institute of Agricultural Research and Training, University of Ife, approximately 50 miles north of the Nigerian capital city, Lagos. The year before the experiment was established, the soil was cropped to soybeans. Single superphosphate had been applied to the soybean crop at the rate of 60 kg P_2O_5/ha. Ikenne has a bimodal rainfall distribution with a total annual precipitation averaging 1,700 mm. The soil belongs to the Alagba series which are derived from aranaceous, Pleistocene, sedimentary rocks [9] and is classified as an Oxic Paleustalf (*Soil Taxonomy*) [18]. The soil is deeply weathered and has higher contents of amorphous iron and aluminum than that at the other benchmark sites.

The trial at Mokwa was located at the research station of the Institute for

Agricultural Research, Ahmadu Bello University. Mokwa receives from 1,300 to 1,800 mm of rainfall a year spread over 5-7 months. The rainfall distribution pattern is unimodal. During the 1981 cropping season, the land was used for a herbicide trial on kenaf. It had received P fertilizer at the rate of 60 kg P_2O_5/ha. The soil, which is derived from weathered, soft, coarse-grained cretaceous sandstone, belongs to the Danggappe series. It is classified according to *Soil Taxonomy* as a Typic Paleustalf [18].

The experiment at Sadore was located at the ICRISAT Sahel Center. The land had been previously cropped by local farmers, primarily to millet. No record of previous fertilization was known. On the average, Sadore has about 100 rainy days a year with an annual rainfall of less than 600 mm. The soil is derived from aeolian sand deposits and is classified according to *Soil Taxonomy* as a Torripsamment. A site description of the benchmark trials is presented in Table 1.

Some of the chemical and physical characteristics of the three sites are presented in Table 2. As would be expected, the highest organic matter content is associated with the humid forest environment at Ikenne, whereas the organic matter content at Sadore was the lowest. The nature of parent materials greatly affected the amount of total P in the soils. Also, P content increased with increasing clay content. Because of previous fertilization,there was no difference in the initial Bray 1 P contents of the Ikenne and Mokwa soils.

Soils from the three sites have a negative delta pH [$\Delta pH = (pH\ CaCl_2) - (pH\ H_2O)$]. This property, coupled with the fact that the parent materials are coarse-textured sedimentary rocks and aeolian sands, is largely responsible for low P-sorption capacities.

Response functions for maize and millet

The multiyear average regression estimates for yield response functions of maize and millet to phosphorus applied as SSP at the three benchmark sites are presented in Table 3. Because SSP is the most readily available commercial P fertilizer in the regions of the benchmark sites and because yield of cereals in some soils in these environments has been known to be limited by sulfur deficiency, the response of the cereal crops to SSP has been used as a model in the discussions that follow. Both maize and millet responded significantly to phosphorus application. The higher general fertility of the sites in the humid and subhumid regions has resulted in relatively high yields when all factors except phosphorus were nonlimiting ($b_{11} >> 0$).

The response function of maize to SSP at Ikenne and Mokwa is presented in Figure 1. A consequence of the initial high fertility level of the humid

Table 1 Benchmark experiments: site description

Soil series	Location	Agroclimatic zone	Rainfall	Previous management	Parent material	Classification
			(mm)			
Alagba	Ikenne, Nigeria	Tropical rain forest	> 1700	Fertilized and cropped	Sedimentary rock	Oxic Paleustalf
Danggappe	Mokwa, Nigeria	Southern Guinea savanna	> 1200	Fertilized and cropped	Sandstone	Typic Paleustalf
Sadore	Sadore, Niger	Sahel	< 600	Local farmers, unfertilized	Aeolian sands	Torripsamment

Table 2 Benchmark experiments: some chemical and physical characteristics

Soil	Organic matter matter	pH		Total P	Organic P	Bray 1 P	ECEC[a]	Sand	Silt	Clay	Texture
		H_2O	$CaCl_2$								
	(%)				(ppm)		(me/100g)		(%)		
Alagba	1.66	5.9	5.3	135.92	35.20	11.8	4.14	72	7.9	20.1	Silt loam
Danggappe	0.41	5.8	4.8	62.60	17.61	11.2	1.85	76.9	10.4	12.7	Loamy sand
Sadore	0.29	4.7	4.1	40.84	7.04	2.4	1.14	93.6	5.2	1.2	Sand

[a] ECEC = Effective cation exchange capacity.

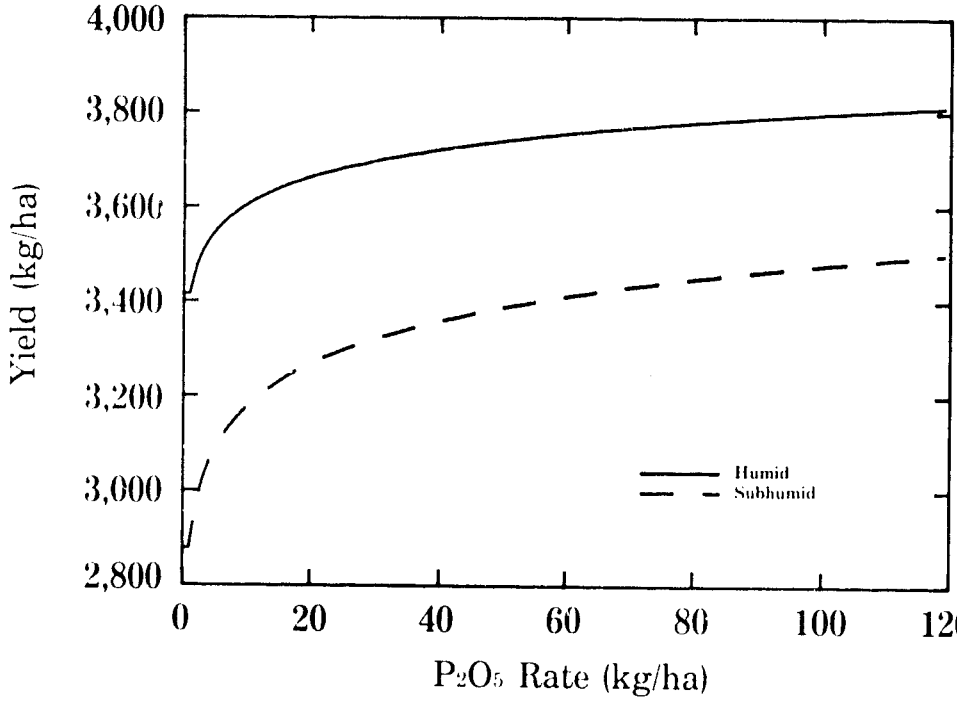

Figure 1. Response function of maize to phosphorus in major agroecological zones of sub-Saharan Africa.

forest environment at Ikenne (Table 2) is that less response is obtained for each unit of P_2O_5 applied in this environment than in the subhumid ecosystem. For example, for 2 years when the treatments were applied, the addition of the first 20 kg P_2O_5/ha increased yield by 13% at Mokwa and by only 8% at Ikenne.

At both Ikenne and Mokwa, 98% of maximum yield was produced at the application rate of 60 kg P_2O_5/ha. Although this rate should not be regarded as optimal for the virgin or newly cleared land (because of the history of previous fertilization at both sites), the generally low phosphorus requirement in these Alfisols must be pointed out. On a newly cleared land at the same site at Ikenne, Kang and Osiname [22] observed no significant yield increases of maize beyond the application rate of 90 kg P_2O_5/ha. The low P requirement of the Alfisols is the result of the relatively low P-sorption capacity of the soils. Similar observations have been made by Fox and Kang [8] for these Alagba series at Ikenne.

Application of the first 10 kg P_2O_5/ha as SSP on the Entisol at Sadore increased millet yield by 17% averaged over the 3 years the treatment was applied (Figure 2). The importance of P fertilizers in the semiarid ecosystems is amply demonstrated by the results of the benchmark trial at Sadore. Thus,

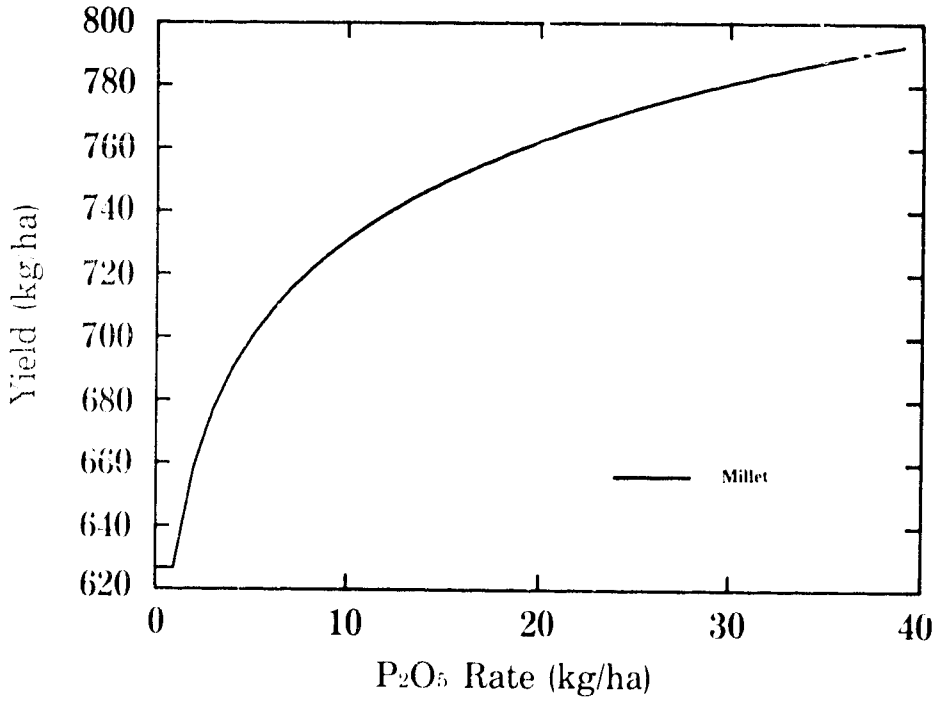

Figure 2. Response function of millet to phosphorus in semiarid sub-Saharan Africa.

the yield of millet when P was absent but all other factors were nonlimiting was not significantly different from zero (Table 3). Ninety-eight percent of maximum yield of millet was obtained at a P rate of 30 kg P_2O_5/ha. The very limited capacity of this Entisol to adsorb phosphorus was pointed out earlier.

The relationship between soil P levels (as measured by Bray P1 extraction procedure) and the expected increases in yield from applied fertilizer in the different ecological zones is summarized in Figure 3. Thus, if the Bray P1 P

Table 3 Regression estimates for yield response functions to single superphosphate (SSP) at the benchmark sites

Variate	Function $\tilde{\ } = b_0 + \Sigma\Phi_i \ln X_i$	Humid[b] Ikenne	Subhumid[b] Mokwa	Semiarid[c] Sadore
Intercept	b_0	3,414.67[a]	2,877.59[a]	624.6
SSP	$\ln X_{SSP}$	83.00[a]	130.32[a]	45.32[a]

[a] Significant at the 0.01 level.
[b] Maize.
[c] Millet.

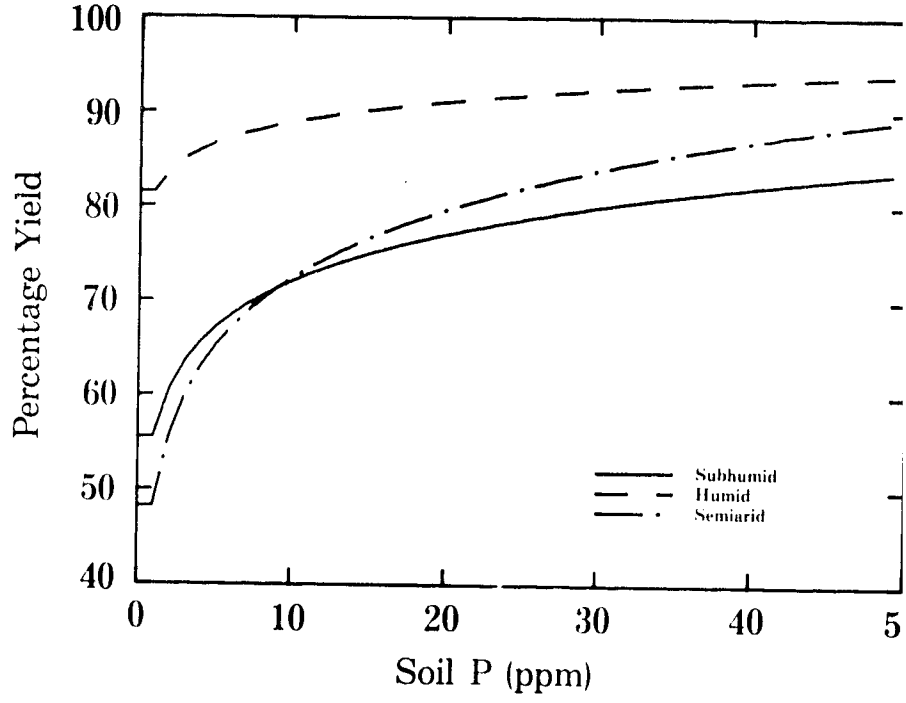

Figure 3. Critical soil P levels associated with maize yields in major agroecological zones sub-Saharan Africa.

level is 10 ppm, addition of P fertilizer would raise the yield by almost 30% in the lower P fertility environments of the subhumid and semiarid region On the other hand, in the relatively more fertile humid ecosystems, at th same level of P in the soil, additional P fertilizer would raise the yield by onl 10%.

The lesson to be learned from these trials is that phosphorus is needed fc sustained food production in the humid, subhumid, and semiarid zones c tropical Africa. However, because of the nature of the parent materials of th soils and the colloidal systems present, the quantities of P fertilizers neede to obtain maximum crop yields are not high. The myth that tropical Africa soils have unquenchable thirst for phosphorus may be finally put to rest especially for these Alfisols and Entisols in West Africa. For quite some time the belief in this myth stymied work on the residual value of P fertilizers i tropical African soils [37]. We take note of the fact that there are pocket within all ecological zones where high contents of allophane and other amor phous materials result in the sorption of large quantities of phosphorus, bu these are the exceptions rather than the rule. Also, it is evident that one ca build up the P fertility of these soils by repeated applications of P fertilizer as shown by the low P requirements at Ikenne and Mokwa with a history o

previous P fertilization. The residual value of P fertilizers in these soils will be examined in another section of this report.

Phosphorus fertilizer source evaluation

There are suspected or confirmed deposits of phosphate rock in at least 27 countries in sub-Saharan Africa. Finely ground phosphate rock may be a viable alternative to expensive imported phosphate fertilizers. However, the agronomic effectiveness of phosphate rock is dependent of the soil, and the characteristics of the crop to be grown. This section of the paper deals with the results of agronomic trials with different crops and in different soils, primarily in West Africa.

There have been a number of trials, especially in Francophone West Africa, where the agronomic effectiveness of the phosphate rocks occurring in the region has been evaluated [7,1,15,29,6,40]. The consensus is that apart from Tahoua (Niger) and Tilemsi (Mali) phosphate rocks the rocks are not suitable for direct application. The ineffectiveness of the African rocks is due to low reactivity which results in their inability to supply P in adequate amounts in the soil solution to sustain the growth of crops. One way to overcome the problem of low solubility is to partially acidulate the rock. The agronomic work on PAPR has produced conflicting results. Some workers have found PAPR to be agronomically as good as concentrated superphosphate (TSP) even at low degrees of acidulation [25,26,24]. On the other hand, in a series of experiments with powdered PAPR, Terman [38,39] found that PAPR was inferior to TSP.

The regression estimates for the response functions of Togo PR, PAPR 25% (PA25), PAPR 50% (PA50), SSP, and TSP at the benchmark sites at Ikenne and Mokwa are presented in Table 4. At Ikenne maize responded only to application of the water-soluble sources (SSP and TSP). However, the response to PA50 at Mokwa was highly significant. Apparently, because of the relatively high fertility of the Alagba soil, the contribution from the insoluble sources was insufficient to show up in the statistics. It should be noted that yield levels with all sources were high for the region. During 1982 and 1983 when the treatments were applied at Ikenne, there was no difference between the agronomic efficiencies of the rock and the partially acidulated forms as shown by the agronomic efficiency indices (Table 5). However, these products were significantly inferior to SSP, and TSP was the best P fertilizer for the Alagba soil. This observation tends to confirm the findings by Kang and Osiname [22] that maize crops at Ikenne always benefited from freshly applied superphosphates even though residual P fertility was high. Such benefits were not derived from the less soluble P forms in these trials.

At Mokwa, Togo PR and PA25 were inferior to SSP. PA50 was 85% as good as SSP. Yield of maize with PA50 was not significantly different from the yield with SSP (Table 5).

Parc W PR and PAPR (PA25 and PA50) were applied for 3 consecutive years at Sadore. The data in Table 4 suggest that millet did not derive any

Table 4 Regression estimates for yield response functions to phosphorus sources in major agroecological areas in West Africa

Variate	Function $b_0 + \Sigma\Phi_i \ln X_i$	Humid[b] Ikenne	Subhumid[b] Mokwa	Semiarid[c] Sadore
Intercept	b_0	3,414.67[a]	2,877.59[a]	624.6
Phosphate rock annual (PRA)	$\ln X_1$	46.32	7.70	-.09
PA25	$\ln X_2$	45.17	56.86	15.12
PA50	$\ln X_3$	46.05	110.20[a]	34.61[a]
SSP	$\ln X_4$	83.00[a]	130.32[a]	45.32[a]
TSP	$\ln X_5$	131.92[a]	101.08	46.68[a]
R^2		59.52	33.16	16.00
Syy		589.42	727.26	192.57
$\bar{X}$		3,180.00	2,846.30	656.27
N		183	196	431

[a] Significant at the 0.01 level.
[b] Maize field.
[c] Millet field.

Table 5 Agronomic efficiency index for phosphorus sources (as compared with single superphosphate) in major agroecological areas in West Africa

P Source	Humid Ikenne	Subhumid Mokwa	Semiarid Sadore
		(%)	
Phosphate rock (PRA)	55.8[a]	5.9[b]	0[b]
Partially acidulated phosphate rock 25% (PA25)	54.4[a]	43.6[a]	33.4[b]
Partially acidulated phosphate rock 50% (PA50)	56.0[a]	84.6	76.4[a]
Triple superphosphate (TSP)	158.9[b]	77.6	103.0
Single superphosphate Mean yield (kg/ha)	3,299.33	3,104.5	656.03

[a] Significant at 0.05 level.
[b] Significant at 0.01 level.

benefit from the application of finely ground rock. Acidulation increased efficiency (from 0% to 76% at 50% acidulation), but the yield of PA50 was significantly inferior (P = 0.05) to yield of SSP (Table 5). Because of moisture limitations during 2 of the 3 years of the trial, the less soluble P forms performed relatively poorly at Sadore.

During 1983 and 1984 the evaluation of Togo PR and PAPR was carried out in additional sites in Nigeria, Togo, and Sierra Leone. In Nigeria trials were set up in both the northern Guinea savanna region (at Zaria) and the southern Guinea savanna region (Mokwa) and in Ultisols in the forest zone (Nteje and Owerri). The trial in Togo was on an Alfisol at Sarakawa, and the trial in Sierra Leone was on an Ultisol at Njala. Some of the properties of these soils are presented in Table 6. The yield response of maize to the P fertilizers at these sites is summarized in Table 7. At every site, maize responded highly significantly to P fertilization, dramatizing the low P fertility (in their natural state) of the Ultisols and Alfisols of the humid and subhumid agroclimates. Togo PR performed poorly (P = 0.05) compared with SSP in the two Guinea savanna sites in Nigeria (Figure 4). Partial acidulation increased the agronomic effectiveness. The agronomic efficiency index of PA50 in the Alfisols of subhumid West Africa was 82% compared with SSP. This effectiveness was statistically equal to that of SSP (Table 8). Across this region the need to use phosphate fertilizers containing sulfur is demonstrated by the significantly lower efficiency index for TSP (Figure 5).

Togo PR performed relatively better in the Ultisols than in the Alfisols. The lower pH values of the Ultisols apparently encouraged greater solubilization of the rock. In spite of this fact, however, maize yields with PR and PA25 were significantly inferior to those with SSP (Table 8 and Figure 6). The agronomic efficiency index of PA50 was 103% (Table 8), indicating that under these acid conditions PA50 can substitute for SSP with no reduction in yields.

At Sapu, on an Oxisol in the dry region of Gambia, the agronomic effectiveness of Tilemsi PR and PAPR (PA15 and PA30) was monitored. Maize and groundnuts were grown, and both crops responded highly significantly to P fertilization (Table 9). Although 1984 was a dry year in this location, finely ground Tilemsi PR was 74% and 92% as efficient as SSP for maize and groundnuts, respectively. This confirms the finding of Thibout et al. [40] that Tilemsi PR is reactive enough to be used for direct application. Acidulating the rock at 15% did not improve its performance on maize (Figure 7) but raised the efficiency to 108% (Figure 8) on groundnuts most likely because of the sulfur content [4]. However, at 30% acidulation the agronomic index compared with SSP increased to 96% (Table 10) for maize.

With the assistance of the Institut National de Recherches Agronomique du Niger, several trials were set up on Alfisols in Niger to evaluate agronomic

Table 6 Selected chemical and physical properties of soils at some of the P evaluation sites

Ecological zone	Location	Soil classification, USDA	Organic matter	Total N	Soil pH	Available P Bray P1	CEC	Base saturation	Sand	Clay
			(%)			(ppm)	(meq/100 g)		(%)	
Humid	Ikenne (Nigeria)	Oxic Paleustalf	1.66	0.11	5.2	11.8	4.14	88.70	72	20
	Owerri (Nigeria)	Ultisol	2.17	.13	4.3	4.22	2.38	69	88	7
	Ikole (Nigeria)	Alfisol	1.02	.11	5.5	8.50	5.07	88	86	11
	Ikare (Nigeria)	Alfisol	.83	.08	5.5	7.94	4.09	74	86	9
	Nteje (Nigeria)	Ultisol	.99	ND[a]	4.7	3.22	1.26	61	ND	ND
	Njala (Sierra Leone)	Oxidic Plintic Paleudult	5.2	.3	4.0	8	ND	ND	57	19
	Kabete (Kenya)	Oxic Paleustult	ND	ND	5.88	15.79[b]	24	ND	ND	79
Subhumid	Mokwa (Nigeria)	Typic Paleustalf	.41	.06	5	11.2	2.22	2	82	7
	Sarakawa (Togo)	Paleustalf	.52	.032	6.6	9.7[b]	3.45	69	85	6.8
	Zaria (Nigeria)	Typic Paleustalf	1.02	.1	5.8	3.5	4.7	93		17
	Bida Junction	Alfisol	ND	.04	ND	ND	ND	ND	ND	ND
Semiarid	Sadore (Niger)	Alfisol	.29	0.02	4.7	2.4	1.2	60	92	2
	Gobery (Niger)	Alfisol	.30	.02	5.2	2.6	1	55	95	2
	Mai-Gamji (Niger)	Alfisol	.11	.01	5.6	3.2	1.3	58	93	3
	Sapu (Gambia)	Ultic Eutrustox	.9	.041	5.3	8.2[b]	4.7	59.14	68	7.3
	Saria (Burkina Faso)	Alfisol	ND	ND	ND	ND	ND	ND	ND	ND

[a] ND = not determined.

[b] Available P determined with Olson method.

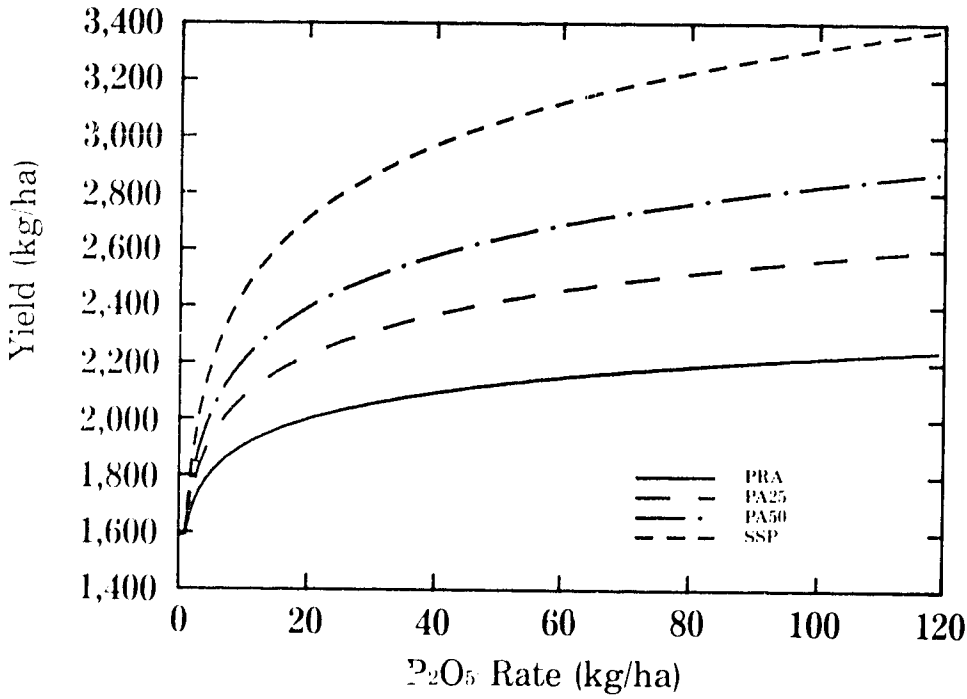

Figure 4. Maize yield response to phosphorus sources in Alfisols in the Guinea savanna zones of Nigeria.

Table 7. Maize yield response to phosphorus sources in major soil orders occurring in West Africa

P Source	Function $\tilde{Y} = b_0 + \Sigma\Phi_i X_i$	Alfisol Guinea Savanna	Alfisol Savanna West Africa	Ultisol West Africa
Intercept	b_0	1,591.29[a]	2,636.04[a]	1,136.50[a]
Phosphate rock (PRA)	$\ln X_1$	136.28[a]	23.91	89.33[a]
Partially acidulated phosphate rock 25% (PA25)	$\ln X_2$	211.28[a]	156.28[a]	134.14[a]
Partially acidulated phosphate rock 50% (PA50)	$\ln X_3$	267.81[a]	171.16[a]	199.59[a]
Single Superphosphate (SSP)	$\ln X_4$	373.41[a]	208.35[a]	193.24[a]
Triple superphosphate (TSP)	$\ln X_5$	=	119.51[a]	–
R^2		.77	.62	.52
Sxy		822.11	686.37	448.77
Y		3,797.10	2,332.36	1,547.34
N		207	369	206

[a] Significant at 0.01 level.

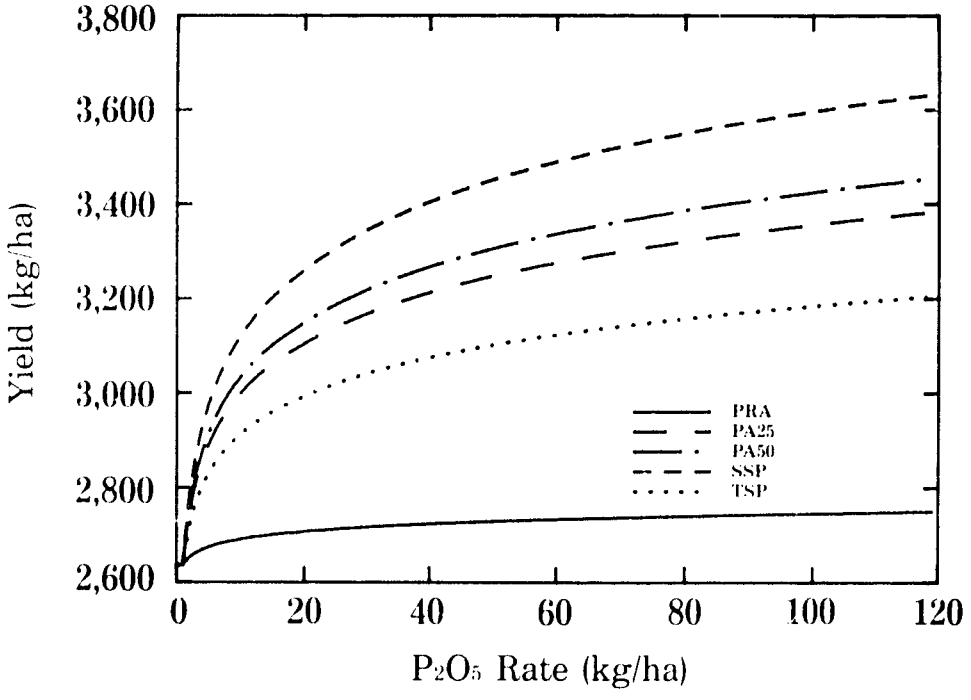

Figure 5. Maize yield response to phosphorus sources in savanna Alfisols in West Africa.

Table 8 Agronomic efficiency index for maize yield response to phosphorus sources in major soil orders occurring in West Africa

P Source	Alfisol Savanna West Africa	Ultisol West Africa
	%	
Phosphate rock (PRA)	11.4[b]	46.2[b]
Partially acidulated phosphate rock 25% (PA25)	75.0[a]	69.4[a]
Partially acidulated phosphate rock 50% (PA50)	82.2	103.3
Triple superphosphate (TSP)	57.3[a]	–
Mean Yield, kg/ha		
Single superphosphate (SSP)[c]	2,673.08	1,784.68

[a] Significant at the 0.05 level.
[b] Significant at the 0.01 level.
[c] SSP was used as standard fertilizer.

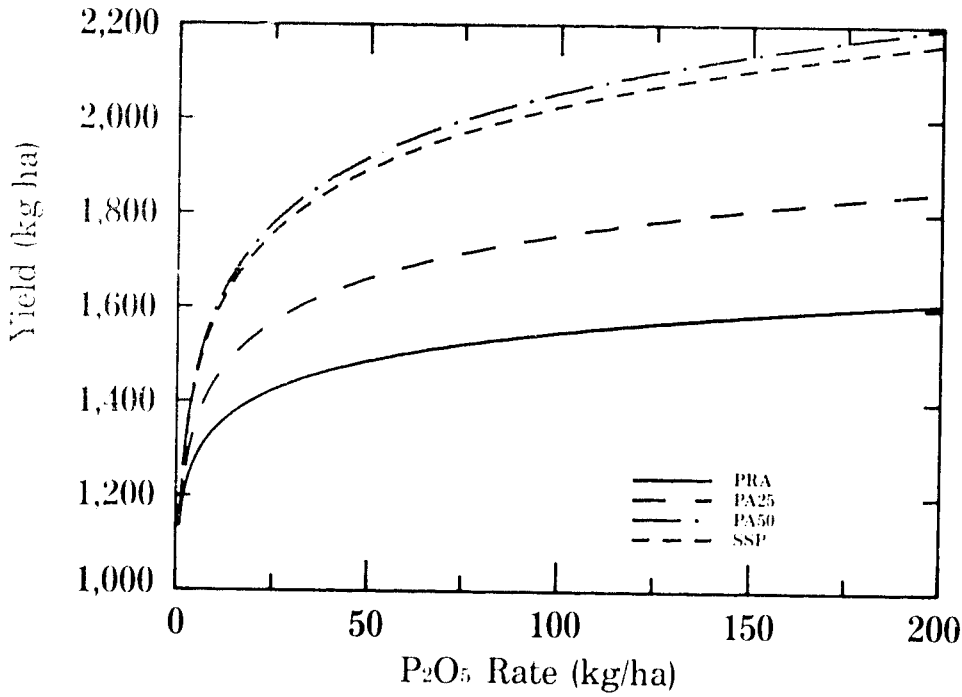

Figure 6. Maize yield response to phosphorus sources in Ultisols in West Africa.

Table 9 Response by maize and groundnuts to phosphorus sources in an oxisol in Gambia

P Source	Function $\hat{Y} = b_0 + \Sigma\Phi_i X_i$	Yield response	
		Maize	Groundnuts
Intercept	b_0	168.52	910.35[a]
Phosphate rock (PRA)	$\ln X_1$	185.72[a]	256.77[a]
Partially acidulated phosphate rock 15% (PA15)	$\ln X_2$	180.49	301.57[a]
Partially acidulated phosphate rock 30% (PA30)	$\ln X_3$	238.31[a]	273.55[a]
Single superphosphate (SSP)	$\ln X_4$	249.50[a]	279.71[a]
Triple superphosphate (TSP)	$\ln X_5$	246.52[a]	284.57[a]
R^2		0.68	0.22
S_{xy}		308.45	374.32
$\bar{X}$		1,023.01	1,710.85
N		243	122

[a] Significant at the 0.01 level.

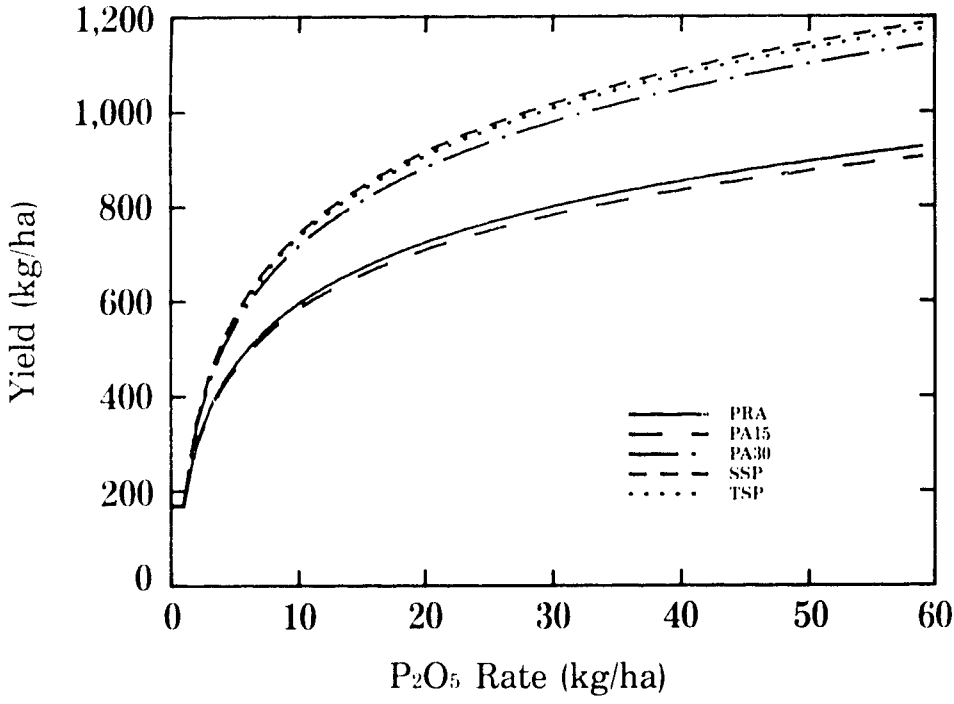

Figure 7. Maize yield response to phosphorus sources in an Oxisol in Sapu, Gambia.

performance of Parc W PR and PA40. The response by millet to P fertilizers is presented in Table 11 and the response functions for the different P sources are shown in Figure 9. At all sites in Niger, the response to P by millet was highly significant (Table 11). The performance of the partially acidulated products improved with increase in degree of acidulation. The agronomic

Table 10. Agronomic efficiency index for maize and groundnut response to phosphorus sources in an oxisol in Gambia

P Source	Agronomic efficiency index	
	Maize	Groundnut
	(%)	
Phosphate rock (PRA)	74.4[a]	91.8
Partially acidulated phosphate rock 15% (PA15)	72.3[a]	107.8
Partially acidulated phosphate rock 30% (PA30)	95.5	97.8
Triple superphosphate (TSP)	98.8	101.7
Mean yield response to SSP (kg/ha)[b]	1,157.72	1,744.95

[a] Significant at the 0.05 level.
[b] SSP was used as standard fertilizer.

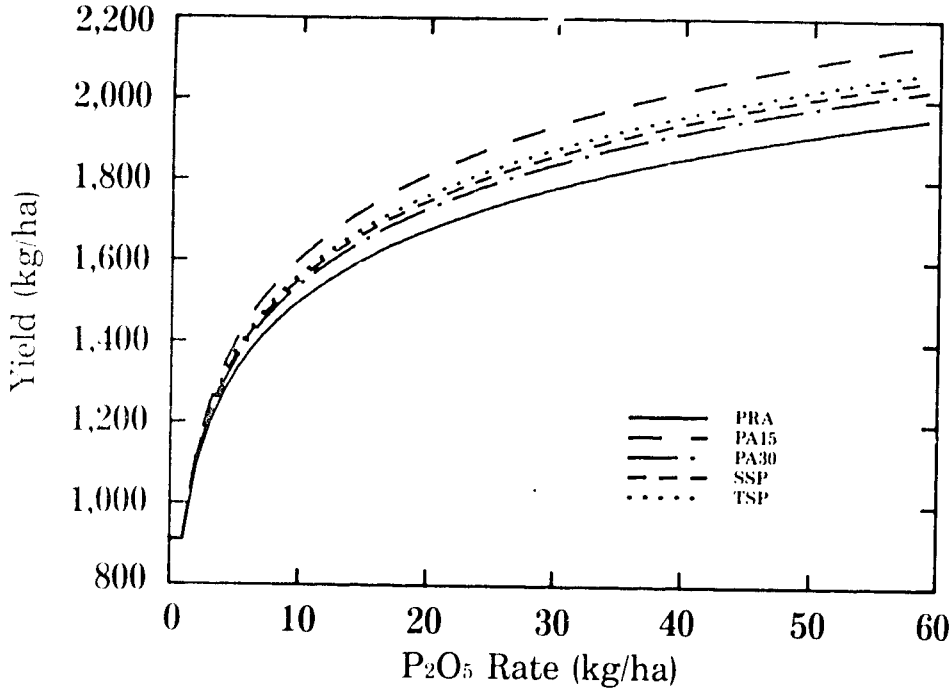

Figure 8. Groundnut yield response to phosphorus sources (soil: Oxisol; experimental site: Gambia, West Africa).

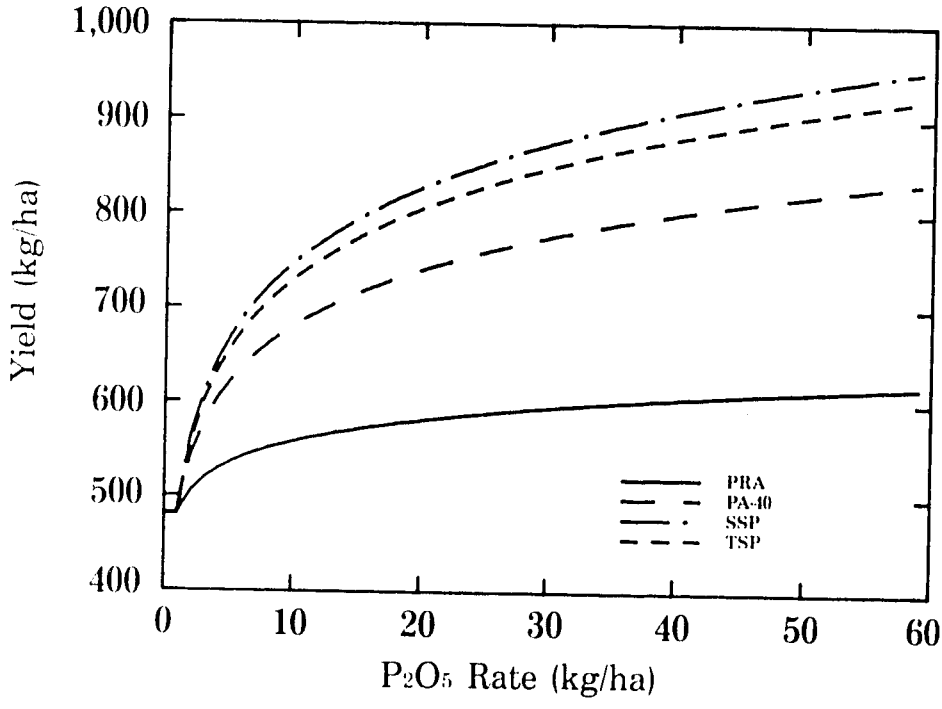

Figure 9. Millet yield response to phosphorus sources (soil: Alfisol; experimental sites in Niger).

efficiency index presented in Table 12 shows that finely ground Parc W PR is inferior to SSP and to the partially acidulated forms of the rock. At 50% acidulation, the agronomic efficiency index increased to 93% which is statistically equal to the performance of SSP. These tests do indeed suggest that PAPR at 50% acidulation is a viable alternative fertilizer for Niger.

The results for a trial on sorghum in Burkina Faso are included in Tables 11 and 12. Kodjari PR, PA25, and PA50 were evaluated. The effect of acidulation is clearly shown by the response functions for the different P fertilizers (Figure 10). The agronomic efficiency index (Table 12) of PA50 was 109% compared with 62% for the finely ground rock.

Residual effectiveness of P fertilizers at benchmark sites

As noted previously, one of the treatments included in the benchmark experiments was phosphate rock basally applied at three times the rates apllied on an annual basis. This treatment (designed PRB) was an attempt to raise substantially the P fertility of the soils with one large dressing of phosphate

Table 11 Yield response of millet and sorghum to phosphorus sources in alfisols in the semiarid region of West Africa

P Source	Function $\tilde{Y} = b_0 + \Sigma\Phi_i X_i$	Millet Alfisol: Niger[c]	Millet Alfisol: Niger[d]	Sorghum Alfisol: Burkina Faso
Intercept	b_0	481.22[b]	374.67[b]	1,520.30[b]
Phosphate rock (PRA)	$\ln X_1$	33.47[a]	59.56[b]	101.71[b]
Partially acidulated phosphate rock 25% (PA25)	$\ln X_2$	–	75.68[b]	121.68[b]
Partially acidulated phosphate rock 40% (PA40)	$\ln X_3$	86.42[b]	–	–
Partially acidulated phosphate rock 50% (PA50)	$\ln X_4$	–	92.29[b]	177.84[b]
Single superphosphate (SSP)	$\ln X_5$	115.37[b]	98.84[b]	–
Triple superphosphate (TSP)	$\ln X_6$	107.94[b]	104.84[b]	163.37[b]
R^2		.44	.28	.24
S_{xy}		233.85	189.03	469.47
$\bar{X}$		641.90	636.39	2,006.95
N		222	435	83

[a] Significant at the 0.05 level.
[b] Significant at the 0.01 level.
[c] Sites where PA40 was evaluated.
[d] Sites where PA25 and PA50 were evaluated.

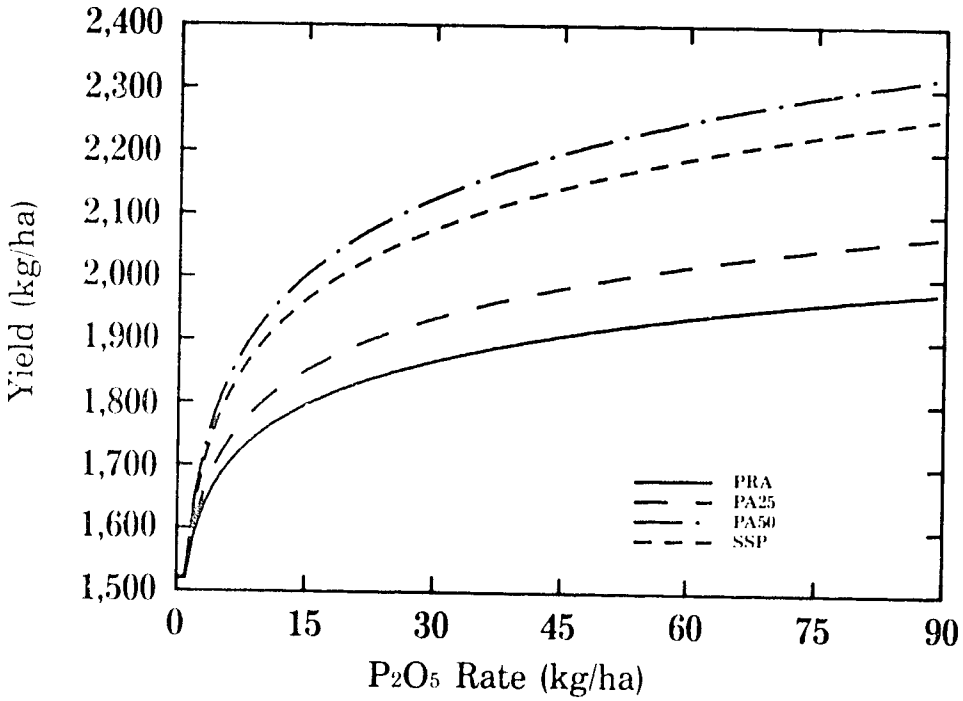

Figure 10 Sorghum yield response to phosphorus sources in an Alfisol in West Africa.

Table 12 Agronomic efficiency index of millet and sorghum to phosphorus sources in alfisols in the semiarid region of West Africa

P Source	Millet Alfisol: Niger[c]	Millet Alfisol: Niger[d]	Sorghum Alfisol: Burkina Faso[e]
Phosphate rock (PRA)	29.0[b]	60.3[a]	62.3[a]
Partially acidulated phosphate rock 25% (PA25)	–	76.5[a]	74.4[a]
Partially acidulated phosphate rock 40% (PA40)	74.9	–	–
Partially acidulated phosphate rock 50% (PA50)	–	93.4	108.9
Triple superphosphate (TSP)	93.5	106.1	–
Mean yield response (kg/ha)			
Single superphosphate (SSP)	754.88	705.80	5,375.22

[a] Significant at the 0.05 level.
[b] Significant at the 0.01 level.
[c] Sites where PA40 was evaluated.
[d] Sites where PA25 and PA50 were evaluated.
[e] TSP used as standard fertilizer.

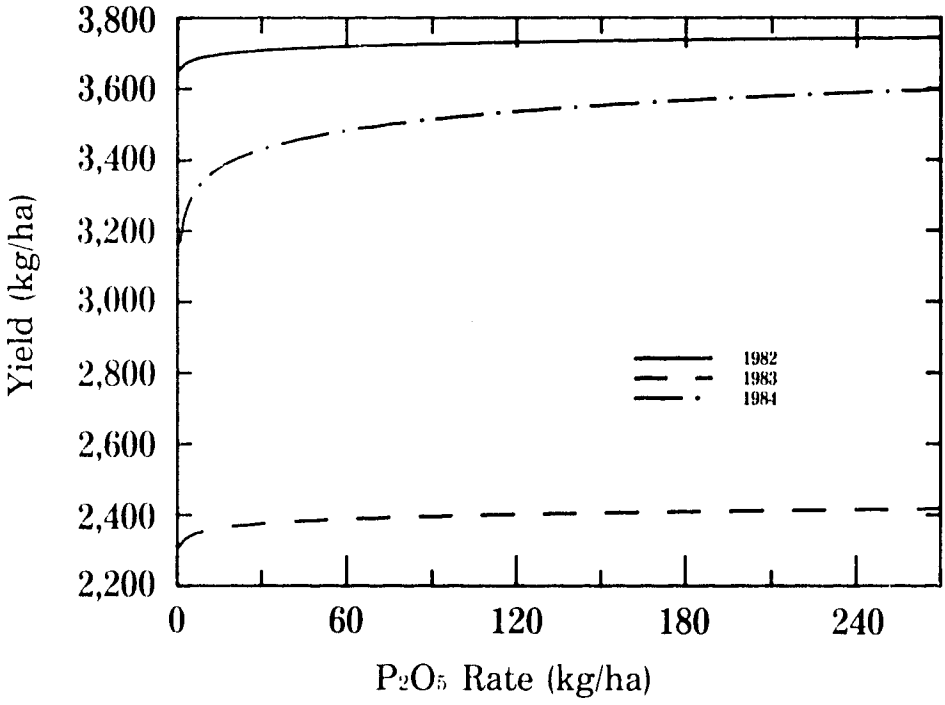

Figure 11. Maize yield response to basal P applications (soil: Alfisol; site: Ikenne).

rock. The success of this practice depended on the capacity of the soils to promote high residual effectiveness of P fertilizers.

The response by maize to the basal application of Togo PR at Ikenne and Mokwa is presented in Figures 11 and 12, respectively. Compared with the response to SSP already discussed (Figure 1), the application of the large dose of PR maintained the yield of maize close to the maximum. The yield of maize declined in subsequent years, but even at Mokwa in 1984 it was possible to obtain 2,000 kg/ha of maize from the fertilizer applied in 1982. The performance was more impressive at Ikenne where, with adequate moisture supply, the maize yield in 1984 was over 3,400 kg/ha. At both Ikenne and Mokwa, the response of maize per unit of P applied as PR was lowest in the year of application. This is not unexpected considering the large dose that was applied. Response per unit of P increased with time as the figures clearly indicate.

Using the 1984 yield data for all P sources and the expected value of P remaining in the basal treatments, an agronomic efficiency index was calculated to compare the basal treatment with the annual treatments. The results are presented in Table 13. In the relatively rich environment at Ikenne, all P sources were able to maintain the P fertility of the soil. Substantial residual effectiveness could be observed for all P sources even when applied annually

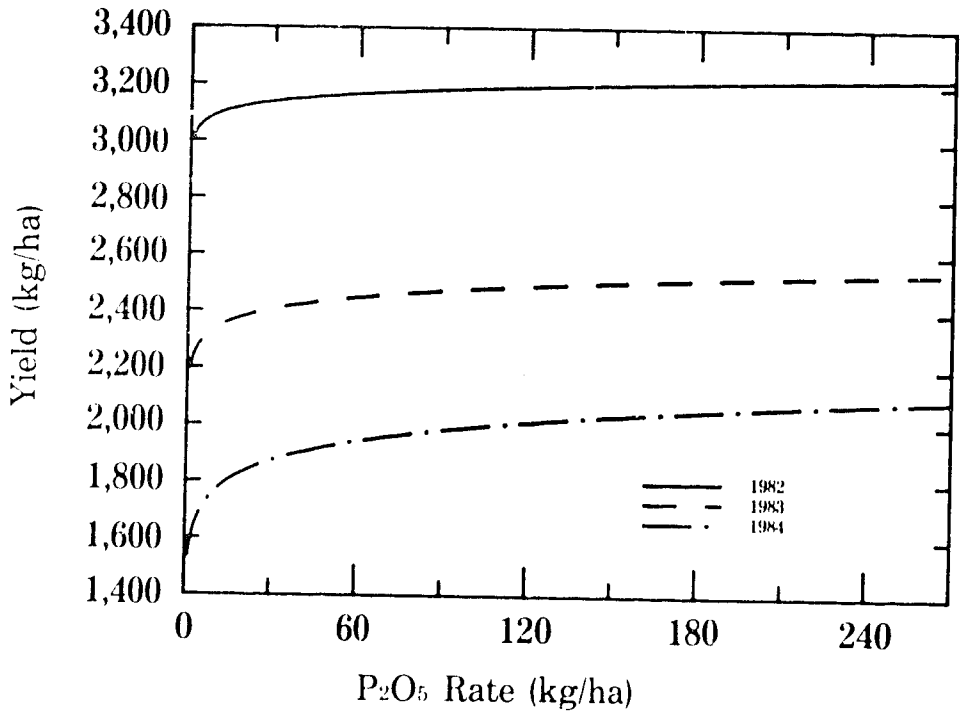

Figure 12. Maize yield response to basal P applications (soil: Alfisol; site: Mokwa).

Table 13. Agronomic efficiency index[c] for evaluating yield response to residual effect of P sources applied annually (using 1984 yield data)

P Source	Alfisol Ikenne[d]	Alfisol Mokwa[d]	Entisol Sadore[e]
Phosphate rock annual (PRA)	93.4	83.6[b]	118.7[b]
Partially acidulated phosphate rock 25% (PA25)	93.3	75.5[b]	110.5[a]
Partially acidulated phosphate rock 50% (PA50)	98.4	98.7	118.2[b]
Single superphosphate (SSP)	103.2	113.0[a]	120.3[b]
Triple superphosphate (TSP)	101.8	74.6[b]	114.9[a]
Mean yield, kg/ha			
Phosphate rock basal (PRB)	3,546.44	2,057.09	513.96

[a] Significant at the 0.05 level.
[b] Significant at the 0.01 level.
[c] Basal PR treatment takes as standard.
[d] Refers to maize yield.
[e] Refers to millet yield.

and in small doses. The best environment for basal application of PR appears to be in the Alfisols of the subhumid region. Residual effectiveness of the basal PR treatment was superior to that of the annually applied quantities of PR and was overwhelmingly superior to that of TSP.

The situation is different in the Entisols at Sadore. It would appear that lack of adequate moisture imposed a limitation on the residual value of the basally applied phosphate rock.

Significant residual responses to P fertilizers have been reported in many locations in tropical Africa even when the rates of fertilizer applied were minimal [28,19,34,22]. In areas where rainfall is not limiting, it may be profitable to take advantage of the high residual effectiveness of P fertilizers in these soils to practice basal fertilization. More work needs to be done on the rates of PR for basal fertilization and the effect of the chemical and mineralogical properties of PR on its use for basal fertilization.

Farm-level evaluation of P fertilizers: Nigeria

Many countries in tropical Africa are landlocked. A suitable fertilizer for these countries should be concentrated so as to minimize transportation costs. Diammonium phosphate with 64% nutrient content appears admirably suited to fill this bill.

The response of maize to DAP, 15-15-15, SSP, and 50% partially acidulated Togo phosphate rock (PA50) in Alfisols in both the forest (Ikole and Ikare) and savanna (Bida Junction) zones of Nigeria is shown in Table 14. The response was highly significant for the partially acidulated phosphate rock

Table 14 Maize yield response to phosphorus sources in farm-level trials in Nigeria

P Sources	Function $\bar{Y} = b_0 + \Sigma\Phi_i X_i$	Bida junction	Ikole (1983 + 1984)	Ikare (1983 + 1984)
Intercept	b_0	804.83[a]	1,075[a]	3,543[a]
15-15-15	$\ln X_1$	67.68	382.42	230.70
Diammonium phosphate (DAP)	$\ln X_2$	137.17	350.33	285.07
Partially acidulated 50% (PA50)	$\ln X_3$	771.27[a]	1,288.28[a]	721.84[a]
Single superphosphate (SSP)	$\ln X_4$	745.64[a]	905.98[a]	529.33[a]
R^2		0.56	0.69	0.94
S_{xy}		530.69	1,053.65	588.24
$\bar{X}$		1,369.00	2,014.72	4,041.41
N		39	75	75

[a] Significant at the 0.01 level.

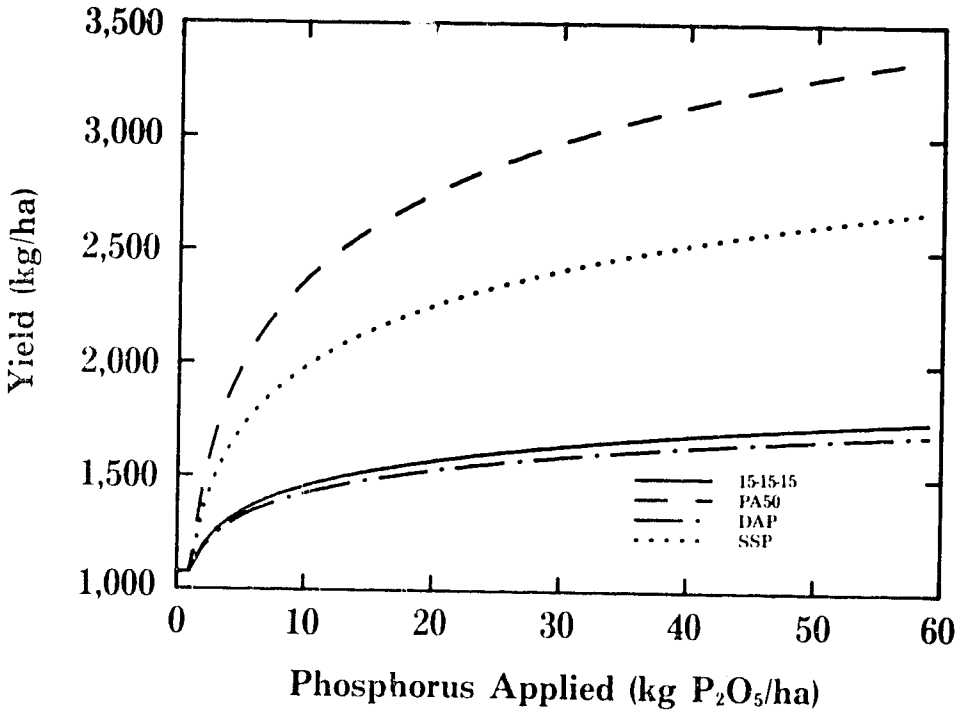

Figure 13. Response to phosphorus source and rate of maize grain yield (Ikole, 1983 and 1984).

and SSP, whereas no response was observed for DAP and 15-15-15. The response curves bases on data for 2 years each at Ikole and Ikare are depicted in Figures 13 and 14. Figure 15 depicts the first year's result at Bida Junction. At Bida Junction, PA50 was equal in efficiency to SSP. However, both 15-15-15 and DAP were significantly inferior to SSP (Table 15). The same situation was repeated for 2 years in the humid forest region sites at Ikole and Ikare. At both sites, PA50 actually performed better than SSP.

All other factors being equal, it appears that absence of sulfur in DAP and 15-15-15 resulted in their poor performance in these environments. The need to apply sulfur-containing fertilizers to many soil-crop systems in Nigeria has been recognized for a long time [12,3,21,5]. This need was met by use of ammonium sulfate and SSP. Acidification problems caused by application of ammonium sulfate and the high cost of SSP, which is a low-analysis fertilizer, have led to efforts to adopt high-analysis fertilizers containing little or no sulfur. The results obtained in these farm trials coupled with the poor performance of TSP at Mokwa (Table 5) are reason enough for second thoughts before making a wholesale switch from SSP to the high-analysis fertilizers. As conclusive as these results are, however, there is obviously a need to expand this type of trial to more sites so as to more accurately delineate those

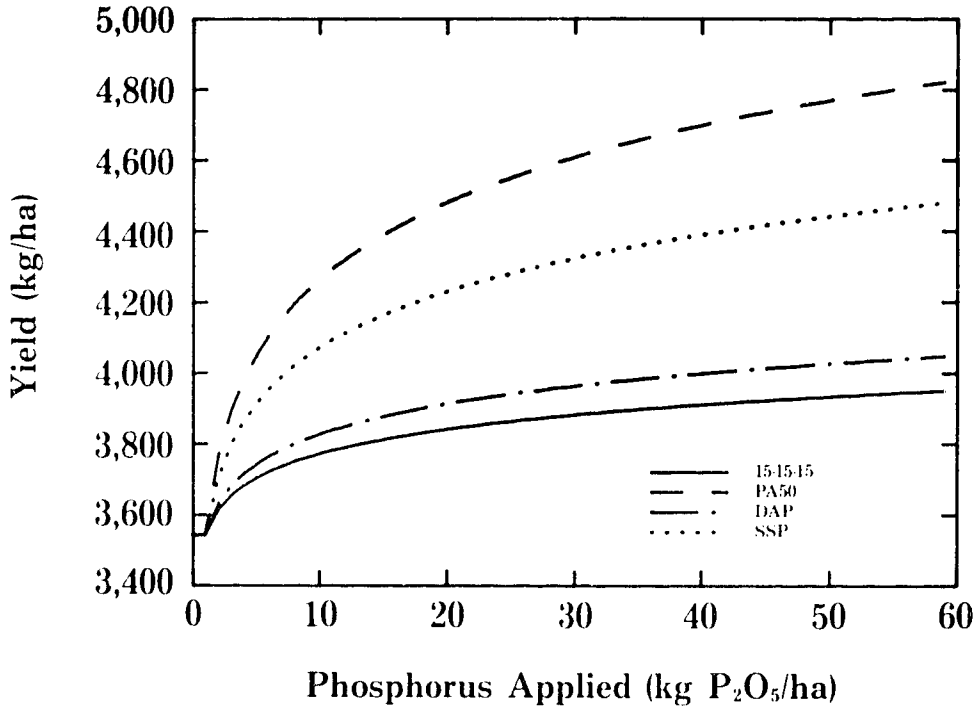

Figure 14. Response to phosphorus source and rate of maize grain yield (Ikare, 1983 and 1984).

areas where lack of sulfur could reduce the effectiveness of phosphate fertilizers.

Farm-level evaluation of P fertilizers: Niger

In 1984 rainfall was 369 mm in Fabidji, 422 mm in Gobery, 215 mm in Sadeize Koira, and 160 mm in Samari. This was substantially lower than the long-term average in all the villages. While sufficient in the southern villages to allow crops to reach maturity and be harvested, the rainfall in the north (Sadeize Koira and Samari) was only 60% and 46%, respectively, of 1983 rainfall. This was insufficient to allow a harvest, particularly as 33% of the total in Sadeize Koira and 16% of that in Samari fell in September, too late to be of use to the millet crop. Thus the farmers' tests in these two villages produced no yield, as was true of virtually all the farmers' fields.

Because of the drought situation millet grain yields were very low. Mean grain yields were 44%-130% higher for the fertilized plots than for non-fertilized treatments, except for the lowest (12 kg P_2O_5) rate as PAPR in Fabidji. However, these increases were significant (P = 0.05) (using two-

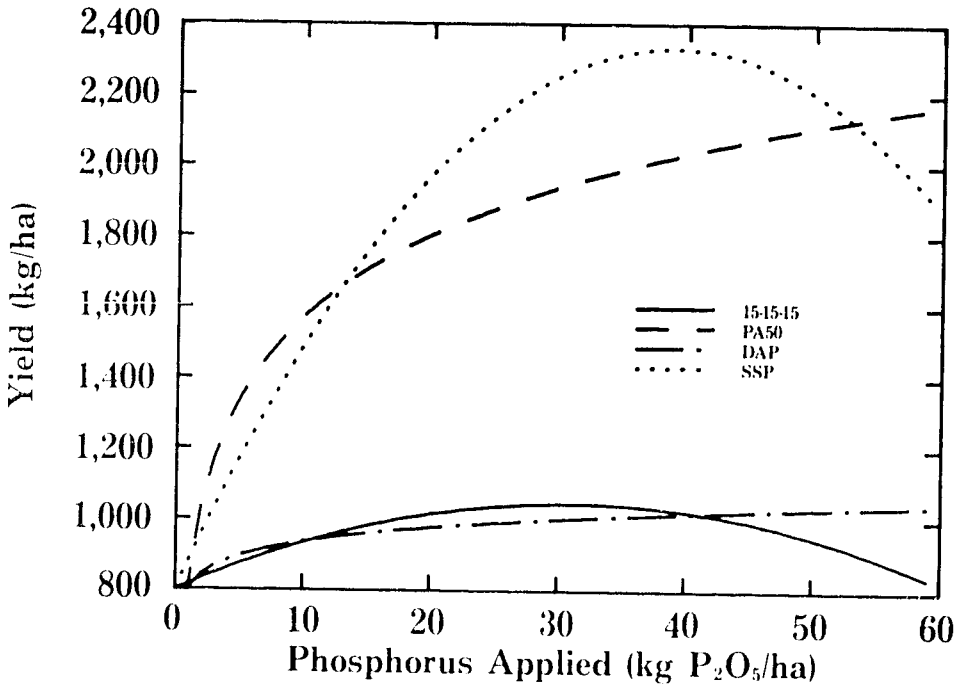

Figure 15. Response to phosphorus rate and source of maize grain yield (Bida junction, 1984).

tailed t-tests) only at the 24 and 36 kg P_2O_5 levels except for PAPR which was not significant at the rate of 36 kg P_2O_5/ha (Table 6).

Multiple regression equations were fitted to the pooled data from the two villages in order to quantify the effect of the treatment and nontreatment variables on grain as well as straw yield. Table 17 contains the descriptive

Table 15. Agronomic efficiency index for maize to P fertilizers in farm-level trials in Nigeria

P Sources	Agronomic efficiency index[c]		
	Bida junction	Ikole	Ikare
		(%)	
15-15-15	9.00[b]	42.21[b]	43.58[b]
Diammonium phosphate (DAP)	18.40[b]	38.67[b]	53.85[b]
Partially acidulated (PA50)	103.43	142.20[b]	136.37[a]
Mean yield of single superphosphate (kg/ha)	2,053.88	2,546.57	4,404.12

[a] Significant at the 0.05 level.
[b] Significant at the 0.01 level.
[c] SSP as standard fertilizer.

statistics and the regression coefficients. The regression equation for grain yield shows that the quantity of phosphorus was highly significant (P = 0.01) in explaining yield. Delay in seeding, soil organic matter, and silt content of the soil, as well as lack of adequate rainfall were also highly significant explanatory variables. It is interesting to note that the *Striga* variable has a positive sign and is significant (P = 0.05). This result, which appears strange at first sight, is in line with results obtained also for sorghum in Burkina Faso (P. Matlon – Personal Communication). It would appear that at very low levels of *Striga* infestation and low soil fertility, there might be a positive correlation between *Striga* population and grain yield. Unlike results obtained in preceding years the shibras population did not significantly affect yields, but bird damage did.

In a similar regression (not shown) with straw yield as the dependent variable, only rainfall and the soil variables (preplant Bray P1 phosphorus, organic matter, and sand fraction) were significant (P = 0.05).

In order to determine whether the source of phosphorus affected grain yield, the equation was rerun with a binary variable for SSP (n = 146). The resulting equation (not shown) had the same set of significant variables at P = 0.05 except for units of phosphorus whose significance level dropped to 0.22, although the regression coefficient remained almost unchanged (4.35 versus 4.63). The fertilizer source dummy was significant (P = 0.01), thus indicating that SSP gave significantly higher yields than PAPR.

It can be concluded from the analysis that the quantity of phosphorus

Table 16 Mean yields for local varieties of millet at four levels of phosphorus; Farmer's test results, Western Niger, 1984

P Level	Fabidji				Gobery			
	PAPR		SSP		PAPR		SSP	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
(kg P_2O_5/ha)	(kg/ha)							
12	140	118	210	122	190	118	190	84
24	220*	72	260*	123	200*	109	320*	148
36	210	122	230*	99	240*	139	290*	104
SE	44		25		26		68	

Note: Probability levels of significance of difference of mean yields between each level/source of fertilizer and the zero treatment using two-tailed t-tests are * = 0.05, ** = 0.01, *** = 0.001. The mean yield (kg/ha) of the plots with zero P were 140 ± 65 and 130 ± 109 in Fabidji and Gobery, respectively.

applied as well as the source did significantly affect millet grain yield on farmers' fields in a rainfall-deficit year, when the rainfall was sufficient to obtain some output. Among nontreatment variables, the amount of rainfall, the delay in planting after the first major rain, soil conditions, and the amount of bird damage were important in explaining yield variation. The results suggest that if PAPR is to be used, full incorporation into the soil is a required technology, especially in rainfall-deficit years.

Partial budget analysis was used to examine the economics of fertilizer use under the conditions prevailing in 1984. Since regression analysis had indicated the importance of date of planting, rainfall, and quantity of fertilizer in explaining yields, the farmers were divided into 15 groups based on these criteria (with village location replacing rainfall). The characteristics of the groups are shown in Table 18.

Table 17. Effect of treatment and nontreatment variables on millet yield in Fabidji and Gobery: farmer's tests, 1984

Variables	Units	Mean	S.D.[a]	Coefficient[b]
Grain yield	kg/ha	200.6	121.8	
Delay in seeding after first rain	days	4.6	5.9	7.2•
Units of P	kg P_2O_5/ha	18.0	13.5	4.6
Units of P, squared	kg P_2O_5/ha	511.3	507.8	0.0
Shibras population		9.0	7.3	−59.2
Plants infested by mildew	%	1.7	2.2	51.1
Pockets with at least 1 Striga plant	%	0.4	1.5	1,393.2*
Internodes pierced by stemborers	%	23.4	13.7	6.0
Heads with Raghuva damage	%	7.7	5.4	128.3
Heads with bird damage	%	16.0	8.6	−240.5*
Preplant P, Bray P1	ppm	10.9	12.4	−0.4
Soil pH	%	5.0	0.4	23.7
Soil organic matter	%	0.4	0.1	214.1**
Soil clay content	%	1.5	0.6	38.4
Soil silt content	%	2.8	1.3	−30.8*
Soil fine sand content	%	95.1	1.2	3.3
W.H.C.	%	6.4	1.6	6.8
Available soil water	%	2.1	0.8	−1.1
Rainfall	mm	05.0	19.2	2.4•
Constant				−1,043.2
R^2				0.4
F				7.3•
SEE				96.8
N				196

[a] Standard deviation.

[b] Probability of t: * = 0.05, ** = 0.01, • = 0.001.

On the average, financial returns were positive for all groups and were highest at 24 units phosphorus when the crop was planted on time (within 4 days after the first major rainfall) (Alternative A). Late planting resulted in substantial decreases in net revenue, particularly in Fabidji, where total rainfall was lower than in Gobery. At unsubsidized world market prices (Alternative B), net returns were substantially reduced but remained positive for all groups in the higher rainfall village (Gobery), while they were negative for late planted crops in Fabidji and with 36 kg phosphorus, even when planted on time.

Table 15. Effect of phosphorus level, timeliness of planting and alternative price assumptions on grain yield, and profitability of fertilizer use on traditional varieties in Western Niger, 1984

P[a]	kg/ha	kl/P[b]	Profit ratio[c]					
			A	B	C	D	E	F
0*	154.9	-	–	–	–	–	–	–
12*	215.6	5.1	3.3	1.4	1.0	2.3	1.2	2.0
24*	265.0	4.6	3.1	1.3	0.9	2.1	1.1	1.9
36*	230.7	2.1	1.6	0.7	0.4	1.0	0.6	0.9
0	102.0	–	–	–	–	–	–	–
12	118.7	1.4	1.2	0.5	0.3	0.6	0.4	0.7
24	142.2	1.4	1.1	0.5	0.3	0.8	0.4	0.7
0*	151.1	–	–	–	–	–	–	–
12*	207.9	4.7	3.3	1.4	0.9	2.2	1.2	2.0
24*	264.6	4.7	3.5	1.5	0.9	2.2	1.2	2.1
36*	288.2	3.8	2.8	1.2	0.8	1.8	1.0	1.7
0	65.4	–	–	–	–	–	–	–
12	118.1	4.4	3.1	1.3	0.9	2.0	1.1	1.1
24	172.2	4.4	3.3	1.4	0.9	2.0	1.2	2.0
36	188.4	3.4	2.5	1.1	0.7	1.6	0.9	1.5

[a] kg/ha P_2O_5. * = crops planted on time, i.e., within 4 days of first major rainfall.

[b] Kg millet grain/kg phosphorus.

[c] Francs CFA per franc CFA spent on phosphorus fertilizer under the following alternatives:

A: Domestic market price for grain (130 F/kg), and straw (8 F/kg) and subsidized fertilizer prices (109 F/kg for P_2O_5).

B: Domestic market prices for grain and straw, and world market prices for fertilizers (253 F/kg for N and 464 F/kg for P_2O_5).

C: Government minimum grain price (91 F/kg), no straw value, world fertilizer price.

D: Government minimum grain price, no straw value, world fertilizer price.

E: Domestic market prices for grain and straw, 20% increase in world fertilizer prices.

F: 40% increase in domestic market prices for grain and straw, world market fertilizer prices.

In order to examine the riskiness of fertilizer use under the low-rainfall conditions, a number of other alternatives were examined. If farmers were forced to accept government minimum prices for their grain while paying the unsubsidized fertilizer prices (Alternative C), net return would be negative for all farm groups. If there was a 20% increase in world fertilizer prices (Alternative E), even the 36 kg/ha dose would yield negative returns in all locations. It is concluded that phosphorus fertilization of farmers' traditional varieties up to the level of 24 kg P_2O_5/ha is likely to be financially and economically profitable, provided there is sufficient rainfall to harvest a crop and provided farmers plant their millet crop on time.

Summary

For 3 years (1982-84) several trials were conducted in sub-Saharan Africa to (1) monitor the extent of phosphorus deficiency by studying the response of the principal cereals to P fertilizers in different agroclimatic zones, (2) evaluate the agronomic effectiveness of various P fertilizer sources including phosphate rocks indigenous to the sub-Saharan region, and (3) study the effect of management practices on fertilizer use and efficiency. Several national and international research organizations participated in this effort.

There is widespread deficiency of phosphorus in the soils of sub-Saharan Africa. Across all agroecological zones, cereals responded highly significantly to P fertilizers. Because of the coarse nature of the parent materials and because the resulting colloidal systems in the Oxisols, Ultisols, and Alfisols have low adsorption capacity for phosphate, large quantities of P fertilizers are not needed for maximum crop production in these environments. Phosphorus deficiency was least in the humid forest region and greatest in the semiarid region. However, maximum response to P fertilizers was obtained in the subhumid savanna region.

The results of several trials demonstrated the need for use of sulfurcontaining P fertilizers. There are indications that sulfur deficiency may be more prevalent in the savanna zones.

With the exception of Tilemsi phosphate rock from Mali, the West African rocks tested have little or no potential for direct application. However, partial acidulation of the rocks dramatically improved their agronomic effectiveness. PR and PAPR performed best under the acid, wet conditions of the Ultisols.

All phosphate fertilizers produced significant residual effects even at low rates of application. The low P 'fixation' capacities of these soils account for this phenomenon. In the humid and subhumid zones, basal application of phosphate rock may serve as a means to rapidly build up the P fertility of the

soils and thereby take advantage of the high residual effectiveness of P fertilizers in these soils.

Farm-level tests in Niger, during which all cultural operations were carried out by farmers, showed significantly high increases in millet yield when fertilizers were applied. Fertilizer use was profitable even in a year when less than adequate rainfall was received. In these farm-level trials, SSP proved superior to PAPR from Parc W phosphate rock when both were applied on the soil surface without subsequent incorporation into the soil. Method of P fertilizer application signficantly influences its efficiency. The results of an on-going trial at Sadore show that in a dry year, nonsoluble or partially soluble P fertilizers are ineffective unless incorporated into the soil.

Notes

1. These tests were designed and conducted jointly by IFDC soil scientists and ICRISAT economists working at the ICRISAT Sahelian Center, Niamey, Niger. The collaborative efforts of Dr. J. McIntire and Dr. D. Spencer are greatly appreciated.

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Economic evaluation of alternative fertilizer technologies for tropical African agriculture

Carlos A. Baanante

Introduction

The production of crops in tropical Africa, which is carried out by farmers under diverse soil-agroclimatic and market environments, involves the use of various inputs or factors of production. The management and levels of use of these inputs depend upon the soil-agroclimatic and market (prices) environments and the crop production technology. Farmers' decisions on the use of these inputs reflect their economic motivation in the face of physical and economic constraints and the limitations in crop production technology and knowledge.

The input-output relationships which characterize crop production underline the existence of a production function. To formalize these relationships a general model of the production function can be expressed as follows:

$$Y = F(X,Z) \tag{1}$$

where: Y = crop output per hectare.
X = vector of variable inputs.
Z = vector of soil-agroclimatic factors.

Here, agricultural production (crop output) is a function of the qualities and quantities of variable inputs (X) and the 'levels' of the soil-agroclimatic factors (Z). The inherent soil properties and agroclimatic conditions are beyond the control of the farmer. The qualitative and quantitative use of variable inputs (X) such as fertilizers depends upon the soil-agroclimatic conditions (Z), the prices of variable inputs (X), the price of crop output, the production technology, and the nature (shape) of the production function.

The economic evaluation of fertilizer technologies should be conducted in this context whether data and results from field experiments or farm survey

data are used for this purpose. In the following sections the general approach, methodology, and results of the economic evaluation of fertilizer technologies for selected regions and crops in sub-Saharan Africa, using data and results from field experiments, are presented and discussed.

Methodology

The economic evaluation of fertilizer technologies involves the estimation (and comparison) of the potential direct net economic benefits that these technologies can provide to the farmers and countries. The direct net economic benefits of fertilizer use are measured by the increment in value of agricultural output associated with the use of fertilizer less the cost of the fertilizer. Thus, they are determined by (1) the response of agricultural output to fertilizer use obtained at given levels of use of all other factors, (2) the cost (prices) of fertilizers, and (3) the prices of agricultural output.

The response of agricultural output to fertilizer use can be represented by a quantitative continuous relationship between agricultural output and fertilizer use, i.e., a continuous fertilizer response function. For this purpose, both agricultural output and fertilizer use must be measured in perfectly divisible and homogenous units. Moreover, if the objective is to measure the direct benefits of fertilizer use, the fertilizer response function must reflect quantitatively the influence of fertilizer use on agricultural output holding all other factors constant. The shape of the fertilizer response function is expected to change with (1) the range in the levels of fertilizer use; (2) the levels at which all other factors of production are held constant (including the crop and its biological characteristics, all agroclimatic and soil factors, and the quantitative, qualitative, and management levels associated with the use of all other variable inputs); and (3) the quality and management of fertilizer (use) which are an integral part of the 'fertilizer technology'.

Fertilizer response functions can be estimated by using information obtained from properly designed experiments in which quantitative, qualitative, and management levels of fertilizer use are predetermined by properly specified treatments and attempts are made to keep all other factors of production *constant* across all experimental plots. In general, the levels at which some of these other factors of production are held constant are established with the objective of obtaining maximum yields rather than obtaining maximum profits. Therefore, fertilizer response functions estimated from experimental data, in general, do not necessarily reflect the physical and economic constraints farmers face. Thus, average response ratios computed from these functions at given levels of fertilizer use are usually greater than those that farmers obtain. These differences are explained mostly by the magnitude of

the physical and economic constraints farmers face as compared with the conditions under which the experiment was conducted.

The direct economic benefits of fertilizer technologies obtained by using data and results of field experiments should be treated as estimates of the *potential* benefits of these technologies rather than as estimates of the actual benefits that the farmers will obtain. Estimation of potential net economic benefits permits a comparison of the profitability of different fertilizer technologies to determine their relative economic effectiveness.

Fertilizer response function estimates

In this study, data from field experiments conducted in locations and sites within different agroclimatic regions (humid, subhumid, and semiarid), were used to obtain estimates of response of crop output to (1) applications of nitrogen using different sources of nitrogen fertilizers (calcium ammonium nitrate [CAN], urea, and urea supergranules [USG]) under different management conditions such as time of application (basal and split) and methods of application (banded, broadcast and incorporated, point placed) and (2) applications of phosphorus (P_2O_5) using different sources of P such as finely ground phosphate rock and partially acidulated Togo and Parc W phosphate rock, single superphosphate (SSP), and triple superphosphate (TSP).

The following quadratic and semilog response function models were used to estimate the response of crop output to nitrogen and phosphorus (P_2O_5) using the different fertilizer technologies (nutrient sources, time and method of application):

Quadratic Model:

$$Y = \alpha + \sum_{i=1}^{n} \beta_i F_i + \sum_{i=1}^{n} \Theta_i F_i^2 + e \qquad (2)$$

Semilog Model:

$$Y = \Phi + \sum_{i=1}^{n} \gamma_i \ln F_i + e \qquad (3)$$

i = 1,2,3.....n fertilizer use technologies

where: Y = crop yields in kg/ha.

F_i = quantity of N or P_2O_5 applied using the fertilizer use technology i in kg/ha.

α, β, Φ, and γ are parameters of the response functions, and e is a random error with normal properties.

In order to obtain response function estimates that could be considered representative of each agroclimatic region, data from several experiments were pooled. For this purpose, tests of homogeneity of variances were conducted, and the estimating models were modified by including dummy 0-1 variables in the intercept of the response functions to account for the variability in crop yields among experimental sites that is related to factors other than fertilizer use.

Fertilizer response function estimates can be used to conduct the agronomic and economic evaluation of fertilizer technologies. The agronomic and economic performance of fertilizer technologies depends upon the magnitude and reliability of fertilizer response function estimates. Fertilizer response functions with reliable parameter estimates and low predicting errors are needed to properly conduct the agronomic and economic evaluation of fertilizer technologies. Parameter estimates of the response function can be used to evaluate fertilizer technologies in terms of their agronomic effectiveness or technical performance on crop yields. For this purpose, ratios of relative agronomic effectiveness (RAE) can be calculated and their variability explained in terms of soil and agroclimatic factors.

The economic evaluation of nitrogen and phosphorus fertilizer technologies was made by using estimates of either semilog or quadrate fertilizer response function models. Thus, the methodology for both of these cases is described in the following sections.

1. *Use of semilog model*

In this case, experimental data and ordinary least squares were used to estimate the semilog model (3) and to obtain, for given fertilizer technologies i = 1 and i = 2, the following fertilizer response function estimate:

$$\hat{Y} = \underset{(S_{\Phi})}{\hat{\Phi}} + \underset{(S\gamma_1)}{\hat{\gamma}_1} \ln F_1 + \underset{(S\gamma_2)}{\hat{\gamma}_2} \ln F_2 + \hat{e} \qquad (4)$$

where: $\hat{\Phi}$, $\hat{\gamma}_1$, and $\hat{\gamma}_2$ are parameter estimates and S_{Φ}, $S\gamma_1$, and $S\gamma_2$ are the standard errors of these estimates; $\hat{Y}$ is the predicted yield in kg/ha, and $\hat{e}$ the predicting error or residual.

This response function estimate was then used to conduct the economic evaluation of fertilizer technologies 1 and 2 as follows:

First, the profitability or net benefits of both fertilizer technologies can be estimated by imposing unrestricted profit-maximizing conditions to the response function estimate (4) at given prices of crop output and costs of using each fertilizer technology.

Let

P_y = price of crop output in US \$/kg and
Pf_i = cost of using fertilizer technology i in US \$/kg of plant nutrient.

Then, the profit-maximizing conditions

$$\frac{\delta Y}{\delta F_i} = \frac{Pf_i}{Py} \; ; \; \frac{\delta^2 Y}{\delta^2 F_i} < 0$$

permit an estimate of the profit-maximizing rate of plant nutrient ($\hat{F}_i^*$):

$$\hat{F}_i^* = \hat{\gamma}_i \left(\frac{Py}{Pf_i}\right) \quad , \quad \hat{\gamma}_i > 0.$$

The variance of $\hat{F}_i^*$ at given level of prices Py and Pf_i, is

$$Vr(\hat{F}_i^*) = \left(\frac{Py}{Pf_i}\right)^2 Vr(\hat{\gamma}_i)$$

and the standard error of $\hat{F}_i^*$, say $S_{F_i^*}$, is

$$S_{F_i^*} = \left(\frac{Py}{Pf_i}\right) S_{\gamma_i}.$$

The reliability (variance) of the estimated profit-maximizing rates of plant nutrients (F_i^*) depends on the reliability (variance) of parameter estimates $\hat{\gamma}_i$.

At the *given profit-maximizing rate* $\hat{F}_i^*$, the gross benefit of fertilizer technology i, (GB_i^*), is determined by the resulting increment in crop yield ($\Delta\hat{Y}_i^*$) and the price of crop output (Py):

$$GB_i^* = Py \cdot \Delta\hat{Y}_i^*$$

where: $\Delta\hat{Y}_i^* = \hat{\gamma}_i \cdot \ln\hat{F}_i^*$

and, the estimated net benefit (NB_i^*) is

$$NB_i^* = Py \cdot \Delta\hat{Y}_i^* - Pf_i \cdot \hat{F}_i^*$$

Hence, at the given $\hat{F}_i^*$, Py, and Pf_i, the variance of net benefits is

$$Vr(NB_i^*) = Py^2 \cdot Vr(\Delta\hat{Y}_i^*)$$

or,

$$Vr(NB_i^*) = (Py \cdot \ln\hat{F}_i^*)^2 \cdot Vr(\hat{\gamma}_i)$$

and the standard error of net benefits, $S_{NB_i^*}$, is given by

$$S_{NB_i^*} = (Py \cdot \ln\hat{F}_i^*) \cdot S_{\hat{\gamma}_i}.$$

This shows that the reliability (variance) of net benefit estimate NB_i^*depends on the reliability of parameter estimate $\hat{\gamma}_i$, and that, for any $\hat{\gamma}_i$, the variance of net benefits increases as the price of crop output (Py) and/or the rate of plant nutrient F_i^*increases.

The magnitude of the variance (standard error) of net benefits is of extreme importance in conducting the economic evaluation of fertilizer technologies. This evaluation can be properly conducted only if *reliable estimates* of net benefits for the different technologies are obtained. Unreliable estimates of net benefits can easily lead to incorrect conclusions about the profitability of fertilizer technologies.

A clear indication of the reliability of net benefit estimates (NB_i^*) and of the probability of a fertilizer technology i is indirectly provided by calculating the probability of losses ($NB_i \leq 0$) associated with the use of this technology. The profitability of losses can be calculated using the probability distribution of NB_i^*. However, it is important to note that this probability of losses is a conditional probability for the given soil-agroclimatic environments and crop production technology that characterize the experiment or set of experiments used to estimate the fertilizer response function. Therefore, this probability of losses does not necessarily include the probability of losses associated with stochastic climatic factors. Experimental data over a period of several years would be required to estimate the total probability of losses. Simulation modeling may provide an additional way of including the influence of stochastic climatic factors to calculate the total probability of losses and to provide better recommendations on fertilizer use.

The probability distribution of the t statistics with n-k-l degrees of freedom (n observations and k independent variables in estimating model) can be used to calculate the probability of losses. This is derived from the basic assumption that the error term of the fertilizer response function estimating

equation is normally distributed with mean zero and variance σ^2.

If $$t^* = \frac{0 - NB_i^*}{S_{NB_i^*}}$$

then, probability of losses[1] = $P(NB_i < 0) \leqq P(t < t^*)$.

Since fertilizer is a *variable* factor of production, its profitability is determined by the magnitude and reliability of NB_i^*estimates. Value or benefit: cost ratios of fertilizer use were calculated only to provide an estimate of returns to expenditures in fertilizer. It is well known that, in general, farmers use variable inputs to maximize returns to limited fixed factors of production (NB_i^*) rather than returns to expenditures in variable inputs such as fertilizer (benefit: cost ratios).

$$\text{Benefit: cost ratio} = B/C = \frac{GB_i^*}{Pf_i \cdot F_i^*}$$

Second, the profitability or net benefits of fertilizer technologies were estimated by imposing restrictions on profit-maximizing conditions in order to obtain reliable estimates of net benefits.

The reliability of net benefit estimates $NB_i^*$and the probability of losses are inversely related to the variance of NB_i^*(or the standard error $S_{NB_i^*}$). For a given fertilizer response function estimate and level of prices of crop output and fertilizers, the magnitude of $S_{NB_i^*}$decreases as the rate of plant nutrient applied F_i^*decreases. Hence, the reliability of NB_i^*estimates is increased and the probability of losses decreased by adjusting downward the profit-maximizing rate of plant nutrient F_i^*. Therefore, reliable estimates of net benefits were obtained by adjusting downward the rates of plant nutrient whenever the probability of losses calculated at profit-maximizing rates was greater than 5%. The following two criteria or methods were used to adjust F_i^*downward:

(a) By using the t statistics' probability distribution to find a value of F_i^*, say Fa_i^*, such that:

$$P(F_i^* \leqq Fa_i^*) = w \quad ; \quad Fa_i^* \leqq \hat{F}_i^*$$

where $0 < w < 0.5$ was set at the preestablished level $w = 0.25$. This is equivalent to find the Fa_i^* value that satisfies

$$P(t \leqq t^*) = 0.25, \text{ t with n-k-l degrees of freedom}$$

where: $t^* = \dfrac{F^*_{a_i} - \hat{F}^*_i}{S_{F_i^*}}$

The use of the t statistics distribution is based on the fact that, at given levels of prices Py and Pf_i, F^*_i is normally distributed with

$$\text{mean} = \gamma_i \left(\frac{Py}{Pf_i}\right) \text{ and variance} = \left(\frac{Py}{Pf_i}\right)^2 Vr\,(\gamma_i)\,.$$

In this report, this method is used to calculate the 'adjusted' rates of nitrogen application in the evaluation of nitrogen fertilizer technologies.

(b) An alternative and perhaps less arbitrary method is to adjust $\hat{F}^*_i$ downward to a level, say Fb_i, such that:

$$P(NBb_i < 0) \leq \lambda$$

where λ is an 'acceptable' level of probability of losses. A 5% probability of losses ($\lambda = 0.05$) was used as an 'acceptable' level.

Because different NB_i estimates and probability of losses are obtained for each value of F_i, the Fb_i values were obtained through a recursive process of approximation. In this process the profit-maximizing rate $\hat{F}^*_i$ is gradually reduced until the restriction on probability of losses ($\lambda = 0.05$) is satisfied.

This method was used for adjusting rates of application of P_2O_5 in the evaluation of phosphorus fertilizer technologies.

I. Relay Cropping and Intercropping

– The previously described methodology was modified to conduct the economic evaluation of the use of fertilizer technologies on maize/cowpeas relay cropping in selected sites of Nigeria and maize/beans intercropping in Kenya.

Semilog fertilizer response function estimates were obtained for these crops, and the methodology was modified in the following manner.

Profit-maximizing rates of plant nutrient were obtained by imposing profit-maximizing conditions on fertilizer response function estimates of both crops. Then, if the crops included in the association (relay cropping or intercropping) are designated as crops 1 and 2, the profit-maximizing rate $\hat{F}^*_i$ is given by

$$\hat{F}^*_i = \hat{\gamma}_{i,1}\left(\frac{Py_1}{Pf_1}\right) + \hat{\gamma}_{i,2}\left(\frac{Py_2}{Pf_i}\right)$$

where: $\hat{\gamma}_{i,1}$ and $\hat{\gamma}_{i,2}$ are parameter estimates of fertilizer response functions for crops 1 and 2, respectively.
Py_1 and Py_2 are the corresponding prices of crop output.
Pf_i is the price or unit-cost of using fertilizer technology i.

Then, the variance of $\hat{F}_i^*$ becomes:

$$Vr(\hat{F}_i^*) = (\frac{Py_1}{Pf_i})^2 \, Vr(\hat{\gamma}_{i,1}) + (\frac{Py_2}{Pf_i})^2 \, Vr\,(\hat{\gamma}_{i,2}).$$

The standard error:

$$S_{F_i^*} = (\frac{Py_1}{Pf_i}) \, S_{\gamma_{i,1}} + (\frac{Py_2}{Pf_i})^2 \, S\gamma_{i,2}.$$

Predicted increment in yields of crops 1 and 2:

$$\Delta\hat{Y}_{i,1}^* = \gamma_{i,1} \cdot \ln F_i^* \,, \quad \text{and,} \quad \Delta\hat{Y}_{i,2}^* = \gamma_{i,2} \cdot \ln F_i^*.$$

Gross benefits:

$$GB_i^* = Py_1 \cdot \Delta\hat{Y}_{i,1}^* + Py_2 \cdot \Delta\hat{Y}_{i,2}^*.$$

Net benefits:

$$NB_i^* = GB_i^* - Pf_i \cdot F_i^*.$$

And, the standard error of net benefits:

$$S_{NB_i^*} = (Py_1 \cdot \ln F_i^*) \, S_{\gamma_{i,1}} + (Py_2 \cdot \ln F_i^*) \cdot S_{\gamma_{i,2}}.$$

Other aspects of the methodology are the same as those described before for the case of a single crop[2].

B. Use of the Quadratic Model

For the case of two fertilizer technologies, i = 1 and i = 2, the following fertilizer response function estimate can be obtained using the quadratic model (2):

$$Y = \underset{(S_\alpha)}{\alpha} + \underset{(S_{b_1})}{\hat{\beta}F_1} + \underset{(S_{\theta_1})}{\hat{\theta}_1 F_1^2} + \underset{(S_{b_2})}{\beta_2 F_2} + \underset{(S_{\theta_2})}{\hat{\theta}_2 F_2^2} + \hat{e}$$

Unrestricted profit maximization results in

Profit-maximizing rate of plant nutrient ($\hat{F}_i^*$):

$$\hat{F}_i^* = \frac{(Pf_i/Py) - \hat{\beta}_i}{2\hat{\theta}_i} \; ; \; \hat{\beta}_i > 0, \hat{\theta}_i < 0$$

Variance of $\hat{F}_i^*$ at given levels of prices Py and Pf_i:

$$Vr(\hat{F}_i^*) = (\frac{1}{2\hat{\theta}_i})^2 \, [(\frac{(Pf_i/Py)^2 + \hat{\beta}_i^2}{\hat{\theta}_i^2}) \cdot Vr(\hat{\theta}_i) + Vr(\hat{\beta}_i)]$$

Standard error of $\hat{F}_i^*$:

$$S_{F_i^*} = (\frac{1}{2\hat{\theta}_i}) \cdot [S_{b_i}^2 + (\frac{(Pf_i/Py)^2 + \hat{\beta}_i^2}{\hat{\theta}_i^2}) \cdot S_{\theta_i}^2]^{1/2}$$

Predicted increment in crop yields ($\Delta\hat{Y}_i^*$):

$$\Delta\hat{Y}_i^* = \beta_i \cdot \hat{F}_i^* + \hat{\theta}_i \cdot \hat{F}_i^{*2}$$

Gross benefits (GB_i^*) and net benefits (NB_i^*):

$$GB_i^* = Py \cdot \Delta\hat{Y}_i^* \; ; \quad NB_i^* = GB_i^* - Pf_i \cdot \hat{F}_i^*$$

Variance of net benefits:

$$Vr(NB_i^*) = (Py \cdot \hat{F}_i^*)^2 \, [Vr(\hat{\beta}_i) + \hat{F}_i^{*2} \cdot Vr(\hat{\theta}_i)]$$

And, the standard error of NB_i^*:

$$S_{NB_i^*} = Py \cdot \hat{F}_i^* [S_{b_i}^2 + \hat{F}_i^{*2} \cdot S_{\theta_i}^2]^{1/2}.$$

At given levels of prices and F_i^*, the reliability of net benefit estimates (NB_i^*) depends on the reliability of the response function parameter estimates $\hat{\beta}_i$ and $\hat{\theta}_i$.

Calculation of probability of losses and other aspects of the economic evaluation under restricted profit maximization were made in the same way as described previously for the case of the semilog model.

This methodology is designed to easily include cash constraints to expenditures in fertilizers and land tenure arrangements as restrictions in the profit maximization of fertilizer use. However, because of the lack of detailed information about these constraints in these countries, these restrictions were not included in the evaluation at this time.

In the following sections results of the economic evaluation of nitrogen and phosphorus fertilizer technologies are presented and discussed.

Economic evaluation of nitrogen fertilizer technologies

Average 1983 domestic prices of crops and fertilizers and fertilizer response function estimates relevant for the humid, subhumid, and semiarid regions in 1983 and 1984 were used in this evaluation according to the previously described methodology.

Nitrogen fertilizer technologies were evaluated on maize in the humid and subhumid regions and on millet in the semiarid region. Results were obtained at unrestricted profit-maximizing rates of fertilizer application as well as at 'adjusted' rates by region, year, and country.

The following average 1983 prices of fertilizers, maize, and millet were used to conduct this evaluation:

Country	Fertilizer prices			Crop prices	
	Urea	CAN	USG	Maize	Millet
			(US $/kg)		
Nigeria	0.10	0.10	0.12	0.13	–
Togo	0.11	0.11	0.13	0.13	–
Sierra Leone	0.12	–	0.14	0.13	–
Kenya	0.30	–	0.34	0.13	–
Niger	0.11	0.09	0.13	–	0.16

These prices should be considered as reference prices used to conduct this evaluation so that results could be aggregated by regions and the profitability of different fertilizer technologies could be properly compared within each region. Considerable seasonal variability in crop prices and even higher intercountry variability in crop and fertilizer prices may actually exist. The price of USG was calculated by using a markup of 12% over the price of urea.

Humid region (maize)

Economic evaluation of the following N fertilizer technologies was conducted across this region:

1. Split application of urea banded and incorporated.
2. Split application of CAN broadcast and incorporated.
3. Split application of USG placed on hill.

The results of this evaluation at profit-maximizing rates of application are shown in Table 1, and at 'adjusted' rates of application in Table 2.

These results indicate the following:

1. The split application of urea banded was consistently the most profitable technology. The highest net benefits and benefit: cost ratios were obtained with this technology followed by the split application of USG placed on hill and the split application of CAN broadcast and incorporated. This result is very consistent among years and countries and does not change when these technologies are evaluated at 'adjusted' rates of fertilizer application (Table 2).
2. At profit-maximizing rates of application (100-120 kg of N/ha), the probability of losses was quite significant (9%-16%) and reflected in part the high variability across sites. Therefore, the 'adjusted' rates of application were substantially lower (35-78 kg of N/ha). At these rates fertilizer costs decreased proportionately less than net benefits, the benefit: cost ratios increased significantly, and the probability of losses was not greater than 4%.

Subhumid region (maize)

In addition to the nitrogen fertilizer technologies evaluated in the humid region, the split application of urea broadcast and incorporated was also evaluated in this region by using results of experiments conducted in 1983. Results of this evaluation at profit-maximizing and at 'risk-adjusted' rates of application are presented in Tables 3 and 4, respectively. These results show the following:

1. Estimates of net benefits obtained at profit-maximizing rates of application using the fertilizer response functions estimated for year 1983 were quite unreliable. This is indicated by the relatively high levels of probability of losses obtained for all technologies (Table 3). Results for 1984 and those obtained at 'adjusted' rates of application (Table 4) are more reliable for determining the relative profitability of these fertilizer technologies.

Table 1 Economic benefits, costs and probability of losses of using nitrogen fertilizers at profit maximizing rates of application. Humid region, Africa (maize)

Country	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Year 1983								
Nigeria	Urea SP BD	126.3	1,202	156.3	27.8	128.5	5.6	15
	CAN SP BC INC	106.5	951	123.7	40.5	83.2	3.0	20
	USG SP on hill	117.0	1,064	138.4	29.3	109.1	4.7	16
Togo	Urea SP BD	125.6	1,201	156.1	28.9	127.2	5.4	15
	CAN SP BC INC	104.5	945	122.9	42.8	80.1	2.9	20
	USG SP on hill	115.4	1,061	137.9	32.2	105.7	4.3	16
Sierra Leone	Urea SP BD	123.8	1,198	155.7	32.2	123.5	4.8	15
	USG SP on hill	113.9	1,058	137.5	34.2	103.3	4.0	17
Year 1984								
Nigeria	Urea SP BD	100.1	1,175	152.8	22.0	130.8	6.9	1
	CAN SP BC INC	112.1	924	120.1	42.6	77.5	2.8	12
	USG SP on hill	106.4	1,030	133.9	26.6	107.3	5.0	4
Togo	Urea SP BD	99.7	1,174	152.7	22.9	129.8	6.7	1
	CAN SP BC INC	109.6	917	119.2	45.0	74.2	2.7	12
	USG SP on hill	104.8	1,027	133.5	29.3	104.2	4.5	4
Average	Urea SP BD	115.1	1,190	154.7	26.7	128.0	5.9	9
	CAN SP BC INC	108.2	934	121.5	42.7	78.8	2.9	16
	USG SP on hill	111.5	1,048	136.2	30.3	105.9	4.5	11

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Table 2 Economic benefits, costs and probability of losses of using nitrogen fertilizers at adjusted rates of application. Humid region, Africa (maize)

Country	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Year 1983								
Nigeria	Urea SP BD	59.9	817	106.2	13.2	93.0	8.1	3
	CAN SP BC INC	35.9	463	60.2	13.6	46.6	4.4	4
	USG SP on hill	52.5	685	89.1	13.1	76.0	6.8	3
Togo	Urea SP BD	59.3	810	105.4	13.7	91.7	7.7	3
	CAN SP BC INC	33.7	439	57.1	13.8	43.3	4.1	4
	USG SP on hill	50.5	666	86.5	14.1	72.4	6.1	3
Sierra Leone	Urea SP BD	57.3	791	102.8	14.9	87.9	6.9	3
	USG SP on hill	49.2	652	84.8	14.8	70.0	5.7	3
Year 1984								
Nigeria	Urea SP BD	78.2	1,090	141.7	17.2	124.5	8.2	0
	CAN SP BC INC	54.2	595	77.5	20.6	56.9	3.8	2
	USG SP on hill	74.0	891	115.9	18.5	97.4	6.3	1
Togo	Urea SP BD	77.8	1,087	141.4	17.9	123.5	7.9	0
	CAN SP BC INC	51.6	574	74.6	21.2	53.4	3.5	2
	USG SP on hill	72.4	880	114.5	20.3	94.2	5.6	1
Average	Urea SP BD	66.5	919	119.5	15.4	104.1	7.8	2
	CAN SP BC INC	43.9	518	67.4	17.3	50.1	4.0	3
	USG SP on hill	59.7	755	98.2	16.2	82.0	6.1	2

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Table 3 Economic benefits, costs and probability of losses of using nitrogen fertilizers at profit maximizing rates of application. Subhumid region, Africa (maize)

Country	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Year 1983								
Nigeria	Urea SP BC INC	137.2	1.003	130.5	30.2	100.3	4.3	36
	CAN SP BD	105.7	936	121.8	23.3	98.5	5.2	17
	CAN SP BC INC	87.4	763	99.3	34.1	65.2	2.9	25
	USG SP on hill	88.3	1.007	130.9	22.0	108.9	5.9	13
Kenya	Urea SP BC INC	96.8	869	112.9	62.9	50.0	1.8	39
	CAN SP BD	81.3	855	111.2	52.9	58.3	2.1	22
	USG SP on hill	71.1	942	122.5	51.9	70.6	2.4	17
Year 1984								
Nigeria	Urea SP BD	108.3	1.774	230.7	23.8	206.7	9.6	0
	CAN SP BC INC	113.1	1.776	229.7	43.0	186.7	5.3	1
	USG SP on hill	144.2	1.436	186.7	36.0	150.7	5.2	8
Togo	Urea SP BD	108.0	1.774	230.6	24.8	205.8	9.2	0
	CAN SP BC INC	112.1	1.763	229.3	46.0	183.3	5.0	1
	USG SP on hill	142.1	1.431	186.1	39.8	146.3	4.7	8
Average	Urea SP BC INC	117.0	936	121.7	46.5	75.2	2.6	38
	Urea SP BD	100.8	1.334	173.4	31.2	142.2	5.5	9
	CAN SP BC INC	104.2	1.434	186.4	41.0	145.4	4.5	9
	USG SP on hill	111.4	1.204	156.5	37.0	119.1	4.2	11

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Table 4 Economic benefits, costs and probability of losses of using nitrogen fertilizers at adjusted rates of application. Subhumid region, Africa (maize)

Country	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Year 1983								
Nigeria	Urea SP BC INC	0	0	0	0	0	0	0
	Urea SP BD	48.4	617	80.2	10.6	69.6	7.5	5
	CAN SP BC INC	17.0	227	29.6	6.7	22.9	4.5	8
	USG SP on hill	49.4	769	100.0	12.3	87.7	8.1	4
Kenya	Urea SP BC INC	0	0	0	0	0	0	0
	Urea SP BD	22.3	324	42.1	14.5	27.6	2.9	7
	USG SP on hill	31.3	549	71.4	22.9	48.5	3.1	5
Year 1984								
Nigeria	Urea SP BD	89.4	1,694	220.2	19.6	200.6	11.2	0
	CAN SP BC INC	89.4	1,634	212.5	34.0	178.5	6.2	0
	USG SP on hill	84.1	1,119	145.5	21.0	124.5	6.9	1
Togo	Urea SP BD	89.1	1,692	220.0	20.5	199.5	10.7	0
	CAN SP BC INC	88.4	1,625	211.3	36.2	175.1	5.8	0
	USG SP on hill	82.0	1,100	143.0	22.9	120.1	6.2	1
Average	Urea SP BC INC	0	0	0	0	0	0	0
	Urea SP BD	62.3	1,082	140.7	16.3	124.4	8.6	3
	CAN SP BC INC	64.9	1,162	151.0	25.6	125.4	5.9	2
	USG SP on hill	61.7	884	114.9	19.7	95.2	5.9	3

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

2. The most technologies were the split application of CAN broadcast and incorporated and of urea banded and incorporated. Average results as well as the results obtained for 1984 show no significant differences between these two technologies in rates of application (65-90 kg of N/ha), net benefits, or probability of losses. The split application of USG placed on hill was not as profitable. Estimating errors in net benefits associated with the split application of urea broadcast and incorporated were too large to make any significant inferences about the profitability of this technology.

Semiarid region (millet)

In this region, economic evaluation of the following nitrogen fertilizer use technologies was conducted:

1. Split application of urea banded (urea SP BD).
2. Split application of CAN banded (CAN SP BD).
3. Split application of USG placed on hill (USG SP on hill).

The results of this evaluation presented in Tables 5 and 6 indicate the following:

1. The ranking of technologies by their profitability (net benefits) is the same at profit-maximizing rates of application as at 'adjusted' rates. The split application of urea banded and the split application of CAN banded were the most profitable technologies. And, there were no significant differences in the profitability of these two technologies (Table 6). The split application of USG (point placement) was consistently less profitable than the other two technologies.
2. The use of nitrogen, in general, was significantly more profitable in 1983 than in 1984. However, the relative profitability of these technologies, calculated at 'adjusted' economic optimum rates, did not change. In 1983, the rates of application and the corresponding net benefits were more than twice as much as those obtained by using the response functions estimated for 1984 (Table 6).
3. Average results show that split and banded applications of urea or CAN in amounts of about 20-24 kg of N/ha would be profitable and relatively non-risky. These rates of application would increase millet yields by 230-260 kg/ha and provide net benefits of US $32-36/ha. The split application of these fertilizers on millet in the semiarid region has the additional advantage of reducing the amount of losses (cost of fertilizer) that might occur as a result of uncertain climatic factors (lack of rainfall) (Tables 7 and 8).

Table 5 Economic benefits, costs and probability of losses of using nitrogen fertilizers at profit maximizing rates of application. Semiarid region. African (millet)

Country	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Year 1983								
Niger	Urea SP BD	67.8	516	82.6	15.6	67.0	5.3	11
	CAN SP BD	45.1	460	73.7	13.0	60.7	5.6	3
	USG SP on hill	39.9	267	42.8	10.4	32.4	4.1	9
Year 1984								
Niger	Urea SP BD	26.2	162	25.9	6.0	19.9	4.3	6
	CAN SP BD	29.8	248	39.8	8.6	31.2	4.6	21
	USG SP on hill	23.7	148	23.7	6.2	17.5	3.8	6
Average	Urea SP BD	47.0	339	54.3	10.8	43.5	4.8	8
	CAN SP BD	37.5	354	56.6	10.8	45.8	5.2	12
	USG SP on hill	31.8	207	33.3	8.3	25.0	4.0	7

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Table 6 Economic benefits, costs and probability of losses of using nitrogen fertilizers at adjusted rates of application. Semiarid region, Africa (millet)

Country	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Year 1983								
Niger	Urea SP BD	32.5	352	56.3	7.5	48.8	7.5	1
	CAN SP BD	32.0	405	64.8	9.3	55.5	7.0	0
	USG SP on hill	23.7	208	33.3	6.2	27.1	5.4	1
Year 1984								
Niger	Urea SP BD	14.4	119	19.1	3.3	15.8	5.8	4
	CAN SP BD	10.2	128	20.6	2.9	17.7	7.0	5
	USG SP on hill	13.3	109	17.5	3.4	14.1	5.1	4
Average	Urea SP BD	23.4	235	37.5	5.4	32.1	6.9	2
	CAN SP BD	21.2	266	42.6	6.1	36.5	6.9	2
	USG SP on hill	18.5	158	25.3	4.8	20.5	5.3	2

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Table 7 Average economic benefits, costs and probability of losses of using nitrogen fertilizers at profit maximizing rates of application by regions, Africa

Regions	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Humid (maize)	Urea SP BD	115.1	1,190	154.7	26.7	128.0	5.9	9
	CAN SP BC INC	108.2	934	121.5	42.7	78.8	2.9	16
	USG SP on hill	111.5	1,048	136.2	30.3	105.9	4.5	11
Subhumid (maize)	Urea SP BC INC	117.0	936	121.7	46.5	75.2	2.6	38
	Urea SP BD	100.8	1,334	173.4	31.2	142.2	5.5	9
	CAN SP BC INC	104.2	1,434	186.4	41.0	145.4	4.5	9
	USG SP on hill	111.4	1,204	156.5	37.4	119.1	4.2	11
Semiarid (millet)	Urea SP BD	47.0	339	54.3	10.8	43.5	4.8	8
	CAN SP BD	37.5	354	56.6	10.8	45.8	5.2	12
	USG SP on hill	31.8	207	33.3	8.3	25.0	4.0	7

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Table 8 Average economic benefits, costs and probability of losses of using nitrogen fertilizers at adjusted rates of application by regions, Africa

Regions	Fertilizer	N rate	Yields increment	Gross benefit	Fertilizer cost	Net benefit	B:C ratio	Probability of losses
		(kg/ha)		(US $/ha)				(%)
Humid (maize)	Urea SP BD	66.5	919	119.5	15.4	104.1	7.8	2
	CAN SP BC INC	43.9	518	67.4	17.3	50.1	4.0	3
	USG SP on hill	59.7	755	98.2	16.2	82.0	6.1	2
Subhumid (maize)	Urea SP BC INC	0	0	0	0	0	0	0
	Urea SP BD	62.3	1,082	140.7	16.3	124.4	8.6	3
	CAN SP BC INC	64.9	1,162	151.0	25.6	125.4	5.9	2
	USG SP on hill	61.7	884	114.9	19.7	95.2	5.9	3
Semiarid (millet)	Urea SP BD	23.4	235	37.5	5.4	32.1	6.9	2
	CAN SP BD	21.2	266	42.6	6.1	36.5	6.9	2
	USG SP on hill	18.5	158	25.3	4.8	20.5	5.3	2

Note: SP = split, BD = banded, INC = incorporated, BC = broadcast.

Economic evaluation of phosphorus fertilizer technologies

The objective was to evaluate the potential use of indigenous sources of phosphate rock to supply phosphorus for crop production in sub-Saharan Africa. For this purpose the economic evaluation of finely ground phosphate rock (GPR) and partially acidulated phosphate rock (PAPR) products, manufactured from Parc W and Togo phosphate rock ores, was conducted to determine and compare the potential profitability of these products with the profitability of SSP and TSP.

The PAPR products are not commercially available in African countries, and the use of ground phosphate rock in crop production is very limited. However, the increased use of domestic sources of phosphate rock to satisfy the agricultural demand for phosphorus may have an important impact on savings of foreign exchange, employment, and overall economic development of these countries.

The following phosphate fertilizer products were evaluated as alternative sources of phosphorus for crop production:

1. Parc W ground phosphate rock (GPR Parc W).
2. Togo ground phosphate rock (GPR Togo).
3. Parc W 25% partially acidulated phosphate rock (PAPR25 Parc W).
4. Togo 25% partially acidulated phosphate rock (PAPR25 Togo).
5. Parc W 50% partially acidulated phosphate rock (PAPR50 Parc W).
6. Togo 50% partially acidulated phosphate rock (PAPR50 Togo).
7. SSP.
8. TSP.

Average 1983/84 crop and P_2O_5 prices of different fertilizers used in this evaluation are shown in Table 9. Since partially acidulated phosphate rock products are not produced in these countries, the prices (costs) of the P_2O_5 supplied by these products were calculated as a fraction of the price of P_2O_5 supplied by SSP. The prices of P_2O_5 supplied by PAPR50, PAPR40, and PAPR30 were assumed to be equal to 80%, 75%, and 70%, respectively, of the price of P_2O_5 supplied by SSP. And the prices of P_2O_5 supplied by PAPR25, PAPR15, and GPR were assumed to be equal to 65%, 60%, and 30%, respectively, of the corresponding costs of P_2O_5 supplied by SSP[5].

In the following sections, results of the economic evaluation obtained by countries, crops, and locations within each country are presented and discussed.

Table 9 Prices of phosphorus fertilizers and of crop output by country, 1983/84

Countries	Prices of fertilizers								Prices of crops			
	TSP	SSP	PAPR 50	PAPR 40	PAPR 25	PAPR 30	PAPR 15	GPR	Maize	Millet	Cowpeas	Beans
	(US $/kg of P_2O_5)								(US $/kg)			
Nigeria	0.22	0.55	0.44	0.41	0.36	0.38	0.33	0.17	0.13	–	0.30	–
Niger	–	0.42	0.34	0.31	0.27	0.29	0.25	0.13	–	0.16	–	–
Togo	–	0.59	0.47	0.44	0.38	0.41	0.35	0.18	0.13	–	–	–
Kenya	0.90	0.90	0.72	0.67	0.58	–	–	0.27	0.12	–	–	0.38
Gambia	–	0.85	–	–	–	0.60	0.51	0.25	0.22	–	–	–
Sierra Leone	–	0.53	0.42	–	0.34	–	–	0.16	0.24	–	–	–
Price ratio[a]	=	1.00	0.80	0.75	0.65	0.70	0.60	0.30				

[a] Ratio of price of P_2O_5 from different P fertilizers with respect to price of P_2O_5 from SSP.

Nigeria

Maize

– Estimates of the potential economic net benefits and costs of using Togo PAPR50, SSP, diammonium phosphate (DAP), and 15-15-15 as alternative sources of phosphorus on maize are presented in Tables 10 and 11. These estimates were obtained at profit-maximizing rates of application of P_2O_5 restricted by a probability of losses (net benefits less than zero) not greater than 5%. Thus, the economic evaluation of these fertilizers was conducted on the basis of reliable estimates of net benefits. The results shown in Tables 10 and 11 indicate the following:

1. Togo PAPR50 and SSP were the most profitable sources of P in all locations except Mokwa and Ikenne. PAPR50 was the most profitable source of P at Ikole, Ikare, and Bida Junction, followed by SSP. At Zaria and Mokwa cattle ranch locations, however, SSP was more profitable than PAPR50. In most locations, differences between the profitability of PAPR50 and SSP were not substantial.
2. DAP and 15-15-15 were less profitable sources of P. The response of maize yields to DAP and 15-15-15 phosphorus was not significant in two (Ikole and Bida Junction) of the three locations where these fertilizers were tested. Positive and reliable estimates of net benefits of these fertilizers were obtained only at Ikare, but they were substantially lower than the net benefits of PAPR50 and SSP. As pointed out earlier, the benefits of P are not realized with sulfur-free P sources such as DAP and 15-15-15 in these environments.
3. Results for Mokwa ABU, and Ikenne, presented in Table 11, show that, because of low (and statistically not significant) response to P in these locations, net benefit estimates were low and, in almost all cases, highly unreliable (large probability of losses). If rates of P_2O_5 applied are restricted so that the probability of losses is not greater than 5%, then, in most cases, it would not have been profitable to apply P in these locations. The poor response to P applied at these sites may be explained in terms of soil (e.g., previous fertilizer application), agroclimatic, and crop management factors that affected the yields of maize in these sites.
4. Estimates obtained for the Mokwa cattle ranch site indicate that all phosphate fertilizer products were highly profitable in the first crop of maize but their residual benefits (second crop) were not statistically significant (large probability of losses). At this site, SSP was the most profitable source of P and there were no significant differences in the profitability of PAPR50, PAPR25, and GPR.
5. Increments in yields of about 1,000 kg of maize per hectare can be obtained by applying 60-90 kg of P_2O_5 per hectare. Higher rates of applica-

Location	Year	Fertilizer	P_2O_5 rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Ikole	1983	PAPR 50 Togo	60	4,273	555.50	26.4	529.10	0	21.0
		SSP	60	3,477	452.02	33.0	419.02	0	13.6
		DAP	0	0	0	0	0	0	0
		15-15-15	60	1,575	204.80	13.2	191.60	3.6	15.5
Ikole	1984	PAPR 50 Togo	60	903	117.42	26.4	91.03	0	4.4
		SSP	0	0	0	0	0	0	0
		DAP	11	513	66.70	2.4	64.29	0	27.6
		15-15-15	11	513	66.70	2.4	64.29	0	27.6
Ikole	1983/84	PAPR 50 Togo	60	2,290	297.73	26.4	271.33	0	11.3
		SSP	60	1,611	209.43	33.0	176.43	0.1	6.3
		DAP	0	0	0	0	0	0	0
		15-15-15	0	0	0	0	0	0	0
Ikare	1983/84	PAPR 50 Togo	60	1,283	166.89	26.4	140.49	0	6.3
		SSP	60	940	122.28	33.0	89.28	0.3	3.7
		DAP	60	506	65.88	13.2	52.68	5.0	5.0
		15-15-15	4	318	41.45	0.9	40.57	5.0	47.1
Zaria	1984	Togo GPR	90	812	105.57	15.3	90.27	0.6	6.9
		PAPR 25 Togo	90	1,431	186.14	32.4	153.74	0	5.7
		PAPR 50 Togo	90	2,314	300.90	39.6	261.30	0	7.6
		SSP	90	3,150	409.55	49.5	360.05	0	8.3
Bida Junction	1984	PAPR 50 Togo	60	1,371	178.29	26.4	151.89	0	6.8
		SSP	60	1,325	172.36	33.0	139.36	0	5.2
		DAP	0	0	0	0	0	0	0
		15-15-15	0	0	0	0	0	0	0

[a] Probability of losses less than or equal to 5%. Rates of application of P_2O_5 are also restricted by the maximum rate used in the experiment.

Table 11 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates on maize, Ikenne and Mokwa, Nigeria

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Ikenne	1982	PAPR 25 Togo	38 (0)	295	38.36	14.0	24.36	28.6	2.7
		PAPR 50 Togo	19 (0)	113	14.71	8.7	5.98	38.6	1.6
		SSP	35 (17)	474	61.63	19.8	41.85	14.4	3.1
		TSP	51 (35)	639	83.19	11.3	71.92	11.6	7.3
Ikenne	1983	Togo GPR, annual	90 (0)	259	33.80	15.3	18.50	31.7	2.2
		Togo GPR, residual	90 (55)	655	85.21	15.3	69.91	11.1	5.5
		PAPR 25 Togo	33 (0)	400	52.12	12.0	40.16	26.5	4.3
		PAPR 50 Togo	0 (0)	0	0	0	0	.	.
		SSP	45 (0)	595	77.37	25.0	52.41	28.4	3.1
		TSP	67 (0)	882	114.77	14.8	100.00	25.5	7.7
Ikenne	1982/84	Togo GPR	90 (36)	394	51.30	15.3	36.00	12.7	3.3
		PAPR 25 Togo	23 (0)	123	16.09	8.2	7.84	35.0	1.9
		PAPR 50 Togo	0 (0)	0	0	0	0	.	.
		SSP	36 (0)	365	47.54	19.5	28.00	19.7	2.4
		TSP	53 (0)	484	63.05	11.6	51.42	16.5	5.4
Mokwa ABU	1983	PAPR 50 Togo	74 (0)	467	60.72	32.5	28.22	26.0	1.8
		PAPR 25 Togo	32 (0)	312	40.64	11.6	29.08	8.4	3.5
		SSP	90 (90)	982	127.71	49.5	78.21	4.0	2.5
		TSP	90 (0)	643	83.62	19.8	63.82	7.6	4.2

Table 11 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates on maize. Ikenne and Mokwa, Nigeria

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Mokwa ABU	1984	PAPR 50 Togo	60 (0)	364	47.43	26.6	20.81	30.9	1.7
		SSP	90 (0)	790	102.70	49.5	53.20	12.3	2.0
Mokwa ABU	1983/84	Togo GPR	57 (0)	129	16.83	9.6	7.22	37.7	1.7
		PAPR 25 Togo	42 (0)	191	24.91	15.3	9.61	32.7	1.6
		PAPR 50 Togo	79 (0)	506	65.83	34.7	31.13	10.6	1.9
		SSP	86 (86)	705	91.70	47.4	44.32	4.1	1.9
Mokwa ABU Cattle Ranch (annual)	1984	Togo GPR	90 (90)	1.027	133.62	15.3	118.33	1.8	8.7
		PAPR 25 Togo	90 (90)	1.140	148.21	32.4	115.81	2.0	4.5
		PAPR 50 Togo	90 (90)	1.123	146.10	39.6	106.50	2.9	3.6
		SSP	90 (90)	1.522	197.89	49.5	148.39	0.4	4.0
(residual)		Togo GPR	78 (0)	194	25.29	0	25.29	43.0	
		PAPR 25 Togo	81 (0)	429	55.80	0	55.80	30.0	
		PAPR 50 Togo	90 (0)	762	99.11	0	99.11	12.7	
		SSP	83 (5)	677	88.04	0	88.04	20.4	

Figures in parantheses are profit-maximizing rates of application of P_2O_5 restricted by probability of losses less or equal to 5%. P_2O_5 rates of application are also restricted by the maximum rate used in the experiment.

tion of P_2O_5 should have been included in these experiments in order to determine economically 'optimum' rates of application.

Maize/Cowpea relay cropping

– Estimates of the profitability of using alternative sources of P on maize/cowpea relay cropping are shown in Table 12.

These results indicate the following:

1. The use of all P fertilizers, including Togo GPR and PAPR products, was profitable in all sites. This is shown by the magnitude and reliability (low probability of losses) of net benefit estimates.
2. At Owerri and Ilorin, Togo PAPR50 was more profitable than SSP. But at Ilorin, DAP and the NPK compound 15-15-15 were the most profitable sources of P. This is due to the higher yields of the cowpea intercrop in plots where shading by maize was minimal. These fertilizers, however, were not tested on this cropping system at the other sites.
3. Results obtained by use of response function estimates calculated from pooled data for the Mokwa (1983/84) and Zaria (1984) locations show SSP followed by Togo PAPR50 as the most profitable sources of P. Here, important residual benefits of Togo GPR were obtained. The total net benefits of GPR (annual and residual) were higher than the annual benefits of PAPR50 and almost as large as the annual benefits of SSP.
4. In all cases, the profit-maximizing rates of P_2O_5 were restricted by the maximum rate included in the experiments. This indicates that it would have been more profitable to apply P at rates higher than these maxima (60 and 90 kg of P_2O_5 per hectare). Higher rates should be included in future fertilizer experiments on this cropping system.
5. Although the increments in yields associated with the use of P are much greater for maize than for cowpeas, the differences in economic benefits are not as great because the price of cowpeas is about three times as large as the price of maize. Thus, the economic benefits of P fertilizers on cowpeas production are not as small as the increments in yields appear to indicate (see also point 2 above).

In Figure 1, the net benefits of Togo PAPR50 use on maize and maize/cowpea intercropping are compared with those obtained using SSP. It shows that in most locations Togo PAPR50 was more profitable than SSP for both maize and maize/cowpea relay cropping. This implies that it would be economical to use PAPR50 rather than SSP if PAPR50 can be produced at a cost such that the cost of P_2O_5 is about 20% lower than the cost of P_2O_5 supplied by SSP.

Table 12 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates[a] on maize/cowpea relay cropping, Nigeria

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment		Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
				Maize	Cowpea					
				(kg/ha)			(US $/ha)		(%)	
Ilorin	1984	PAPR 50 Togo	60	1,022	108	165.35	26.40	138.9	0	6.2
		SSP	60	784	94	130.17	33.00	97.2	0.3	3.9
		DAP	60	1,408	326	280.85	13.20	267.6	0	21.2
		15-15-15	60	649	367	194.60	13.20	181.4	0	14.7
Owerri	1984	Togo GPR	90	431	111	89.72	15.30	74.4	5.2	5.8
		PAPR 25 Togo	90	491	137	105.19	32.40	72.8	5.6	3.2
		PAPR 50 Togo	90	1,091	258	219.47	39.60	179.9	0	5.5
		SSP	90	777	296	190.11	49.50	140.6	0.1	3.8
Mokwa and Zaria	1982-84	Togo GPR, annual	90	354	61	64.52	15.30	49.2	3.4	4.2
		Togo GPR, residual	90	497	82	89.26	0	89.26	0.2	
		PAPR 25 Togo	90	590	26	84.68	32.40	52.3	2.7	2.6
		PAPR 50 Togo	90	1,005	29	139.73	39.60	100.1	0	3.5
		SSP	90	1,357	78	199.94	49.50	150.4	0	4.0
		TSP	90	527	89	95.35	19.80	75.5	0.4	4.8

[a] Rates of P_2O_5 are restricted by the maximum rate included in the experiments.

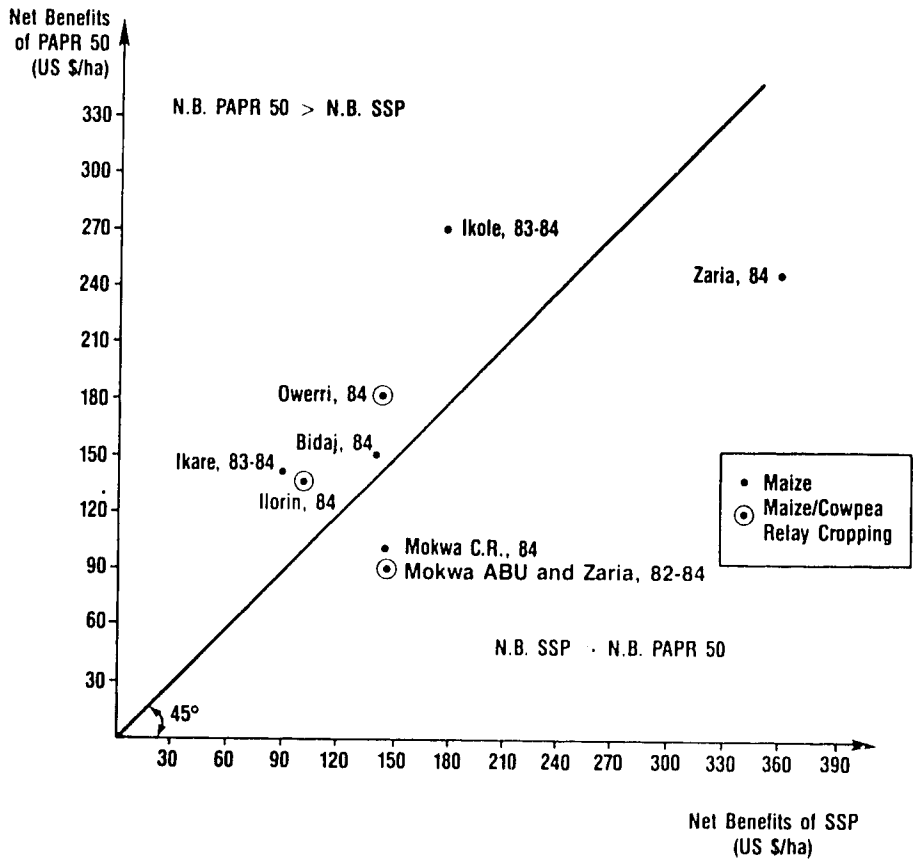

Figure 1. Comparison of net benefits of Togo PAPR 50 and SSP on maize and maize/cowpea relay cropping (Nigeria 1982-84).

Togo

Maize

– Estimates of the economic benefits of using phosphate fertilizers at profit-maximizing rates, restricted by the probability of losses (net benefits less than zero) equal to 5% and by the maximum rates included in the experiments are presented in Table 13. The results shown in this table for the Davie and Sarakawa site locations indicate the following:

1. In both locations, TSP and Togo PAPR25 were the most profitable sources of P followed by PAPR50 which was also profitable in both locations. SSP and Togo GPR were substantially less profitable sources of P. Because the response to P was low and statistically not significant, the use of these last two fertilizers at the Davie site was not profitable.
2. Profit-maximizing rates of P_2O_5 were restricted by the maximum rates

Table 13 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates restricted by the probability of losses. [a]maize, Togo

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Davie	1984	Togo GPR	0	0	0	0	0	0	0
		PAPR 25 Togo	80	698	90.77	30.4	60.37	1.0	3.0
		PAPR 50 Togo	80	624	81.25	37.6	43.65	4.3	2.2
		SSP	0	0	0	0	0	0	0
		TSP	80	606	78.87	19.2	59.67	1.0	4.1
Sarakawa	1983/84	Togo GPR	80	451	58.63	14.4	44.23	3.3	4.1
		PAPR 25 Togo	80	1.389	180.67	30.4	150.28	0	5.9
		PAPR 50 Togo	80	1.289	167.66	37.6	130.06	0	4.5
		SSP	80	955	124.18	47.2	76.98	0	2.6
		TSP	80	1.526	198.40	19.2	179.20	0	10.3

[a] Probability of losses less than or equal to 5%. Rates are also restricted by the maximum rates included in the experiments.

included in the experiments (80 kg of P_2O_5/ha). Higher rates should be included in future experiments to determine economic 'optimum' rates.

3. Increment in maize yields of about 600-700 and 1,300-1,500 kg/ha was obtained at the Davie and Sarakawa locations, respectively, as a result of applying 80 kg of P_2O_5/ha using TSP, PAPR25, or PAPR50.

Sierra Leone

Maize

– Results obtained for an experiment conducted at Njala are shown in Table 14. Here the magnitude and reliability (low probability of losses) of net benefit estimates clearly indicate the profitability of using any one of these fertilizers. It is profitable to use any of these fertilizers, including Togo GPR. However, SSP and PAPR50 were the most profitable sources of P, and the difference in net benefits between these two fertilizers was not significant. Togo PAPR25 and GPR were significantly less profitable sources of P.

Gambia

Maize

– Estimates of economic benefits obtained using results from an experiment conducted at Sapu are presented in Table 15. Large and reliable estimates of net benefits were obtained for all fertilizer products included in this experiment. Tilemsi PAPR30 and SSP were the most profitable sources of P, and the net benefit estimates of these two fertilizers were not significantly different. Tilemsi GPR and PAPR15 were significantly less profitable sources of P.

A summary of results for Togo, Sierra Leone, and Gambia, comparing the net benefits of SSP with the net benefits of PAPR products, is shown in Figure 2. These results show the economic advantage of using PAPR products rather than SSP, given the costs of SSP and the PAPR products used in obtaining these estimates.

Kenya

Maize/beans intercropping

– Estimates of the economic benefits of using alternative sources of P on maize/beans intercropping at Kabete, Kenya, are presented in Table 16. These estimates were obtained using results from two experiments conducted at this location during the first and second crop seasons of 1983. Here, as

Table 14 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates restricted by the probability of losses, [a]maize, Sierra Leone

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Njala	1984	Togo GPR	200	572	137.41	32	105.41	0.2	4.3
		PAPR 25 Togo	200	894	214.65	68	146.65	0	3.2
		PAPR 50 Togo	200	1.155	277.39	84	193.39	0	3.3
		SSP	200	1.294	310.73	106	204.73	0	2.9

[a] Probability of losses less than or equal to 5%. Rates are also restricted by the maximum rate included in the experiment.

Table 15 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates restricted by the probability of losses, [a]maize, Gambia

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Sapu	1984	Mali GPR (Tilemsi)	60	777	171.09	15.0	156.09	0	11.5
		PAPR 15 Mali (Tilemsi)	60	775	170.63	30.6	140.03	0	5.6
		PAPR 30 Mali (Tilemsi)	60	1.105	243.20	36.0	207.20	0	6.8
		SSP	60	1.145	251.92	51.0	200.92	0	4.9

[a] Probability of losses less than or equal to 5%. Rates are also restricted by the maximum rate included in the experiment.

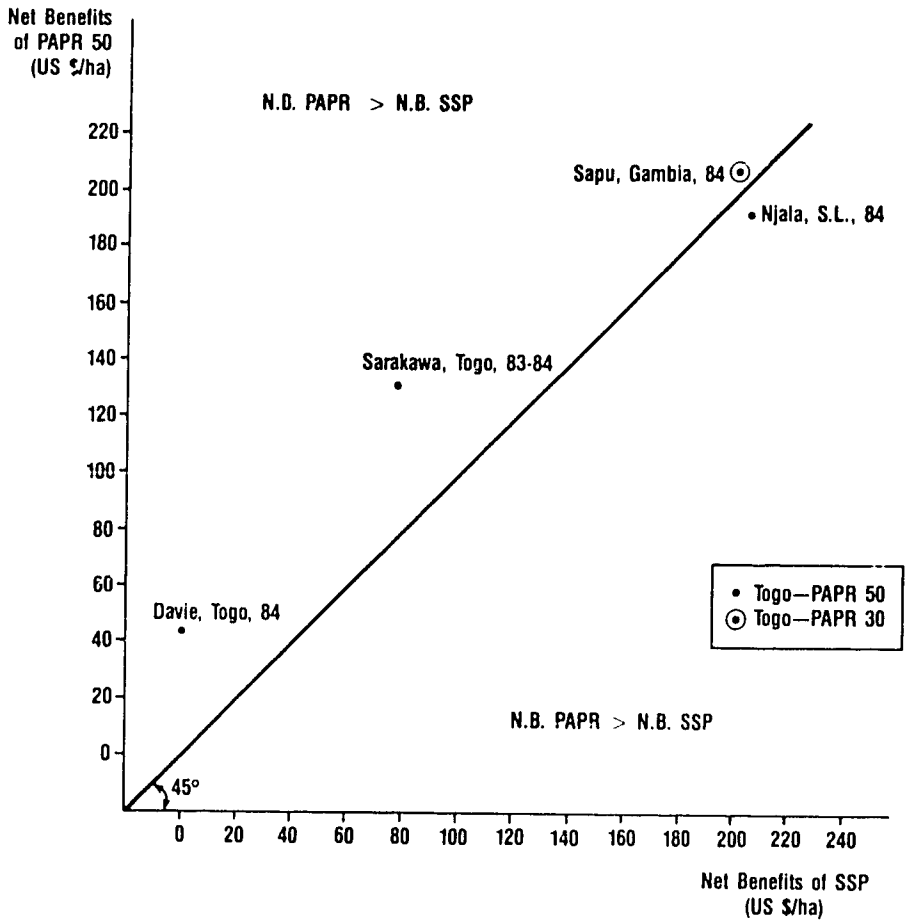

Figure 2. Comparison of net benefits of Togo PAPR 50 and PAPR 30 with SSP on maize (Togo, Sierra Leone, and Gambia).

would be expected, the use of phosphate fertilizers was more profitable in the first season than in the second one. Higher availability of P in the soil appears to have reduced the P response in the second season. Togo GPR, TSP, and Togo PAPR50 were, in that order, the most profitable sources of P in the first season. And net benefit estimates of Togo GPR and TSP were not significantly different during this first season.

The economic benefits associated with residual effects (season 2) were quite important for all P sources. Estimates of net benefits obtained over the two seasons show that TSP was the most profitable source of P and that differences in profitability among the PAPR products and GPR were not significant.

The results of this experiment clearly indicate the economic importance of

Table 16 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates[a] on maize/beans intercropping, Kabete, Kenya

Location	Year	Fertilizer Rate	P_2O_5	Yield increment		Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
				Maize	Beans					
			(kg/ha)			(US $/ha)			(%)	
Kabete (season 1)	1983	Togo GPR	356	1.028	309	245	96	149	1.2	2.5
		PAPR 25 Togo	167	779	314	214	96	118	1.9	2.2
		PAPR 50 Togo	152	588	448	237	109	128	1.1	2.2
		TSP	142	981	408	274	127	147	0.4	2.2
Kabete (season 2) (residual)	1983	Togo GPR		907	52	128	0	128	10.6	2.3
		PAPR 25 Togo		1.272	69	179	0	179	3.7	2.1
		PAPR 50 Togo		1.017	122	168	0	168	5.4	2.0
		TSP		1.394	143	222	0	222	1.5	2.0
Kabete (2 seasons)	1983	Togo GPR	356	1.935	361	373	96	277	–	3.9
		PAPR 25 Togo	167	2.051	383	393	96	297	–	4.1
		PAPR 50 Togo	152	1.605	570	405	109	296	–	3.7
		TSP	142	2.375	551	496	127	369	–	3.9

[a] Rates are also restricted by the maximum rate included in the experiment.

the residual effects of phosphate fertilizers. The application of these fertilizers in the first season provided significant economic benefits during the first and second seasons. An implication of this result is that, disregarding the source of P, it may be economically sound to apply this nutrient only once a year in this high-altitude humid part of tropical Africa.

Niger

Millet

– Results of the economic evaluation of phosphate fertilizer products on millet in different site locations (and years) in Niger are presented in Table 17. These results indicate the following:

1. TSP was the most profitable source of P in all locations. In the Mai Gamji site the net benefits of TSP were not significantly different from the net benefits of SSP.
2. Comparisons of net benefit estimates of SSP with those of the Parc W PAPR products (PAPR50 at Sadore and PAPR40 at the other locations) are shown graphically in Figure 3. These comparisons indicate that (a) in all locations SSP was more profitable than the PAPR products, but differences in net benefits were not significant at Sadore and (b) Parc W PAPR40 was not profitable at Tounga, Serkinyama, and Magaria because of lack of significant response of crop output to PAPR40.
3. Significant net benefits of residual effects of Parc W GPR were obtained at the Mai Gamji site. However, annual applications of GPR and PAPR25 were the least profitable sources of P at Mai Gamji and Sadore.
4. In almost all cases profit-maximizing rates of application of P were restricted by the maximum rates included in the experiments. Higher rates of application should be included in future experimentation on the use of phosphate fertilizer technologies on millet in Niger.

Summary and conclusions

An economic evaluation of alternative fertilizer technologies was made by estimating and comparing the direct economic benefits of these technologies. Estimates of these benefits were obtained by measuring the increment in value of crop output associated with the use of fertilizer at economic 'optimum' rates of application, less the cost of fertilizer. Thus, benefit estimates were determined by (a) response function estimates of crop output to fertilizer use (nitrogen or phosphorus), (b) the costs of fertilizers, and (c) the prices of crop output.

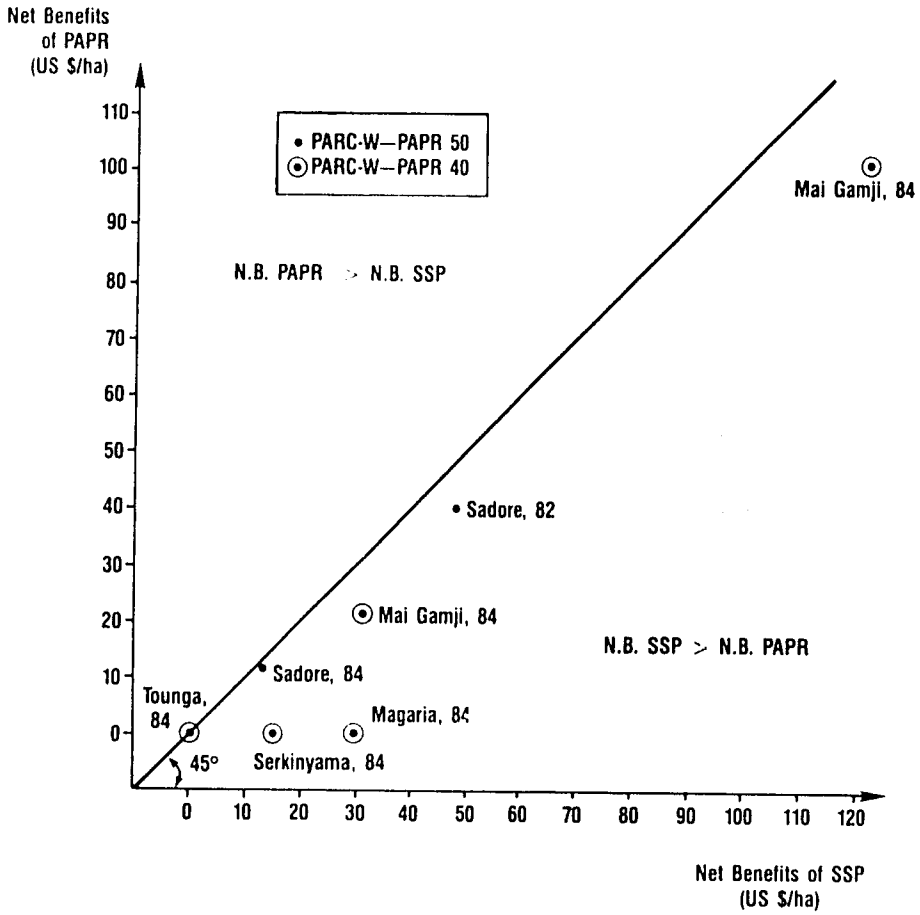

Figure 3. Comparison of the net benefits of PAPR 50 and PAPR 40 with those of SSP on millet (Niger, 1982-84).

Quadratic and semilog or simple translog response function models and experimental data were used to estimate the response of crop output to nitrogen and phosphorus (P_2O_5) applied using different fertilizer technologies (fertilizer products and time and method of application).

Nitrogen fertilizer technologies were evaluated on maize in the humid and subhumid regions and on millet in the semiarid region. Average response function estimates obtained by regions were used for this purpose.

Phosphorus fertilizers were evaluated on maize, maize/cowpeas relay cropping, maize/beans intercropping, and millet. Response function estimates obtained for each site location in different countries were used in the evaluation of these fertilizers.

Average 1983 domestic prices of crops and fertilizers in different countries were used to calculate the economic benefits and costs of the fertilizer tech-

Table 17 Economic benefits and costs of using phosphate fertilizers at profit-maximizing rates restricted by the probability of losses, [a]millet, Niger

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Sadore	1982	Parc W GPR	0	0	0	0	0	0	0
		PAPR 25 Parc W	40	238	38.19	10.8	27.39	0	3.5
		PAPR 50 Parc W	40	338	54.08	13.6	40.49	0	4.0
		SSP	40	405	64.85	16.8	48.05	0	3.9
		TSP	40	446	71.51	8.8	62.72	0	8.1
Sadore	1984	Parc W GPR	40	168	27.01	5.2	21.81	0	5.2
		PAPR 25 Parc W	40	120	19.29	10.8	8.49	0	1.8
		PAPR 50 Parc W	40	165	26.54	13.6	12.94	0	2.0
		SSP	40	178	28.50	16.8	11.70	0	1.7
		TSP	40	146	23.37	8.8	14.57	0	2.7
Sadore	1982-84	Parc W GPR	40	124	19.88	5.2	14.68	0	3.8
		PAPR 25 Parc W	40	180	28.86	10.8	18.06	0	2.7
		PAPR 50 Parc W	40	252	40.37	13.6	26.77	0	3.0
		SSP	40	291	46.68	16.8	29.88	0	2.8
		TSP	40	296	47.47	8.8	38.67	0	5.4
Mai Gamji	1983	Parc W GPR, annual	60	426	68.31	7.8	60.51	0	8.8
		Parc W GPR, residual	60	288	46.19	0	46.19	0	5.9
		PAPR 40 Parc W	60	752	120.46	18.6	101.86	0	6.5
		SSP	60	927	148.38	25.2	123.18	0	5.0
		TSP	60	991	158.60	13.2	145.40	0	12.0

Table 17 (Continued)

Location	Year	Fertilizer	P_2O_5 Rate	Yield increment	Gross benefit	Fertilizer cost	Net benefit	Probability of losses	Benefit: cost ratio
			(kg/ha)		(US $/ha)			(%)	
Mai Gamji	1984	Parc W GPR, annual	40	157	25.24	5.2	20.04	5.0	4.9
		PAPR 40 Parc W	40	210	33.71	12.4	21.31	0.1	2.7
		SSP	40	300	48.12	16.8	31.32	0	2.9
		TSP	40	204	32.78	8.8	23.98	0	3.7
Mai Gamji	1983/84	Parc W GPR, annual	60	250	40.15	7.8	32.35	0	5.1
		Parc W GPR, residual	60	182	29.18	0	29.18	0	3.7
		PAPR 40 Parc W	60	493	78.94	18.6	60.34	0	4.2
		SSP	60	630	100.90	25.2	75.70	0	4.0
		TSP	60	609	97.48	13.2	84.28	0	7.4
Tounga	1984	PAPR 40 Parc W	0	0	0	0	0	0	0
		SSP	0	0	0	0	0	0	0
		TSP	60	213	34.14	13.2	20.94	4.3	2.6
Serkinyama	1984	PAPR 40 Parc W	0	0	0	0	0	0	0
		SSP	51	228	36.62	21.4	15.18	2.2	1.7
		TSP	60	206	33.00	13.2	19.80	0.6	2.5
Magaria	1984	PAPR 40 Parc W	0	0	0	0	0	0	0
		SSP	60	344	55.19	25.2	29.99	0.9	2.2
		TSP	60	298	47.80	13.2	34.60	0.4	3.6

nologies. The prices of USG and PAPR products, which are neither produced nor commercially available in these countries, were calculated using general cost of production estimates. The price of USG was calculated using a markup of 12% over the price of urea. And the prices of PAPR products were calculated as a fraction of the price of SSP, depending on the level of acidulation. In terms of prices of P_2O_5, the PAPR50, PAPR40, PAPR30, PAPR25, and PAPR15 were considered to be 80%, 75%, 70%, 65%, and 60%, respectively, as expensive as SSP. The actual costs of PAPR products may vary depending on the type of phosphate rock and the costs of GPR and sulfuric acid.

In order to use only reliable estimates of net benefits to conduct the economic evaluation, two alternative methods were used to impose restrictions on profit maximization to adjust downward the rates of N and P_2O_5 and, thereby, reduce the standard errors of net benefits and the probability of losses (net benefits less than zero). To evaluate nitrogen fertilizers, the probability distribution of profit-maximizing rates at given prices was used for downward adjustment of the rates of nitrogen whenever the probability of losses was greater than 5%. An alternative method was used in the evaluation of P fertilizers. In this case, the restriction of probability of losses no greater than 5% was explicitly imposed to calculate P_2O_5 rates and net benefit estimates. P_2O_5 rates and net benefits were calculated through a recursive process of approximation which continues to adjust downward the profit-maximizing rates until this restriction is satisfied.

Reliable net benefit estimates, obtained under these restrictions and the restriction imposed by the maximum nutrient rates included in the experiments, were then used to show the relative profitability of fertilizer technologies.

Nitrogen

The following main results were obtained in the evaluation of nitrogen fertilizer technologies:

1. For maize in the humid region – the split application of urea banded, in rates that vary from 35 to 78 kg of N/ha, was consistently the most profitable N fertilizer technology followed by split application of USG (point placement) and the split application of CAN broadcast and incorporated. This result is very consistent among years and countries.
2. For maize in the subhumid region – average results for 1983 and 1984 show that the split application of urea banded and the split application of CAN broadcast and incorporated, in rates of 60-65 kg of N/ha, were the most profitable N fertilizer technologies. Results for 1983, however, indi-

cated that the split application of USG was the most profitable technology. Net benefit estimates obtained for all fertilizer technologies in 1984 were larger than in 1983.

3. For millet in the semiarid region – the most profitable N fertilizer technologies were the split application of CAN banded and the split application of urea banded at rates of 20-30 kg of N/ha. Net benefit estimates for 1983 were considerably higher than for 1984, but the results on relative profitability of the fertilizer technologies under evaluation were the same in each year.

Phosphorus

A summary of results on the relative economic effectiveness (REE) of different phosphorus fertilizer products with respect to SSP, calculated as ratios of net benefit estimates, is presented in Table 18 by country, crop, site-location, and year(s). Only reliable estimates of net benefits (probability of losses less than 5%) were used to calculate the results of REE shown in this table.

Given the cost estimates considered for the PAPR products, the following general conclusions may be drawn from these results:

1. The use of Togo *PAPR50* on maize was (a) more profitable than SSP in most locations of Nigeria and at both locations in Togo and (b) as profitable as SSP at the Njala site location in Sierra Leone. It was more profitable than SSP when used on maize/cowpeas relay cropping at Ilorin and Owerri in Nigeria but only 72% and 88% as profitable as TSP when used on maize/beans intercropping in Kabete, Kenya (SSP was not used in Kenya). Results for millet at Sadore (1982-84) show that Parc W PAPR50 was 90% as profitable as SSP.

   These results indicate that, if PAPR50 could be produced and supplied to farmers in these countries at a price about 20% lower than the price of SSP, it could be an economically effective and competitive source of phosphorus for these crops.
2. Parc W *PAPR40* was tested only on millet at Mai Gamji, Niger. Average results for 1983/84 at this location show that this fertilizer was only 80% as profitable as SSP.
3. Togo *PAPR25* was less profitable than SSP in most locations and crops. The use of this fertilizer on maize was 43%-78% as profitable as SSP in Nigeria and 72% as profitable as SSP in Njala, Sierra Leone, but substantially more profitable than SSP in Davie and Sarakawa, Togo. The use of Togo PAPR25 on maize/cowpeas relay cropping in Nigeria was 51% as profitable as SSP, and on maize/beans intercropping in Kenya it was 81%-86% as profitable as TSP. Results for millet at Sadore (1982-84) show that Parc W PAPR25 was only 60% as profitable as SSP.

Table 18 Relative economic effectiveness (REE) of P fertilizers with respect to SSP, by country, location, and year

Location	Year	Relative economic effectiveness with respect to SSP									Phosphate rock
		Crop	PAPR 50	PAPR 40	PAPR 25	PAPR 30	PAPR 15	GPR	TSP	DAP	15-15-15	
Nigeria												
Ikole	1983/84	Maize	1.54	–	–	–	–	–	–	0	0	Togo
Ikare	1983/84	Maize	1.57	–	–	–	–	–	–	0.58	0.49	Togo
Zaria	1984	Maize	0.72	–	0.43	–	–	0.25	–	–	–	Togo
Bida Junction	1984	Maize	1.09	–	–	–	–	–	–	0	0	Togo
Mokwa, Cattle Ranch	1984	Maize	0.71	–	0.78	–	–	0.80	–	–	–	Togo
Ilorin	1984	Maize/cowpea, relay cropping	1.43	–	–	–	–	–	–	2.75	1.86	Togo
Owerri	1984	Maize/cowpea, relay cropping	1.28	–	0.51	–	–	0.53	–	–	–	Togo
Togo												
Davie	1984	Maize	43/0	–	60/0	–	–	0/0	59/0	–	–	Togo
Sarakawa	1983/84	Maize	1.69	–	1.95	–	–	0.57	2.32	–	–	Togo
Sierra Leone												
Njala	1984	Maize	0.94	–	0.72	–	–	0.51	–	–	–	Togo
Gambia												
Sapu	1984	Maize	–	–	–	1.03	0.70	0.78	–	–	–	Mali

Table 18 (Continued)

Location	Year	Crop	Relative economic effectiveness with respect to SSP									Phosphate rock
	Year		PAPR 50	PAPR 40	PAPR 25	PAPR 30	PAPR 15	GPR	TSP	DAP	15-15-15	
Kenya[a]												
Kabete, first season	1983	Maize/beans intercropping	0.88	–	0.81	–	–	1.02	–	–	–	Togo
Kabete, second season	1983	Maize/beans intercropping	0.72	–	0.86	–	–	0.63	–	–	–	Togo
Niger												
Sadore	1982	Millet	0.84	–	0.57	–	–	0	1.30	–	–	Parc W
Sadore	1984	Millet	1.10	–	0.72	–	–	1.86	1.24	–	–	Parc W
Sadore	1982-84	Millet	0.90	–	0.60	–	–	0.49	1.29	–	–	Parc W
Mai Gamji	1983	Millet	–	0.83	–	–	–	0.49	1.18	–	–	Parc W
Mai Gamji	1984	Millet	–	0.68	–	–	–	0.64	0.77	–	–	Parc W
Mai Gamji	1983/84	Millet	–	0.80	–	–	–	0.43	1.11	–	–	Parc W
Serkinyama	1984	Millet	–	0	–	–	–	–	1.30	–	–	Parc W
Magaria	1984	Millet	–	0	–	–	–	–	1.15	–	–	Parc W

[a] REE with respect to TSP rather than SSP.

Note: REE_i = net benefit of P fertilizer i/net benefit of SSP.

These results indicate that, even if PAPR25 could be produced and supplied at a price 35% lower than SSP, it would not be an economically effective and competitive source of P for these crops in these countries. Moreover, since in almost all site locations PAPR50 was more profitable than PAPR25, the production and supply of PAPR25 cannot be considered as an economically feasible option unless PAPR25 can be produced and supplied at a price substantially lower than the one used in this evaluation.

4. *PAPR30 and PAPR15* products manufactured using Tilemsi phosphate rock from Mali were tested in just one experiment conducted at Sapu, Gambia, in 1984. Here, the use of PAPR30 was somewhat more profitable than SSP, and PAPR15 was 70% as profitable as SSP.
5. The direct application of *GPR* was evaluated in most locations and crops in these countries. With the exception of results obtained for maize/beans intercropping in Kabete, Kenya, 1983, and for millet in Sadore, Niger, 1984, the results presented in Table 18 clearly indicate that, even if GPR was supplied at prices 70% lower than SSP, the direct application of GPR was substantially less profitable than SSP. Also, in most locations it was less profitable to use GPR than the PAPR products.

   Results for maize/beans intercropping at Kabete, Kenya, appear to indicate that, for this cropping system and the soil and agroclimatic conditions in which this experiment was conducted, it may be economically sound to use GPR, TSP, or PAPR only once a year to produce good crops. Economic benefits associated with residual effects in the second season were quite important for the P sources.

In considering the results and conclusions presented above, it is important to keep in mind that only the direct benefits of fertilizer use have been included in the evaluation. However, the use of domestic resources of phosphate rock by these countries to produce and supply phosphate fertilizers such as PAPR or SSP will result in additional secondary benefits in the form of savings in foreign exchange, employment, and self-sufficiency in fertilizers.

Notes

[1] The probability of losses is in fact the level of significance at which the null hypothesis, Ho: $NB_t = 0$, would be rejected, given that the alternative hypothesis is Ha: $NB_t > 0$.

[2] For the case of simultaneous intercropping, methodological improvements can be made by estimating jointly the fertilizer response functions of both crops using Zellner's asymptotically efficient method of estimation.

[3] Studies on the costs of production of PAPR show that this may be a reasonable assumption. However, the actual costs of PAPR may vary depending on the type of rock and the relative costs of GPR and sulfuric acid.